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— The Moraines of the Missouri Coteau and their attendant deposits, by James Edward Todd.

— The Potomac Formation in Virginia, by W. M. Fontaine.

STATISTICAL PAPERS

Mineral Resources of the United States, 1882, by Albert Williams, jr. 1883. 8°. xvii, 813 pp. Price 50 cents.

Mineral Resources of the United States, 1883 and 1884, by Albert Williams, jr. 1885. 8°. xiv, 1016 pp. Price 60 cents.

Mineral Resources of the United States, 1885. Division of Mining Statistics and Technology. 1886. 8°. vii, 576 pp. Price 40 cents.

Mineral Resources of the United States, 1886, by David T. Day. 1887. 8°. viii, 813 pp. Price 50 cents.

Mineral Resources of the United States, 1887, by David T. Day. 1888. 8°. vii, 832 pp. Price 50 cents.

Mineral Resources of the United States, 1888, by David T. Day. 1890. 8°. vii, 652 pp. Price 50 cents.

Mineral Resources of the United States, 1889 and 1890, by David T. Day. 1892. 8°. viii, 671 pp. Price 50 cents.

Mineral Resources of the United States, 1891, by David T. Day. 1893. 8°. vii, 630 pp. Price 50 cents.

Mineral Resources of the United States, 1892, by David T. Day. 1893. 8°. vii, 850 pp. Price 50 cents.

Mineral Resources of the United States, 1893, by David T. Day. 1894. 8°. viii, 810 pp. Price 50 cents.

On March 2, 1895, the following provision was included in an act of Congress:

Provided, That hereafter the report of the mineral resources of the United States shall be issued as a part of the report of the Director of the Geological Survey.

In compliance with this legislation the report Mineral Resources of the United States for the Calendar Year 1894 forms Parts III and IV of the Sixteenth Annual Report of the Survey.

The money received from the sale of these publications is deposited in the Treasury, and the Secretary of the Treasury declines to receive bank checks, drafts, or postage stamps; all remittances, therefore, must be by POSTAL NOTE or MONEY ORDER, made payable to the Director of the U. S. Geological Survey, or in CURRENCY for the exact amount. Correspondence relating to the publications of the Survey should be addressed

TO THE DIRECTOR OF THE
UNITED STATES GEOLOGICAL SURVEY,
WASHINGTON, D. C.

WASHINGTON, D. C., *April, 1896.*

SIXTEENTH ANNUAL REPORT

OF THE

UNITED STATES GEOLOGICAL SURVEY

TO THE

SECRETARY OF THE INTERIOR

1894-95

CHARLES D. WALCOTT
DIRECTOR

IN FOUR PARTS

PART I.—DIRECTOR'S REPORT AND PAPERS OF A THEORETIC NATURE

WASHINGTON
GOVERNMENT PRINTING OFFICE
1896

SIXTEENTH ANNUAL REPORT

OF THE

UNITED STATES GEOLOGICAL SURVEY.

PART I.—DIRECTOR'S REPORT AND PAPERS OF A THEORETIC NATURE.

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DEPARTMENT OF THE INTERIOR,
UNITED STATES GEOLOGICAL SURVEY,
Washington, D. C., July 15, 1895.

SIR: I have the honor to transmit herewith the report of the operations of the United States Geological Survey for the year ending June 30, 1895.

I wish to thank you for the careful and appreciative consideration that you have given to the work of the Survey throughout the year.

I am, with respect, your obedient servant,

Chas. D. Walcott,
Director.

Hon. HOKE SMITH,
Secretary of the Interior.

SIXTEENTH ANNUAL REPORT OF THE UNITED STATES GEOLOGICAL SURVEY.

CHARLES D. WALCOTT, DIRECTOR.

INTRODUCTION.

At the close of the fiscal year 1893–94 the resignation of Maj. John W. Powell, who had been the Director of the Geological Survey for thirteen years, went into effect, and on July 1, 1894, the present Director took charge of the Bureau. Having been a member of the Survey since its organization (July 1, 1879), and geologist in charge for some time previous to his appointment as Director, he was familiar with the policy and administration of the Bureau under his predecessors, King and Powell, which he believed to be, in the main, wise and efficient, and hence he has not found it desirable to make any radical changes, either in policy or personnel. The changes made have been in the nature of readjustments intended to meet new conditions, and, if possible, to bring the Survey more in touch with some of the economic and educational interests of the country. Most of them were the outcome of the natural development of the Survey, which, in turn, has been but the logical consequence of the natural development of the country. These readjustments, briefly outlined, are: The raising of the standard of quality of the topographic maps and the appointment of an editor to assist in securing their greater accuracy and uniformity; the representation on all maps hereafter surveyed in the public-land States of the land-subdivision lines, and, when possible, the location of the position of township and section corners and the determination of their altitude; the enlargement of the work of resurvey of areas the existing maps of which are, from any cause, defective or inadequate for the proper representation of the areal and economic geology; the planning of a system of triangulation to supplement that already done by the Coast and Geodetic Survey and by the Geological Survey; the placing of the entire topographic force within the classified service, so as to limit all appointments to men whose qualifications have been tested by an impartial and thorough examination; the obtaining of authority from Congress to print and sell topographic maps, with text, for educational purposes; the obtaining of authority from Congress to print the annual volume on the mineral resources of the United States as a part of the Annual Report, so that it may have greater distribution, and to issue in pamphlet form, in advance of the publication of the volume, the articles or chapters composing the same, as well as papers on economic geology constituting a portion of the other part of the Annual Report; the enlargement and increase of the work of the Division of Hydrography and of the Division of Mineral Resources; and the making of reconnaissance surveys of regions supposed to contain important economic resources, in order to obtain information which, under the ordinary plan of awaiting a complete survey of the region, would be delayed for years.

Acknowledgments are due the Smithsonian Institution and the National Museum for general cooperation during the year, the Coast and Geodetic Survey and the General Land Office for maps and other data relating to triangulation and land surveys, and the Government Printing Office for assistance in securing prompt publication and in the endeavor to reach a high standard of book-making. The faithful and cordial support that has been rendered the Director and the Bureau by all the members of the Survey finds fitting recognition in this place.

PLAN OF OPERATIONS FOR THE YEAR.

In accordance with custom, a general plan of operations for the fiscal year 1894–95 was laid before the Secretary of the Interior, and was approved by him on the 13th of August. The delay in its submission and approval was occasioned by the failure of Congress to pass earlier the bills which carried the annual appropriations for the work.

That the appropriations would not become available until after the 1st of July became apparent early in June, and, in order that as much as possible of the work of 1894 might be commenced in the earlier part of the field season, a brief preliminary plan of such work was prepared and submitted to the Secretary on the 21st of June. This preliminary plan was based on the anticipated extension of the appropriations for the preceding fiscal year to provide for the interval between the 1st of July and the time of passage of the bills carrying the appropriations for the new fiscal year.

The detailed plan of operations as approved by the Secretary, and in conformity with which the greater portion of the work hereinafter reviewed was executed, is on file in the Department A general statement of appropriations and of allotments for work in geology, paleontology, and topography immediately follows, and where each party worked and what each party and office division accomplished will be found stated further on, under the head "Organization and work of the year."

APPROPRIATIONS AND ALLOTMENTS.

SUMMARY OF APPROPRIATIONS.

The sundry civil appropriation act for the fiscal year 1894–95 appropriated for the work of the United States Geological Survey the sum of $421,600. Separate amounts were by the terms of the act set apart for specific branches of work and for the salaries of persons connected with these branches. For convenience of reference these separate appropriations are here brought together and classified as follows:

For pay of skilled laborers, etc.		$13,000
For topographic surveys	$150,000	
For pay of 2 geographers and 2 topographers	9,200	
Total for topographic work		159,200
For geological surveys	100,000	
For pay of 4 geologists	13,700	
Total for geologic work		113,700
For paleontologic researches	10,000	
For pay of 2 paleontologists	4,000	
Total for paleontologic work		14,000
For chemical and physical researches	7,000	
For pay of 1 chemist	3,000	
Total for chemical work		10,000
For gauging water supply		12,500
For preparation of illustrations		13,000
For preparation of report on mineral resources		15,000
For purchase of books and distribution of documents		2,000
For engraving and printing maps		65,000
For rent		4,200
Total		421,600

Furthermore, there was appropriated in the same act for engraving, printing, and binding publications of the Geological Survey $35,000, this sum to be disbursed, not by the Geological Survey, but by the Public Printer. The items are as follows:

For engraving illustrations for report of the Director	$5,000
For engraving illustrations for monographs and bulletins	10,000
For printing and binding monographs and bulletins	20,000
Total	35,000

Lastly, the legislative, executive, and judicial appropriation act for 1894–95 appropriated for the Geological Survey $41,390, in two items, as follows:

For salaries of Director, chief clerk, chief disbursing clerk, librarian, and photographer, together with clerks, messengers, watchmen, et al, to the number of 30 persons in all	$31,390
For rent	10,000
Total	41,390

Thus the total appropriation for the Geological Survey for the fiscal year 1894–95 is $497,990.

ALLOTMENTS TO GEOLOGIC WORK.

The total appropriation for geologic work for 1894–95 was, as stated above, $113,700.

The following table exhibits the allotments made to the heads of parties for the different sections of work:

Party	Allotment
Shaler, N S. (Massachusetts)	$3,500
Emerson, B K. (Massachusetts)	750
Dale, T. N. (New York and Vermont)	2,700
Wolff, J. E (New Jersey)	750
White, C D (West Virginia, Virginia, and Tennessee)	1,700
Willis, Bailey (Maryland and West Virginia)	7,500
Campbell, M R. (West Virginia)	3,500
Hayes, C. W. (Georgia, Alabama, and Tennessee)	3,500
Keith, A (Tennessee and North Carolina)	3,500
Becker, G F. (Georgia, North Carolina, South Carolina, and Virginia)	7,000
Darton, N. H (Maryland and New Jersey)	1,800
Clark, W B (eastern Maryland and New Jersey)	600
Eldridge, G H. (Florida)	4,000
Van Hise, C R (Lake Superior)	8,000
Chamberlin, T C (Illinois and central interior region)	3,000
Gilbert, G K (Colorado and Kansas)	8,000
Hill, R T. (Texas)	6,000
Weed, W. H (Montana)	3,600
Eldridge, G H. (Idaho)	1,200
Emmons, S. F. (Colorado and Utah)	7,000
Hills, R. C (Colorado)	1,000
Cross, C. W. (Colorado)	5,000
Hague, A (Wyoming)	4,750
Diller, J S. (Oregon and northern California)	5,200
Turner, H. W. (California)	3,600
Lindgren, W. (California)	3,000
Lawson, A. C. (California)	750
Executive office	9,000
Contingent fund	3,800
Total	113,700

ALLOTMENTS TO PALEONTOLOGIC WORK.

The total appropriation for paleontologic work was $14,000. The following table exhibits the allotments made:

Section	Allotment
Paleozoic	$1, 500
Mesozoic	1, 900
Cenozoic	2, 900
Paleobotany	4, 100
Vertebrate paleontology	2, 000
General assistant	1, 200
Unallotted	400
Total	14, 000

ALLOTMENTS TO TOPOGRAPHIC WORK

The amount appropriated for topographic work was $150,000. Of this amount it was provided by law that $35,000 should be expended west of the ninety-seventh meridian, in the States of North Dakota, South Dakota, Nebraska, Kansas, Texas, and the Territory of Oklahoma; and that one-third of the remainder should be expended west of the one hundred and third meridian. The following allotments were in accordance with these provisions. These allotments include certain stated salaries appropriated for men engaged in topographic work, the aggregate amount of which is $9,200, making the total appropriation for topography $159,200:

State	Allotment
Maine	$5,000
Vermont	4,000
New York	10,000
Pennsylvania	5,000
Maryland and West Virginia	2,000
West Virginia	2,000
Virginia	3,000
Tennessee	2,000
Georgia	10,000
Minnesota	5,000
North Dakota	5,000
South Dakota	10,000
Nebraska	10,000
Texas	12,000
Colorado	20,000
Idaho	5,000
Washington	5,000
Oregon	10,000
California	20,000
Administration and office force	14,200
Total	159,200

ORGANIZATION AND WORK OF THE YEAR.

The Geological Survey is now organized into branches and divisions as follows.

Branch.	Division.	
Geologic	Geology	
	Paleontology.	
	Chemistry	
	Hydrography	
	Mineral Resources	
Topographic	Triangulation.	
	Topography.	
Publication	Illustrations.	
	Editorial	Textual publications.
		Geologic maps
		Topographic maps.
	Engraving and Printing	
Administrative	Documents, Correspondence, and Records.	
	The Library.	
	Disbursements and Accounts	

The approved plan of operations was executed in all essential particulars, the slight departures therefrom being due to conditions which could not well be anticipated. Following is a detailed account of the work:

GEOLOGIC BRANCH.

DIVISION OF GEOLOGY.

The organization of the previous year was continued Each of the twenty-six field parties was under the charge of a geologist or an assistant geologist, who reported to the Director.

Nearly all of the field work of the year was areal geologic surveying, for the purpose of delineating on the topographic base maps the distribution and relations of the various rock formations. Considerable energy, however, was expended in making a reconnaissance of the Southern Appalachian gold fields and of the mining districts of central-southern Idaho, and in obtaining data for the completion of the second portion of the report on the Leadville mining district of Colorado.

For convenience of administration and reference the field of operations was divided into six sections or regions, as follows: (1) New England, (2) Appalachian, (3) Atlantic Coastal Plain, (4) Interior or Mississippi, (5) Rocky Mountain, (6) Pacific.

NEW ENGLAND REGION.

This region includes the New England States and the eastern portion of New York. In it three parties were engaged in field work, as follows:

Shaler party—The party in charge of Prof. N. S. Shaler continued and practically completed the survey of the Narragansett coal field of Rhode Island. A few points remain to be examined while he is preparing his report. About 126 square miles were newly mapped, and 25 square miles were revised for the obtainment of boundaries and the interpretation of structure The new work goes far toward clearing up the problems of the coal field. It has for the first time approximately defined the area where coal may reasonably be sought for. The data have been compiled so far as to show features which are of great importance from both an economic and a theoretic point of view Some recent experiments appear to show that by making briquets of the coal, the material being mingled with 1 per cent of coal tar, an excellent fuel can be produced. If this proves to be correct it seems certain that something may now be done with the large stores of anthracite which this district contains.

In connection with the study of the Narragansett basin and the Worcester basin of Massachusetts, two large areas of trappean rocks were discovered and mapped. One is a great diabase dike near Woonsocket, R I., and the other an extensive area of traps near Mansfield, Mass. Both of these localities were previously unknown, and they promise to be of great value to the highway interests of southeastern Massachusetts, as the material is suitable for road building.

In the office Professor Shaler prepared a report on the geology of the road-building stones of Massachusetts, incorporating in it the results of the labors of Mr. F. C. Schrader, an assistant employed for that work, and of the Massachusetts Highway Commission, which has made tests of many kinds of road-building material The paper will be found in Part II of this Annual Report. The writing of the report on the Narragansett coal field was begun and well advanced prior to June 30.

Emerson party.—In continuation of the mapping of the areal geology of central Massachusetts, Prof. B. K. Emerson completed the Marlboro sheet, embracing Worcester and Middlesex counties, and also a portion of the Sheffield sheet, which includes all or parts of Berkshire County, Mass., Columbia County, N. Y, and Litchfield County, Conn. In the latter area the boundaries of the older rocks in Beartown Mountain were traced and platted on the map. The completion of the Marlboro sheet disposes of four sheets that will be combined in a single folio, covering an area of which Worcester is the center.

During the winter Professor Emerson worked upon the chemical and petrographic material collected during the field season, completed a revision of the manuscript of a report upon the geology of Hampshire, Franklin, and Hampden counties, Mass., which will be published as one of the Survey monographs, and prepared a report upon the mineralogy of the same region, which will be issued as Bulletin No. 126 of the Survey series

Dale party.—In eastern New York State. Prof. T. Nelson Dale continued the mapping of the areal geology of the southern portion of the great roofing-slate belt of New York and Vermont. The Cambridge sheet of Washington County, N. Y., containing 250 square miles of territory, was wholly mapped, and about 40 square miles of the Fort Ann sheet, covering part of the same county, were also mapped. The scientific results of the work consist of the careful outlining of the Cambrian and Silurian rocks in a region of great geologic complexity. The areal geology shows the approximate extent and limits of the belts of red, purple, and green roofing slate, and the location of all quarries of importance. But few of the quarries are being worked at present, but when such slates as this region affords again come into demand, the geologic map will be of service to operators. The two sheets next north of the Cambridge sheet will embrace the center of the roofing-slate region of eastern New York.

In the office Professor Dale's principal work was the preparation for publication of the Troy and Cambridge sheets of New York, and the writing of a paper on certain structural details of the Green Mountain region in eastern New York, which is published in this report

APPALACHIAN REGION.

This region embraces the mountain system and adjoining hills and plateaus that extend from the Hudson River on the north to central Alabama on the south. Eight parties were engaged in field work during the summer, as follows:

Wolff party.—In continuation of the work of the field season of 1893 Dr. J. E. Wolff spent a part of the season of 1894 in mapping the areal geology of the Lake Hopatcong sheet of New Jersey, including parts of Morris and Sussex counties. An area of 25 square miles was surveyed In the spring of 1895 the remaining 100 square miles were surveyed, and the geology of this important area was thus completed

Willis party.—In the Elk Garden coal field of western Maryland and West Virginia 922 square miles were studied and mapped by Mr. Bailey Willis, assisted by Messrs. Joseph A. Taff and N. H. Darton. This area includes the Piedmont atlas sheet, embracing all or part of Mineral, Grant, and Tucker counties in West Virginia, and Garrett County, Md. About two-fifths of the tract is occupied by the coal-bearing rocks. Four coal beds are being worked, including the noted Elk Garden seam, at the top of the section. Although it is now many years since mining operations were begun, it was found that operators entertained many and diverse opinions respecting the identification of the coal beds in different parts of the field, and it was clear that it would be of great value to operators and owners to have accurate maps and structure sections showing the true relations of the various beds.

In connection with the coal work the geologic survey was extended over the adjacent areas of Devonian and Silurian rocks, and much valuable information of a scientific character was obtained. In connection with the geologic work a thorough revision of the topography of the area was made by a topographic party, as the original topographic map was not sufficiently detailed and accurate for the purposes of the geologist.

In addition to the editorial work on the Geologic Atlas of the United States, which will be mentioned elsewhere, Mr. Willis was engaged in the office in the preparation for publication of the maps and text of the Piedmont atlas sheet, and in attending to various matters referred to him by the Director.

Campbell party.—The party in charge of Mr M R. Campbell was engaged in the survey of the coal field of southwestern Virginia and southern West Virginia. The Bristol sheet, covering in part Scott, Wise, Russell, and Washington counties in Virginia and part of Sullivan County in Tennessee, was completed by an examination of about 250 square miles around Bristol and of the coal area in the northern part of the tract. The Tazewell sheet extends from Virginia (Buchanan and Tazewell counties) into West Virginia (McDowell County), lying just east of the Kentucky line Of the 960 square miles within its limits, 700 are within the Appalachian coal basin and 260 in the valley to the southeast. The coal territory was worked with great care, and the areal geology of the entire sheet was finished. Mr. Campbell also completed the survey of the Pocahontas sheet, which adjoins the Tazewell sheet on the east, and embraces, in whole or in part, Bland and Tazewell counties, Va., and Mercer and McDowell counties in West Virginia; and in order to connect the coal area of the Pocahontas sheet with that of the New River district to the northwest, 450 square miles of the Raleigh sheet (Raleigh, Fayette, Wyoming, and Mercer counties) of West Virginia, lying north of the Tazewell sheet, were surveyed. About 300 square miles of the Hinton sheet of West Virginia, which adjoins the Raleigh sheet on the north (embracing parts of Summers and Monroe counties), were also surveyed.

The mapping of the areal geology and the determination of the stratigraphic structure of the coal areas are of economic importance, and the tracing of the different members of the Pottsville series of Pennsylvania from New River to Tug River is likewise an important work, as the lack of such information has led to many erroneous correlations. In tracing this series southward determinations were made of the manner in which changes have occurred in the volumes of the various beds that form the series, and it was also observed that the series itself was increased by the addition of lower beds toward the south This information will be of value in the study of the coal-bearing rocks.

Mr. Campbell's office work had reference principally to the Tazewell and Raleigh sheets, and to the preparation of an extended paper on the "Influence of orogenic movements in Appalachian drainage" He also finished, ready for publication, the Pocahontas atlas sheet, the completion of which had been delayed pending necessary topographic correction of the base map.

Hayes party.—In continuation of the mapping of the Appalachian coal fields of eastern Tennessee, Mr. C Willard Hayes, assisted by Mr. A. H. Brooks, completed the Pikeville and McMinnville sheets, which adjoin and cover parts of White, Van Buren, Bledsoe, Rhea, Cumberland, Warren, Dekalb, and Grundy counties This was new work with the exception of about 80 square miles of the Pikeville sheet, of which a reconnaissance had been made the preceding season. There are about 1,000 square miles of coal area on the two sheets Mr. Hayes next proceeded to southeastern Tennessee, where, in cooperation with Mr Arthur Keith, the Murphy sheet (Monroe and Polk counties, Tenn., and Cherokee County, N. C.), which had been previously mapped in part, was completed. Mr. Hayes next took up the areal geology of the Ellijay sheet of northern Georgia, including all or parts of Fannin, Gilmer, Union, and Lumpkin counties, but, owing to the inadequacy of the topographic base, only enough work was done to establish clearly the connection between the formations of the Murphy sheet and those of the Dalton and Cartersville sheets. The Cartersville sheet (Gordon, Pickens, Bartow, Cherokee, Cobb, and Paulding counties), whose northwest corner meets the southwest corner of the Ellijay sheet, was then taken up, and before the close of the field season 406 square miles of new areal mapping were completed, and 306 square miles of old work were revised

In connection with the areal mapping of the coal formation of the Pikeville and McMinnville sheets study was made of the coal of the region, especially the Sewanee seam, which contains the greater part of the workable coal. This was mapped and sections were obtained, so that a fair estimate can be made of the amount of available coal within the area of these two sheets. In the mapping of the Cartersville sheet especial attention was given to the occurrence of iron and manganese. The geologic relations of these ores were inquired into, and the belts in which the various varieties occur were mapped. Mr. Hayes also made a careful examination of the bauxite deposits of Georgia and Alabama, visiting every locality from which bauxite had been reported as occurring. Under special instructions he visited also the phosphate district of Hickman County, Tenn., and a reconnaissance was made to determine the occurrence of phosphate in southeastern Tennessee and in northern Georgia and Alabama. Typical exposures were visited over a large area, and the absence of important deposits of the phosphate was definitely proved

Mr Hayes was engaged during the winter in the preparation for publication of the maps and text of five geologic folios, two of which, the Stevenson and Cleveland, are now in press. In addition, special papers were prepared by Mr Hayes for this report on the Tennessee phosphates and the bauxite deposits.

Keith party —Mr. Arthur Keith, assisted by Mr. H. B. Goodrich, mapped the areal geology of the Wartburg sheet This tract embraces parts of Morgan, Scott, Cumberland, and Fentress counties in Tennessee, and 980 square miles of it are within the Appalachian coal field. The coal measures of this area had suffered very little disturbance, and the mapping was therefore carried forward quite rapidly.

Mr. Keith next took up the Asheville and Cranberry sheets of North Carolina and Tennessee (embracing all or parts of Buncombe, Haywood, Madison, Ashe, Wautauga, Caldwell, and Mitchell counties in the former State, and touching Johnson and Carter counties in the latter State), mapping 850 and 950 square miles, respectively. A reconnaissance was made also of the Pisgah sheet (which includes parts of Transylvania and Henderson counties, in the southwestern corner of North Carolina, adjacent to the South Carolina line), and of the northern part of the Mount Mitchell sheet, which lies mainly in Yancey and McDowell counties, N. C. So much as remained to be mapped of the Murphy sheet, before mentioned, was also completed, which included some 600 square miles of areal mapping.

The principal economic results were the mapping of the coal measures of the Wartburg sheet, the study of the brown hematite deposits of the Cranberry sheet, and the examination of the strata of the Asheville sheet, which were reported to contain deposits of brown hematite and of magnetite. These ores were found, however, to be of relatively small economic importance.

During the winter Mr. Keith was mainly employed in the preparation for publication of material for atlas sheets.

White party.—Mr C. David White was instructed to cooperate with Mr. M. R. Campbell in mapping the Tazewell sheet, previously described, and in collecting and studying the plant remains occurring in the various coal beds in order to obtain data for correlating the various coal horizons, whose connection was interrupted by faults or folds or by the destructive agency of erosion. In October he joined Mr. Bailey Willis in work on the Piedmont sheet, previously mentioned, and made a collection and study of the fossil plants of the coal beds of northern West Virginia for the purpose of obtaining data for correlating the coal beds of Maryland and northern West Virginia with those of southern West Virginia, Tennessee, and other States. Important identifications of coal beds were made by Mr. White, and he found that the New River coal miners are apparently working two seams (the Quinnemont-Fire Creek and the Sewell-Nuttall) instead of four or five, as has generally been believed. The lower coal bed is in the middle of the Flat Top Mountain section, the Pocahontas coal thinning out and occurring much nearer the Red Shales in the New River section than in the Flat Top Mountain. The higher coal (Sewell-Nuttall) belongs to the Sewanee group, and is approximately of the age of the main Sewanee coal in Tennessee

In the office Mr. White was largely engaged in arranging and identifying the contents of over fifty boxes of fossil plants which had been collected during the field season. During the month of March he was employed in identifying and labeling the large collection of Carboniferous coal plants that had been presented to the National Museum by Mr. R. D. Lacoe. The latter collection embraces upward of 80,000 specimens of Paleozoic plants. Its scientific value is great, as it contains nearly two-thirds of the original specimens described and figured from the Carboniferous flora of the United States.

Becker party.—In response to repeated inquiries and requests for information and a pressing demand for the work, a reconnaissance of the gold areas of the southern Appalachians was undertaken, Dr. George F. Becker being instructed to make an examination of the auriferous deposits of Georgia and the Carolinas. These deposits are divisible into three principal groups. One of them lies almost entirely in Georgia, trending in a northeasterly by northerly direction through Dahlonega, in that State. It has important expansions in Alabama and North Carolina. A second belt extends in a similar direction just west of the South Mountains of North Carolina through Brindletown and Rutherfordton. A third belt, more extensive than either of the others, trends in the same direction through Charlotte, N C., reaching into South Carolina and nearly to the Virginia line Dr. Becker examined during the field season all the mines that were being worked and a considerable number that had been worked in these belts—seventy-five in all. Unfortunately, owing to the decomposed condition of the surface rocks, instructive exposures are rarely met with, and many of the mines formerly worked have been shut down, the shafts being either full of water or caved in. In such cases the only sources of information obtainable were the dumps and the more or less trustworthy statements as to yield and richness to be obtained of persons in the neighborhood. Besides the deep mines, there are superficial deposits from which the greater part of the gold product of the South has been obtained.

During the winter Dr. Becker prepared a report of the results of his field work and the conclusions drawn from them, which may be found in Part III of this Annual Report.

ATLANTIC COASTAL PLAIN REGION.

This area embraces the Coastal Plain region extending from the mouth of the Hudson on the north to the Gulf of Mexico on the south

Clark party.—In the northern portion of the region Prof. William B. Clark made a revision of the Cassville sheet of New Jersey (Ocean and Monmouth counties), and with the aid of his assistant, Mr R. M. Bagg, mapped 250 square miles of the Asbury Park sheet, which adjoins the Cassville sheet on the east, special attention being given to the occurrence of clays and marls.

In addition to his field work Professor Clark prepared two paleontologic reports, one dealing with the Eocene fauna of Maryland and Virginia, and the other with the Mesozoic Echinodermata of the United States.

Darton party.—The work upon the areal geology in the vicinity of Washington, D. C., was placed in charge of Mr.

N. H. Darton, who began and prosecuted the revision of the old map. This work was carried forward during the spring and summer, and was practically completed, with the exception of the areas of crystalline rocks Mr. Darton's principal work of the year was the preparation of a report on the artesian-well prospects in the Atlantic Coastal Plain region, which is nearly completed.

Eldridge party in Florida—The work on the phosphate deposits of Florida was not continued during the year, as Mr. G. H Eldridge's time was entirely taken up with his general geologic investigations in Idaho and the preparation of a report thereon.

INTERIOR OR MISSISSIPPI REGION.

This region embraces the area lying between the British boundary on the north, the Gulf of Mexico on the south, the Rocky Mountains on the west, and the western slope of the Appalachians on the east.

Van Hise party.—The field work of the Lake Superior parties, under the charge of Prof. C R. Van Hise, was in the Marquette and Michigamme iron districts. In the former district the work which has been going on for several years was completed by Prof. W S. Bayley, who executed a small amount of magnetic work in certain of the iron-bearing belts and filled in minor deficiencies in the areal work at various points. In the Michigamme iron district detailed maps have been made of one area by Mr. H. L. Smythe and of another by Mr. W N Merriam. This work was done without cost to the Geological Survey by a private organization; but the originals of all maps and note-books and all specimens were placed at the disposal of the Survey. To Mr. J. M. Clements was assigned the task of connecting and ascertaining the relations of the formations of the two areas surveyed by Messrs. Smythe and Merriam.

The tracing of the iron-bearing formations between the two districts had to be done almost entirely by means of the magnetic needle, as there were very few rock exposures. An area of about 142 square miles was covered successfully, despite the difficult nature of the geology. The iron-bearing formation of the Amasa area was connected with that of the Fence

River area. This resulted in the extension of the iron-bearing formation about 15 miles. A belt of volcanic rocks underlying the iron formation in the Fence River district was connected with a broad area of volcanics in the Amasa district, thus enabling the geologist to equate the respective formations of the two series, and place them in the general scheme of formations of the Upper and Lower Huronian. The private organization previously mentioned also made a topographic map of about 1,200 square miles in the Michigamme district. The sheets constituting this map have been controlled by the triangulation of the Geological Survey, and photographs of two complete sheets are now ready for the platting of the areal geology. The areal geologic work, however, extends a considerable distance to the south and east of these tracts, and as soon as the topography of this outlying district is completed several more atlas sheets will be made ready for publication.

In the office Professor Van Hise and his assistants were employed in the preparation of a monograph upon the Marquette iron-bearing district, a voluminous and important work. Professor Van Hise also completed a paper entitled "Principles of Pre-Cambrian North American Geology," which will be found among the papers accompanying this report.

Chamberlin party.—The work upon the glacial deposits of the United States was in charge of Prof. T C. Chamberlin, but owing to his absence in Greenland, where he went early in the summer to study glacial phenomena, Mr. Frank Leverett conducted the operations in the field for the greater part of the time. Work was carried forward in Indiana, Illinois, Iowa, and Wisconsin. In addition to data of much scientific value, many important facts in relation to the several classes and kinds of soils, and in relation to the ice action that produced those soils, were obtained. The question of the presence of an available water supply in the drift formations also received careful attention, a large body of valuable facts touching it being gathered. In many places the drift beds afford small quantities of natural gas, and all information possible was obtained concerning the source and probable abundance of this product. The mapping of the thickened drift formations promises to be of economic value in dissipating false ideas of the underlying geologic structure. In the drift and ridges of Mattoon and at Champaign, in Illinois, small quantities of gas occur, confined in beds of sand, and from this it is inferred by drillers from the gas fields of Pittsburg, who were consulted on the subject, that anticlinal ridges occurred in the underlying strata at the places named, and that gas in quantity could be secured by sinking deep wells. A knowledge of the drift deposits would serve to remove this false impression.

In the office Mr Leverett was engaged in preparing for publication a report upon the drift of the Illinois glacial lobe, and on a manuscript report on the glacial drift of Illinois and western New York.

Gilbert party.—The party in charge of Mr. G K Gilbert surveyed the Apishapa sheet of Colorado and made a preliminary examination of the Nepesta sheet Mr. Gilbert was assisted the greater part of the time by Mr. F. P Gulliver and Mr. G. W. Stose. On his return from the field he visited ten gravity stations of the Coast and Geodetic Survey for the purpose of making geologic observations in connection with that work.

The Apishapa sheet includes all or parts of Pueblo, Huerfano, Las Animas, and Otero counties, and has an area of about 940 square miles. It is occupied in the main by rocks of Cretaceous age. The principal streams of the area and their tributaries run several feet below the general upland surface, occupying valleys and canyons. The lowest formation exposed in the area consists of about 300 feet of the Dakota sandstone The greater part of this is so porous as to receive and transmit water with freedom, and this is the great water-bearing stratum of the region. It is exposed in the region of greatest uplift, and dips under the younger formations in all directions. The latter include the Benton group, composed mainly of shale, but containing also some layers of limestone, with a thickness of about 450 feet. Above the Benton group is the Niobrara group, with a thickness of about 450 feet within the limits of the sheet.

The Nepesta sheet (Pueblo and Otero counties) is occupied in part by the shaly beds of the Niobrara group, in part by the still thicker shales of the overlying Pierre group, which in many areas are covered by broad sheets of gravel This gravel is the source of the principal springs of the region, receiving the water of rains in its porous surface and discharging the same at its margins. Artesian water is at present the principal mineral resource of the region The stream channels of the country afford so precarious a supply of water that the amount necessary for irrigation can be obtained only in the immediate vicinity of the Arkansas River and at a few other favored points Grazing has become the principal industry of the region, and where there are no living springs it is highly possible that by drilling through the shales of the Benton group artesian wells could be obtained in the Dakota sandstone. The areal mapping of this region will approximately indicate the artesian-well districts, and indication will also be made of the regions in which it is possible that water reached by the drill will outflow at the surface.

The following is quoted from Mr. Gilbert's report, made after a personal examination in October, 1894:

> I therefore estimate the depth of the water horizon below the surface at Rocky Ford to be between 735 and 1,135 feet. It is probably less than 1,000 feet. I incline to the opinion that the water will rise above the surface at Rocky Ford, because the physical conditions are very similar to those that obtain at Pueblo, where the water rises 150 feet above the flood-plain of the Arkansas.

A letter from James Dun, chief engineer of the Atchison, Topeka and Santa Fe Railroad, dated July 9, 1895, and addressed to Mr. F. H. Newell, states that at Rocky Ford "a supply of 80 gallons per minute has been secured at a depth of 790 feet."

An examination of certain beds occurring in the upper part of the Dakota sandstone and the lower part of the Benton shale suggests that they may be valuable as fire clays, and a few tests that have been made indicate that a trial, on a larger scale, of several of the deposits is worth the making.

Prof. C. S. Prosser, who had previously commenced the survey, under Mr. Gilbert's supervision, of the Cottonwood Falls sheet (Chase, Butler, and Greenwood counties), of Kansas, completed that sheet and began work on the Parkerville sheet, in which Geary and Morris counties lie These sheets contain rocks of Lower Carboniferous age, and include limestone formations that contain valuable building stone. In mapping the various formations Professor Prosser has traced the continuity of rocks formerly supposed to be distinct, and has clearly indicated the limits of the districts to which future search for valuable building stone should be restricted. The area actually surveyed is about 500 square miles, and a reconnaissance was made of an equal area

During the winter Mr. Gilbert compiled the data for the Apishapa sheet and made a study of the material gathered in the field relating to gravity determinations The results of the study of the latter material were embodied in a report which was forwarded before the close of the year to the Superintendent of the United States Coast and Geodetic Survey.

Hill party—The party in charge of Mr. R T. Hill made a careful areal survey of the Austin sheet of western Texas, which comprises parts of Hays, Travis, and Bastrop counties. This sheet is a very comprehensive one, as it embraces within its area a large variety of geologic formations. Both the rock formations and the surface soils were mapped in detail, and the building stones, road-making materials, rocks adapted to making water-lime cement, and the artesian conditions were all carefully studied, as were also the fossil remains A geologic reconnaissance was also made along the line from Austin southwestward to the Rio Grande, for the purpose of looking into the question of artesian water supply and the spring rivers of that region

For the purpose of obtaining information of those structure characters that influence the distribution of underground water in the Plains region, Mr. Hill made a reconnaissance of the valley of the Medicine Lodge River of Kansas, and of the country lying between Winfield and Belvidere, in the same State

Mr. T. Wayland Vaughan assisted in the work on the Austin sheet, and also visited certain points in Arkansas, Indian Territory, and Louisiana to collect rocks and fossils, including fossil plants. Large collections were obtained by him that will be of service in the correlation of the Cretaceous formations of Texas. Under special instructions from the Director he also obtained some 1,200 pounds of pure white chalk for the series of rocks that the Survey is preparing for distribution to educational institutions.

After his return from the field Mr. Hill was employed in preparing for publication a report on the results of his field work. This included the preparation for publication of the data for several geologic atlas sheets which had been surveyed in previous years and the study of the large collections made during the field season.

ROCKY MOUNTAIN REGION.

This area embraces the Rocky Mountains and their foothills between the British and Mexican boundaries on the north and south, the margin of the Great Plains on the east, and approximately the line of the one hundred and nineteenth meridian on the west

Weed party.—In continuation of the work of the previous year Mr. Walter H. Weed was instructed to survey the Fort Benton sheet of Montana, which includes parts of Cascade, Fergus, Choteau, and Meagher counties. Mr. Weed was assisted by Prof. L. V Pirsson, whose services terminated at the close of the season The areal geology of 3,375 square miles was mapped, and a reconnaissance examination was made of the Judith Mountains and of the St Louis lode, at Marysville, Mont A general study was also made of the mines of the Barker district of the Little Belt Mountains and of the coal lands of the tract, and the outcrops of coal were traced along the flanks of the Little Belt Mountains. The work in the Judith Mountains included an examination of the coal area of that region.

Among the more strictly scientific results were the completion of the study of the Little Belt Mountains, the recognition of the volcanic nature of the Highwood Range, and the collection of a complete series of the rare alkali rocks of those mountains. The Belly River beds of the Canadian coal-bearing series were recognized and determined for the first time in this region.

In addition to the preparation for study of the Little Belt Mountains and Fort Benton geologic folios, Mr Weed assisted Mr. Hague in the preparation of the geologic maps and accompanying text of the Yellowstone Park folio. He also prepared several short papers upon subjects connected with his field of work, for publication in the scientific magazines.

Eldridge party in Idaho.—Mr. George H Eldridge was directed to make a reconnaissance of the Snake River and Salmon River basins of Idaho. His route was from Boise northeastward to the Continental Divide east of Salmon City, thence south to Hailey, in the Wood River region, and west to Boise, along the southern edge of the great mountain ranges of Idaho. From Boise a trip was made southwestwardly to the Oregon line, in the vicinity of De Lamar and Silver City The distance traveled in the course of the reconnaissance was 850 miles, exclusive of the distance covered in doubling back over the same route between local points. A distance of 750 miles was traveled by pack train

The results obtained are a general knowledge of the rocks occurring along the route of the reconnaissance and much information regarding the structural geology and the topographic features of the country traversed. The results of economic value include a knowledge of the occurrence of the ores in the eight or nine mining districts visited, of the general character of the Idaho placer deposits, of the nature of the problems requiring solution for the advancement of the gold and silver mining industries, of the distribution of important building materials, and of the general possibilities of the country for irrigation, grazing, general agriculture, and fruit culture

On his return from the field Mr. Eldridge began at once the preparation of a report upon his reconnaissance in Idaho, which will be found in Part II of this Annual Report.

Emmons party—In order to bring down to date the information gathered during the summer of 1890 for the purpose of preparing a report supplementary to his monograph on the Leadville mining district (Monograph XII, 1886), Mr. S. F. Emmons reexamined during the season of 1894 the underground workings of the mines of that district, since, owing to the physical conditions of the region, the determination of the geologic structure and of the location of the ore bodies must be based almost wholly on facts gathered in this manner. The original field work in the Leadville district was completed in 1880–81. As there have been twelve years of active mining since that time, the area explored by underground workings has been enormously increased. This method of observation involves a great amount of labor, since underground traveling is necessarily slow and the location of subterranean points involves the compilation of a great number of underground surveys. The compilation and correlation of these surveys and the location of various points of contact and other phenomena can be made and determined only by one thoroughly familiar with the whole ground; hence, the person conducting the work must perform an immense amount of purely mechanical labor before trustworthy geologic results can be arrived at. It was necessary that these surveys should be executed in order that corrections in the deductions drawn from the earlier surveys might be made, since those observations might influence both the theoretic conclusions as to the origin and manner of formation of the ore and the more practical ones as to the probable extent and location of as yet undiscovered ore bodies.

The gold deposits of Breece Hill, whose development has given new life to this important district, he does not regard as essentially different in origin and manner of formation from the deposits previously opened, in which the principal value lay in the silver content, the small gold content being neglected. These gold ores still carry a considerable amount of silver, and their increased percentage of gold is probably due to their proximity to a great mass of pyritiferous porphyry, which was shown by previous observations to be gold-bearing. Mr Emmons says:

> If I am correct in my present views, other valuable gold deposits will probably be found along the contacts between this porphyry and the adjoining limestones, but it is almost impossible to determine the probable location of such contacts, owing to the irregular shape of the porphyry intrusions.

The latter part of the field season was spent by Mr Emmons and his assistant, Mr. J. E. Spurr, in examining the Mercur district, in the Oquirrh Mountain range of Utah. This district has excited much scientific interest on account of the peculiar character and association of its gold-bearing ores, which are found in stratified limestones associated with cinnabar and realgar. It was found necessary to construct a detailed topographic map of an area of about 2½ miles square before platting the outlines of the different geologic formations. After getting the work well under way, Mr. Emmons left Mr. Spurr to complete the necessary field observations. The geologists found here a series of very thin sheets of eruptive rock lying approximately parallel with the stratification, which are probably offshoots from cross-cutting dikes. Immediately beneath these sheets ore deposits have formed, in which the values at the upper horizon are in gold and at the lower horizon in silver, the latter having been first formed and the gold deposits being apparently the result of subsequent mineralizing action. The ores occupy a narrow geologic horizon which is probably at the base of the Carboniferous limestone. Accurate and detailed work was done in this smaller area, and reconnaissance maps, both geologic and topographic, were made of the surrounding region, covering an area of about 60 square miles, for the purpose of showing the general geologic relations of the ore bodies. It is thought that the results obtained, when verified by the necessary laboratory experiments, will be of value to the miners and mine owners of the district, as well as of general scientific interest

A visit was also made to the mining districts of Breckenridge in Colorado and Tintic in Utah, for the purpose of determining the approximate area of the ore deposits in case it should be thought desirable later to make detailed examinations of either district.

Mr. Emmons's time was given almost exclusively during the remaining portion of the year to the preparation of the report on the Leadville district, and that of Mr. Spurr to the preparation of a report on the Mercur district. The latter was completed, and it appears in Part II of this Annual Report.

Hills party.—The survey of the iron and coal area of southern-central Colorado was placed in charge of Mr. R. C. Hills, of Denver, whose services were engaged for the purpose. Mr. Hills completed the field work on the Trinidad, El Moro, and Walsenburg sheets (which embrace in whole or in part the counties of Las Animas, Huerfano, and Pueblo), with the exception of certain details which he proposes to add during the ensuing field season. The area covered is fully 3,000 square miles. The results will be published as soon as the topography of the mountain portions of the tracts under consideration can be revised, in order to render them more suitable for the proper presentation of geologic structure

Cross party.—Mr. Whitman Cross was instructed to make a reconnaissance of the western portion of the San Juan Mountains and of the adjacent La Plata Mountains, within the gold and silver district of southwestern Colorado, for the purpose of determining the order in which it is best to take up the survey of the various mining districts of the San Juan region. He began field work by studying the sedimentary rocks of the Animas River and the Post-Laramie rocks that occur below Durango. He then visited the La Plata Mountains, and thence traversed the regions of the Rico (Dolores and Montezuma counties) and Telluride (San Miguel, Dolores, and San Juan counties) sheets, topographic surveys of which were being made at the time of his visit. This reconnaissance work covered an area of approximately 500 square miles, and it will greatly expedite the areal mapping and detailed study of the region during the field season of 1895–96.

Mr. Cross found the gold deposits of the La Plata Mountains to be poorly developed, although evidently of considerable extent throughout the group. The development appears to have been very greatly hindered by erroneous ideas of the geology of the mountains and by misapprehension of the character of the ore deposits. He found that the ores are chiefly impregnations of the Dakota and other sedimentary horizons in the vicinity of diorite stocks. It is thought that the detailed geologic map will be of great service as an aid in prospecting and developing, as the ores are not generally rich enough to be profitably worked except on the basis of a thorough understanding of the deposits themselves. The scientific results obtained from the reconnaissance are of great interest and add materially to our knowledge of the geology of the region of the San Juan area

After completing the work in the San Juan area, Mr. Cross proceeded to the Cripple Creek gold district, to make a detailed geologic map, on a large scale, of this important district. So far as known the Cripple Creek mining district is unique in the character of its geology. This fact, together with the extremely decomposed state of the rocks and the extent to which vegetation has covered the hills, makes it almost impossible for the miner and the mining engineer to gain a true conception of the local geology. It is thought that the detailed geologic map which has been made will be of service in the exploration of the mineral area. A study of the ore deposits was made by Prof. R. A. F. Penrose, jr, which will be of great service in clearly establishing the characteristics of the ore veins and in showing their relations to the geology

During the winter and spring Mr. Cross and Professor Penrose were engaged in preparing a report upon the Cripple Creek gold-mining district. This includes an extended paper which is published in Part II of this Annual Report, and a special geologic map, with text, which is to be inserted in the Pikes Peak geologic folio.

Hague party.—Mr. Arnold Hague has been engaged during the year with office work pertaining to the preparation of the geologic maps for the Yellowstone National Park folio and the monograph upon the same region. The preparatory work upon the folio atlas has been completed, and considerable progress has been made in the preparation of the monograph. Owing to the peculiar natural attractiveness of the area embraced within the limits of the park, the folio and monograph will be of unusual interest.

PACIFIC REGION.

This region embraces the territory lying between the Pacific coast on the west and approximately the one hundred and nineteenth meridian on the east.

Diller party.—Field work in northeastern California and southwestern Oregon was not taken up during the field season of 1895, as Mr. J. S. Diller was detained in Washington. He is now in Oregon, actively at work. The results of the operations of the field season will be reviewed in the next annual report.

In the office the greater part of Mr. Diller's time was given to the preparation of a bulletin to accompany the Educational Series of Rocks. As the preparation of the bulletin advances, the specimens of the series are prepared in the Petrographic Laboratory for distribution, 15,706 having been treated and numbered, and it is anticipated that the bulletin and collection will be ready for distribution at the same time. In order to make the bulletin most useful to teachers and students, it will contain, in addition to a full description of the rocks of the collection, a preliminary section devoted to the subject of the study of rocks The specific descriptions of more than one-third of the rocks of the collection have been completed, and the introductory portion, on the physical analysis of rocks, the principal rock-forming minerals, and the classification of rocks, has been written. In the work of preparing the descriptions Mr. Diller has been materially aided by the following persons: Prof. Joseph P. Iddings, University of Chicago, Chicago, Ill.; Prof. W. S. Bayley, Colby University, Waterville, Me.; Dr. Florence Bascom, State University, Columbus, Ohio; Prof. J. E. Wolff, Harvard University, Cambridge, Mass.; Prof. L. B. Pirsson, Yale University, New Haven, Conn.; Prof. C. R. Van Hise, University of Wisconsin, Madison, Wis.; and Dr. Waldemar Lindgren, of the United States Geological Survey.

Mr. Diller has general supervision of the Petrographic Laboratory of the Survey. The work of the laboratory is directly in charge of Mr. E. G Paul, who is assisted by Messrs. F. C Ohm and W. S. Robbins, all of whom have been continuously engaged in the preparation of specimens for study by the geologists, paleontologists, and petrographers of the Survey. The total number of thin or microscopic sections made during the year is 3,112. Specimens sawed, 987; specimens polished, 775; specimens trimmed, 750.

Turner party.—In continuation of his work of the previous year, Mr. H. W. Turner resumed the surveys in California. He completed the revision of portions of the south third of the Downieville sheet, after which he took up the Bidwell Bar sheet, the entire area of which was gone over and about 600 square miles mapped in detail. It will require about three weeks' additional field work to complete that sheet.

On the Bidwell Bar sheet the distribution of the gold veins in the talc schists and the amphibolite rocks was mapped, and the mode of occurrence of gold in barite, or heavy spar, on Big Bend Mountain was studied. The principal gold deposits, however, occur in altered eruptive rocks, all of which were studied in detail.

Mr. Turner also made collections of andalusite schist for the Educational Series of Rocks. A fact of scientific importance brought out by the season's work is that some of the metamorphosed Mariposa slates are thoroughly crystalline and contain abundant fossil shells, proving their Jurassic age. These rocks are the youngest of the sedimentary rocks forming the auriferous series of the Sierra Nevada

Mr. Turner spent the winter and spring in Washington in the study and preparation of material for the Downieville sheet and in the preparation of papers for journal publication.

Lindgren party—Mr. Waldemar Lindgren surveyed an area of 950 square miles in Eldorado and Amador counties, Cal., comprising the Pyramid Peak sheet of the Gold Belt. He also completed the survey of the Nevada City and Grass Valley special maps, covering parts of Nevada County. Comparative studies were made of the mines along the Mother Lode of the Gold Belt and the districts previously surveyed. These studies led to the determination of certain leading and characteristic features of the gold-quartz veins of California, which may be of service in future development in that region.

A study was made of the granitic rocks of the Sierra Nevada, which are typically represented in the Pyramid Peak sheet. The character of the Neocene topography of the Sierra Nevada was also studied, and a determination was made of the eastern margin of the gold-bearing region in the latitude of the Pyramid Peak sheet.

In the office Mr. Lindgren was occupied during the winter and spring in the preparation of the special maps of the Nevada City, Grass Valley, and Banner Hill mining districts. The maps, sections, and descriptive texts were all completed, and in addition some time was given to the Marysville and Smartsville sheets, which were in part revised and rewritten. A detailed microscopic study was made of some of the rocks of that part of the Gold Belt in which Mr. Lindgren's field of work is located, and a part of the final report was written.

Lawson party.—The work in the vicinity of San Francisco was conducted by Dr. Andrew C. Lawson, who mapped 27 square miles of the areal geology of the Concord sheet, which covers parts of Alameda and Contra Costa counties, and about the same amount of the areal geology of the San Francisco sheet, which embraces San Francisco Bay and County and parts of San Mateo, Contra Costa, and other counties. This mapping has advanced several lines of investigation, both economic and scientific. The question of artesian water supply is of much importance to the numerous towns on the eastern side of San Francisco Bay, and a knowledge of geologic structure is necessary in order to carry on the exploitation for water.

Much of the area mapped consists of a peculiar siliceous shale which in the southern portion of the State is characterized by the presence of oil and asphaltum. The study of the stratigraphy of these rocks will advance the knowledge of their nature and origin and enable the geologist to advise more intelligently touching any prospecting that may be undertaken in the vicinity of San Francisco with a view to the discovery of these useful products. Information was also acquired in relation to the distribution of limestone, building stone, clays, and materials suitable for macadamizing public highways and for railroad ballast, all of which are in local demand.

The scientific results are contributions to the data which are accumulating with respect to the geology of this portion of the Coast Ranges. Large collections of fossils were made by Dr J C. Merriam and Mr. F. L. Ransome, temporary assistants.

In the time at his disposal Professor Lawson redrew the areal and structural geology surveyed in the field, wrote out field notes, and made studies of the materials collected.

FIELD WORK BY THE DIRECTOR

In September the Director proceeded to Denver, Colo , where he consulted with a large number of mining engineers and others interested in geologic work in Colorado. From Denver he went to Cripple Creek, in the same State, in company with Mr. S. F. Emmons, of the Survey staff, and visited the district in which Messrs. Cross and Penrose were conducting work. The next stop was at Big Pine, Inyo County, Cal., where a camp outfit had been received by Mr. F. B. Weeks, who accompanied the Director as a field assistant and stenographer. Two weeks were spent in a reconnaissance of the White Mountain Range, which extends along the boundary between California and Nevada. It resulted in the determination of the general structure of the range mentioned and the discovery of the fact that the rocks forming it are of essentially the same geologic age as those of the Basin Ranges of western Utah and Nevada, and that the Cambrian rocks, which had hitherto been unknown in California, occur in great development in the White Mountain Range. On the completion of this reconnaissance the Director proceeded to San Francisco and held numerous conferences with mining engineers, geologists, and others, not only in the city, but also at the University of California and at the Leland Stanford Junior University. Portland, Oreg., was next visited for the same purpose; and conferences were held in Seattle, Wash , and Boise, Idaho, with reference to the work of the Survey in the Northwestern States, before returning to Washington on November 1.

DIVISION OF PALEONTOLOGY.

The field work of the paleontologist is usually undertaken with a view to obtaining paleontologic evidence upon which to base determinations of the stratigraphic succession of the rocks and of their age in the geologic series when broken or disturbed by faulting or folding. Incidentally, the paleontologists frequently make determinations of paleontologic material for the officers of State geological surveys and of educational institutions, inasmuch as such institutions often lack the collections and libraries that are necessary for the making of their own determinations. The knowledge thus gained by the expert is in nearly every instance a full equivalent to the national Survey for the service rendered. Private students likewise frequently make application for aid of this kind, and their requests are often complied with.

The work on the Paleozoic fossils was in the immediate charge of the Director. In the field collections were made from the Cambrian rocks of northern Alabama and eastern California. Some assistance was given Prof. H. S. Williams in his work on the Devonian faunas, Prof. Alpheus Hyatt on the Triassic fauna, and Dr. R. R. Gurley in the preparation of material for a monograph of North American graptolites. Mr. G. H. Girty was appointed an assistant in April, and worked on the collections from the Middle Cambrian. A number of collections of Devonian and Carboniferous fossils were identified by Mr. Charles Schuchert, of the United States National Museum, the most important of which is that from the Yellowstone National Park.

Stanton party.—Mr. T. W. Stanton was engaged in central California in the study of the Cretaceous and Eocene strata of the Coast Ranges, the primary object being the determination of the field relations of the Upper Cretaceous (Chico) and the Eocene (Tejon), and the collection of stratigraphic data and of fossils for a comparative study of these formations. The localities visited are all in the area between Clear Lake on the north and New Idria on the south. The evidence collected shows that the Chico and the Tejon have very distinct faunas, and that the supposed blending of the two faunas was largely due to errors in identification of both strata and species.

In October Mr. Stanton joined Mr. H. W. Turner's party, and spent about ten days with it, searching for fossils to aid in the determination of horizons in the areas then being mapped. Later an examination was made of the Lower Cretaceous beds in the neighborhood of Riddles, Oreg. A large collection of fossils was obtained, and the Horsetown and Knoxville beds of this region were clearly discriminated

Mr. Stanton next proceeded to Fort Benton, Mont, and joined Mr. W. H. Weed, for the purpose of examining the Cretaceous strata exposed along the Missouri River from Fort Benton to the mouth of the Judith River.

As in previous years, a considerable portion of Mr. Stanton's time was devoted to examining and reporting on the Mesozoic fossils collected by the geologic field parties of the Survey. The larger part of his own collection was also identified and made available for study. The Jurassic and Triassic fossils of the Yellowstone Park were studied, and the report of the results includes descriptions of new species and notes which will be published in connection with Mr. Hague's work.

The collections from the Knoxville (Lower Cretaceous) beds of California were studied and the new forms included in a paper on the fauna of the Knoxville formation, which was presented by Mr Stanton for publication and will appear as Bulletin No. 133 of the Survey series.

Dall party.—Dr. W. H. Dall, accompanied by Mr. J. B. Woodworth, one of Professor Shaler's assistants, visited Marthas Vineyard, Mass., for the purpose of studying the Tertiary beds of the Gay Head section. An examination was also made of similar beds on Block Island. The results of these observations are: (1) The establishment of the Miocene age of the fossiliferous strata and their reference to the upper part of the Chesapeake Miocene; (2) the discovery of Pliocene strata in the section, hitherto unrecognized; and (3) the determination of some drift fossils found on Block Island as of accidental occurrence. The stratigraphic determination resulted in showing the Miocene age of the phosphate rock of South Carolina, which had before been regarded as Eocene.

In November Dr. Dall's assistant, Mr. Frank Burns, visited Mississippi and western Alabama, and later western Florida, for the purpose of obtaining a series of Tertiary fossils of that region and of determining whether or not certain collections previously made were mixed material from distinct beds of different age. Mr. Burns secured large collections of Tertiary fossils, and, incidentally, a number of remains of Zeuglodon, which will form the fullest series now known of that curious animal.

Dr. Dall has reported upon the various collections submitted to him by members of the Survey in order to determine the age of the beds in which fossils were found. He also prepared a number of papers on the subject-matter of his work. This includes a monograph on the Tertiary Mactridæ and an essay on the classification of the bivalve shells. Mr. Burns's time was given principally to the cleaning, separating, and arranging of the field collections and the selecting of duplicate sets for exchange.

Dr. Dall reports that he received courtesies during the year from various private individuals interested in the progress of geology, especially from Mr. Joseph Willcox, Mr Charles W. Johnson, Mr. H. A. Pilsbry, and Mr. F. J La Penotière.

Ward party.—The most important field work of Prof. Lester F. Ward, paleobotanist, was the correlation of the older Potomac formation of the Atlantic Coastal Plain with the later Tuscaloosa formation of the Gulf States. In company with Prof. Arthur Bibbins, of Baltimore, he visited various localities of the iron-ore region of Maryland, and made considerable collections of fossil plants, which determined the age of the iron-ore beds. With Dr. Arthur Hollick, of New York, a reconnaissance was made of a number of localities on Long Island and in New Jersey, and important collections were obtained. Later in the year Professor Ward visited Tuscaloosa, Ala., and thence traced the Tuscaloosa formation across Georgia into South Carolina, and on through Aiken to Columbia. Accompanied by Prof. W. M. Fontaine, of the University of Virginia, and Prof. J. A. Holmes, State geologist of North Carolina, Professor Ward made an examination of the formations in the vicinity of Weldon, N. C., and visited various places on the line of the strike of those formations southward to the South Carolina boundary, correlating, in connection with the work of the previous year, the formations of the Potomac horizon throughout the Atlantic Coastal Plain.

In order to obtain data for comparison with the European formations, Professor Ward took leave of absence during the summer and visited various parts of Europe. In England he made a special study of plant-bearing formations, and in France, Portugal, and Italy he made examinations of large and important collections in various museums, public and private. While in Europe he attended the International Geological Congress, which was held in Zurich, Switzerland.

Professor Ward's principal work in the office related to the preparation of a paper on "Some Analogies in the Lower Cretaceous of Europe and America," which is published in this report. Work on the "Compendium of Paleobotany" was steadily advanced by Miss L. M. Schmidt, under Professor Ward's general supervision.

In the advancement of the report upon the fossil plants of Marthas Vineyard and Long Island, Professor Ward had the efficient cooperation of Dr. Hollick, who began work upon the collections and will prepare a report for publication as a bulletin of the Survey. He also had the valuable aid and cooperation during the year of Professoı Fontaine, who undertook the study of a large collection of fossil plants sent in by Dr. W. P. Jenney from the Lower Cretaceous of the Black Hills. Further mention should be made also of the valuable aid rendered during the year by Professor Bibbins, who extended to Professor Ward many courtesies in presenting and loaning rare specimens and in furnishing information in relation to the plant-bearing formations of Maryland.

Knowlton party.—It was deemed best that Dr. F. H. Knowlton should devote his time entirely to the study of collections already in hand and the writing of reports upon the same. The first six months of the year were given to the revision of the flora of the Laramie and allied formations. This work, which had previously engaged his attention, was resumed and pushed to practical completion It embraces the description of about 400 species of plants, and will be of service in working out the stratigraphic succession of the series of rocks in which the coal seams of the Laramie formation of the Rocky Mountains occur. On the completion of this task Dr. Knowlton took up the study of the rich collections of plants from the Yellowstone Park. At the close of the fiscal year more than 100 species had been determined and 200 pages of manuscript prepared. Over 50 per cent of the species were found to be new, and these were carefully described. The study of the Yellowstone collections thus far has resulted in the complete differentiation of three horizons by means of the plant remains, viz, Laramie, Fort Union, and Miocene. In addition to these more important studies, many small collections were determined by Dr. Knowlton from time to time, as they came in from members of the Survey and others.

Marsh party.—Prof. O. C Marsh continued the study of the collection of vertebrate fossils gathered by him during the period 1882 to 1890. The general work on the monographs was continued, and the special paper on the "North American Dinosaurs" which is published in this report was prepared

DIVISION OF CHEMISTRY.

Prof. F W Clarke, chief chemist, was in charge of the division during the year. He was assisted by Dr. W. F. Hillebrand, Mr. George Steiger, and Dr. H. N. Stokes. Some important cooperation was also secured from Prof. C. E. Munroe, of the Columbian University. The larger part of the work was in the line of routine analyses, of which 304 were made and reported during the year. Of these some of the more important were those of 42 phosphates from Florida, 12 phosphates from Tennessee, 25 coals from West Virginia, and a large group of rocks collected in the mining districts by Mr. W H. Weed in Montana, Messrs. H. W. Turner and Waldemar Lindgren in California, and Mr. Whitman Cross in Colorado Some detailed and elaborate chemical work was done by Dr. Hillebrand on ores from Cripple Creek and Leadville, Colo., and from the Mercur district in Utah. Dr. Stokes analyzed two meteoric irons, one from Cherokee County, Ga., and the other from El Capitan Mountain, Lincoln County, N. Mex.

Professor Clarke was employed largely in administrative work in connection with the Department of the Interior exhibit at the Cotton States and International Exposition, at Atlanta, and in the preparation of a paper on the "Constitution of the Silicates," which has already been published as Bulletin No. 125 of the Survey. This bulletin sums up results of studies made during the past eleven years, and presents in complete form the general theory upon the subject. Other purely scientific work done in the laboratory during the year is an investigation by Dr. Hillebrand into the estimation of titanium and an elaborate research by Dr. Stokes upon the chloro-nitrides of phosphate. The latter investigation led to the discovery of a remarkable series of acids containing phosphorus and nitrogen, which are still under examination.

DIVISION OF HYDROGRAPHY.

This division was placed on a permanent footing by a provision contained in the sundry civil act approved August 18, 1894, which reads as follows.

> For gauging the streams and determining the water supply of the United States, including the investigation of underground currents and artesian wells in arid and semiarid sections, twelve thousand five hundred dollars.

This definite recognition of the value of the hydrographic work of the Survey gave it new life, and for the first time rendered possible the extension of field work and the carrying forward with thoroughness of the examination of the water resources of the country.

The surveys and examinations now under way were initiated by the Irrigation Survey created by act of Congress in 1888. Previous to that time some stream measurements and studies of the water supply, especially of the arid public-land States, had been made by geologic and topographic parties, but the systematic work may be said to have begun in 1888. The Irrigation Division of the Geological Survey ceased to exist on August 30, 1890, owing to lack of further appropriations, but under the wording of laws still in force the Geological Survey was authorized to continue some related investigations of a scientific character. Among these were questions of water supply for the arid region, including the location and volume of the rivers. The field work of this division, being related to the general mapping of the country, was carried on in connection with topographic surveying. The greater part of the work, however, was in the office, and consisted of completing and preparing for publication data which had been obtained by the Irrigation Survey.

Mr. F. H Newell was continued in charge of the hydrographic work. The general work of the division may be summed up as (1) field operations, consisting of the measurement of the volume of water in various streams, mainly in the western part of the country, and (2) office work, consisting of various lines of investigation through the use of printed schedules, preparation of results for publication, and general correspondence with all classes of citizens

Field work was begun as soon as possible after the appropriations were made. The first operations consisted of river measurements and the reestablishment of stations in Colorado. The general supervision and inspection of Western river work was assigned to Mr. Arthur P. Davis, who was transferred from the Topographic Branch. His long experience in Western work, his thorough acquaintance with the country, and his strong personal interest in all matters pertaining to irrigation development and water supply render his services exceptionally valuable and efficient. Mr. Newell visited a number of river stations with Mr. Davis and arrived at a thorough understanding as to the methods and results desired. Mr. Davis then visited points in Utah, Idaho, Washington, Oregon, California, Arizona, and New Mexico, spending nearly five months in this general trip before taking up work in Kansas. The work in these States having been laid out, Mr. Newell proceeded to the east and north, in order to obtain general information concerning the local conditions and to start field work in the subhumid States. The services of Prof. Robert Hay were secured, and under general directions he made a reconnaissance of the country along the one hundred and second meridian, from a point near the North Platte River in Nebraska, through eastern Colorado and western Kansas, to a point on the headwaters of Smoky Hill River. This reconnaissance occupied portions of October, November, and December. Upon its completion the results were at once prepared for publication by Professor Hay, and they may be found in one of the papers accompanying Part II of this Annual Report.

Mr Newell next went to the James River Valley, in South and North Dakota, visiting the artesian wells at various points and obtaining a personal acquaintance with the conditions prevailing there. Later he measured the St. Louis River at Cloquet, Minn., and, going southward through Kansas and Oklahoma to Texas, met Prof. Robert T. Hill, with whom he spent some time examining the springs and artesian conditions of a portion of the last-named State.

In the latter part of 1894 field work in the East was resumed, Mr. Cyrus C. Babb, who had formerly assisted in stream measurement, being placed in immediate charge The stations on the Potomac River were renewed and extended so as to cover systematically this important drainage system. Preliminary work was also begun looking toward an investigation of the rivers of Maine and other New England States. Later in the season, the appropriation for the next fiscal year being assured, similar work was started in Virginia and North Carolina, with the intention of taking up a systematic examination of the water powers of the Appalachian area.

The office work of this division is in many respects as essential as the field work, and at all times demands careful consideration. In addition to the correspondence with field assistants and observers, independent investigations have been set on foot by means of schedules. These are designed to obtain general information from every part of the country concerning its water resources and needs. The replies can not be expected to be exact or wholly reliable, but they serve to indicate the ideas and wants of the people, and round out or confirm many of the statements of facts the bare details of which were obtained through exact measurements. The replies to these schedules are systematically filed for reference and are consulted whenever reports concerning any particular area are in course of preparation. The inquiries sent out from this office, and also the reports issued from time to time, necessarily give rise to a somewhat voluminous correspondence, resulting in a diffusion through newspapers and other channels of publication of the facts which later are embodied in official publications. Every attempt is made to give the utmost publicity to this work in order that the results may be utilized by those interested at the earliest moment.

A brief review of the operations of the fiscal year can best be given by States, arranging these in alphabetical order:

Arizona.—The attempt to maintain work in this Territory has not as yet been successful, owing largely to the expense of transportation and the great distance from towns of points at which river measurements can be made. The only station of interest now maintained in this Territory is that at Yuma, on the Colorado River, this being conducted in connection with river measurements in California. The need of further work in the Territory is apparent, but the expense of taking it up on a suitable scale is so great that, with present appropriations, it seems hardly feasible.

California.—The work in this State has been carried on by Mr. J. B. Lippincott, of Los Angeles, who, with the assistance of Mr. Arthur P. Davis, established a number of stations and has expanded the work as far as expenditures can be authorized. Measurements of the Sacramento, of tributaries of the San Joaquin, and of a few southern streams have been made. The river stations in this State, though widely scattered, are relatively accessible to railroad lines, and therefore the demand for information can be more readily met than in some of the less advanced areas.

Colorado.—This State is one of the few having an engineer or official charged with the consideration of the distribution of waters for irrigation. The duties of the State engineer are, however, so varied in character that it is only occasionally that this officer can devote time or funds to investigation of water supply. Mr. Arthur P. Davis has arranged for cooperation by which the facilities possessed by the State engineer will be shared by this Survey and the measurement of streams pushed forward in the most economic manner possible. Besides the stations previously established on the Arkansas and Rio Grande rivers others have been established in the western and southwestern portions of the State.

Idaho—Mr V C Tompkins, of Boise, has undertaken the supervision of river measurements in this State and has conducted them successfully By act of legislature of March 9, 1895, the office of State engineer was created, and Mr F J Mills, the lieutenant-governor, was appointed to the place Mr Tompkins is working in harmony with Mr Mills, to the end that the data collected for the benefit of the Geological Survey shall be of immediate utility in the State engineer's office

Kansas—In the western part of this State Prof Robert Hay conducted a reconnaissance, previously mentioned, and later Mr Arthur P Davis established a number of river stations at points where the results appear to be of the first importance In this work he was aided by the State Board of Irrigation, the observers at a number of points being employed by the State

Montana—Prof A M Ryon, of Bozeman, has had supervision of the measurements of the tributaries of the upper Missouri The station on the Yellowstone has been abandoned, owing to the death of the observer, but it is intended to continue and expand these observations at the earliest opportunity

Nebraska—Measurements of the Platte and Republican rivers have been made by Prof Oscar V P Stout, of Lincoln, Nebr, who has taken a personal interest in the work, and also brought to bear on it facilities possessed through his connection with the State University At North Platte a number of measurements of the North Platte River have been made by Mr Charles P Ross In addition, some work was done in the western part of the State by Prof Robert Hay, as before mentioned

Nevada—River stations were established on the Humboldt and other streams by Mr L H Taylor, of Reno, who, through his acquaintance with the needs of the State, has been induced to take up work of this character In this State, as in Arizona, the expense of transportation and the inaccessibility of important points have operated to deter rapid extension of field work

New Mexico—The stations in this Territory have been under the charge of Mr P E Harroun, of Santa Fe, a resident engineer connected with various local improvements He has given the greater part of his time to consideration of problems along the Rio Grande, having made measurements at various points from Embudo to El Paso, Tex.

North Dakota.—In this State a reconnaissance was made in the fall of 1894, and considerable information has been collected through the topographic parties and by means of schedules. The problems in this State at present under consideration are mainly connected with deep artesian wells, as the rivers offer peculiar difficulties, not only to their utilization for irrigation, but also to obtaining accurate measurements of them.

Oregon.—The investigation of water resources in the western part of this State has been carried on by Mr. V. C. Tompkins, in connection with his work in Idaho. It has been possible for him to visit some of the more important eastern rivers of the State, these being more accessible from the Idaho side than from the more populous centers of Oregon.

South Dakota.—A reconnaissance of this State was made in connection with that of North Dakota, and at a later time schedules were sent out in the attempt to obtain recent information concerning the artesian wells. The information is being brought together for publication, and, when supplemented by field work, should be of considerable value to the State.

Texas.—Besides the reconnaissance in this State made in the fall of 1894, a considerable amount of information has been obtained by means of schedules sent to owners of artesian and deep wells. The geologic work of Prof. Robert T. Hill is throwing light upon the structural problems, and will lead to an interpretation of many facts at present apparently anomalous. A number of large springs were measured, but no permanent stations have been established.

Utah.—Prof. Samuel Fortier, of Logan, Utah, who has given much of his own time to the study of the water resources of the Territory, has taken local charge, and has pushed forward the work vigorously whenever opportunity offered. With the assistance of Mr. Arthur P. Davis, he restored many of the old stations, and, later, established new ones, these being mainly upon streams belonging to the Salt Lake drainage.

Washington.—In this State Mr. Samuel Storrow, of North Yakima, has undertaken measurements of the Yakima River and its tributaries Various causes have, however, conspired to prevent the extension of the work beyond this basin, although the attempt is being made to do so.

Wyoming.—Prof Elwood Mead, State engineer, has assumed the supervision of the details of river work in this State, and with his assistant, Mr W. M. Gilcrest, is conducting a series of measurements upon the North Platte, Laramie, Green, and other important streams.

Eastern States.—In Maryland, Virginia, and West Virginia measurements of tributaries of the Potomac River were carried on during the spring of 1895, and preparations have been made to extend this work, with the ultimate object of ascertaining the water power available from the streams of the Atlantic Slope, and also from those tributary to the Mississippi River. A number of localities have been selected in North and South Carolina, Virginia, and West Virginia at which it is desired to establish river stations.

The details of the location of the river stations and of the results accomplished at each have been prepared for publication as Bulletin No. 131 of this Survey, covering the calendar years 1893 and 1894. In addition to this, a paper has been written by Mr. Newell relating mainly to the vacant public lands of the United States and their water supply, it being a review of the present condition of the public domain and of what is now known of the amount of water available for its development. This paper will be found in Part II of this Annual Report

DIVISION OF MINERAL RESOURCES.

The Division of Mineral Resources, under the charge of Dr David T Day, was engaged during the year in the preparation of the eleventh annual report on the Mineral Resources of the United States The first ten volumes constitute a distinct series, but under an act of Congress approved March 2, 1895, the volume on Mineral Resources becomes a part of the Director's Annual Report; thus the eleventh report of this series, for the calendar year 1894, becomes Parts III and IV of this Annual Report. By authority granted in the act mentioned, the principal chapters were sent to the Public Printer in advance of the complete report, and a pamphlet edition of them has been issued This has been done heretofore through the courtesy of the several Secretaries of the Interior.

The following review from the report presents a summary of the chief developments in the mineral industries during the calendar year 1894:

Comparing the total value of the product in 1894 with the value of 1893, a great decline is evident, the obvious cause of which is the general financial depression. But besides this general depressing element there were several special features which affected the net result. The most notable was the strike of the bituminous coal miners, which accounts quite largely for the greatly decreased production and increase in price for part of the year The strike naturally increased the use of anthracite, which partially made up for the decreased demand for this substance due to the depression of manufactures The low price of silver is responsible for the decreased production of that metal. The consumption of petroleum exceeded the production, greatly decreasing the stocks at the wells and increasing the price. The other principal features are summarized below.

METALS

Iron and steel.—The declining tendency noted in the report for 1893 continued in 1894. The production of pig iron decreased from 7,124,502 long tons in 1893 to 6,657,388 long tons in 1894. The decrease in value was nearly $20,000,000; from $84,810,426 in 1893 to $65,007,247 in 1894. The value of the pig iron produced in the United States in 1894 was less than half that in 1892, two years previous, though the decline in production was only about 27 per cent Production of steel of all kinds increased from 4,019,995 long tons in 1893 to 4,927,581 tons in 1894 Limestone used for iron flux in 1894 was 3,698,550 long tons, valued at $1,849,275, against 3,958,055 long tons, valued at $2,374,833, in 1893.

The total product of iron ores in 1894 was 11,879,679 long tons, valued at $13,577,335, as compared with 11,587,629 long tons in 1893, valued at $18,265,273. This is an increase in production of 292,050 long tons, though the value decreased $4,687,938. The value per ton in 1894 was $1.14, as compared with $1.66 in 1893

Gold and silver.—The gold product increased from 1,739,081 troy ounces, with a coining value of $35,950,000, in 1893 to 1,910,816 ounces, worth $39,500,000, in 1894 This product is the largest since 1878. Silver production declined in 1894, so that the total was less than in 1893 by over 10,000,000 ounces, as follows: 1893, 60,000,000 ounces, coining value $77,575,757; 1894, 49,501,122 ounces, coining value $64,000,000.

Copper.—The industry took little notice of the depressed money market and the decreased consumption, but showed a noteworthy increase. The product from American ores aggregated 360,844,218 pounds, valued at $33,141,142, against 337,416,848 pounds in 1893, worth $32,054,601. In addition 6,655,844 pounds were produced in 1894 from imported pyrites. The necessary expenditures were also made for keeping up future production.

Lead—Product: 159,331 short tons, worth $9,942,254, compared with 163,982 short tons in 1893, worth $11,839,590.

Zinc.—The rapidly increasing product of late years was checked in 1893 and 1894 and a slight decline noted in both years Product: 75,328 short tons, valued at $5,288,026, compared with 78,832 short tons, worth $6,306,560, in 1893, and 87,260 short tons, worth $8,027,920, in 1892.

Quicksilver—The product showed a noteworthy increase, from 27,993 flasks in 1892 to 30,164 flasks in 1893 and 30,416 flasks in 1894 The price fell, making the total value $934,000 in 1894, $1,108,527 in 1893, and $1,245,689 in 1892. The increased product came chiefly from the New Almaden, Mirabel, and Ætna mines.

Manganese—The quantity declined from 7,718 long tons in 1893 to 6,308 tons in 1894. This was less than half the output in 1892. This decrease was caused principally by the exhaustion of the Virginia pockets of ore. The product of manganiferous iron ore increased, while manganiferous silver and zinc ores declined in product and value.

Aluminum—The usual increase in product continued. In 1893, 339,629 pounds were made, chiefly by the Pittsburg Reduction Company; it was valued at $266,903 in the producer's hands In 1894 the output was 550,000 pounds; value, $316,250. The largest single use is for adding to steel before casting. It is also used for improving iron castings, for ornamental fancy articles, and for aluminum cooking utensils, which are being generally introduced.

The Southern deposits of bauxite furnish more and more of the raw material.

Tin.—More careful examinations of the Kings Mountain, North Carolina, locality furnish indications of considerable ore which may yield 3 per cent No work was done at the other deposits.

Nickel.—The United States product was greatly reduced, amounting to only 9,616 pounds, less than one-fifth the output in 1893 and not much more than 10 per cent of the product in 1892. The Nevada and Oregon mines have not become producers, but prospecting and development continues. The New Caledonia mines increased their product.

Antimony.—The value decreased from $45,000 in 1893 to $36,000 in 1894. The product came from Nevada and was smelted in San Francisco

Platinum.—Product from the gold placers is still insignificant. The production in 1894 was 100 ounces, valued at $600.

FUELS

Coal.—The product of coal of all kinds in 1894 was 152,447,791 long tons, or 170,741,526 short tons, valued at $186,141,564, against 162,814,977 long tons, or 182,352,774 short tons, valued at $208,436,696, in 1893 This indicates a decrease in 1894 of 10,367,186 long tons, or 11,611,248 short tons, or about 6 per cent, and a decline in value of $22,297,132, or a little over 10 per cent. The product in 1894 consisted of 46,358,144 long tons, or 51,921,121 short tons, of Pennsylvania anthracite, a decrease from 1893 of 1,827,262 long tons, or 2,046,422 short tons, and of 106,089,647 long tons, or 118,820,405 short tons, of bituminous coal (including scattering lots of anthracite from Colorado and New Mexico), a decrease compared with 1893 of 8,540,916 long tons, or 9,565,826 short tons. The value of Pennsylvania anthracite decreased from $85,687,078 in 1893 to $78,488,063 in 1894, a loss of $7,199,015 The value of bituminous coal declined from $122,751,618 to $107,653,501, a loss of $15,098,117. The average price per ton for marketable anthracite declined from $1.94 per long ton in 1893 to $1.85 in 1894. In arriving at the average price for anthracite the amount of coal used at the collieries is not included. This factor consists of culm, or slack, which would otherwise be thrown on the dump and wasted, and no account of it is taken in the valuation. The average price of bituminous coal declined from 96 cents in 1893 to 91 cents in 1894. In determining the average price of bituminous coal all the coal mined and not actually thrown away is considered.

In addition to the general trade depression and decline in values, which affected both the anthracite and bituminous interests; the production of bituminous coal was seriously disturbed by a prolonged strike, inaugurated in April and continuing in some cases until September. The adverse influences of this strike were felt in nearly all the important producing centers, particularly in the Appalachian, Central, and Western fields. The anthracite and a few bituminous regions which were not affected by the strike were temporarily benefited The Pocahontas region in Virginia and West Virginia, some portions of the New River and Kanawha, and the Upper Monongahela regions in West Virginia, and some portions of Kentucky, were exempted from its operations, and for a while production in these regions was greatly stimulated and increased prices for the product were obtained; but the temporary benefit derived from the disturbance in other regions was not sufficient to offset the general decline in values, and the output for the year even in these favored regions shows a decrease in value compared with the preceding year. An estimate of the loss to the labor interests, based upon the average number of employees and the average working time in 1894 compared with 1893, shows one day's labor lost by 5,167,357 men, or

17,224 men thrown out of employment for a full year of 300 working days. Computing the average wages per diem at $3, a total loss in wages to the miners and other employees thrown out of work amounted to $15,502,071.

Coke.—The total product of coke in the United States in 1894 was 9,196,244 short tons, as compared with 9,477,580 short tons in 1893. There was a slight increase of coke-made pig iron, from 5,390,184 long tons in 1893 to 5,520,224 long tons in 1894, which would indicate an increased production of coke for iron reduction.

Petroleum.—The most notable features in connection with the production of petroleum in 1894 are: (1) The continued decline in production in the older fields and the increase in the newer, especially in the Lima-Indiana field and California, the total production of the United States showing an increase; (2) the increase of consumption over production and heavy decline in stocks at wells; and (3) the increase in price as compared with 1893.

Pennsylvania declined from 19,283,122 barrels in 1893 to 18,077,559 barrels in 1894; New York, from 1,031,391 barrels in 1893 to 942,431 in 1894 West Virginia about held its own, the production being 8,445,412 barrels and 8,577,624 barrels in 1893 and 1894, respectively. Ohio increased from 16,249,769 barrels in 1893 to 16,792,154 barrels in 1894. The chief increase in this State was in the Macksburg or Eastern Ohio district, the Lima district producing about the same as in 1893. Indiana increased from 2,335,293 barrels in 1893 to 3,688,666 barrels in 1894. Colorado decreased from 594,390 barrels in 1893 to 515,746 barrels in 1894, and California increased from 470,179 barrels in 1893 to 705,969 barrels in 1894 The stocks held at the wells declined from 12,316,611 barrels at the close of 1893 to 6,499,880 barrels at the close of 1894.

The total increase in the United States was from 48,412,666 barrels in 1893 to 49,344,516 in 1894

The average value of certificate oil in the Appalachian field in 1894 was 83⅞ cents, as compared with 64 cents in 1893, an increase of 19⅞ cents. In the Lima field the average price advanced from 47¼ cents in 1893 to 48 cents in 1894. The total value of the 48,412,666 barrels produced in 1893 was $28,932,326, or 59¾ cents per barrel, while the product of 1894, 49,344,516 barrels, was worth $35,522,095, or nearly 72 cents per barrel.

The exports in 1894 were 908,225,314 gallons, being over 100,000,000 gallons more than in 1893. This is the largest export yet recorded.

STRUCTURAL MATERIALS.

Stone.—The value of the total product of stone of all kinds increased from $33,885,573 in 1893 to $37,377,816 in 1894. The increase noted is probably not so much due to an increase in actual production as it is to the fact that the canvass of the stone producers of the country for this year is a complete census.

Soapstone.—The production of soapstone in the form of slabs, etc, amounted to 23,141 short tons in 1894, worth $401,325, compared with the production of 21,071 short tons in 1893, worth $255,067. The production of fibrous talc in 1894 was 39,906 short tons, worth $435,060, compared with 35,861 short tons in 1893, worth $403,436.

Clays—For the first time in the history of the Geological Survey an attempt has been made to make a complete canvass of the clay-workers of the United States. This work has been highly satisfactory, and the value of the clay products is shown to be $65,389,784. The only figures with which comparison can be made is the statement published by the Eleventh Census, which shows that the value of the finished brick, tile, terra cotta, etc., in 1890 was $67,770,695.

Cement.—The production of natural-rock cement increased slightly; that is, from 7,411,815 barrels in 1893 to 7,563,488 barrels in 1894. Artificial Portland cement increased from 590,652 barrels in 1893 to 798,757 barrels in 1894. The value of natural-rock cement decreased from $5,104,708 in 1893 to $3,646,608 in 1894; that of Portland increased from $1,158,138 in 1893 to $1,383,473 in 1894, making a total value of all cements in 1894 of $5,030,081, as compared with $6,262,846 in 1893. This decrease in total value is due to the fact that the value of the barrels is not included in the 1894 figures, while it has been included heretofore.

ABRASIVE MATERIALS

Millstones—The value decreased from $16,645 in 1893 to $13,887 in 1894. The product came from New York, Pennsylvania, and Virginia.

Grindstones.—The value in 1894 was $223,214, as compared with $338,787 in 1893. These values include $10,143 and $19,159 worth of whetstones made from sandstone, chiefly in Ohio, in 1894 and 1893, respectively.

Corundum and emery.—The product decreased slightly in 1894, or from 1,713 short tons, worth $142,325, in 1893 to 1,495 short tons, worth $95,936, in 1894.

Oilstone.—The Arkansas, New Hampshire, and other whetstones made in 1894 from novaculite had a value of $136,873, against $135,173 in 1893. This does not include the sandstone product of Ohio.

MINERALS USED FOR CHEMICAL PURPOSES.

Phosphate rock.—Florida produced 527,653 long tons and South Carolina 429,218 long tons in 1894, as compared with 438,804 long tons and 502,564 long tons in 1893. The value of Florida's product in 1894 was $1,666,813, and South Carolina's $1,662,017, making a total of $3,328,830 The total value of this product in 1893 was $4,136,070. The chief event of importance in 1894 was the appearance of Tennessee in the list of producing States. The product in this State in that year was 19,188 long tons, worth where produced $67,158. Tennessee promises to be in the future an important producer of a high grade of phosphate rock.

Marls.—The local use of marls in New Jersey, Virginia, and Alabama continues to decrease, being displaced by commercial fertilizers

Gypsum.—The product in 1894 was 239,312 short tons, worth $761,719; in 1893 it was 253,615 short tons, worth $696,615.

Salt—The product in 1894 was 12,967,417 barrels (of 280 pounds each), which was an increase over the product of 1893, when 11,816,772 barrels were produced. The total value shows an increase from $4,054,668 in 1893 to $4,739,285 in 1894.

Bromine.—The increased price noted in the last report has declined very slightly, the product in 1894 being 379,444 pounds, worth $102,450, compared with 348,399 pounds in 1893, worth $104,520.

Iodine—Search is still being made for large quantities of salt brines containing even traces of iodine, with a view to using new processes for extracting it.

Sulphur.—The product continues to decrease. In 1894 it was 500 short tons, worth at Salt Lake City $20,000. In 1893 it was 1,200 short tons, worth $42,000. This product, as heretofore, comes entirely from the Western mines.

Pyrites.—The product increased from 83,277 long tons in 1893, worth $275,302, to 105,940 long tons in 1894, worth $363,134 New sources of supply are being developed in North Carolina.

Borax.—The product increased from 8,699,000 pounds in 1893, worth $652,425, to 14,680,130 pounds in 1894, worth $974,445. This entire product came from California and Nevada.

Fluorspar.—The product and value of this substance showed a decline in 1894 from 1893, being 7,500 short tons, valued at $47,500, in the former year, and 12,400 short tons, worth $84,000, in the latter year.

Chromic iron ore.—The product in 1894 was 3,680 long tons, worth $53,231 in San Francisco, as compared with a product of 1,450 long tons in 1893, worth $21,750. All of this product was from California. The consumption is chiefly supplied from imports from Asia Minor.

MINERAL PIGMENTS.

Barytes.—The promise of an increase in production of this substance made in the last report was not fulfilled, the production being 23,335 short tons, worth $86,983, as compared with a product of 28,970 short tons in 1893, worth $88,506.

Metallic paint.—The product of metallic paint increased from 19,960 short tons in 1893, valued at $297,289, to 25,375 short tons in 1894, valued at $284,883, showing an increase in product of 5,415 tons and a decrease in value of $13,406.

Ocher, umber, etc.—The product of ocher decreased from 10,517 short tons, valued at $129,393, in 1893, to 9,768 short tons, valued at $96,935, in 1894. Umber declined from 480 short tons, valued at $7,560, to 265 short tons, valued at $3,830. The product of sienna increased from 150 to 160 short tons, but the value declined from $4,875 to $3,250. The amount of soapstone ground for pigment was 75 tons, valued at $525, against 100 tons, valued at $700, in 1893. Slate ground for pigment decreased from 3,183 short tons to 2,650 short tons.

Venetian reds.—The product decreased from 3,214 short tons to 2,983 short tons, while the value increased from $64,400 to $73,300.

Cobalt oxide.—The total product in 1894 was 6,763 pounds, worth in the condition in which it was first sold $10,145. The price of pure cobalt oxide ready for pottery or paint use was $2 per pound.

Zinc white.—The product declined slightly, from 24,059 short tons in 1893, worth $1,804,420, to 21,443 short tons in 1894, worth $1,500,975. The price decreased from $75 per ton in 1893 to $70 in 1894.

Graphite.—The product, 918,000 pounds in 1894, includes the crude material mined for crucible and all purposes, as well as that for pencils. Its value was $64,010 in the state in which it was first mined. In 1893 the product was 843,103 pounds, worth $63,232.

MISCELLANEOUS.

Precious stones.—The value of the rough gems found in the United States decreased from $264,041 in 1893 to $132,250 in 1894.

Mica.—The industry is still crippled by irregularity in mining methods. The value of the product in 1894 was $52,388, as compared with $88,929 in 1893.

Feldspar.—The product and value increased from 18,391 long tons in 1893, worth $68,037, to 17,200 long tons in 1894, worth $167,700.

Flint.—This product also shows an increase in production and value, the figures being, in 1893, 29,671 long tons, worth $63,792, as compared with 38,000 long tons, worth $319,200, in 1894.

Asphaltum.—As in 1893 the most of this product came from California, with small amounts from Utah and Kentucky. This product includes ozocerite, produced in Utah, and amounting in 1894 to 60,570 short tons, worth $353,400. This shows a slight increase in production and decrease in value. In 1893 the product was 47,779 short tons, worth $372,232

Asbestos.—The deposits of chrysotile near Casper, Wyo., mentioned in the last report, still lack development. The product in California, however, increased quite significantly, or from 50 tons in 1893, worth $2,500, to 325 tons in 1894, worth $4,463.

Infusorial earth.—The product continues to decline, the value of that produced in 1894 being but $11,718, as compared with $22,582 in 1893.

Magnesite.—California continues to be the only State producing this substance. The product in 1894 was 1,440 tons, valued at $10,240 in San Francisco. In 1893 the product was 704 tons, worth $7,040.

Mineral waters.—The statistics are limited to the actual amount sold. In 1894 the product declined to 21,569,608 gallons, worth $3,741,846, as compared with a product of 23,544,495 gallons in 1893, valued at $4,246,734.

Metallic products of the United States in 1894.

Products		Quantity	Value
Pig iron	long tons	6, 657, 388	$65, 007, 247
Silver	troy ounces	49, 501, 122	64, 000, 000
Gold	do	1, 910, 816	39, 500, 000
Copper	pounds	360, 844, 218	33, 141, 142
Lead	short tons	159, 331	9, 942, 254
Zinc	do	75, 328	5, 288, 026
Quicksilver	flasks	30, 416	934, 000
Aluminum	pounds	550, 000	316, 250
Antimony	short tons	200	36, 000
Nickel	pounds	9, 616	3, 269
Platinum	troy ounces	100	600
Total			218, 168, 788

Nonmetallic mineral products of the United States in 1894.

Products.	Quantity	Value
Bituminous coal............short tons..	118,820,405	$107,653,501
Pennsylvania anthracite ....long tons..	46,358,144	78,488,063
Building stone..................	....	37,377,816
Petroleum....................barrels .	49,344,516	35,522,095
Natural gas	....	13,954,400
Brick clay (all, except potter's clay), long tons..............	....	9,000,000
Clay (all, except brick)	360,000	800,000
Cement ....barrels..	8,362,245	5,030,081
Mineral waters............gallons sold..	21,569,608	3,741,846
Phosphate rock........ .... long tons..	976,059	3,395,988
Salt .... barrels..	12,967,417	4,739,285
Limestone for iron flux......long tons..	3,698,550	1,849,275
Zinc, white................short tons..	21,443	1,500,975
Gypsum ....short tons..	239,312	761,719
Borax ....pounds..	14,680,130	974,445
Mineral paints.............short tons..	41,926	498,093
Grindstones	....	223,214
Fibrous talc...... ....short tons..	39,906	435,060
Asphaltum......................do....	60,570	353,400
Soapstone......................do....	23,141	401,325
Precious stones..................	....	132,250
Pyrites...................long tons..	105,940	363,134
Corundum.................short tons..	1,495	95,936
Oilstones, etc.................pounds..	....	136,873
Mica...........................do ...	....	52,388
Barytes ....short tons..	23,335	86,983
Bromine. ....pounds..	379,444	102,450
Fluorspar ....short tons..	7,500	47,500
Feldspar ....long tons..	17,200	167,700
Manganese ore ....do....	6,308	53,635
Flint ....do....	38,000	319,200
Graphite ....pounds..	918,000	64,010
Sulphur ....short tons..	500	20,000
Marls ....do....	75,000	40,000
Infusorial earth................do....	....	11,718
Millstones........................	....	13,887
Chromic iron ore ....long tons..	3,680	53,231
Cobalt oxide ....pounds..	6,763	10,145
Magnesite ....short tons..	1,440	10,240
Asbestos ....do....	325	4,463
Rutile.......................pounds..	150	450
Ozocerite ....do....	(*a*)	(*a*)
Total value of nonmetallic mineral products................	....	308,486,774
Total value of metallic products.	....	218,168,788
Estimated value of mineral products unspecified	....	1,000,000
Grand total	....	527,655,562

(*a*) Included in asphaltum

The chief work of this division, in addition to the preparation of the report, has been a study of the mineral resources of the Southern States, made possible by the request from the directors of the Cotton States and International Exposition Company that the mineral portion of this exposition should include systematic representation of the mineral resources of the Appalachians The organization of this work was assigned to Dr. Day, and has been in progress since November, 1894. The method adopted in this study has been to select representative localities where minerals of economic importance are found, and there to secure such specimens as will clearly show the characteristics of the minerals as to quality, the quantity available for commerce, the mineral associations, and the development which they have received The natural conditions of occurrence are illustrated by geologic sections, by charts, and by photographs. The important problem of systematic arrangement of the material collected has been met by a double grouping by States and by minerals, so that an alignment in one direction groups the exhibits by mineral association, while the alignment at right angles is by State divisions. The work is at this date in the stage of collecting the exhibits, and is progressing rapidly. Practically the same executive subdivision is made in this work as in the statistical organization, and the aid of many of the statistical experts has been utilized, but several State officials have also aided greatly in securing exhibits.

The office force of the division, in addition to Dr. Day, has consisted of Messrs. E. W. Parker, statistician; W. A. Raborg, assistant geologist; and Jefferson Middleton, stenographer; with the usual corps of statistical experts temporarily employed.

TOPOGRAPHIC BRANCH.

At the beginning of the fiscal year radical changes were made in the organization of the topographic work. The two independent divisions under which it had been carried on were consolidated under the name of the Topographic Branch and placed in the charge of Mr Henry Gannett. The branch was organized by class of work in two divisions, triangulation and topography, and by locality of work in four sections, known as the Atlantic, Central, Rocky Mountain, and Pacific sections.

The Atlantic section includes the area of all work done within the Appalachian Mountain region and the Atlantic Coastal Plain.

The Central section includes the area of all work done in the States of the Mississippi Valley, including Minnesota, the Dakotas, Nebraska, and eastern Wyoming.

The Rocky Mountain section includes the area of all work done in the Rocky Mountain States and Territories, including Texas.

The Pacific section includes the area of all work done in the Pacific States, including California, Oregon, Washington, and Idaho.

DIVISION OF TRIANGULATION.

In the Atlantic section, before commencing the topographic mapping of several of the sheets whose survey was planned during the season, it became necessary to extend primary triangulation over them for the ultimate control of the work. In July Mr. G. T. Hawkins was sent to the field for the purpose of supplying triangulation in the Sebago Lake sheet of Maine and the Pawlet sheet of Vermont. This work was begun and ended during the month, and upon its completion Mr. Hawkins returned to Washington for other assignment. During most of the field season he was under detail to the General Land Office, and was engaged in examining and verifying the survey of the north boundary of Nebraska The line was rerun and double-chained by him, and, thus verified, it will serve as an excellent means of control of the system of land surveys in its vicinity, since the township corners have been connected with it.

For establishing primary triangulation for the control of the Lake George sheet, Mr. S. S. Gannett took the field in July and occupied six points upon that and adjoining sheets. In the following month he was similarly engaged upon the Norristown sheet, Pennsylvania, where he occupied four points. The remainder of the season was consumed by him in running traverse lines for the control of the Monroe sheet in Georgia, and this occupied him until November 7, when he left the field and returned to Washington

Upon an examination of the primary control of the work upon the plains in Colorado, it was found that this was insufficient in accuracy, and in order to supply this deficiency Prof. A. H Thompson was instructed to extend triangulation from the transcontinental belt of the United States Coast and Geodetic Survey over as great an extent of the plains as the season would permit. Accordingly, he commenced work on September 2, connecting with three Coast Survey stations, known as Cramer, Adobe, and Square Bluff. From these points triangulation was extended southward across the Arkansas River, and thence southwestward to a connection with Fisher Peak, at Trinidad, near the south line of the State. Altogether twenty-four stations were located in this work during the season, which closed on November 23, the cold weather and frequent storms preventing its further prosecution. The triangulation executed by this party controls three atlas sheets, besides furnishing excellent opportunities for extension both eastward and westward into adjoining sheets.

Work was begun in western Oregon in May. The latitude and longitude of a point in the city of Eugene were determined astronomically by Mr. S S. Gannett. The latitude was obtained by zenith telescope, observations therefor having been made upon ten nights. For the comparison of local time for longitude determination, connection was had, through the courtesy of the Superintendent of the United States Coast and Geodetic Survey, with San Francisco, and five nights' comparison, with the requisite transit observations for local time, was obtained. Through the courtesy of the Western Union Telegraph Company its wires were used for time comparisons.

Meantime, Mr. W. T. Griswold measured a base-line in the neighborhood of Eugene 18,630 feet in length. This base was measured twice with a 300-foot steel tape standardized by comparison with the standard of the United States Coast and Geodetic Survey in Washington. This base was expanded and triangulation was extended southward by Mr. Griswold, supplying control for three atlas sheets. Altogether fourteen stations were occupied in the expansion and triangulation.

DIVISION OF TOPOGRAPHY.

ATLANTIC SECTION.

The Atlantic section, which comprises the northeastern and southeastern sections of the preceding year, was placed in charge of Mr. H. M. Wilson, and has remained in his charge throughout the year. By this section 7,000 square miles have been surveyed, completing seventeen atlas sheets and parts of six others. Of this area, 3,000 square miles have been mapped upon the scale of 1:62500 in contours of 20 feet, and 4,000 square miles upon a scale of 1:125000 in contours of 50 or 100 feet.

The area surveyed by this section is distributed as follows among the various parties and fields of work:

Areas surveyed by the Atlantic section of topography during 1894-95.

Chief of party	Atlas sheets	Area in square miles
Lovell, W H	Bridgton and Sebago Lake, in Maine	500
Hyde, George E	Strafford and Pawlet, in Vermont	500
Jennings, J. H	Ontario Beach, Fonda, and Hoosick, in New York, and Manchester in Vermont.	625
Chapman, R H	Lake Placid and Ticonderoga, in New York.	375
Sutton, Frank, et al	Philadelphia, Germantown, Norristown, and Chester, in Pennsylvania	1,000
Hackett, Merrill, et al	Piedmont, in Maryland and West Virginia.	1,000
Munroe, Hersey	Raleigh, in West Virginia	500
Thompson, Gilbert	Bristol, in Virginia	500
Murlin, A E	Standing Stone, in Tennessee	500
Blair, H B	Monroe, in Georgia	1,000
Beaman, W M	Dahlonega, in Georgia	500

CENTRAL SECTION

This section has been throughout the year in charge of Mr. J. H. Renshawe. Work has been prosecuted in Minnesota, North and South Dakota, Wyoming, and Nebraska. An area of 10,475 square miles has been surveyed, of which 750 square miles are upon a scale of 1:62500, and 9,725 square miles upon a scale of 1:125000. This area completes ten sheets, three of them upon a scale of 1:62500, and seven upon a scale of 1·125000.

The results are summarized in the following table:

Areas surveyed by the Central section of topography during 1894-95.

Chief of party	State	Area in square miles
Baldwin, H L, jr	Minnesota	500
Manning, Van H	North Dakota	2,000
Harrison, D C	South Dakota	2,225
Wallace, H S.	Wyoming	1,000
Towson, R M	Nebraska	3,500
Peters, W J	.....do	1,250

ROCKY MOUNTAIN SECTION.

This section has been in charge of Mr E. M. Douglas. Work has been prosecuted in Colorado by three parties and in Texas by an equal number. An area of 5,963 square miles has been surveyed, of which 38 square miles were on a scale of 1:25000, 575 on a scale of 1:62500, and 5,350 on a scale of 1:125000 This area completes eight sheets, one of them, the Cripple Creek sheet, being upon a scale of 1:25000, with a contour interval of 50 feet Two of them, the Telluride and Rico sheets, are upon a scale of 1:62500, with a contour interval of 100 feet, the remaining five being upon a scale of 1:125000. Three of these, namely, Pueblo, Walsenburg, and Nepesta, are upon the plains of Colorado, and the work upon them has consisted of a resurvey. The contour interval on these sheets is 50 feet The other two, the Valentine and Fort Davis sheets, are in western Texas, and the contour interval of these sheets is 100 feet.

The results of the work of this section are summarized in the following table:

Areas surveyed by the Rocky Mountain section of topography during 1894–95.

Chief of party	Locality	Area in square miles
Douglas and Corse	Cripple Creek, Colorado	38
Tweedy, Frank	San Juan Mountain, Colorado	325
Bannon, T. M	do	250
Gordon, R. O	Plains, Colorado	2,000
Tweedy, Frank	do	1,000
Urquhart, C. F	West Texas	1,000
Bassett, C C	do	1,000
Corse, W. B	Central Texas	350

PACIFIC SECTION.

This section has been in charge of Mr. R. U. Goode It has surveyed during the season an area of 6,975 square miles, of which 3,475 are upon a scale of 1:62500 in contours of 25 or 50 feet, and 3,500 upon a scale of 1.125000 in contours of 100 feet. There have been completed by this section during the season fifteen atlas sheets, and work has been commenced upon six others Of the completed sheets, two are upon a scale of 1:125000, with a contour interval of 100 feet, and the remainder upon a scale of 1·62500, with a contour interval of 25 or 50 feet.

The results of the work of this section are summarized in the following table:

Areas surveyed by the Pacific section of topography during 1894–95.

Chief of party	State	Area in square miles
Perkins, E. T, jr.	Idaho	2,000
McKee, R H	Washington	300
Griswold, W T	Oregon	300
Barnard, E C	do	700
Johnson, W. D	Central California	500
Marshall, R. B	do	1,000
McKinney and Holman	Southern California	675
Fletcher and Gerdine	do	1,000
Post, W S	do	500

OFFICE WORK.

During the winter the surveying force was engaged, as usual, in reducing and transferring the plane-table sheets and in inking and lettering the original maps. The work has gone on rapidly and efficiently, and all the work of the past season has been put in shape and made ready for the engraver.

Messrs. S. S. Gannett and G. T. Hawkins have been engaged in the reduction of triangulation and primary traverse lines

SUMMARY OF THE WORK OF THE FIELD SEASON.

The total area surveyed was 30,413 square miles, of which 23,563 square miles are newly mapped, while 6,850 square miles consist of revision of earlier work. Classified by scale of publication, the above surveyed area consists of 22,613 square miles upon a scale of two miles to the inch (1:125000) and 7,800 square miles upon a scale of one mile to the inch (1·62500).

The number of atlas sheets completed is forty-nine, of which forty-one are new work and nine are revision Of the new work, one sheet is on the scale of 1.25000, twenty-nine sheets are on the scale of 1:62500, and eleven sheets on the scale of 1:125000. Of the revision, three sheets are on the scale of 1:62500 and six sheets on the scale of 1:125000 Besides these, twenty-nine sheets were surveyed in part.

The area surveyed is distributed in twenty-one States, as shown in the following table and on the map which accompanies this report (Pl. I):

Topographic surveys by the United States Geological Survey in 1894-95.

State	Scale of publication		Contour interval
	1:62500	1:125000	
	Square miles	*Square miles*	*Feet.*
Maine	500	....	20
Vermont	750	....	20
New York	750	....	20
Pennsylvania and New Jersey	1,000	....	20
West Virginia and Maryland	....	1,500	100
Virginia	....	500	100
Tennessee	....	500	100
Georgia	....	1,500	50
Minnesota	500	....	20
North Dakota	....	2,000	20
South Dakota	....	2,225	20
Wyoming	....	1,000	50
Nebraska	250	4,500	20
Colorado	*a*575	*a*3,000	50 and 100
Texas	....	2,350	20 and 100
Idaho	....	2,000	100
Washington	300	....	25
Oregon	....	1,000	100
California	3,175	500	25 and 100
Total	7,800	22,595	....

[a] Besides 38 square miles mapped on scale of 1:25000

The following are the sheets completed by this season's work:

Topographic sheets completed during 1894–95.

Locality and name of sheet	Scale	Contour interval
Maine:		*Feet.*
Sebago Lake	1:62500	20
Bridgton	1:62500	20
Vermont		
Strafford	1:62500	20
Pawlet	1:62500	20
Manchester	1:62500	20
New York:		
Ticonderoga	1:62500	20
Hoosick	1:62500	20
Fonda (part in 1893)	1:62500	20
Lake Placid (part in 1893)	1:62500	20
Ontario Beach	1:62500	20
Pennsylvania:		
Norristown	1:62500	20
Chester	1:62500	20
Philadelphia (revision)	1:62500	20
Germantown (revision)	1:62500	20
Maryland and West Virginia		
Piedmont (revision)	1:125000	100
Georgia:		
Monroe	1:125000	50
Minnesota		
St Paul	1:62500	20
Minneapolis	1:62500	20
North Dakota		
Valley City	1:125000	20
South Dakota		
Huron	1:125000	20
Wyoming:		
Sundance	1:125000	50
Nebraska		
Lincoln	1:62500	20
Hebron	1:125000	20
York	1:125000	20
Superior	1:125000	20
Grand Island	1:125000	20
Colorado:		
Cripple Creek	1:25000	50
Telluride	1:62500	100

Topographic sheets completed during 1894–95—Continued.

Locality and name of sheet	Scale	Contour interval
Colorado—Continued		
Rico	1:62500	100
Pueblo (revision)	1:125000	50
Walsenburg (revision)	1:125000	50
Nepesta (revision)	1:125000	50
Texas:		
Valentine	1:125000	100
Fort Davis	1:125000	100
Idaho:		
Weiser	1:125000	100
California		
Yosemite (part revision)	1:125000	100
Los Angeles (revision)	1:62500	25
Pasadena	1:62500	25
Santa Ana	1:62500	25
Downey	1:62500	25
San Francisco	1:62500	25
Cucamonga	1:62500	25
Pomona	1:62500	25
Redondo	1:62500	25
Las Bolsas	1:62500	25
San Mateo	1:62500	25
San Bernardino	1:62500	25
Anaheim	1:62500	25
San Pedro	1:62500	25

The following sheets were commenced during the season, but not completed:

Topographic sheets commenced during 1894–95.

Locality and name of sheet.	Scale.	Contour interval.
New York:		*Feet.*
Bolton	1 : 62500	20
Virginia:		
Bristol (revision)	1 : 125000	100
West Virginia:		
Raleigh (revision)	1 : 125000	100
Tennessee:		
Standing Stone	1 : 125000	100
North Carolina:		
Morganton (revision)	1 : 125000	100
Georgia:		
Dahlonega (revision)	1 : 125000	100
North Dakota:		
Fargo	1 : 125000	20
Casselton	1 : 125000	20
Tower	1 : 125000	20
South Dakota:		
Desmet	1 : 125000	20
Mitchell	1 : 125000	20
Alexandria	1 : 125000	20
Nebraska:		
Wahoo	1 : 125000	20
Loup	1 : 125000	20
Mason	1 : 125000	20
Gothenburg	1 : 125000	20
Brady Island	1 : 125000	20
Colorado:		
Engineer Mountain	1 : 62500	100
Texas:		
Austin (revision)	1 : 125000	20
Idaho:		
Hailey	1 : 125000	100
Huntington	1 : 125000	100
Washington:		
Tacoma	1 : 125000	25
Oregon:		
Roseburg	1 : 125000	100
Yoncalla	1 : 125000	100
California:		
Concord	1 : 62500	25
Tamalpais	1 : 62500	25
Haywards	1 : 62500	25

During the field season there were 120 men, on an average, in the employ of the Topographic Branch, of which number 68 men were of the permanent force, engaged in professional work, consisting of topographers and assistant topographers, 13 were field assistants, and the remainder constituted the laboring force, such as cooks, drivers, and signal builders. During the winter there were 65 men employed, on an average.

SURVEYS IN THE INDIAN TERRITORY.

In addition to the regular work of the fiscal year, the Geological Survey was charged in March, 1895, with the duty of executing certain subdivision surveys of the lands of the Indian Territory. Although this work was not undertaken until the fiscal year was well advanced, the authority and plans therefor are here set forth

In the Indian appropriation act for the fiscal year 1895–96, approved March 2, 1895, it was provided that the Secretary of the Interior might, in his discretion, direct that the surveys for the subdivision of the lands of the Indian Territory be made under the supervision of the Director of the Geological Survey by persons employed by or under him for that purpose. Under instructions from the Secretary, the Director of the Survey assumed charge of this work on March 13, and submitted on the same date a plan for its execution in conformity with the statute. The plan, which was at once approved by the Secretary, is as follows:

PLAN FOR SURVEYS IN THE INDIAN TERRITORY

WORK TO BE DONE

The total area of the Territory, excluding the Chickasaw Nation, which is already surveyed, is estimated to be 23,550 square miles, or 654 townships. The survey of this area involves the running of 1,920 miles of standard lines, which are to be run at every four townships or 24 miles, 7,000 miles, more or less, of township exteriors in addition to the above, and 38,000 miles, more or less, of subdivision lines, a total of nearly 47,000 linear miles.

Assuming that the appropriation of $200,000 is intended to provide for a survey of one-half the area, there is to be surveyed under it a total of 23,500 linear miles, including 1,000 miles of standard lines, 3,500 miles of township exteriors in addition to the above, and 19,000 miles of subdivision lines, besides providing for the office work, including the preparation of plats and the copying of field notes

METHOD OF DOING THE WORK.

It is proposed to survey all township exterior and standard lines, a total of 4,500 miles, by men who are experienced in that kind of work, who are now connected with the United States Geological Survey. This will probably require four parties, each of which will consist, besides the surveyor, of a rodman, two chainmen, one or two cornermen, a cook, and a driver; and in the case of the standard lines, two additional chainmen and one additional rodman, since these lines must be double-chained. These parties will live in camp and will be provided with facilities for moving camp frequently. The surveyors will not only run and locate the lines, but will make profiles of them by vertical angles.

The subdivision of the townships will be done by men of experience in that class of surveying, who will be hired temporarily for that purpose. The subdivision parties will consist, besides the surveyor, of a rodman, two chainmen, and one or two cornermen. They will be provided with camp outfits and animals for carrying the surveying corps to and from their work, but will, as a rule, hire the facilities for moving camp, inasmuch as they will move camp infrequently. At least twelve such subdivision parties, and very likely more, will be found necessary, and they will, if practicable, be grouped, two, three, or four parties in one camp. Each such group of subdivision parties will be placed in charge of a topographer of this office, who will measure elevations in the interior of the townships, resting his measurements upon the heights determined on the township exteriors, and who will sketch the topography. He will have control of the surveyors who are making the subdivisions and will superintend their work. A thorough examination will be made of every township monument, as the topographer must occupy every corner in making his map.

LOCALITIES OF WORK

It is proposed to commence work in the western portion of the Choctaw Nation by extending eastward the base-line of the Chickasaw Nation, to establish a new principal meridian on or near the eastern line of range 8 east, and to build up on these lines a system of surveys which will be consistent with those of the Chickasaw Nation so far as the latter may be accurate and correct, but will not conform to any irregularities which may exist in those surveys. The plan of work will of course conform to the requirements of the General Land Office, as specified in its manual.

It is proposed to survey first the western half of the Choctaw Nation, working generally from the west northward and eastward and extending the work into the Creek, Cherokee, and Seminole country as far as time and money will permit.

OFFICE WORK

For the drawing of plats and the making of fair copies of field notes, it is proposed to employ draftsmen and clerks in the office in Washington. Rough plats of the township exteriors and of subdivisions, and the original field notes, will be prepared in the field and forwarded to this office for the preparation of these copies

FIELD WORK

It is proposed to send parties to the field as soon as the necessary arrangements in Washington can be made, the expectation being that field work can be commenced by the 1st of April upon the standard lines; that as soon as a block of townships has been outlined, the work of surveying township exteriors will be commenced, and that as soon as the exteriors of such a block have been surveyed the subdivision parties will be organized and the work of subdivision taken up. It will be entirely feasible to continue field work until the end of November, and if necessary it can be continued through the winter, although the shortness of the days will render it less economical than to work in summer.

It is proposed to put two triangulation parties in the field, with a view to carrying over the entire area a system of primary triangulation, permanently marked, and connecting the points in this primary triangulation with township corners, some corner of each township to be connected with a primary triangulation point. The purpose of this is, first, to serve as a check upon the accuracy of the work, and, second, to furnish permanent points from which corners may be recovered in case the marks should be lost These parties will measure a base on the Missouri, Kansas, and Texas Railway, and expansion will be carried eastward, northward, and southward therefrom

The triangulation will, as stated above, serve the purpose of an examination of all exterior lines, and the topographers who prepare the topographic map will, in the course of their duties, thoroughly examine the subdivision work.

For outfitting these parties there are available thirteen animals near Austin, Tex., and eight near Marfa, Tex., with camp equipage; these can be shipped to the outfitting point in the Choctaw Nation. In the north there are, at Rapid City, S. Dak, fifteen animals, and in central Nebraska six animals, with large amounts of camp equipage, which can also be transported, making a total of forty-two animals and camp equipage, which will be sufficient for at least half a dozen parties.

For outfitting the remaining parties, it is suggested that animals and camp equipage be purchased rather than hired, inasmuch as they will in all probability be used throughout two long seasons, and the expense of hiring will probably be greater than that of purchasing.

EMPLOYEES

The general charge of the work will be in the hands of the chief topographer of the Survey, Mr. Henry Gannett. As he has many other duties to perform, and will therefore be unable to give the close personal attention to the details of this work which is necessary, it will be needful to have a division chief in immediate charge, who shall have a knowledge of triangulation, topography, and Land Office surveys, and in whom implicit confidence can be placed. The only person possessing these qualifications with whom I am acquainted is Mr. Charles H. Fitch. The duty of such division chief will be to take immediate charge of all the work and see that it is done in conformity with the laws governing land surveys and the general regulations governing topographic surveys.

The men employed as surveyors on subdivision work should be men experienced in this class of surveying, and I have had full assurance that such men can be obtained for from $100 to $125 per month, to be hired at the outfitting point and discharged at the same point immediately upon the completion of the work for which engaged; the assistants, such as rodmen, chainmen, cornermen, and general campmen, to be employed under the existing regulations governing the employment of such men in the Geological Survey. Such men can be hired at from $30 to $35 per month, being taken up at the outfitting point and discharged under the same conditions as the subdivision surveyors are

INSPECTION

The subdivision surveys will be made by parties working in advance of the topographer who has them immediately in charge. The exterior lines will be connected with stations in a primary triangulation carried on independently, and the topographer will visit every section corner while making his topographic map, thus inspecting every corner with relation to the marking thereof on the ground by stakes, pits, etc. Moreover, he will be working directly in connection with the surveyors and will be able to inspect their notes at night and to keep informed as to their methods of work.

WORK ACCOMPLISHED TO JUNE 30, 1895

Under the plans above outlined, work was begun in the Territory in April. Two parties were organized for primary triangulation, in charge, respectively, of Messrs. S. S. Gannett and C. F. Urquhart. The position of a point in the village of Savanna was determined by astronomic means as the initial point, a base-line was measured on a tangent of the railroad in the immediate neighborhood of this village, and expansion was effected. Work was prosecuted so rapidly that by the end of June the entire western part of the Choctaw Nation, that is, that part lying west of longitude 95° 30′, was controlled. Twenty-four stations had been selected, signals erected upon them, and the observations completed

During April four additional parties were placed in the field, two of them, in charge, respectively, of Messrs. George T Hawkins and W. J. Peters, for the purpose of running standard lines, and two, in charge, respectively, of Messrs. H L. Baldwin, jr, and R. O. Gordon, for running township exteriors Up to the close of June, the standard-line parties had run a total of, approximately, 275 miles, and the township exterior parties of 230 miles.

During the month of May eight surveyors were employed for the purpose of subdividing townships. These were grouped in four parties, the heads of which were Messrs. Van H. Manning, D. C. Harrison, R. M. Towson, and R. A. Farmer, topographers, who had been selected from the permanent force of the office for the purpose of supervising the work of the surveyors and preparing contour maps of the townships surveyed. By July 1 these parties had subdivided fourteen full townships and four fractional townships, being the equivalent of sixteen full townships. These involved the running of 960 miles of line The total output of mileage to July 1 of twelve surveyors engaged in line work was 1,465 miles.

In the latter part of June two additional parties for running township exteriors, in charge, respectively, of Messrs. R. A. Farmer and Jeremiah Ahern, were organized, and eight additional surveyors were employed for subdivisional work, outfitted, and placed in the field. At the close of the month these additional parties were just commencing work. The difficulties of organizing a new large survey have been overcome, and it is anticipated that the work will be pushed forward during the summer and fall, and, it may be, throughout the winter if the weather is favorable

PUBLICATION BRANCH

DIVISION OF ILLUSTRATIONS.

The Division of Illustrations has been, as in previous years, under charge of Mr De Lancey W. Gill, assisted by Messrs. John L. Ridgway, Daniel W. Cronin, H. Hobart Nichols, F. W. von Dachenhausen, H. Chadwick Hunter, and Wells M. Sawyer. Miss Frances Wieser was employed a portion of the time on special work. Mr. Daniel P. O'Hare resigned, and Mr. Joseph H. Wheat was transferred to the Topographic Branch. Both of these men were engaged during part of the year on miscellaneous geologic work.

Mr. Ridgway assisted Mr. Gill during the year in the general work of the division, and also made many paleontologic and lithologic drawings. He completed a series of colored plates of stratified and brecciated rocks that are a departure in this line of illustration, and which will prove most valuable as realistic illustrations. Mr. Cronin was engaged in the preparation of geologic maps and sections; Mr. Nichols, in the preparation of geologic landscapes and the retouching of photographs; Mr. von Dachenhausen and Mr Hunter, in the making of paleontologic drawings; Mr. Sawyer, in the preparation of geologic sections, the classification of engraved rocks, and the examination of lithographic proofs.

Drawings to the number of 1,604 were prepared by the draftsmen during the year. Engraved proofs of 579 drawings have been received from the Public Printer and examined The full editions of all chromolithographs used in the Survey publications were examined by Mr. Gill at the Government Printing Office. The illustrations for two annual reports, two monographs, and six bulletins were prepared and transmitted to the Public Printer. These illustrations were classified for engraving as follows: Chromolithography, 61; lithography, 21; half-tone engraving, 152; photoengraving, 198.

This division examines and corrects all proofs, and keeps complete records of all drawings and proofs transmitted to and from the Government Printing Office.

THE PHOTOGRAPHIC LABORATORY

The photographic laboratory, as in previous years, has been under the supervision of Mr. J. K. Hillers, assisted by Messrs. Charles C. Jones, John Erbach, and Charles A. Ross.

In connection with the preparation of the Department of the Interior exhibit at the Cotton States and International Exposition, at Atlanta, Mr Hillers spent two months in the States of North Carolina, Tennessee, Georgia, and Florida, taking photographic views. More than one hundred fine negatives of subjects illustrating the mineral resources and industries of the Southern States were obtained. The following is a summary of the work done in the laboratory during the year:

Photographic negatives and prints made during 1894–95.

Negatives		Prints	
Size	Number	Size	Number
28 by 34	64	28 by 34	273
22 by 28	41	22 by 28	160
20 by 24	351	20 by 24	2, 165
14 by 17	91	14 by 17	392
11 by 14	121	11 by 14	1, 373
8 by 10	358	8 by 10	750
6 by 8	167	6 by 8	1, 255
5 by 8	229	5 by 8	547
4 by 5	284	4 by 5	1, 615

EDITORIAL DIVISION.

TEXTUAL PUBLICATIONS

Mr. W. A. Croffut remained in charge of the general editing of the publications of the Survey until September 15, when Mr. P. C. Warman was detailed to take charge of the work. Assistance in this work was rendered throughout the year by Mr. George M Wood, and for a portion of the time by Miss A. B. Dawson. The work progressed satisfactorily and was well in hand at the close of the fiscal year. Following is a condensed statement of the manuscripts and proofs read and corrected during the year:

Manuscript read during the year 1894–95.

	Pages
Fifteenth Annual Report	1,413
Sixteenth Annual Report (in part)	1,864
Monograph XXV	862
Monograph XXVI	260
Two unnumbered monographs (Emerson, Stone), in part	750
Bulletins 125, 126, 127, 128, 129, 130, 131, and three unnumbered bulletins (Bascom, Hay, Todd)	2,439
Text for geologic folios 4, 8, 10, 11, 12, 14, 15, 16, and for two unnumbered folios (Stevenson, Knoxville)	400

Proof read during the year 1894–95.

Fourteenth Annual Report, Parts I and II
Fifteenth Annual Report.
Sixteenth Annual Report, portions of Parts II, III, and IV.
Monograph XXV.
Bulletins 119, 120, 121, 122, 123, 124, 125, 127 (in part), 128, 129
Geologic folios 4, 8, 10, 11, 12, 14, 15, 16, and one unnumbered folio (Marysville)
Total proof read, 1,817 galleys, 8,133 pages

The publications received from the Public Printer during the year are listed on p. 85

GEOLOGIC MAPS

The work of editing the geologic maps was formerly done entirely by Mr. Bailey Willis, but owing to the increase of work and the necessity of preparing perfect copy for the engraver from the sketch drawings furnished by the geologists, the services of a draftsman especially familiar with geologic work were required. This need was met by the appointment in August of Mr. O. A. Ljungstedt; and in January following Mr. G. W. Stose, assistant geologist, was appointed to assist Mr. Willis in the preparation of original maps and in proof reading The textual descriptions of the sheets were edited by Mr. Willis and Mr. Warman conjointly.

Following is a tabulated statement of the present condition of publication of the Geologic Atlas:

Geologic folios ready for distribution.

No	Name of sheet	State	Limiting meridians	Limiting parallels	Area in square miles	Price in cents
1	Livingston	Montana	110°–111°	45°–46°	3, 354	25
2	Ringgold	Georgia Tennessee	85°–85° 30′	34° 30′–35°	980	25
3	Placerville	California	120° 30′–121°	38° 30′–39°	932	25
4	Kingston	Tennessee	84° 30′–85°	35° 30′–36°	969	25
5	Sacramento	California	121°–121° 30′	38° 30′–39°	932	25
6	Chattanooga	Tennessee	85°–85° 30′	35°–35° 30′	975	25
7	Pikes Peak	Colorado	105°–105° 30′	38° 30′–39°	932	25
8	Sewanee	Tennessee	85° 30′–86°	35°–35° 30′	975	25
9	Anthracite Crested Butte	Colorado	106° 45′–107° 15′	38° 45′–39°	465	50
10	Harpers Ferry	Virginia West Virginia. Maryland	77° 30′–78°	39°–39° 30′	925	25
11	Jackson	California	120° 30′–121°	38°–38° 30′	938	25
12	Estillville	Virginia Kentucky Tennessee	82° 30′–83°	36° 30′–37°	957	25
13	Fredericksburg	Maryland Virginia	77°–77° 30′	38°–38° 30′	938	25
14	Staunton	Virginia West Virginia	79°–79° 30′	38°–38° 30′	938	25

Geologic folios in press.

No	Name of sheet	State	Limiting meridians	Limiting parallels	Area in square miles	Price in cents
15	Lassen Peak	California	121°–122°	40°–41°	...	...
16	Knoxville	Tennessee North Carolina	83° 30′–84°	35° 30′ 36°	...	...
17	Marysville	California	121° 30′–122°	39°–39° 30	...	...
18	Smartsville	do	121°–121° 30′	39°–39° 30′	...	...
19	Stevenson	Alabama Georgia Tennessee	85° 30′–86°	34° 30′–35°	...	...
20	Cleveland	Tennessee	84° 30′–85°	35°–35° 30′	...	...

There is in course of printing, also, a special map of the Cripple Creek mining district of Colorado, which will form a part of the Pikes Peak folio, mentioned above.

Geologic folios in process of engraving.

No	Name of sheet	State	Limiting meridians	Limiting parallels	Area in square miles	Price in cents
	Loudon	Tennessee	84°–84° 30′	35° 30′–36°		
	Three Forks	Montana	111°–112°	45°–46°		
	Pocahontas	Virginia West Virginia	81°–81° 30′	37°–37° 30′		
	Greeneville	Tennessee North Carolina	82° 30′–83°	36°–36° 30′		

There is in preparation also a special folio of the Nevada City mining district, California, which will contain three maps—the Banner Hill, Grass Valley, and Nevada City.

An important question considered during the autumn of 1894 related to the scale of publication of maps in the Geologic Atlas in the case of States which, like Maryland and those of New England, have been surveyed on the scale of 1 mile to the inch. It having been shown that there can be much speedier publication, a saving of many thousands of dollars, and no corresponding loss of scientific or educational value in publishing on a scale of 2 miles to the inch, this scale has been adopted for the Geologic Atlas, except in special cases.

The question of the plan of distribution of the geologic folios of the Survey was referred during the year to a special committee named for the purpose, consisting of Messrs. Gilbert, Emmons, and Willis. The report of this committee was approved by the Director, and the editor of geologic maps was charged with the duty of directing the distribution under the rules laid down.

TOPOGRAPHIC MAPS

Formerly the manuscript maps, as prepared by the Topographic Branch, were approved and sent to the engraver without special editorial examination or revision. These manuscripts, produced by many men working independently, were unequal in character and quality, and it was decided to refer to an editor of topographic maps every topographic manuscript submitted for publication. Mr. Marcus Baker was assigned to this position. The work was made to cover not only the new maps, but all the old ones when a revision is to be made for the purpose of printing a new edition or when any sheet is to be prepared for use as a topographic base for the maps of one of the geologic folios. But few of the 900 topographic atlas sheets engraved by the Survey have had the form or application of the geographic names upon them authoritatively established. To bring about uniformity in this respect is one of the duties of the editor of topographic maps. The accumulated work having been found too great for Mr. Baker to dispose of, Mr. H. W. Elmore, of the Division of Engraving and Printing, was transferred December 1 to assist in the detail of proof reading.

During the year the manuscripts of 125 new sheets have been critically examined and approved for engraving. Proofs, usually two, but occasionally three, have been read of 41 new sheets. Old sheets to the number of 91 have been revised, corrected, and the correction proof read. All known correction material has been collected and systematically arranged. It is believed that a steady improvement in the quality of the maps has been and will continue to be the result of this editorial work.

As secretary of the United States Board on Geographic Names, Mr. Baker has served continuously in connection with the work of that Board, a work intimately related to his duties in the Survey.

DIVISION OF ENGRAVING AND PRINTING.

Mr. S. J. Kübel continued in charge of this division as chief engraver, assisted by Mr. Henry C. Evans, foreman of the copperplate engravers; Mr. Robert H. Payne, in charge of the transferring to stone; Mr. Joseph Eckert, superintendent of the work of the lithographic power presses; and Mr. Schleichert, in charge of all stone work.

During the year almost the entire time of the employees of this division was devoted to the engraving and printing of geologic folios and topographic atlas sheets. No contracts for engraving were made, as it was decided to have all engraving for the Survey done in this division, and six engravers were added to the force already employed.

Under this new organization better control, a higher standard of excellence, greater uniformity in execution, and cheaper and prompter output of work followed.

Engraving of topographic sheets.—New sheets to the number of 49 were engraved, distributed by States as follows· New York, 25; Florida, 6; Nebraska, 5; New Hampshire, 2; Colorado, 2, and 1 each in Washington, Louisiana, Michigan, West Virginia and Tennessee, Maryland and Virginia, Pennsylvania, Wisconsin, and Oklahoma Territory. In addition to the preceding, there are 16 partially engraved sheets in the hands of the engraver, upon which work is well advanced.

Engraving of geologic folios —The following-named geologic folios were engraved: Anthracite and Crested Butte, Colo.; Lassen Peak, Cal.; Jackson, Cal.; Estillville, Kentucky-Virginia-Tennessee; Sewanee, Tenn.; Knoxville, Tenn.; Chattanooga, Tenn.; Harpers Ferry, Virginia-Maryland-West Virginia; Staunton, Virginia-West Virginia.

The following are in hand and well advanced: Fredericksburg, Va.; Pikes Peak, Colo.; Marysville, Cal ; Stevenson, Tenn

Others in preparation are as follows: Smartsville, Cal.; Cleveland, Tenn.; Three Forks, Mont.; Loudon, Tenn.; Nevada City, Cal.; Grass Valley, Cal.; Banner Hill, Cal ; Yellowstone Park; McMinnville, Tenn.; Morristown, Tenn.; Cranberry, Tennessee-North Carolina; Briceville, Tenn.; Pikeville, Tenn.; Pocahontas, Virginia-West Virginia; Piedmont, Maryland-West Virginia; Nomini, Maryland-Virginia; Washington, D. C ; Holyoke, Mass.

Completed work was delivered as follows: Atlas sheets, 119,927 copies; geologic folios, 34,699 copies.

ADMINISTRATIVE BRANCH.

DIVISION OF DOCUMENTS, CORRESPONDENCE, AND RECORDS.

This division is in general charge of the chief clerk, Col. H. C Rizer, the custody and distribution of the public documents being under the immediate charge of Dr. W. D. Wirt, and the files and records of correspondence and appointments under the immediate charge of Mr J. R Walsh.

DOCUMENTS AND STATIONERY.

The handling of the documents has necessitated a heavy correspondence and has required the full energies of the small force employed in the work. The distribution of the surplus copies of the office editions of the topographic sheets has been of advantage to many personal and public enterprises, as is made manifest by the tenor of the letters requesting these sheets and the reports that come in subsequently of the practical uses to which they have been put The publication by Messrs. Dodd, Mead & Co. of a pamphlet on The Use of Governmental Maps in Schools has had a wide and strong influence in the educational centers of the country, and has created a large demand for the maps. Owing to the fact that the editions are limited, however, only the higher-grade schools and the colleges have received the maps. In the sundry civil act approved March 2, 1895, authority is granted to sell topographic maps and text at cost and 10 per cent added. Under this authority topographic folios containing a series of maps will be prepared for sale.

A tabulated statement of public documents received and distributed during the year follows:

Publications received at the Survey document rooms during 1894–95.

Thirteenth Annual Report, Part III
Fourteenth Annual Report, Parts I and II, and separates
Monographs XXIII and XXIV.
Bulletins 118, 120, 121, 122, 125, and 129.
Mineral Resources 1893, and separates.
Geologic folios 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, and 14

Publications distributed during the year 1894–95.

Volumes	89,733
Folios	10,564
Maps	86,974
Total	187,271

Sales of publications during the year 1894–95.

Month.	Monographs	Bulletins	Mineral Resources	Folios	Maps	Total
July	$45.65	$19.55	$35.50	....	....	$100 70
August.......	7 60	17.80	213.50	....	....	238 90
September ...	19.50	15.35	133 10	....	....	167.95
October	453.05	21.70	53.30	....	....	528.05
November....	133.90	47.10	124.00	....	....	305.00
December	63 75	28.25	74.10	....	....	166.10
January......	60 30	66.95	31 40	....	....	158.65
February.....	52 05	68.30	22.50	$8 50	....	151.35
March.........	60 80	28.05	12 90	10 75	$7 50	120 00
April..........	29.10	23.15	30.50	15 25	....	98 00
May...........	41.45	13 10	4.00	22.75	....	81 30
June	7.35	13 30	5.00	29.00	10 00	64.65
Total...	974 50	362 60	739 80	86.25	17 50	2,180.65

In addition to the public documents, Dr. Wirt has charge of the stationery supplies, and the drawing and filling of requisitions for these consumes much time. During the year 240 requisitions were sent to the Department and 3,104 office requisitions were filled. Letters received, 21,322; letters sent, 19,931.

CORRESPONDENCE AND RECORDS.

The register of general correspondence for the year, in charge of Mr. Walsh, shows that 3,720 letters were briefed, indexed, and referred to proper divisions or otherwise disposed of. The record of letters sent aggregates approximately 2,860 pages of type-written matter There has been the customary routine work, including the monthly report of all official changes, the semimonthly report of leaves of absence granted, and the keeping of the time records connected with the latter.

Associated with this division are Dr. W. F. Morsell, stenographer and general assistant to the Director and the chief clerk, and Miss Jean F. Kaighn, confidential clerk to the Director.

THE LIBRARY.

The library was continued under the charge of Mr. Charles C. Darwin, who was assisted by Miss Julia L. McCord and Mr Harry W. Meredith.

During the year 1,330 books, 3,560 pamphlets, and 320 maps were added to the library, increasing the total contents in books, pamphlets, and maps to 115,553. The following table shows in detail the growth of the library during the year:

Contents of the library, June 30, 1895.

BOOKS			
On hand June 30, 1894:			
Received by exchange	24,405		
Received by purchase	10,265		
		34,670	
Received during the past year			
By exchange	1,153		
By purchase	177		
		1,330	
			36,000
PAMPHLETS.			
On hand June 30, 1894:			
Received by exchange	44,259		
Received by purchase	5,379		
		49,638	
Received during the past year			
By exchange	3,320		
By purchase	240		
		3,560	
			53,198
MAPS			
Geologic and topographic maps.			
On hand June 30, 1894		26,035	
Received during the year		320	
			26,355
Total number of books, pamphlets, and maps			115,553

These accessions have all been catalogued under author entry. The average of circulation has continued, and the number of books consulted at the reading tables has greatly increased.

Owing to the crowded condition of the shelves, it has been necessary to place certain classes of books in rooms remote from the library, and for the same reason it has not been possible to properly classify the new accessions. To obviate this difficulty for the present, the Director has had the partition between the library and his private office removed, so as to add the latter to the library room. The cases put up in this addition afford space capable of shelving 14,700 books. This will make it possible to arrange accessibly the books now stored elsewhere, and to rearrange the books now on shelves in crowded spaces.

As a result of exchange, 2,473 books and pamphlets were received during the year. The distribution by exchange during the year is detailed in the following table.

Distribution of publications by exchange.

	Volumes
Twelfth Annual Report	3, 230
Thirteenth Annual Report	4, 845
Fourteenth Annual Report	3, 238
Bulletin 97	950
Bulletin 98	950
Bulletin 99	950
Bulletin 100	950
Bulletin 101	950
Bulletin 102	950
Bulletin 103	950
Bulletin 104	950
Bulletin 105	950
Bulletin 106	950
Bulletin 107	950
Bulletin 108	950
Bulletin 109	950
Bulletin 110	950
Bulletin 111	950
Bulletin 112	950
Bulletin 113	950
Bulletin 114	950
Bulletin 115	950
Bulletin 116	950
Bulletin 117	950
Bulletin 118	950
Bulletin 119	950
Bulletin 120	950
Bulletin 121	950
Bulletin 122	950
Monograph XIX	950
Monograph XXI	950
Monograph XXII	950
Monograph XXIII	950
Monograph XXIV	950
Mineral Resources for 1892	950
Mineral Resources for 1893	950
Total	42, 663

The exchange list of the Survey prepared in 1883 has been materially changed from time to time on account of death of individuals, etc., until its reconstruction became necessary. During the year a greatly enlarged and practically new list, which embodies the results of ten years of correspondence, has been prepared, and is now ready for the printer.

It is not practicable to state in tables as statistics the work done in a library. The function of the library is to furnish books, pamphlets, and maps to the working force of the Survey, and also to assist in verifying imperfect references, finding papers, identifying authors, and attending to requests for information and facts which come to it from within and without the Survey.

DIVISION OF DISBURSEMENTS AND ACCOUNTS.

This division is still in charge of Mr. John D. McChesney, who as chief disbursing clerk has served the Geological Survey so faithfully and so well from the date of its organization until the present time. Summarized and detailed statements of disbursements follow.

FINANCIAL STATEMENT

Amounts appropriated for and expended by the United States Geological Survey, for the fiscal year ended June 30, 1895.

	Expenses, Geological Survey	Engraving and printing the geological maps of the United States	Salaries, office of Geological Survey	Total
Appropriation for fiscal year, 1895 (joint resolution approved June 29, 1894, acts approved July 31, 1894, August 18, 1894, January 25, 1895, March 2, 1895, and from other sources).	$359,600 00	$65,199 90	$31,634 57	$456,434 47
Amounts expended, classified as follows				
A Services	258,863 67	38,973 84	31,601 27	329,438 78
B Traveling expenses	20,190 11	63 50		20,253 61
C Transportation of property	3,481 85	18 48		3,500 33
D Illustrations for reports	647 20			647 20
E Office rents	4,199 88			4,199 88
F Storage	679 30			679 30
G Correspondence	63 60			63 60
I. Field subsistence	18,237 87			18,237 87
K Field and office supplies	27,635 12			27,635 12
L Instruments	1,244 41			1,244 41
M Field material	3,758 29			3,758 29
N Office furniture	790 00			790 00
O Books and maps	1,629 97			1,629 97
P Stationery and drawing material	1,257 61			1,257 61
Q Photographic material	1,598 26			1,598 26
R Laboratory material	1,144 70			1,144 70
S Material for engraving and printing geological maps		19,698 26		19,698 26
T Bonded railroad accounts				
Passenger	1,873 27			1,873 27
Freight	540 05			540 05
Total expenditures	347,835 16	58,754 08	31,601 27	438,190 51
Balance unexpended July 1, 1895	11,764 84	6,445 82	33 30	18,243 96
Probable amount required to meet outstanding liabilities	11,764 84	6,445 82		18,210 66

ANALYSIS OF DISBURSEMENTS

Under the following heads appear the total expenditures under the various appropriations:

1.	Salaries, office of Geological Survey	$31,601.27
2	Salaries of scientific assistants	29,900 00
3	Skilled laborers and various temporary employees	12,997.28
4	Topography	149,376.94
5	Geology	93,089 73
6	Paleontology	9,413.78
7	Chemical and physical researches	6,899.59
8	Preparation of illustrations	12,991 74
9	Mineral Resources of the United States	16,757 74
10	Books for library, etc	1,298 48
11	Gauging streams, etc	10,910.00
12	Rent of office rooms	4,199 88
13.	Engraving and printing geological maps of the United States	58,754 08
	Total	438,190 51

RECAPITULATION

	Expenses Geological Survey	Engraving and printing the geological maps of the United States	Salaries office of Geological Survey	Total
Appropriation fiscal year ending June 30, 1895, and from other sources	$359,600 00	$65,199 90	$31,634 57	$456,434 47
Expended as per detailed statement herewith	345,421 84	58,754 08	31,601 27	435,777 19
Bonded railroad accounts settled at United States Treasury	2,413 32			2,413 32
Balance on hand July 1, 1895	11,764 84	6,445 82	33 30	18,243 96

DETAILED STATEMENT OF EXPENDITURES.

Abstract of disbursements made by John D. McChesney, chief disbursing clerk, United States Geological Survey, from July 1, 1894, to June 30, 1895.

SALARIES, OFFICE OF GEOLOGICAL SURVEY

Date of payment	No of voucher	To whom paid	For what paid	Amount
1894				
July 31	1	R T Hill	Services, July, 1894	$252 70
31	2	Pay roll of employees	do	2,643 60
Aug 31	1	do	Services Aug, 1894	2,611 81
Sept 11	1	Caleb I Taylor	Services, Sept 1-3, 1894	4 89
30	2	Pay roll of employees	Services, Sept, 1894	2,555 32
Oct 31	1	do	Services Oct., 1894	2,643 60
Nov. 30	1	do	Services, Nov, 1894	2,560 30
Dec 31	1	do	Services Dec, 1894	2,643 60
1895				
Jan 31	1	do	Services, Jan., 1895	2,702 90
Feb 28	1	do	Services, Feb, 1895	2,441 70
Mar 31	1	A B Dawson	Services, Mar 1-12, 1895	33 33
31	2	Pay roll of employees	Services, Mar, 1895	2,664 02
Apr 30	1	H C Rizer	Services, Apr, 1895	185 40
30	2	Pay roll of employees	do	2,397 90
May 31	1	do	Services, May, 1895	2,672 90
June 30	1	do	Services, June, 1895	2,587 30
		Total		31,601 27

ENGRAVING AND PRINTING THE GEOLOGICAL MAPS OF THE UNITED STATES

1894				
July 19	1	C & W Pyle Co	Engravers' supplies	$27 93
19	2	Geo Meier & Co	do	48 50
31	3	James C Pritchard	Services, July 1 13, 1894	35 70
31	4	Pay roll of employees	Services, July, 1894	2,183 00
31	5	A Lisner	Engravers' supplies	10 20
31	6	Charles Hellmuth	do	210 00
31	7	do	do	5 00
31	8	Z D Gilman	do	14 42
31	9	Melville Lindsay	do	4 50
31	10	William Gay	do	3 00
31	11	Geo Meier & Co	do	13 85
31	12	C R Carver	do	3 90
Aug 9	1	Charles Hellmuth	do	80 00
18	2	Geo F Muth & Co	do	5 20
18	3	Peter Adams	do	24 64
18	4	The Celluloid Co	do	85 00
31	5	Z D Gilman	do	23 27
31	6	S. J Kubel	Traveling expenses	25 90
31	7	Pay roll of employees	Services, Aug, 1894	1,349 78
31	8	do	do	1,343 50
Sept 12	1	R Hoe & Co	Dampening-rollers	41 55
15	2	Peter Adams Co	Lithograph paper.	168 00
15	3	A Lisner	Engravers' supplies	11 38
21	4	Lansburgh & Bro	do	5 27
29	5	Fuchs & Lang Manufacturing Co	Lithograph stones	728 78
29	6	Pay roll of employees	Services, Sept, 1894	1,314 20
29	7	do	do	1,306 65
Oct 9	1	J R Hurley	Repairs	5 38
9	2	Fuchs & Lang Manufacturing Co	Supplies	39 00
9	3	R Hoe & Co	do	34 59
9	4	W C Newton & Co.	do	32 97
10	5	Charles Hellmuth.	do	25 00
10	6	Department of the Interior.	do	288 00
10	7	United States Express Co	Freight	1 40
10	8	Adams Express Co	do	25
10	9	do	do	2 50
12	10	A D. Farmer & Son	Type	3 35
15	11	Bureau Engraving and Printing	Ink.	12 50
17	12	M. W Beveridge	Supplies	1 08
20	13	J B Parks	Head to press.	14 00
27	14	Lansburgh & Bro	Supplies	10 12
29	15	do	do	2 76
31	16	Pay roll	Services, Oct, 1894	1,357 90
31	17	do	do	1,407 15
Nov 14	1	Peter Adams Co	Engravers' supplies	44 19
14	2	M Siebold	do	19 58

Abstract of disbursements made by John D. McChesney, chief disbursing clerk, United States Geological Survey, etc.—Continued

ENGRAVING AND PRINTING THE GEOLOGICAL MAPS, ETC —Continued

Date of payment	No of voucher	To whom paid	For what paid	Amount
1894				
Nov 15	3	C & W Pyle Co	Engravers' supplies	$24 00
15	4	S J Kubel	Traveling expenses	16 50
15	5	C F Scott	Services, Nov 1-14, 1894	11 00
17	6	Department of the Interior	Supplies	2,054 71
20	7	Ernest Kubel	Copper plates	245.43
22	8	W C Newton & Co	Engravers' supplies	26 11
22	9	Z D Gilman	do	1 72
24	10	R Hoe & Co	do	12 50
28	11	Pay roll of employees	Services, Nov, 1894	1,372 90
28	12	do	do	1,388 20
Dec 6	1	Meyer Bros Drug Co	Engravers' supplies	4 20
7	2	Adams Express Co	Freight charges	3 35
8	3	H Hoffa	Engravers' supplies	9 60
8	4	W C Newton & Co	do	45 95
14	5	M Siebold	do	13.42
12	6	The Fairbanks Co	do	5 06
14	7	Charles Helmuth	do	12 50
24	8	Meyer Bros Drug Co	do	4 80
28	9	Mackall Bros & Flemer	do	37 44
28	10	L H Schneider's Son	do	94 45
29	11	Pay roll of employees	Services, Dec, 1894	1,536 65
29	12	do	do	1,600 15
1895				
Jan 9	1	James S Topham	Engravers' supplies	7 50
15	2	Ernest Kubel	Copperplates	245 43
15	3	Geo F Muth & Co	Engravers' supplies	7 80
15	4	Z. D Gilman	do	7 20
16	5	Department of the Interior	do	2,934 59
16	6	E E Jackson & Co	Lumber	14 64
16	7	Thomas W Smith	Engravers' supplies	27 00
16	8	Hugh Reilly	do	60
16	9	Department of the Interior	do	240 90
22	10	Ernest Kubel	Electrotyping bassos	57 12
22	11	United States Express Co	Freight charges	1.25
25	12	Stephenson's Express	do	1 33
25	13	Herman Baumgarten	Supplies	5 00
31	14	John F Hutcherson	Services Jan 1-9, 1895	18 40
31	15	J T Scott	Services, Jan 18-29, 1895	25 00
31	16	Pay roll of employees	Services, Jan., 1895	1,839 03
31	17	do	do	1,547 30
31	18	do	do	244 80
Feb 2	1	C B Fenton & Co	Repairs	16 98
8	2	C & W Pyle Co	Engravers' supplies	140 21
8	3	Electro Light Engraving Co	Reproducing map	1 50
8	4	Louis Gehlert	Engravers' supplies	65 00
8	5	A D Farmer & Son Type Founding Co	do	67 41
14	6	Fred A Schmidt	do	28 50
14	7	Lansburgh & Bro	do	23 03
14	8	M W Beveridge	do	1 21
14	9	Mackall Bros & Flemer	do	103 05
14	10	Z D Gilman	do	2 82
14	11	Geo F Muth & Co	do	37 28
14	12	Robert Boyd	do	38 93
14	13	Department of the Interior	Lithographic paper	7,300 80
14	14	Geo W Knox's Express	Freight charges	5 67
18	15	Geo Meier & Co	Engravers' supplies	104 27
20	16	Fuchs & Lang Manufacturing Co	do	18 00
23	17	S Oppenheimer	do	4 80
23	18	Z D Gilman	do	.16
28	19	Pay roll of employees	Services, Jan and Feb, 1895	209 70
28	20	do	Services, Feb, 1895	1,791 80
28	21	do	do	1,548 80
28	22	do	do	40 50
Mar. 6	1	Ernest Kubel	Copperplates	245 43
6	2	U S Electric Lighting Co	Incandescent lamps	3 00
6	3	Charles Helmuth	Engravers' supplies	9 00
6	4	American Typs Founders Co	do	12 00
6	5	Robert Mayer & Co.	Heads for lithographic hand presses	49 50
8	6	Lansburgh & Bro.	Engravers' supplies	9 92
14	7	H Hoffa	do	8 50
14	8	Easton & Rupp	do	1 25
14	9	F. W Gesswein	do	12 45
21	10	J E Hurley	Material and repairs	109 98
21	11	Melville Lindsay	Engravers' supplies	2 81

Abstract of disbursements made by John D McChesney, chief disbursing clerk, United States Geological Survey, etc.—Continued

ENGRAVING AND PRINTING THE GEOLOGICAL MAPS ETC —Continued

Date of payment	No of voucher	To whom paid.	For what paid	Amount
1895				
Mar 25	12	Lansburgh & Bro	Engravers' supplies	$2 24
23	13	W A Swan	Services, Mar 1-23, 1895	13 60
30	14	Pay roll of employees	Services, Mar , 1895	1,979 10
30	15	do	do	1,755 23
30	16	E E Jackson & Co	Engravers' supplies	26 85
30	17	Peter Adams Co	do	37 45
Apr 11	1	R. Hoe & Co	do	5 25
12	2	Thomas W Smith	do	26 00
12	3	John C Parker	do	2 10
12	4	Ernest Kubel	Copperplates	245 43
12	5	S J Kubel	Traveling expenses	21 10
12	6	Department of the Interior	Supplies	1,013 60
15	7	Adams Express Co	Freight charges	1 65
17	8	Woodward & Lothrop	Engravers' supplies	7 89
17	9	M Siebold	do	18 00
17	10	Z D Gilman	do	2 60
20	11	Lansburgh & Bro	do	28 44
22	12	Mackall Bros. & Flemer	do	75
24	13	Charles Helmuth	do	25 00
24	14	Robert Meyer & Co	do	10 00
24	15	Geo Meier & Co	do	16 00
24	16	Geo F Muth & Co	do	21 00
26	17	S F Ware	do	32
29	18	F Wesel Manufacturing Co	Cast iron plate	35 00
29	19	L H Schneider's Son	Engravers' supplies	22 71
30	20	do	do	2 50
30	21	Pay roll of employees	Services, Apr 1895	1,924 35
30	22	do	do	1,624 20
30	23	do	do	172 90
May 10	1	Wm F Lutz	Engravers' supplies	1 50
10	2	Shoemaker & Busch	do	72
10	3	Mutual District Messenger Co	Services, etc	87 38
11	4	Fuchs & Lang Manufacturing Co	Lithographic stones	498 12
16	5	S F Ware	Engravers' supplies	3 60
18	6	W C Newton & Co	do	37 99
24	7	M Siebold	do	8 00
24	8	E E Jackson & Co	Map cases and dial	49 00
24	9	Ernest Kubel	Copperplates	245 43
25	10	James J Bellew	Services, May 1-25, 1895	22 00
31	11	Pay roll of employees	Services, May, 1895	2,015 40
31	12	do	do	2,072 55
June 3	1	Department of the Interior	Engravers' supplies	96 75
10	2	W A Pate	do	1 50
11	3	H Hoffa	do	18 70
10	4	Department of the Interior	do	397 60
13	5	Shoemaker & Busch	do	2 95
15	6	Geo F Muth & Co	do	25 30
13	7	Geo W Knox's Express	Freight charges and hauling	1 08
15	8	Fuchs & Lang Manufacturing Co	Engravers' supplies	91 68
15	9	M Siebold	do	17 23
15	10	Mutual District Messenger Co	Services, May, 1895	8 00
19	11	L H. Schneider's Son	Engravers' supplies	24 55
21	12	W C Newton & Co	do	20 55
29	13	Fred A Schmidt	do	2 80
29	14	Mackall Bros & Flemer	do	70
30	15	Pay roll of employees	Services, June, 1895	1,952 30
30	16	do	do	1,874 60
		Total		58,754 08

GENERAL EXPENSES OF THE GEOLOGICAL SURVEY

JULY, 1894

July 12	1	Robert Beall	Publications	$69 00
31	2	R P Carleton	Services July 1-20, 1894	32 25
31	3	H S Wallace	Services, July, 1894	134 80
31	4	Pay roll of employees	do	1,196 20
31	5	do	do	998 19
31	6	do	do	728 66
31	7	do	do	599 10
31	8	do	do	3,270 81
31	9	do	do	1,612 30

Abstract of disbursements made by John D. McChesney, chief disbursing clerk, United States Geological Survey, etc.—Continued

GENERAL EXPENSES OF THE GEOLOGICAL SURVEY—Continued

JULY, 1894—Continued

Date of payment	No of voucher	To whom paid	For what paid	Amount
July 31	10	Pay roll of employees	Services, July 1894	$393 98
31	11	do	do	328 50
31	12	do	do	817 10
31	13	do	do	673 90
31	14	C C Willard	Rent of office rooms, July, 1894	349 99
31	15	R P Carleton	Services, July 26-31, 1894	9 67
31	16	F Berger	Services, July, 1894	80 00
31	17	L P Bush	do	65 00
31	18	H C Rizer	Traveling expenses	50 50
31	19	John Moore	Publications	8 00
31	20	Henry Bufford	Services, July 2-18, 1894	30 00
31	21	Elizabeth A Balloch	Services, July, 1894	62 50
31	22	Francis Wieser	Original drawings	103 40
		Total		11,613 85

AUGUST, 1894

Date of payment	No of voucher	To whom paid	For what paid	Amount
Aug 4	1	David T Day	Traveling expenses	$40 88
8	2	James W Spencer	do	48 50
8	3	William C Day	Services, July, 1894	125 00
9	4	James G Bowen	Hire of transportation	16 00
14	5	H M Wilson	Traveling expenses	122 53
18	6	John Moore	Publications	7 00
18	7	George F Kunz	Services, July, 1894	60 00
20	8	Quartermaster's Department, U S A.	Field material	74 39
21	9	H M Wilson	Traveling expenses	34 52
25	10	Thomas W Smith	Illustration supplies	47 00
27	11	William A Raborg	Traveling expenses	22 58
28	12	E W Parker	do	69 40
31	13	F B Scott	Services, Aug, 1894	50 00
30	14	Pennsylvania R R Co	Transportation of assistant	13 07
31	15	Robert Beall	Publications	28 00
31	16	C C Willard	Rent of office rooms, Aug, 1894	349 99
31	17	C Kirchhoff	Services, July and Aug, 1894	260 00
31	18	Joseph D Weeks	do	260 00
31	19	F Berger	Services, Aug, 1894	80 00
31	20	L P Bush	do	65 00
31	21	Z D Gilman	Illustration supplies	169 71
31	22	Pay roll of employees	Services, Aug, 1894	1,196 20
31	23	do	do	1,044 78
31	24	do	do	559 30
31	25	do	do	187 19
31	26	do	do	736 30
31	27	do	do	2,840 00
31	28	do	do	353 80
31	29	do	do	395 40
31	30	do	do	328 50
31	31	do	do	867 10
31	32	do	do	673 90
		Total		11,126 04

SEPTEMBER, 1894

Date of payment	No of voucher	To whom paid	For what paid	Amount
Sept 5	1	J H Wheat	Traveling expenses	$5 75
5	2	Frank Sutton	do	302 37
5	3	F B Scott	do	39 13
5	4	William A Raborg	do	21 36
5	5	Elizabeth A Balloch	Services, Aug, 1894	62 50
6	6	Victoria Essex	Services, Aug 14 to Sept 6	40 00
5	7	W H Morrison's Sons	Publications	16 00
6	8	John H Renshawe	Traveling expenses	38 15
7	9	H M Wilson	do	124 50
7	10	R U Goode	do	57 50
7	11	do	Field expenses	14 80
7	12	J. H Jennings	do	130 25
8	13	S S Gannett	Traveling expenses	34 09
8	14	Horsey Monroe	Field expenses	25 70

Abstract of disbursements made by John D. McChesney, chief disbursing clerk, United States Geological Survey, etc.—Continued.

GENERAL EXPENSES OF THE GEOLOGICAL SURVEY—Continued

SEPTEMBER, 1894—Continued

Date of payment	No of voucher	To whom paid.	For what paid	Amount
Sept 8	15	C C Bassett	Field expenses	$136 12
10	16	W H Lovell	do	150 32
10	17	R C McKinney	do	26 50
10	18	W. A Rogers	Field subsistence	27 00
10	19	Humphries & Co	Pasturage	9 78
10	20	T. W Tigner	Services, Aug 28-31, 1894	5 40
10	21	John L Williams	do	5 40
10	22	Whitman Saddle Co	Repairs	11 00
10	23	Office Specialty Manufacturing Co	Geologic supplies	75 00
12	24	Francis Wieser	Original drawings	73 60
12	25	James W Spencer	Services, Aug, 1894	151 60
15	26	Houston and Texas Central R R	Transportation of assistant	25 35
15	27	A Lisner	Topographic supplies	10 35
15	28	John C Parker	Mineral resources supplies	57 00
15	29	William Walker	Services, Sept 1-3, 1894	5 87
17	30	William C Day	Services, Aug 1 to Sept 15, 1894	200 00
17	31	H M. Wilson	Traveling expenses	38 47
17	32	P H Christie	do	13 76
19	33	Western Union Telegraph Co	Telegrams, July, 1894	15 28
21	34	Atchison, Topeka and Santa Fe Rwy	Transportation of assistants	8 10
20	35	Baltimore and Ohio R R	do	70 74
21	36	James S Topham	Topographic supplies	7 00
20	37	Thos Somerville & Sons	do	6 80
19	38	A P Davis	Traveling expenses	56 00
20	39	E W Parker	do	43 42
22	40	William C Day	do	10 55
22	41	A H. Thompson	do	41 00
22	42	Vaux & Coe	3 horses	265 00
22	43	do	Stabling, fuel, etc	22 32
22	44	J S J Lallie	Repairs	22 10
22	45	F H Newell	Cash paid for services	54 18
22	46	Theodore Johnson	Services, Aug 13 to Sept 22, 1894	87 50
24	47	Fayette R Plumb	Geological hammers	209 55
24	48	Northern Pacific R R Co	Transportation of assistants	15 00
24	49	Burlington and Missouri River R R in Nebraska	do	29 50
26	50	S S Gannett	Traveling expenses	44 23
27	51	Spratlen & Anderson	Field supplies	126 96
27	52	F H Newell	Traveling expenses	93 45
27	53	do	Field expenses	45 38
27	54	Stephenson's Express	Freight charges and hauling	81 30
27	55	Southern Rwy Co	Transportation of assistants	132 40
29	56	do	do	15 20
27	57	Rio Grande Southern R R	do	44 65
29	58	Pennsylvania R R Co	do	321 20
29	59	Denver and Rio Grande Rwy	do	53 25
29	60	do	Transportation of property	87 45
29	61	Edward Kubel	Repairs to instruments	66 00
29	62	H C Hunter	Original drawings	96 20
29	63	Elizabeth A Balloch	Services, Sept. 14-26, 1894	25 00
29	64	W C Day	Traveling expenses	94 99
29	65	S S Gannett	Field expenses	11 80
29	66	R T Hill	Services, July 31, 1894	8 13
30	67	C C Willard	Rent of office rooms, Sept, 1894	349 99
30	68	R U Goode	Services, Sept, 1894	203 80
30	69	F H Newell	do	163 00
30	70	T W Stanton	do	114 20
30	71	F Berger	do	80 00
30	72	L. P Bush	do	65 00
30	73	Pay roll of employees	do	280 80
30	74	Heisey Monroe	do	97 80
30	75	Pay roll of employees	do	953 80
30	76	do	do	1,052 03
30	77	do	do	1,179 00
30	78	do	do	342 40
30	79	do	do	220 00
30	80	do	do	318 00
30	81	do	do	840 80
30	82	do	do	702 20
		Total		11,209 07

Abstract of disbursements made by John D. McChesney, chief disbursing clerk, United States Geological Survey, etc —Continued

GENERAL EXPENSES OF THE GEOLOGICAL SURVEY—Continued

OCTOBER, 1894

Date of payment	No of voucher	To whom paid	For what paid	Amount
Oct 8	1	William A Raborg	Traveling expenses	$12 12
8	2	do	do	29 37
6	3	F B Scott	do	54 49
3	4	H M Wilson	do	89 50
4	5	Henry Gannett	do	129 70
9	6	Rio Grande Western Rwy Co	Transportation of assistants	16 50
9	7	Houston and Texas Central Rwy	do	38 00
9	8	G N Saegmuller	Instruments	190 00
9	9	P H Christie	Services, Aug 1-18, 1894	88 04
10	10	F H Newell	Field expenses	138 37
10	11	Department of the Interior	Topographic supplies	15 80
10	12	do	Geologic supplies	18 92
10	13	do	Illustration supplies	13 37
10	14	Adams Express Co	Freight, July, 1894	30 50
10	15	do	Freight, Aug, 1894	52 35
10	16	United States Express Co	Freight, July and Aug, 1894	318 05
12	17	A P Davis	Traveling expenses	47 80
12	18	J W Drew & Co	Geologic supplies	2 25
12	19	M. G Copeland & Co	do	6 00
12	20	Fred A Schmidt	Topographic supplies	26 40
12	21	V Shoonmaker	Geologic supplies	33 00
16	22	William A Croffut	Services, Oct 1-15, 1894	105 98
15	23	R L Packard	Services, Sept 28 to Oct 15, 1894	75 00
15	24	Smith Premier Typewriter Co	Repairs	5 00
15	25	Baltimore and Ohio R R Co	Transportation of assistants	793 45
13	26	Southern Rwy Co	do	19 25
13	27	Swem Supply and Construction Co	Supplies and repairs	44 79
13	28	Geo H Murch	do	36 45
16	29	David T Day	Traveling expenses	54 57
17	30	E E Jackson & Co	Topographic supplies	31 25
17	31	Andrew Renz	Repairs	2 00
17	32	Queen & Co (incorporated)	Instruments	90 00
17	33	A P Davis	Field expenses	56 70
17	34	Southern Rwy Co	Transportation of assistant	24 15
17	35	E J Pullman	Supplies	52 65
18	36	H N Stokes	Services Sept 25-30, 1894	22 83
18	37	E W Parker	Traveling expenses	52 74
20	38	J S J Lallie	Repairs to current meters	58 63
22	39	Virginia and Truckee R R Co	Transportation of assistants	30 00
22	40	Robert Hay	Services, Oct 1-15, 1894	130 00
23	41	Theodore Johnson	Services, Sept 24 to Oct 22, 1894	62 50
23	42	F B Weeks	Traveling expenses	100 50
23	43	H M Wilson	do	86 60
24	44	Pennsylvania R R Co	Transportation of assistants	113 65
26	45	Burlington and Missouri River R R in Nebraska	do	20 40
26	46	Denver and Rio Grande R R Co	Transportation of property	2 15
26	47	Spratlen & Anderson	Supplies	37 16
26	48	Smith Premier Typewriter Co	Geologic repairs	15 00
29	49	New York Safety Steam Power Co	Geologic supplies	3 00
29	50	John Birkinbine	Services, July 2-21 1894	75 00
29	51	A P Davis	Field expenses	66 45
29	52	Rio Grande Western Rwy Co	Transportation of assistants	13 00
31	53	Southern Pacific Co	do	11 80
31	54	Rio Grande Southern Rwy Co	do	18 15
31	55	G N Saegmuller	Repairs	12 00
31	56	A H Thompson	Field expenses	60 05
31	57	N D C Hodges	Publications	7 00
31	58	Will H Grosscup	do	8 50
31	59	A P Davis	Services, Oct, 1894	168 50
31	60	Hersey Munroe	do	101 10
31	61	T W Stanton	do	117 90
31	62	Eimer & Amend	Laboratory supplies	9 10
31	63	H C Hunter	Original drawings	95 75
31	64	Frank Burns	Traveling expenses	34 15
31	65	Northern Pacific Rwy Co	Transportation of assistants	44 28
31	66	Southern Rwy Co	do	17 50
31	67	C C Willard	Rent of office rooms, Oct, 1894	349 99
31	68	R U Goode	Services, Oct, 1894	210 60
31	69	F H Newell	do	168 50
31	70	Pay roll of employees	do	985 60
31	71	do	do	997 94
31	72	do	do	1,247 35
31	73	do	do	227 50

Abstract of disbursements made by John D. McChesney, chief disbursing clerk, United States Geological Survey, etc.—Continued.

GENERAL EXPENSES OF THE GEOLOGICAL SURVEY—Continued

OCTOBER, 1894—Continued

Date of payment		No of voucher	To whom paid	For what paid	Amount
Oct	31	74	Pay roll of employees	Services, Oct , 1894	$446 40
	31	75	do	do	867 60
	31	76	do	do	723 90
	31	77	do	do	168 70
	31	78	do	do	248 50
			Total		10,979 82

NOVEMBER, 1894

Nov	3	1	Pay roll of employees	Services, Oct , 1894	$174 20
	3	2	Jos A Taff	do	101 10
	5	3	Chas D Walcott	Traveling expenses	355 02
	6	4	S F Emmons	do	115 70
	6	5	do	do	109 70
	6	6	H Gibb	Services, Sept and Oct , 1894	140 00
	6	7	F Berger	Services, Oct 1894	80 00
	6	8	L P Bush	do	65 00
	6	9	Robert Beall	Publications	6 75
	6	10	Chas L Condit	do	15 00
	6	11	do	do	22 50
	6	12	John Moore	do	8 50
	9	13	National Press Intelligence Co	do	16 20
	9	14	Alpheus Hyatt	Services, Sept 20 to Oct 31, 1894	75 00
	9	15	Chesapeake and Ohio Rwy Co.	Transportation of assistants	9 30
	9	16	Denver and Rio Grande Rwy Co	do	37 10
	9	17	Rio Grande Southern Rwy	do	38 00
	9	18	Wm C Day	Services, Sept 17 to Oct 31, 1894	150 00
	10	19	Z D Gilman	Laboratory supplies	43 80
	10	20	S J Haislett	Geologic supplies	9 00
	14	21	Union Pacific, Denver and Gulf Rwy	Transportation of assistant	2 75
	14	22	Atchison, Topeka and Santa Fe Rwy	do	46 81
	15	23	Louisville and Nashville R R Co	do	5 50
	14	24	A H Thompson	Field expenses	67 83
	15	25	F H Newell	do	61 35
	15	26	Spratlen & Anderson	Field subsistence	20 39
	15	27	Henry Heil Chemical Co	Illustration supplies	2 48
	15	28	Robert Hay	Services, Oct 16-31, 1894	140 00
	15	29	Henry Gannett	Traveling expenses	178 65
	13	30	David T Day	do	21 90
	16	31	F H Newell	do	95 88
	15	32	S S Gannett	do	47 79
	17	33	Lester F Ward	do	76 61
	16	34	Chicago, Milwaukee and St Paul Rwy	Transportation of assistants	49 10
	20	35	Great Northern Rwy	do	35 00
	20	36	Atchison, Topeka and Santa Fe Rwy	do	18 00
	20	37	New York Central and Hudson River Rwy	do	9 25
	20	38	Nashville, Chattanooga and St Louis Rwy	do	9 60
	20	39	S A Cuddy	Services Oct 13 to Nov 16, 1894	60 00
	20	40	Annie L Arnold	Services Oct 15 to Nov 17, 1894	60 00
	20	41	Joseph D Weeks	Services Sept 1 to Oct 31, 1894	250 00
	20	42	F H Newell	Field expenses	25 00
	21	43	Conrad Becker	Illustration supplies	10 00
	21	44	T W Stanton	Traveling expenses	304 57
	22	45	Pennsylvania R R Co	Transportation of assistants	13 71
	24	46	A P Davis	Field expenses	116 75
	24	47	J D Groesbeck	Field supplies	106 72
	24	48	Cutter & Wood	Geologic supplies	15 45
	26	49	B Westermann & Co	Publications	3 91
	26	50	H M Wilson	Traveling expenses	10 50
	26	51	Robert Hay	Services Nov 1-15 1894	130 00
	28	52	E E Jackson & Co	Illustration supplies	450 00
	30	53	A H Thompson	Field expenses	73 12
	30	54	F Berger	Services Nov , 1894	80 00
	30	55	H Gibb	do	70 00

Abstract of disbursements made by John D McChesney, chief disbursing clerk, United States Geological Survey, etc —Continued.

GENERAL EXPENSES OF THE GEOLOGICAL SURVEY—Continued

NOVEMBER, 1894—Continued

Date of payment	No of voucher	To whom paid	For what paid	Amount
Nov 30	56	L P Bush	Services, Nov , 1894	$65 00
30	57	Hersey Munroe	do	97 80
30	58	A P Davis	do	163 00
30	59	F H Newell	do	163 00
30	60	Pay roll of employees	do	1,157 60
30	61	do	do	1,001 86
30	62	do	do	2,781 20
30	63	do	do	334 20
30	64	do	do	432 20
30	65	do	do	833 30
30	66	do	do	702 20
30	67	C W Hayes	Traveling expenses	122 65
30	68	H C Hunter	Drawings	94 50
30	69	C C Willard	Rent of office rooms	349 99
		Total		12,538 99

DECEMBER, 1894

Date of payment	No of voucher	To whom paid	For what paid	Amount
Dec 4	1	Pay roll of employees	Services, Nov , 1894	$170 44
4	2	M A Tappan	Topographic supplies	2 50
4	3	John C Parker	Geologic supplies	31 50
4	4	Burlington and Missouri River R R in Nebraska	Transportation of assistant	33 80
4	5	R M Towson	Traveling expenses	64 94
4	6	R U Goode	do	139 50
4	7	W H Lovell	do	27 25
4	8	William A Raborg	do	52 40
4	9	G E Hyde	Field expenses	118 84
4	10	R U Goode	do	8 25
6	11	F H Newell	do	83 00
6	12	do	Traveling expenses	198 90
6	13	do	Field expenses	46 00
6	14	Meyer Bros Drug Co	Illustration supplies	30
6	15	Henry Bufford	Services, Sept 3 to Oct 6, 1894	60 00
6	16	N S Shaler	Services, Oct 1 to Nov 30, 1894	300 00
6	17	John Birkinbine	Services, July 23 to Nov 30, 1894	530 00
6	18	C Kirchhoff	Services, Sept 1 to Nov 30, 1894	250 00
7	19	Medo Shortley	Services, Nov 1-21, 1894	24 50
7	20	Basil Duke	Services, Nov , 1894	73 40
7	21	S Celestin	Pasturage, Sept , 1894	7 00
7	22	Save Celestin	Pasturage, Oct and Nov , 1894	10 73
7	23	Wykoff, Seamans & Benedict	Topographic repairs	40 00
7	24	S F Ware	Laboratory supplies	6 15
7	25	Southern Pacific Co	Transportation of assistants	37 40
7	26	Adams Express Co	Freight charges	82 46
8	27	Shoemaker & Busch	Laboratory supplies	3 30
8	28	do	Illustration supplies	38
8	29	A Lisner	Laboratory supplies	1 75
8	30	Will H Grosscup	Publications	8 50
8	31	Union Pacific, Denver and Gulf Rwy	Transportation of assistant	3 70
8	32	W F Hillebrand	Traveling expenses	8 68
10	33	U S Express Co	Freight charges	64 03
14	34	Wykoff, Seamans & Benedict	Geologic repairs	125 00
14	35	Smith Premier Typewriter Co	Paleontologic repairs	8 00
12	36	R R Bowker	Publications	8 50
14	37	Robert Beall	do	32 75
14	38	George T Hawkins	Services, Nov 27-30, 1894	17 39
12	39	Alpheus Hyatt	Services, Nov , 1894	75 00
12	40	William C Day	do	125 00
12	41	W M Gilcrest	Services, Oct 1-17, 1894	90 00
14	42	Robert Hay	Services, Nov 16-30, 1894	120 00
12	43	P C Warman	Services, Nov , 1894	146 80
12	44	J S J Lallie	Repairs and supplies	41 20
14	45	F H Newell	Field expenses	65 50
14	46	Baltimore and Ohio R R Co	Transportation of assistant	12 75
14	47	Southern Railway	do	7 01
14	48	Franklin & Co	Geological supplies	2 00
17	49	J F Manning	Laboratory supplies	41 25
17	50	James H McGill	do	5 70

Abstract of disbursements made by John D McChesney, chief disbursing clerk, United States Geological Survey, etc —Continued

GENERAL EXPENSES OF THE GEOLOGICAL SURVEY—Continued

DECEMBER, 1894—Continued

Date of payment	No of voucher.	To whom paid	For what paid	Amount
Dec 17	51	H C Hunter	Drawings	$48 75
17	52	G W Tigner	Services, Dec 1-3, 1894	3 87
17	53	John L Williams	Services, Dec 1-8, 1894	11 61
17	54	Oregon Rwy and Navigation Co.	Transportation of assistants	32 20
17	55	Louisville and Nashville R R Co	do	16 50
17	56	Baltimore and Ohio R R Co	Transportation of property	1 72
22	57	Will H Grosscup	Publications	15 00
22	58	Caleb I Taylor	Services, Dec 10-20, 1894	15 00
22	59	Lewis Drummond	Services, Dec 11-21, 1894	15 00
22	60	Elizabeth A Balloch	Services, Nov 14 to Dec 20, 1894	60 00
22	61	Julia M Corse	do	60 00
22	62	Annie L Arnold	Services, Nov 19 to Dec 14, 1894.	40 00
24	63	V C Tompkins	Services, Dec 4 to Dec. 13, 1894	45 00
24	64	Coffin & Northrop	Field supplies	29 70
24	65	A P Davis	Field expenses	162 30
24	66	Robert Hay	Services, Dec 1-15, 1894	130 00
24	67	Rio Grande Western Rwy	Transportation of assistants	54 25
24	68	International and Gt North'n Rwy	do	8 60
24	69	Chicago and Northwestern Rwy	do	12 50
24	70	Lake Shore and Mich Sou Rwy	do	9 15
24	71	Northern Pacific Rwy Co	do	32 95
24	72	do	do	38 50
28	73	S F Ware	Laboratory supplies	10 56
28	74	Mackall Bros & Flemer	Supplies	18 31
28	75	F H Newell	Field expenses	48 00
28	76	Department of the Interior	Supplies	229 46
28	77	do	do	29 01
28	78	L H Schneider's Son	do	15 14
31	79	Burlington and Missouri River R R in Nebraska	Transportation of assistants	86 65
31	80	St Paul and Duluth R R Co	do	8 60
31	81	Chicago, Milwaukee and St Paul Rwy	do	19 86
31	82	Atchison, Topeka and Santa Fé Rwy.	do	51 90
31	83	N S Shaler	Services Dec, 1894	170 00
31	84	F Berger	do	80 00
31	85	H Gibb	do	70 00
31	86	L P. Bush	do	65 00
31	87	Minnie Milligan	Services Dec. 7-31, 1894	40 32
31	88	H C Hunter	Drawings	42 50
31	89	U S Express Co	Freight charges	212 70
31	90	Frank Burns	Traveling expenses	67 18
31	91	C C Willard	Rent of office rooms Dec, 1894	349 99
31	92	Southern California R R Co	Transportation of assistants	61 40
31	93	Rio Grande Western Rwy	do	32 50
31	94	Daniel Stewart	Services Dec 9-31, 1894	37 09
31	95	F H Newell	Services Dec, 1894	168 50
31	96	A. P Davis	do	168 50
31	97	Pay roll of employees	do	1,364 70
31	98	do	do	1,108 79
31	99	do	do	3,113 20
31	100	do	do	1,536 50
31	101	do	do	2,128 00
31	102	do	do	345 40
31	103	do	do	446 40
31	104	do	do	867 60
31	105	do	do	757 96
		Total		18,007 73

JANUARY, 1895

Jan 3	1	William A. Raborg	Traveling expenses	$6 84
3	2	do	do	53 63
7	3	Richard M Webster	Services, Dec. 26-31, 1894	14 67
7	4	William H Herron	Services, Dec 17-31, 1894	57 07
7	5	William S Post	Services, Dec, 1894	101 10
7	6	M Hackett	do	151 60
9	7	Charles B Green	do	84 20
9	8	Alpheus Hyatt	do	75 00

Abstract of disbursements made by John D McChesney, chief disbursing clerk, United States Geological Survey, etc —Continued

GENERAL EXPENSES OF THE GEOLOGICAL SURVEY—Continued

JANUARY, 1895—Continued

Date of payment	No of voucher	To whom paid	For what paid	Amount
Jan 8	9	A C Peale	Services, Dec 15-20 1894	$30 00
9	10	Warren Upham	Services, Dec 31, 1894, to Jan 8, 1895	40 00
9	11	James Storrs	Services Dec 12-22 1894	20 00
9	12	do	Traveling expenses	25 30
9	13	A P Davis	do	41 50
9	14	do	Field expenses	4 75
9	15	Melville Lindsay	Illustration supplies	8 30
10	16	Southern Pacific Co	Transportation of assistants	24 05
10	17	Denver and Rio Grande R R Co	Transportation of property	.95
10	18	do	do	4 84
10	19	Pennsylvania R R Co	do	.72
10	20	do	do	10 38
10	21	Baltimore and Ohio R R Co	do	20 58
12	22	Texarkana and Fort Smith Rwy	do	5 38
12	23	Great Western Rwy Co	Transportation of assistants	27 50
12	24	Carson and Colorado R R Co	do	19 75
12	25	Southern Pacific Co	do	135 80
12	26	C D White	Traveling expenses	160 02
9	27	Mary C Mahon	Services, Dec 3, 1894, to Jan 9, 1895	60 00
14	28	Nashville, Chattanooga and St Louis Rwy	Transportation of assistants	8 60
14	29	Virginia and Truckee R R Co	do	17 75
14	30	L H Taylor	Services, Dec 3-5, 1894	15 00
14	31	C Kirchhoff	Services, Dec , 1894	90 00
14	32	R L Packard	Services, Jan 2-10, 1895	30 00
14	33	J E H Post	Illustrations	10 00
15	34	Charles E Munroe	Analyses of specimens	70 00
15	35	S F Emmons	Field expenses	17 00
15	36	H M Wilson	Traveling expenses	14 50
15	37	H C Rizer	do	35 80
15	38	Geo F Muth & Co	Geologic supplies	9 50
15	39	Z D Gilman	Supplies	37 85
15	40	Stephenson's Express	Freight charges and hauling	47 81
16	41	Hugh Reilly	Illustration supplies	9 12
16	42	Thomas W Smith	Supplies	91 00
16	43	E E Jackson & Co	do	86 34
16	44	Department of the Interior	do	6 63
16	45	do	do	5 14
16	46	do	do	22 91
16	47	do	do	234 22
18	48	John W Parker	Forage, storage, etc	44 50
21	49	Louis Dutertre	Services, Oct 24 to Dec 24, 1894	14 00
21	50	Henry V Smith	Services, Nov 1-30, 1894	7 50
21	51	Mrs J M Brown	Services, Dec , 1894	5 00
21	52	J L Wright jr	do	5 00
21	53	J S Regan	do	7 50
21	54	L Morse	do	5 00
21	55	J M Reed	do	5 00
21	56	J L Prentiss	do	3 00
21	57	M Savage	do	5 00
21	58	Baltimore and Ohio R R Co	Transportation of assistant	5 25
21	59	Carson and Colorado R R Co	Transportation of property	8 70
21	60	Virginia and Truckee R R Co	do	2 03
22	61	Oregon Railway and Nav Co	Transportation of assistant	16 10
22	62	Louisville and Nashville R R Co	do	27 50
22	63	National Press Intelligence Co	Publications	10 20
22	64	E W Woodruff	Geologic supplies	65 00
22	65	William H Rau	Illustration supplies	12 50
22	66	Rand, McNally & Co	Mineral Resources supplies	7 50
22	67	Library Bureau	File and pamphlet cases	4 80
23	68	Charles D Walcott	Traveling expenses	24 25
22	69	People's Dispatch Co	Freight charges and hauling	11 78
25	70	A P Davis	Field expenses	67 05
25	71	H L Moore	Services, Oct 1 to Dec 31, 1894	15 00
25	72	John Murdock	Services, Dec. 1894	5 00
25	73	B Peyton Legare	Services, Jan 1-7, 1895	17 50
25	74	Annie L Arnold	Services, Dec 15, 1894 to Jan 23, 1895	60 00
25	75	Belle Worth Bagley	Services, Dec 18, 1894, to Jan 23, 1895	60 00
25	76	Ellen Macfarland	Services Nov 30, 1894	1 96
25	77	Oregon Railway and Nav Co	Transportation of assistant	6 94
25	78	John Birkinbine	Traveling expenses	9 83

Abstract of disbursements made by John D McChesney, chief disbursing clerk, United States Geological Survey, etc —Continued

GENERAL EXPENSES OF THE GEOLOGICAL SURVEY—Continued

JANUARY, 1895—Continued

Date of payment	No of voucher	To whom paid	For what paid	Amount
Jan 25	79	John Birkinbine	Traveling expenses	$9 08
26	80	E W Parker	do	9 85
22	81	United States Express Co	Freight charges	94 25
26	82	Pennsylvania Co	Transportation of assistants	35 00
25	83	W Andrew Boyd	Publications	25 00
25	84	M Siebold	Laboratory supplies	2 52
25	85	Herman Baumgarten	Supplies	13 50
26	86	Theodore Johnson	Services, Dec 17, 1894 to Jan 21, 1895	75 00
31	87	John Birkinbine	Services, Dec. 1, 1894 to Jan 15, 1895	170 00
31	88	Eudora Magill	Services, Dec 17, 1894 to Jan 22, 1895	60 00
31	89	Victoria Essex	do	34 00
31	90	Julia M Corse	Services, Dec 21, 1894 to Jan 26, 1895	60 00
31	91	Elizabeth A Balloch	do	60 00
31	92	H B C Nitze	Report on monazite	5 00
31	93	Frank Burns	Traveling expenses	81 87
31	94	Alpheus Hyatt	Services, Jan , 1895	80 00
31	95	F Berger	do	80 00
31	96	H Gibb	do	70 00
31	97	L. P Bush	do	65 00
31	98	Z D Gilman	Laboratory supplies	211 84
31	99	A P Davis	Services, Jan , 1895	172 20
31	100	Pay roll of employees	do	1,394 90
31	101	do	do	1,190 20
31	102	do	do	3,104 83
31	103	do	do	2,027 10
31	104	do	do	2,750 30
31	105	do	do	353 10
31	106	do	do	456 50
31	107	do	do	916 93
31	108	do	do	775 10
31	109	do	do	249 70
31	110	O A Ljungstedt	Services, Jan 15-31, 1895	66 11
31	111	C C Willard	Rent of office rooms, Jan , 1895	349 99
		Total		17,632 36

FEBRUARY, 1895.

Feb 5	1	Minnie Milligan	Services, January, 1895	$50 00
8	2	J B Lippincott	Services, January, 8-18, 1895	70 00
8	3	S Fortier	Services, Nov 28 to Dec 27, 1894	54 00
8	4	James T White & Co	Publications	8 00
8	5	W H Morrison's Son	do	14 85
8	6	E D Franz	Supplies	36 20
8	7	Fred Reh	Geological supplies	17 75
8	8	Southern California Rwy Co	Transportation of assistant	57 00
8	9	Oregon Railway and Nav Co	do	16 10
8	10	Pennsylvania R R Co	Transportation of property	5 94
8	11	do	do	7 52
8	12	Atchison, Topeka and Santa Fe Rwy Co	do	5 85
11	13	A P Davis	Field expenses	153 75
12	14	Baltimore and Ohio R R Co	Transportation of property	10 40
12	15	Robert Hay	Services, Dec 17, 1894, to Jan 4, 1895	150 00
12	16	C Gustavus Meninger	Report on phosphate	50 00
12	17	Mrs Marie E Webb	Services, Feb 5-12, 1895	14 00
12	18	Elizabeth Downing	do	14 00
12	19	Mattie H Maddox	do	14 00
12	20	Florence Pollock	do	14 00
11	21	Robert Beall	Publications	32 25
12	22	Chicago, Milwaukee and St Paul Rwy Co	Transportation of assistants	29 00
14	23	Mackall Bros & Flemer	Laboratory supplies	12 77
14	24	W H Morrison's Son	Publications	16 00
14	25	The E F Brooks Co	Geologic supplies	10 50
14	26	John C Parker	Supplies	5 20

Abstract of disbursements made by John D. McChesney, chief disbursing clerk, United States Geological Survey, etc —Continued.

GENERAL EXPENSES OF THE GEOLOGICAL SURVEY—Continued

FEBRUARY, 1895—Continued

Date of payment	No of voucher	To whom paid	For what paid	Amount
Feb 14	27	Alice M Hayden	Services, Feb 2-11, 1895	$16 00
14	28	E J Lewis	Paleontologic supplies	4 50
14	29	Robert Boyd	Supplies	16 38
14	30	Geo F Muth & Co	do	2 57
14	31	John Steffian	do	34 55
14	32	Geo W Knox's Express	Freight charges	57 25
15	33	Charles E Munroe	Assay of ores and rocks	50 00
15	34	Pennsylvania R R Co	Transportation of assistants	10 00
15	35	Jean F Kaighn	Services, Jan 30 and 31, 1895	3 87
18	36	B W Vedder	Services, Oct 18, 1894, to Jan 31, 1895	10 35
18	37	A L Williams	Services, Nov. 25, 1894 to Jan 31, 1895	4 40
18	38	J W Lane	Services, Dec 5, 1894, to Jan 31, 1895	9 35
18	39	Murray Mott	Services, Dec 7, 1894, to Jan 31, 1895	9 03
18	40	D T Rigsby	Services Dec 9, 1894, to Jan 31, 1895	8 70
18	41	E R Murray	Services, Dec 11, 1894, to Jan 31, 1895	8.38
18	42	Barry Cronin	Services, Dec 15, 1894, to Jan 31, 1895	4 50
18	43	Edward Kubel	Topographic repairs	8 00
18	44	Shoemaker & Busch	Supplies	47 80
18	45	Thomas Somerville & Sons	Laboratory supplies	14 66
18	46	E E Jackson & Co	do	40 38
20	47	Z D Gilman	Illustration supplies	1 20
20	48	Samuel Storrow	Gauging streams supplies	29 50
20	49	G N Saegmuller	Supplies and repairs	56 75
25	50	James D Hillhouse	Services, January, 1895	25 00
23	51	Eudora Magill	Services, Jan 23 to Feb 14 1895	40 00
23	52	Fred A Schmidt	Topographic supplies	7 20
23	53	Fred Reh	Geologic supplies	21 00
23	54	Edward P North	Publications	5 00
23	55	Thomas W Smith	Supplies	191 00
25	56	Henry Gannett	Traveling expenses	25 14
20	57	Samuel Springmann	Hauling specimens	5 69
25	58	A P Davis	Traveling expenses	73 35
23	59	Z D Gilman	Supplies	75 33
23	60	Daniel Crumbaugh	Services, Dec 18, 1894, to Jan 31, 1895	7 25
27	61	R L Ogden	Services, Dec 13, 1894, to Feb 12, 1895	150 00
28	62	S Fortier	Services, Jan 28-31, 1895	24 00
27	63	Julia M Corse	Services, Feb, 4-25, 1895	30 00
28	64	Mrs Jennie T Davis	Services, Feb 9-28, 1895	42 86
28	65	A P Davis	Field expenses	50 50
28	66	John C Parker	Supplies	5 30
28	67	M Siebold	Laboratory supplies	2 52
23	68	H Baumgarten	Stamps and repairs	6 25
28	69	C C Willard	Rent of office rooms, Feb 1895	349 99
28	70	Pay roll of employees	Services, February, 1895	1,260 20
28	71	do	do	1,038 00
28	72	do	do	2,531 64
28	73	do	do	1,830 80
28	74	do	do	2,484 40
28	75	do	do	378 80
28	76	do	do	412 00
28	77	do	do	820 60
28	78	do	do	699 80
28	79	do	do	381 20
		Total		14,302 02

MARCH, 1895

Date of payment	No of voucher	To whom paid	For what paid	Amount
Mar 4	1	E W. Parker	Traveling expenses	$26 39
4	2	Annie L Arnold	Services, Jan 24 to Mar 1, 1895	60 00
4	3	Belle Worth Bagley	do	60 00
6	4	Altha T Coons	Services, Feb, 1895	34 50
6	5	Alpheus Hyatt	do	70 00

Abstract of disbursements made by John D. McChesney, chief disbursing clerk, United States Geological Survey, etc.—Continued

GENERAL EXPENSES OF THE GEOLOGICAL SURVEY—Continued.

MARCH, 1895—Continued

Date of payment		No of voucher	To whom paid.	For what paid	Amount
Mar	6	6	F Berger	Services, Feb , 1895	$80 00
	6	7	H Gibb	do	70 00
	6	8	L P Bush	do	65 00
	6	9	Minnie Milligan	do	50 00
	6	10	Charles P. Ross	Services, Nov. 6, 1894, to Feb 20, 1895	30 00
	6	11	H. V Hinckley	Services, Feb 19 and 20, 1895	10 00
	6	12	R R Bowker	Publications	3 50
	6	13	Edward Kubel	Repairs to instruments, etc	39 14
	6	14	Pennsylvania R R Co	Freight	3 17
	6	15	Missouri Pacific Rwy Co	do	12 42
	7	16	Wyckoff, Seamans & Benedict	Remodeling and repairs	63 00
	7	17	C E Munroe	Assay of 3 ores	7 50
	8	18	William Kerr	Geologic supplies	12 00
	8	19	Charles L Condit	Publications	7 50
	12	20	Robert Beall	do	51 25
	14	21	Daniel Appleton & Co	do	6 54
	14	22	T Hudson Willis	Report on phosphate rock	25 00
	14	23	Library Bureau	Supplies	12 00
	14	24	do	do	12 55
	14	25	William C Day	Traveling expenses	8 45
	14	26	F W von Dachenhausen	do	29 15
	14	27	DeLancey W Gill	do	23 50
	14	28	Henry Heil Chemical Co	Laboratory supplies	2 50
	14	29	Fuchs & Lang Manufacturing Co	Topographic supplies	10 00
	14	30	Meyer Brothers Drug Co	Illustration supplies	2 40
	14	31	E Morrison Paper Co	Library supplies	1 26
	14	32	John C Parker	Mineral Resources	40 00
	14	33	Easton & Rupp	Geologic supplies	.50
	14	34	Thomas Somerville	Gauging streams supplies	18 70
	14	35	Theodore Johnson	Services, Jan 25 to Mar 6, 1895	75 00
	14	36	Elizabeth A Balloch	Services, Feb 4 to Mar 7 1895	30 00
	14	37	Henry S Williams	Services, Sept 1, 1894, to Feb 28, 1895	300 00
	16	38	Kennedy & DuPerow	Laboratory supplies	3 30
	16	39	J W Drew & Co	Supplies	13 50
	16	40	Pennsylvania R R Co	Freight	9 59
	15	41	Griffith Thornton	Services, Mar 8-15 1895	14 00
	20	42	James P Iddings	Services, Jan 21 to Feb 23, 1895	203 00
	20	43	Charles M Rolker	Services, Feb 8 to Mar 15, 1895	150 00
	20	44	Cyrus C Babb	Services, Jan , 1895	36 00
	20	45	do	Services, Feb , 1895	66 00
	20	46	Daniel Crumbaugh	do	5 00
	20	47	Charles E Munroe	Analyses of coals	150 00
	20	48	J E Hurley	Repairs	6 00
	20	49	do	Labor and material	49 60
	20	50	John C Entriken	Repairs	7 00
	20	51	W Zinsser	Geologic supplies	5 50
	21	52	Eimer & Amend	Supplies	27 30
	20	53	The E F Brooks Co	do	5 90
	21	54	Stephenson's Express	Freight and hauling	9 15
	22	55	E W Parker	Traveling expenses	41 37
	22	56	William F Porter	Publications	7 00
	23	57	Ginn & Co	do	94 00
	23	58	A C. Peale	Services, Feb 4-16, 1895	72.00
	25	59	Baltimore and Ohio R R Co	Transportation of assistants	11 50
	26	60	Geo W Plumley Co	Geologic supplies	3 75
	26	61	E J Pullman	Illustration supplies	85 10
	26	62	Geo W Knox Express Co	Freight and hauling	5 66
	25	63	William H Butler	Supplies	1 50
	30	64	John C Parker	Publications of Mineral Resources	162 00
	30	65	William C Day	Traveling expenses	11.45
	30	66	George H Harris	Report on slate deposits, etc	25 00
	30	67	Marie E Webb	Services, Mar 8-30, 1895	40 00
	30	68	Sanella J D Cooley	Services, Mar 12-30, 1895	30 00
	30	69	Griffith Thornton	Services, Mar 16-30, 1895	26 00
	31	70	Mrs Jennie T Davis	Services, Mar , 1895	60 00
	31	71	Pay roll of employees	do	1,394 90
	31	72	do	do	1,133 65
	31	73	do	do	2,778 20
	31	74	do	do	2,027 10
	31	75	do	do	2,750 30
	31	76	do	do	672 99
	31	77	do	do	456 50
	31	78	do	do	947 20

Abstract of disbursements made by John D. McChesney, chief disbursing clerk, United States Geological Survey, etc.—Continued

GENERAL EXPENSES OF THE GEOLOGICAL SURVEY—Continued

MARCH, 1895—Continued

Date of payment		No of voucher	To whom paid	For what paid	Amount.
Mar	31	79	Pay roll of employees	Services, March 1895	$775 10
	31	80	do	do	421 90
	31	81	Lizzie M Alexander	Services, Mar 18-31, 1895	33 87
	31	82	Theodore Johnson	Services, Mar 7-30, 1895	52 50
	31	83	F Berger	Services, Mar, 1895	80 00
	31	84	H Gibb	do	70 00
	31	85	L P Bush	do	65 00
	31	86	The E F Brooks Co	Geologic supplies	3 50
	31	87	G N Saegmuller	Instruments and repairs	76 00
	31	88	E E Jackson & Co	Supplies	17 31
	31	89	C C Willard	Rent of office rooms, Mar, 1895	349 99
	31	90	Belle Worth Bagley	Services, Mar 2-30, 1895	50 00
	31	91	Julia M Corse	Services, Mar 11-30, 1895	35 00
			Total		16,981 10

APRIL, 1895

Date of payment		No of voucher	To whom paid	For what paid	Amount.
Apr	10	1	Morgan Flaherty	Services, Aug 1, 1894, to Mar 31, 1895	$16 00
	11	2	Henry V Smith	Services, Dec 1, 1894, to Mar 31, 1895	28 00
	10	3	Patrick Liston	do	8 00
	11	4	J M Reed	Services, Jan, Feb, and Mar 1895	15 00
	11	5	M Savage	do	15 00
	11	6	J S Regan	do	22 50
	11	7	James L Wright, jr	do	15 00
	10	8	John Murdoch	do	15 00
	10	9	L Morse	do	15 00
	10	10	H L Moore	do	15 00
	10	11	George H Hickman	Services, Feb 14-28, 1895	1 60
	10	12	Barry Cronin	Services, Feb and Mar, 1895	6 00
	10	13	Thomas Dupré	do	10 00
	10	14	J W Lane	do	10 00
	10	15	E R Murray	do	10 00
	10	16	Murray Mott	do	10 00
	10	17	C T Pelham	do	10 00
	11	18	A L Williams	do	4 00
	11	19	D T Rigsby	do	10 00
	11	20	B W Vedder	do	6 00
	11	21	J. B Lippincott	Services, Mar 16-20, 1895	70 00
	11	22	L H Taylor	Services, Mar. 20-27, 1895	38 00
	10	23	George H Hickman	Services, Mar, 1895	3 00
	10	24	Bert Halseth	do	3 00
	11	25	Alpheus Hyatt	do	80 00
	11	26	Altha T Coons	do	39 00
	11	27	Mary G Quitman	Services, Mar 12 to Apr 4, 1895	42 00
	10	28	S. C Stallings	Services, Mar 13 to Apr 10, 1895	50 00
	11	29	E W Parker	Traveling expenses	42 95
	11	30	F H Newell	do	23 00
	11	31	National Press Intelligence Co	Publications	10 95
	11	32	C R Savage	do	5 50
	11	33	Charles Cooper & Co	Geologic supplies	10 00
	11	34	Library Bureau	Gauging streams supplies	8 00
	11	35	W & L E Gurley	Supplies	146 00
	12	36	Cyrus C Babb	Services, Mar. 1-30, 1895	90 00
	12	37	Department of the Interior	Supplies	160 25
	12	38	do	do	2 00
	12	39	do	do	59 89
	12	40	do	do	78 10
	12	41	do	do	2 35
	12	42	Baltimore and Ohio R. R Co	Freight	15 34
	13	43	Fred Reh	Geologic supplies	3 00
	13	44	Louis Dutertre	Services, Dec 24, 1894, to Mar 31, 1895	22 75
	13	45	Daniel Crumbaugh	Services, Mar, 1895	5 00
	13	46	Mattie H Maddox	Services, Mar 6 to Apr 2, 1895	66 00
	13	47	Maggie M Loeffler	Services, Mar 12 to Apr 9, 1895	50 00
	13	48	Minnie Milligan	Services, Mar., 1895	50 00
	13	49	F H Newell	Field expenses	16 35

Abstract of disbursements made by John D McChesney, chief disbursing clerk, United States Geological Survey, etc —Continued.

GENERAL EXPENSES OF THE GEOLOGICAL SURVEY—Continued

April, 1895—Continued

Date of payment		No of voucher	To whom paid	For what paid	Amount.
Apr	15	50	John C Parker	Mineral Resources supplies	$5 00
	15	51	Adams Express Co	Freight	325 05
	17	52	James D & E S Dana	Publications	6 00
	17	53	Hugh Reilly	Illustration supplies	9 50
	17	54	Henry Gannett	Traveling expenses	30 70
	16	55	Lizzie M Alexander	Services, Apr 1-16, 1895	40 00
	17	56	William A Raborg	Traveling expenses	3 45
	17	57	do	do	64 60
	17	58	Z D Gilman	Supplies	67 89
	20	59	Department of the Interior	do	2 70
	20	60	R A Daniell	Geologic supplies	22 00
	22	61	Mackall Bros & Flemer	Illustration supplies	35 25
	22	62	do	Laboratory supplies	1 16
	20	63	C D White	Traveling expenses	19 35
	20	64	Baltimore and Ohio R R Co	Freight	20 65
	20	65	Northern Pacific R R Co	do	7 14
	20	66	Great Northern Rwy Co	do	6 73
	22	67	J B Lippincott	Altitude tables	25 00
	24	68	Geo F Muth & Co	Geologic supplies	6 00
	24	69	G N Saegmuller	Instruments	50 00
	24	70	J. H Quinten	Services, Jan 2-24, 1895	100 00
	24	71	Gustav E Stechert	Publications	296 75
	26	72	Henry Bufford	Services, Mar 1-23, 1895	40 00
	26	73	Meyer Bros. Drug Co	Illustration supplies	1 20
	26	74	Southern Pacific Co	Freight charges	5 97
	26	75	John Birkinbine	Traveling expenses	16 03
	26	76	S F Ware	Laboratory supplies	11 18
	26	77	P E Harroun	Services, Apr 8-19, 1895	66 00
	29	78	W. F Hillebrand	Traveling expenses	16 60
	29	79	Hersey Munroe	do	4 64
	29	80	L H Schneider's Son	Supplies	12 98
	30	81	Robert Beall	Publications	42 50
	30	82	William M Fontaine	Services, July 1, 1894, to Apr 30, 1895	150 00
	30	83	C C Willard	Rent, Apr, 1895	349 99
	30	84	Pay roll of employees	Services, Apr, 1895	1,334 95
	30	85	do	do	1,093 60
	30	86	do	do	2,255 00
	30	87	do	do	1,621 02
	30	88	do	do	2,484 10
	30	89	do	do	522 30
	30	90	do	do	552 30
	30	91	do	do	906 60
	30	92	do	do	626 45
	30	93	do	do	403 80
			Total		15,096 66

May, 1895

May	1	1	A P Davis	Traveling expenses	$76 25
	1	2	Cyrus C Babb	Services, Apr, 1895	114.00
	1	3	P E Harroun	Services, Apr 20-27, 1895	42 00
	1	4	Mrs Jennie T Davis	Services, Apr, 1895	60 00
	1	5	Theodore Johnson	do	65 00
	1	6	Griffith Thornton	do	52 00
	1	7	Alice M Onthank	Services, Apr 10-30, 1895	35 00
	1	8	C E Munroe	Analyses	55 00
	1	9	William A. Raborg	Traveling expenses	40 43
	2	10	E W Parker	do	42 25
	8	11	Jefferson Middleton	do	60 60
	3	12	Sanella J D Cooley	Services, Apr, 1895	45 00
	3	13	Belle Worth Bagley	do	50 00
	3	14	Marie E Webb	do	49 00
	9	15	F Berger	do	80 00
	9	16	H Gibb	do	70 00
	9	17	L P Bush	do	65 00
	9	18	Minnie Milligan	do	50 00
	9	19	A P Davis	Field expenses	91 96
	9	20	R S Holder	Services, Mar and Apr, 1895	6 00
	9	21	P. L Brown	do	6 00

Abstract of disbursements made by John D. McChesney, chief disbursing clerk, United States Geological Survey, etc.—Continued.

GENERAL EXPENSES OF THE GEOLOGICAL SURVEY—Continued

MAY, 1895—Continued

Date of payment	No of voucher	To whom paid	For what paid	Amount
May 9	22	J N Lane	Services, Mar and Apr, 1895	$6 00
9	23	V C Tompkins	Services, Apr 18-27, 1895	63 00
9	24	J W Nisewaner	Services, Apr 15-30, 1895	1 50
9	25	Daniel Crumbaugh	Services, Apr, 1895	5 00
9	26	George H Hickman	do	3 00
9	27	James Jardine	Services, Mar and Apr, 1895	6 00
9	28	Frank Jacobs	do	6 00
9	29	Frank Flaiz	do	6 00
9	30	Frank Adair	do	6 00
9	31	W A Shannon	Services, Apr, 1895	3 00
9	32	H E Bidwell	do	7 00
10	33	E S Ritchie & Sons	Supplies	10 44
9	34	C J Norwood	Services, Apr, 1895	100 00
10	35	Julia M Corse	Services, Apr 1 to May 8, 1895	65 00
10	36	Shoemaker & Busch	Laboratory supplies	1 36
10	37	Baker & Co	do	171 16
10	38	J B Lippincott	Services, Apr. 2-20, 1895	52 50
10	39	W & L E Gurley	Supplies	4 20
10	40	Robert Boyd	do	17 75
10	41	Baker & Co	Repairs	11 50
10	42	William H Dall	Cash paid for expenses	5 00
11	43	Lester F Ward	Traveling expenses	129 11
10	44	Atchison, Topeka and Santa Fe Railway Co	Freight	15 39
11	45	Northern Pacific R R Co	do	1 16
13	46	E W Parker	Traveling expenses	25 19
15	47	Jos P Iddings	Services, April, 1895	161 00
15	48	William C Day	Traveling expenses	23 61
15	49	do	Services, Dec 1, 1894, to Jan 31, 1895	250 00
15	50	Elizabeth A Balloch	Services, Mar. 25 to May 15, 1895	90 00
15	51	Florence Pollock	Services, May 1-15, 1895	25 00
15	52	A M Ryan	Services, Apr 24-27, 1895	28 00
10	53	Willam H Rau	Illustration supplies	10 00
16	54	J. W Drew & Co	Geologic supplies	4 50
16	55	Franklin & Co	Paleontologic supplies	15 00
16	56	John C Entriken	Laboratory repairs	4 50
16	57	E P Rider	Publications	6 00
15	58	Julius Bien & Co	Maps	256 00
18	59	Royce & Marean	Supplies	3 75
17	60	Fred Hanlon	Services, Mar and Apr, 1895	10 00
17	61	O V P Stout	Services, Mar 29 to Apr 22, 1895	83 00
17	62	Samuel Fortier	Services, Apr 5-30, 1895	132 00
17	63	Wm Westley & Son	Publications	99 13
17	64	George Griffith	do	6 81
17	65	Dietrich Reimer	do	5 76
17	66	Citizens' National Bank	Bills of exchange	1 03
17	67	Charles D. Walcott	Field expenses	39 00
17	68	do	Traveling expenses	33 47
17	69	Jefferson Middleton	do	12 79
17	70	Z D Gilman	Supplies	33 70
17	71	Jos D Weeks	Services, Jan, 1895	125 00
21	72	Altha T Coons	Services Apr, 1895	39 00
21	73	Dennis Boyle	Services, Mar and Apr, 1895	6 00
21	74	F Connors	do	6 00
21	75	Thomas Judge	do	6 00
21	76	J B Lippincott	Services, Apr 23 to May 9, 1895	101 50
21	77	John Warner	One animal	80 00
21	78	Frank Burns	Traveling expenses	15 55
24	79	E J Pullman	Illustration supplies	231 95
24	80	M Siebold	Supplies	3 47
24	81	Kennedy & DuPerow	do	5 94
24	82	Geo F Muth & Co	do	108 00
24	83	E E Jackson & Co	do	41 78
24	84	Southern Railway Co	Transportation of assistant	19 50
25	85	A P Davis	Field expenses	67 70
29	86	C G Sloan & Co	Publications	3 15
29	87	Southern Railway Co	Transportation of assistants	56 75
29	88	do	do	35.00
31	89	H M Wilson	Traveling expenses	23 25
31	90	Alpheus Hyatt	do	36 00
31	91	F Berger	Services, May, 1895	80 00
31	92	H Gibb	do	70 00
31	93	L P Bush	do	65 00
31	94	Florence Pollock	Services, May 16-31, 1895	28 00

Abstract of disbursements made by John D. McChesney, chief disbursing clerk, United States Geological Survey, etc—Continued.

GENERAL EXPENSES OF THE GEOLOGICAL SURVEY—Continued

MAY, 1895—Continued

Date of payment	No of voucher	To whom paid	For what paid	Amount
May 31	95	George F Kunz	Services, Jan , 1895	$125 00
31	96	Joseph Moijet	List of quarrymen	5 00
31	97	E L McKinnon	Services, Mar 1 to Apr 13, 1895	4 30
31	98	A M Ryan	Services, May 10 and 11 1895	14 00
31	99	Minnie Milligan	Services, May 1-9, 1895	16 00
31	100	Belle Worth Bagley	Services, May, 1895	53 00
31	101	Griffith Thornton	do	54 00
31	102	C C Willard	Rent of office rooms, May, 1895	349 99
31	103	Nellie F Sargent	Services, Apr 26 to May 31, 1895	87 50
31	104	Alice M Onthank	Services, May, 1895	50 00
31	105	A H Thompson	do	213 00
31	106	R H Chapman	do	136 20
31	107	E B Clark	do	119 20
31	108	Pay roll of employees	do	1,209 70
31	109	do	do	1,127 80
31	110	do	do	3,447 91
31	111	do	do	557 05
31	112	do	do	424 20
31	113	do	do	570 40
31	114	do	do	846 29
31	115	do	do	647 10
31	116	do	do	477 40
		Total		14,951 38

JUNE, 1895

Date of payment	No of voucher	To whom paid	For what paid	Amount
June 3	1	Department of the Interior	Supplies	$189 02
3	2	do	do	266 37
3	3	do	do	75
3	4	do	do	20 82
4	5	Marie C Webb	Services, May 16, 1895	27 00
4	6	Sanella J D Cooley	Services, May, 1895	44 00
4	7	Theodore Johnson	do	55 00
10	8	Altha D Coons	do	40 50
10	9	Elizabeth Downing	Services, May 13, to June 5, 1895	42 00
10	10	Cyrus C Babb	Services, May, 1895	132 00
10	11	Mrs A. E Keeler	Clippings	18 84
10	12	James S Topham	Geologic supplies	10 00
10	13	James B Lambie	Topographic supplies	1 33
10	14	Frances Wieser	Original Drawings	70 00
10	15	The Hammond Typewriter Co	Remodeling typewriter	28 75
10	16	B F Phillips	Services, May 7-31, 1895	32 26
10	17	John Birkinbine	Traveling expenses	6 33
10	18	A P Davis	do	43 35
10	19	do	Field expenses	53 05
10	20	Herman Baumgarten	Topographic supplies	3 00
11	21	Marie E Webb	Services, May 17 to June 5, 1895	33 00
10	22	Department of the Interior	Supplies	7 00
10	23	do	do	1 97
10	24	do	do	45 00
11	25	Geo F Muth & Co	do	132 60
11	26	J L. Prentiss	Services, Jan 1 to March 31, 1895	9 00
11	27	Emmett Grover	Repairs, etc	4 55
11	28	P E Harroun	Services, May 11-21, 1895	54 00
11	29	Elwood Mead	Services, May 1-25, 1895	54 00
11	30	Missouri, Kansas and Texas Ry Co	Transportation of assistant	1 85
11	31	Southern Pacific Co	do	53 20
11	32	Mining Review and Metallurgist	Mineral resources supplies	4 00
11	33	Henry Romeike	Publications	15 12
11	34	R R Bowker	do	3 50
11	35	F A Brockhaus	do	228 30
11	36	Citizens' National Bank	Bills of exchange	3 12
13	37	G F Becker	Traveling expenses	39 13
13	38	William H Dall	do	38 25
13	39	Chester W Purington	do	38 00
13	40	Stewart & Holmes Drug Co	Photographic plates	9 90
13	41	T W Stanton	Traveling expenses	26 00
13	42	Frank Burns	Field expenses	25 67
13	43	Robert T Hill	Traveling expenses	26 00
13	44	Shoemaker & Busch	Supplies	144 91

Abstract of disbursements made by John D. McChesney, chief disbursing clerk, United States Geological Survey, etc.—Continued.

GENERAL EXPENSES OF THE GEOLOGICAL SURVEY—Continued

JUNE, 1895—Continued.

Date of payment	No of voucher	To whom paid	For what paid	Amount.
June 15	45	Geo F Muth & Co	Supplies	$35.25
13	46	Geo W Knox's Express	Freight and hauling	3 41
15	47	M Siebold	Illustration supplies	3 20
15	48	J L Prentiss	Services, Apr and May, 1895	6 00
17	49	V. C Tompkins.	Services, May 11-29, 1895	70 00
17	50	J D Bush	Services, Apr 15 to May 31, 1895	4 50
17	51	W A Shannon	Services, May, 1895	3 00
17	52	J W Nisewaner	do	3 00
17	53	Daniel Crumbaugh	do	5 00
17	54	George H Hickman	do	3 00
17	55	F H Newell	Field expenses	50 78
17	56	H M Wilson	Traveling expenses	43 63
20	57	Southern Railway Co	Transportation of assistants	20 65
19	58	L H Schneider's Son	Supplies	39 58
21	59	Stephenson's Express	Freight and hauling	7 53
21	60	Pennsylvania R R Co	Transportation of assistants	522 75
21	61	Z D Gilman	Laboratory supplies	4 38
21	62	do	Supplies	23 73
26	63	Baltimore and Ohio R R Co	Freight	2 61
26	64	do	do	72
26	65	Vaux & Coe	Forage supplies, etc	9 90
25	66	William A Raborg	Traveling expenses	24 17
26	67	Joseph Goodman	Field supplies	35 00
26	68	T W Stanton	Field expenses	72 10
26	69	do	Traveling expenses	22 10
27	70	A P Davis	do	45 50
27	71	F H Newell	do	30 70
27	72	do	Field expenses	17 26
26	73	E J Pullman	Supplies	187 71
27	74	Z D Gilman	do	89 37
28	75	E C Murphy	Services, May 1 to June 7 1895	24 00
28	76	Samuel Fortier	Services, May, 10, to June 14, 1895	132 00
28	77	Cyrus C Babb	Services, June 1-26, 1895	120 00
28	78	Queen & Co, Incorporated	Geologic supplies	4 50
28	79	Bert Halseth	Services, April and May, 1895	6 00
29	80	F Berger	Services, June, 1895	80 00
30	81	H Gibb	do	70 00
30	82	L P Bush	do	65 00
30	83	Henry Heil Chemical Co	Laboratory supplies	3 43
29	84	Baker & Co	Repairs	51 66
29	85	Northern Pacific R R Co	Transportation of assistants	50 00
29	86	Cincinnati, New Orleans and Texas Pacific Rwy Co	do	20 30
29	87	St Louis, Keokuk and Northwestern Rwy Co	do	11 50
29	88	Houston and Texas Central Railway Co	do	11 90
29	89	William Kerr	Geologic supplies	12 00
29	90	Arthur Winslow	Services, July 1, 1894, to June 1, 1895	500 00
29	91	Julia M Corse	Services, May 9-17, 1895	12 00
29	92	Mackall Bros. & Flemer	Supplies	44 38
30	93	C C Willard.	Rent of office rooms, June, 1895	349 99
30	94	Maggie M Loeffler	Services, June 10-30, 1895	36 00
30	95	W A Shannon	Services, June, 1895	3 00
30	96	J W Nisewaner	do	3 00
30	97	George H Hickman	do	3 00
30	98	David T Day	do	247 25
30	99	Pay roll of employees	do	799 35
30	100	do	do	1,093.60
30	101	do	do	959 40
30	102	do	do	1,031 60
30	103	do	do	297 50
30	104	do	do	552 30
30	105	do	do	552 20
30	106	do	do	247 30
30	107	do	do	388 50
30	108	do	do	496 80
30	109	do	do	254 80
		Total		12,003 23

Abstract of disbursements made by C. D Davis, special disbursing agent, United States Geological Survey, during the fiscal year 1894-95.

JULY, 1894

Date of payment	No of voucher	To whom paid	For what paid	Amount
July 9	1	W. S Bayley	Traveling expenses	$52 50
17	2	T Nelson Dale	do	34 23
17	3	C Willard Hayes	do	73 26
17	4	Arthur Keith	do	22 60
16	5	James L Johnson	do	10 25
17	6	M R Campbell	Field expenses	53 86
17	7	J H Jennings	do	97.75
17	8	do	Traveling expenses	10 66
18	9	Redick H McKee	Field expenses	36 55
18	10	W B Corse	do	45 30
18	11	L E Shepherd	Supplies	28 01
19	12	Oscar Foss	Photographic supplies	12 90
19	13	H L Baldwin	Field expenses	99 30
19	14	George T Hawkins	do	87 10
20	15	do	Traveling expenses	6 45
20	16	R M Towson	do	49 10
21	17	Frank Sutton	do	120 29
23	18	Main & Winchester	Field material	20 30
23	19	W. A Rogers	Boarding and lodging	18 00
24	20	do	do	13 25
24	21	G E Hyde	do	73 54
24	22	E T Perkins, jr	Field expenses	54 00
25	23	H W Turner	do	20 80
25	24	Nick Lorselying	Hire of horse	23 00
25	25	John P Outhwaite	Boarding	66 34
30	26	Harold B Goodrich	Traveling expenses	9 75
31	27	C Whitman Cross	Services, July, 1894	168 50
31	28	H W Turner	do	151 60
31	29	W Lindgren	do	151 60
31	30	T Nelson Dale	do	168 50
31	31	George T Hawkins	do	134 80
31	32	R M Towson	do	117 90
31	33	Pay roll of employees	do	289 80
31	34	do	do	117 90
31	35	do	do	487 70
31	36	do	do	120 80
31	37	do	do	205 60
31	38	do	do	247 70
31	39	do	do	309 80
31	40	do	do	399 30
31	41	do	do	311 70
31	42	do	do	227 40
31	43	do	do	202 10
31	44	H W Turner	Field expenses	23 03
31	45	H L Baldwin	do	55 25
31	46	James Storrs	Services, July, 1894	38 71
31	47	Pay roll of employees	do	257 90
31	48	do	do	403 34
31	49	do	do	195 32
31	50	do	do	203 50
31	51	R M Towson	Field expenses	122 00
31	52	do	do	9 06
31	53	Arthur Stiles	Traveling expenses	43 80
31	54	Perkins & Wise	Supplies	39 65
31	55	J J Fawbush	Forage of animals	35 00
31	56	C Whitman Cross	Traveling expenses	104 50
31	57	Edward B Mathews	do	66 50
31	58	Pay roll of employees	Services, July, 1894	258 01
31	60	Felitz Bros	Supplies	29 94
31	61	Walker H Weed	Services, July, 1894	151 60
31	62	Arnold Hague	do	337 00
31	63	Pay roll of employees	do	817 10
31	64	do	do	1,104 20
31	65	do	do	307 40
31	66	W H Lovell	Field expenses	34 50
31	67	Rahlfs & Schoder	Field material	10 85
31	68	H G McCall	Care of animals	20 00
31	69	T Nelson Dale	Traveling expenses	36 22
		Total		9,656 17

Abstract of disbursements made by C. D Davis, special disbursing agent, United States Geological Survey, etc —Continued

AUGUST, 1894

Date of payment	No of voucher	To whom paid	For what paid	Amount
Aug 1	1	S S Gannett	Traveling expenses	$50 30
2	2	Pay roll of employees	Services, July, 1894	397 70
3	3	W S Bayley	do	130 00
3	4	George O Smith	do	50 00
3	5	Garry E Culver	do	60 00
3	6	Charles Oley	do	60 00
3	7	Oscar J Weller	do	45 00
3	8	J Morgan Clements	do	100 00
3	9	Gus Johnson	do	40 00
3	10	Ira B Weller	do	55 00
3	11	T H Gibson	Hauling property	10 00
3	12	Haley Grocery Co	Subsistence	39 11
3	13	Frank Sutton	Traveling expenses	177 00
3	14	H L Baldwin, jr	Field expenses	62 35
3	15	R O Gordon	do	237 90
3	16	C Willard Hayes	do	110 18
3	17	Pay roll of employees	Services, July, 1894	597 66
3	18	S S Gannett	Field expenses	89 88
3	19	M R Campbell	do	70 55
3	20	J H Hagerty	Forage, July, 1894	40 00
3	21	Redick H McKee	Field expenses	38 78
3	22	do	do	44 10
6	23	George T Hawkins	do	87 15
6	24	do	Traveling expenses	38 35
6	25	Duncan Hannegan	Services, July, 1894	70 80
7	26	W B Corse	Field expenses	90 80
10	27	T Nelson Dale	Traveling expenses	45 74
10	28	W Lindgren	Field expenses	131 67
10	29	J L Hughes	Services, July, 1894	25 80
10	30	F H Kearney & Co	Supplies	33 57
10	31	D E Lord	Boarding	71 62
10	32	Humphris & Co	Pasturage	13 00
10	33	F O Perry	do	15 00
10	34	Spatlen & Anderson	Subsistence	53 10
10	35	Buchanan & Brooke	Material	23 15
10	36	Schwabacher Hardware Co	do	14 51
10	37	G E Hyde	Field expenses	294 71
10	38	W H Lovell	do	127 65
10	39	R H Chapman	do	53 00
10	40	E M Douglas	do	71 10
10	41	Tie Sing	Services, July, 1894	15 97
10	42	Peter Johnson	do	15 97
10	43	A P Davis	Field expenses	71 13
10	44	D C Harrison	do	131 00
10	45	H L Baldwin, jr	do	48 00
10	46	R H Chapman	Traveling expenses	4 12
10	47	W B Corse	Field expenses	146 41
10	48	C J Bickford	Hay and grain	16. 55
10	49	Lee & Glass	Shoeing	10 00
10	50	J Jepsen & Son	Material, etc	20 60
10	51	T G Gerdine	Field expenses	72 67
10	52	Paul Holman	do	70 90
11	53	W. L Miller	Traveling expenses	16 01
11	54	A M Walker	do	8 07
13	55	Reynolds & Wheeler	Repairs to wagons	17 75
13	56	Anderson & Chanslor	Subsistence	32 13
13	57	Forrestell & Co	Hay	1 90
13	58	Highsmith & Winter	Shoeing etc.	33 30
13	59	E J Owenhouse	Repairs to property	8 45
13	60	Frederick Koch	Services, July 1-9 1894	9 00
13	61	do	Services, July 10-31, 1894	47 41
13	62	A J Steele	Services, July 12-31, 1894	36 76
13	63	Willard D Johnson	Traveling expenses	36 00
13	64	W T Griswold	Field expenses	57 30
13	65	do	do	27 55
13	66	do	do	36 75
13	67	E. M Douglas	do	67 47
13	68	Edward B Mathews	Services, July 10-31, 1894	53 22
14	69	The Telluride Mercantile Co	Subsistence	29 65
14	70	Frank Tweedy	Traveling expenses	26 95
14	71	do	Field expenses	38 90
14	72	Samuel Storrow	Pasturage and storage	11 50
14	73	R B Marshall	Field expenses	185 26
14	74	Thomas Parry	Traveling expenses	21 15
14	75	Robert T Hill	do	77 58
14	76	C Whitman Cross	Field expenses	123 80
16	77	G O Glavis, jr	Traveling expenses	13 00
16	78	W. B Corse	do	7 75

Abstract of disbursements made by C D Davis, special disbursing agent, United States Geological Survey, etc —Continued

AUGUST, 1894—Continued

Date of payment	No of voucher	To whom paid	For what paid	Amount
Aug 16	79	T M Bannon	Traveling expenses	$16 40
16	80	H L Baldwin, jr	Field expenses	72 32
16	81	C N Gould	Services	7 00
16	82	Charles H Medley	Subsistence	15 04
16	83	Southworth, Grattan & Co	Field material, etc	93 51
17	84	M R Campbell	Field expenses	61 31
17	85	G E Hyde	do	118 59
18	86	Arthur Keith	do	86 40
18	87	G K Gilbert	do	31 80
18	88	do	do	36 61
18	89	do	do	43 45
18	90	do	do	60 70
18	91	The Georgia Pacific Rwy Co	Freight	153 00
18	92	H W Turner	Field expenses	33 10
20	93	E T Perkins, jr	do	94 95
20	94	J W Madore	2 animals	260 00
20	95	Jacob Boor	1 horse	125 00
20	96	C M King	2 animals	325 00
20	97	The Gladen Mercantile Co	Field supplies, etc	51 41
20	98	E M Douglas	Field expenses	214 67
20	99	H B Blair	Traveling expenses	6 55
20	100	R E Dodge	do	59 10
20	101	Redick H McKee	Field expenses	43 90
20	102	do	do	23 60
21	103	C Willard Hayes	do	96 28
21	104	Lewis Kirtz	Camp outfit	48 13
21	105	R H Shearer	Field outfit	174 25
21	106	Frank B Reid	Repairs to outfit	66 30
21	107	B H Doughtrey & Co	Subsistence	30 09
21	108	C H Medley	do	8 71
21	109	do	do	43 22
21	110	L Newmayer & Co	do	40 67
21	111	E C Palmer	Feeding stock	29 50
21	112	William H Otis	Field expenses	16 77
21	113	Alex C Barclay	do	36 51
21	114	E M Douglas	Traveling expenses	34 20
24	115	T Nelson Dale	do	38 39
24	116	W E Beckwith	do	21 25
24	117	James McCormick	do	8 56
24	118	W H Lovell	do	14 35
24	119	Isaac I Lewis	Subsistence	96 15
24	120	H B Blair	Field expenses	22 15
24	121	T McCauley	Boarding, etc	14 00
23	122	Southern Railway Co	Freight charges	81 53
24	123	B Peyton Legare	Traveling expenses	30 50
24	124	H R Crocker	Hay, grain, etc	60 22
24	125	A J Henry	Boarding, etc	16 25
24	126	Hersey Munroe	Field expenses	32 35
24	127	H L Baldwin, jr	do	21 75
24	128	W C Cannon	Traveling expenses	7 25
24	129	James Macfarland	do	7 25
24	130	A C Lederman	Camp outfit	22 40
24	131	Van H Manning	Traveling expenses	31 00
24	132	Louis F Lenard, jr	do	26 00
24	133	H S Wallace	do	26 00
24	134	M P Henderson & Co	Field repairs, etc	58 65
24	135	Roy Levi	Hire of team	12 00
24	136	John A Webb	Wagon	110 00
25	137	R T Hill	Field expenses	162 17
25	138	do	Traveling expenses	29 25
25	139	William H Herron	do	11 80
25	140	do	do	22 50
25	141	do	do	15 00
27	142	Charles W Barnes	Subsistence	45 85
27	143	Nat Tyler jr	Traveling expenses	34 50
27	144	Smith Collum	do	11 45
27	145	Basil Duke	do	20 75
27	146	W J Peters	do	20 75
27	147	Redick H McKee	Field	15 35
27	148	T M Bannon	do	51 20
27	149	Van H Manning	do	130 41
27	150	Somers & Mears	Supplies	84 95
27	151	S A Oliver	do	13 00
27	152	Oberpeck Bros	Repairs, etc	14 00
30	153	Y Cramer Dry Plate Works	Geologic supplies	19 20
30	154	T M Bannon	Field supplies	77 20
30	155	H B Blair	do	152 89
30	156	A H Brooks	Traveling expenses	43 41

Abstract of disbursements made by C D. Davis, special disbursing agent, United States Geological Survey, etc.—Continued

AUGUST, 1894—Continued

Date of payment	No of voucher.	To whom paid	For what paid	Amount
Aug 30	157	L C Fletcher	Traveling expenses	$44 50
30	158	F H Ainsworth	do	30 95
30	159	J E Spurr	Services, Aug , 1894	48 91
30	160	C W Cross	do	168 50
30	161	W H Herron	do	117 90
30	162	C W Purington	do	36 29
30	163	Frank Tweedy	do	151 60
30	164	Thomas W Vaughan	do	78 80
30	165	W Lindgren	do	151 60
30	166	H W Turner	do	151 60
30	167	J L Hughes	do	40 00
30	168	James Storrs	do	50 00
30	169	Charles Perry	do	44 00
30	170	Pay roll of employees	do	311 70
30	171	do	do	247 70
30	172	do	do	308 02
30	173	do	do	284 80
30	174	do	do	48 22
30	175	do	do	399 30
30	176	do	do	117 90
30	177	do	do	188 70
30	178	do	do	227 40
30	179	do	do	289 80
30	180	do	do	120 80
30	181	do	do	175 56
30	182	A P Davis	Services, Aug 1-17, 1894	92 39
30	183	Pay roll of employees	Services, Aug , 1894	307 40
30	184	do	do	257 90
30	185	do	do	205 60
30	186	do	do	188 39
30	187	do	do	248 50
30	188	J B Woodworth	do	100 00
30	189	C H Stuver	do	33 38
30	190	A H Houston	do	17 74
31	191	W. H. Walker	do	9 68
31	192	J H Hagerty	do	29 03
31	193	J E Elliott	do	20 32
31	194	Samuel Payne	do	14 52
31	195	A W Lamson	do	12 90
31	196	T Nelson Dale	do	168 50
31	197	John L Mendenhall	Subsistence	75 89
31	198	Charles H Kipp	do	26 80
31	199	Rosette & Beaty	Repairs	62 65
31	200	do	Shoeing	13 75
31	201	T McCauley	Boarding, etc	24 75
31	202	Merrill Hackett	Traveling expenses	26 34
31	203	Robert A Farmer	do	20 00
31	204	E C Barnard	do	46 25
31	205	W H Weed	do	46 95
31	206	L V Pirsson	do	50 20
31	207	Robert A Farmer	Field expenses	4 85
31	208	R M Towson	do	192 95
31	209	W. T Griswold	do	83 42
31	210	W J Peters	do	121 20
31	211	H W Turner	do	41 27
31	212	Pay roll of employees	Services, Aug , 1894	162 90
31	213	do	do	817 10
31	214	Arnold Hague	do	337 00
31	215	C D White	do	117 90
31	216	W H Weed	do	151 60
31	217	Robert T Hill	do	252 70
31	218	S F Emmons	do	195 65
31	219	George F Becker	do	195 65
31	220	Pay roll of employees	do	884 98
31	221	George T Hawkins	do	86 96
31	222	J S Diller	do	202 20
31	223	F. H Newell	do	168 50
31	224	G F Becker	Traveling expenses	53 11
31	225	G E Hyde	Field expenses	376 18
31	226	E B Mathews	Services, Aug , 1894	75 00
31	227	C Whitman Cross	Field expenses	94 04
31	228	Thomas W Vaughan	Traveling expenses	50 95
31	229	A R Willmann	Tents	12 40
31	230	W T Walker	Services, Aug , 1894	33 39
31	231	L A Brown	do	7 90
31	232	J H Carlock	do	15 48
31	233	A L Whitworth	do	15 83
31	234	W D Johnson	do	168 50

Abstract of disbursements made by C. D Davis, special disbursing agent, United States Geological Survey, etc.—Continued.

AUGUST, 1894—Continued

Date of payment	No of voucher	To whom paid	For what paid.	Amount
Aug 31	235	Pay roll of employees	Services, Aug , 1894	$257 90
31	236	do	do	533 33
31	237	do	do	237 09
31	238	do	do	340 60
31	239	do	do	38 70
31	240	do	do	198 70
31	241	do	do	323 67
31	242	A P Davis	Field expenses	103 00
31	243	A E Murlin	do	55 43
31	244	H L Baldwin	do	64 39
31	245	Charles Urquhart	Traveling expenses	32 90
31	246	Nat G Van Doren	do	8 75
31	247	Charles B Green	do	41 20
31	248	C C Bassett	do	29 75
		Total		22,920 23

SEPTEMBER, 1894

Date of payment	No of voucher	To whom paid	For what paid.	Amount
Sept 5	1	Charles D Walcott	Traveling expenses	$39 53
5	2	William H Hoegee	Repairs, etc	6 95
5	3	Neal Glass	Shoeing	6 00
5	4	W & L E Gurley	Repairs	2 50
5	5	W T Griswold	Field expenses	25 10
5	6	W M Beaman	Traveling expenses	56 40
6	7	S F Emmons	do	83 25
6	8	J A Taff	Services, Aug , 1894	58 70
6	9	Pay roll of employees	do	64 84
7	10	A B Searle	Traveling expenses	25 50
10	11	Spratlen & Anderson	Subsistence	50 25
10	12	S Newmayer & Co	do	47 67
10	13	Anderson & Chanslor	Supplies	23 50
10	14	Humphris & Co	do	109 96
10	15	Ad Frese & Co	Repairs	20 60
10	16	Reynolds & Wheeler	do	46 95
10	17	Goldberg, Bowen & Lebenbaum	Supplies	7 85
10	18	A B Kirk	Forage	11 50
10	19	W H Ferguson	do	36 00
10	20	D E Lord	Hire of transportation	24 84
10	21	Joseph Goodman	Saddle pony	30 00
10	22	N B Dunn	Forage, etc	49 50
10	23	H G McCall	do	15 97
10	24	Joseph Marian	Storage	8 00
10	25	John Riss	Field material	23 70
10	26	J M McCausland & Co	Field supplies	21 75
10	27	Bethune & White	Supplies	16 43
10	28	J G Mossin	Rent of storeroom	22 00
10	29	S Celestin	Pasturage	27 90
10	30	J Jepsen & Son	Material	40 85
10	31	Shields & Humphrey	Field supplies	39 60
10	32	S J Johanson	Shoeing	4 00
10	33	Haley Grocery Co	Subsistence	30 24
10	34	E C Buchanan	Feeding	12 00
10	35	Stearns & Chenoweth	Supplies	20 20
10	36	L W Estes	Forage	37 15
10	37	Occidental Hotel	Boarding	20 00
10	38	Van H Manning	Field expenses	55 95
10	39	Redick H McKee	do	15 75
10	40	W M Beaman	do	49 00
10	41	R B Marshall	do	2 85
10	42	F P Gulliver	Services, Aug , 1894	62 89
10	43	C K Leith	do	67 00
10	44	W E Beckwith	do	20 32
10	45	George W Stone	do	40 32
10	46	Charles S Prosser	do	96 00
10	47	Charles Oley	do	60 00
10	48	Garry E Culver	do	60 00
10	49	Gust Johnson	do	40 00
10	50	J Morgan Clements	do	108 00
10	51	Ira B Weller	do	55 00
10	52	Oscar J Weller	do	45 00
10	53	W S Bayley	do	135 00
10	54	George O Smith	do	50 00
10	55	Nick Loiselving	Hire of horse	14 50
7	56	R T. Seaman	Two horses	250 00

Abstract of disbursements made by C D. Davis, special disbursing agent, United States Geological Survey, etc.—Continued

SEPTEMBER, 1894—Continued

Date of payment	No of voucher	To whom paid	For what paid	Amount
Sept 10	57	W E Beckwith	Traveling expenses	$8 91
10	58	W. S Bayley	do	64 90
10	59	C Whitman Cross	do	67 45
10	60	do	Field expenses	129 65
10	61	Charles S Prosser	do	79 50
10	62	C Willard Hayes	do	158 62
10	63	H W Turner	do	64 97
10	64	A T Elliott	Hauling	4 75
10	65	J M Buler	Pasturage	9 85
10	66	J J Fawbush	Forage, etc	21 25
10	67	Fred A Fielding	Repairs	7 20
10	68	John P Outhwaite	Boarding	59 51
11	69	G K Gilbert	Traveling expenses	80 16
11	70	do	Field expenses	131 36
11	71	W Lindgren	do	175 50
11	72	do	Traveling expenses	39 50
11	73	H G Wallace	Field expenses	49 75
11	74	Frank Tweedy	do	103.65
11	75	R O Gordon	do	118 71
11	76	T M. Bannon	do	105.70
11	77	Telluride Mercantile Co	Subsistence	40 54
11	78	J H Jennings	Traveling expenses	28 83
11	79	Pay roll of employees	Services, Aug , 1894	5 16
11	80	Goldberg, Bowen & Lebenbaum	Supplies	70 15
11	81	Perkins & Wise	do	34 45
11	82	M Gleason & Son	Subsistence	53 29
11	83	Bailey Willis	Field expenses	72 88
11	84	do	do	37 05
11	85	T Nelson Dale	Traveling expenses	33 88
11	86	Charles Harvey	Services, July 25 to Aug 31	61 29
11	87	W L Wilson	Services, July 19 to Aug 31.	85 16
11	88	John J Williams	Services, Aug , 1894.	24 50
11	89	R Fee	Feeding stock	13 25
11	90	Commercial Hotel	Boarding etc	10 00
11	91	J Jepson & Son	Harness, etc	29 00
11	92	L C Fletcher	Field expenses	49 35
11	93	Willard D Johnson	do	32 79
11	94	do	do	36 44
11	95	E C. Barnard	do	69 48
11	96	do	do	55 50
11	97	T G Gerdine	do	112 99
11	98	H B Blan	do	62 45
11	99	S B Luttrell & Co	Supplies	25 96
11	100	Haynes Bros	Camp outfit	62 30
11	101	N S Shaler	Services, July 1 to Aug 31	350 00
11	102	M. R Campbell	Field expenses	78 46
12	103	Paul Holman	do	155 94
12	104	John H Renshawe	Traveling expenses	40 25
12	105	W T. Griswold	Field expenses	37 55
12	106	do	do	35 05
12	107	E G Young & Co	Supplies	55 12
13	108	T McCauley	Boarding, etc	16 25
13	109	Andrew C Lawson	Traveling expenses	56 10
13	110	do	Services, July 1 to Sept 1, 1894	150 00
13	111	J C Merriam	Services, July 11 to Sept 1, 1894	56 00
13	112	F Leslie Ransome	Services, July 21 to Aug 13, 1894.	35 00
13	113	H L Baldwin, jr	Field expenses	44 90
14	114	D C Harrison	do	159 95
14	115	Frank B. Reid	Repairs to wagons	31 25
14	116	Joseph Goodman	Subsistence	47 69
14	117	Jas Richmond & Co	do	14 15
14	118	J H Lewis	Boarding	15 50
14	119	John T Callaghan, jr	Services, Sept 1–12, 1894	20 00
15	120	W B Corse	Traveling expenses	22 75
15	121	Robert T. Hill	Field expenses	103 62
17	122	Gurley & Bro	Subsistence	19 12
17	123	Thomas Hughes	do	54 81
17	124	B O Paulson	Repairs to wagons	61 80
17	125	C F Edin	Forage	45 48
17	126	R M Towson	Field expenses	140 65
17	127	E M Douglas	do	53 35
17	128	William J Peters	do	83 80
17	129	Redick H McKee	do	39 60
17	130	A E Murlin	Traveling expenses	4 50
18	131	J H Jennings	Field expenses	124 43
18	132	W H Lovell	do	80 35
18	133	Gilbert Thompson	do	41 65

Abstract of disbursements made by C D. Davis, special disbursing agent, United States Geological Survey, etc.—Continued.

SEPTEMBER, 1894—Continued

Date of payment	No of voucher	To whom paid	For what paid	Amount
Sept 18	134	The Denver Transit and Warehouse Co	Rent of storeroom	$25 00
18	135	L C Fletcher	Field expenses	69 22
18	136	E T Perkins	do	151 80
18	137	Merrill Hackett	do	124 16
19	138	R H Shearer	Umbrellas, etc	9 90
19	139	Charles T. Babcock.	Services	5.00
20	140	G E Hyde	Field expenses	166 77
20	141	George H Eldridge	do	258 82
20	142	do	Traveling expenses	32 05
20	143	T M Bannon	Field expenses	94 28
20	144	T C Dickey	Subsistence.	29 76
20	145	Hersey Munroe	Field expenses.	40 00
20	146	Main & Winchester.	Material	41 09
20	147	A Bishop, sr	Pasturage	14.71
21	148	Van H Manning.	Field expenses.	74 55
21	149	H S Wallace	do	50 55
21	150	A P. Davis	do	5 50
20	151	H L Baldwin, jr	do	38 02
20	152	T Nelson Dale	Traveling expenses	43 08
21	153	R H McKee	Field expenses	36 15
24	154	W S Post	do	91 50
24	155	C C. Bassett	do	67 82
24	156	R C McKinney	Traveling expenses	44 75
24	157	Frank Tweedy	Field expenses	50 99
24	158	C W Hayes	do	69 47
24	159	G K Gilbert	do	72 74
24	160	Andrew C Lawson	do	33 75
24	161	W C Walsh	Pasturage	10 00
25	162	W. M Lockhart.	Boarding, etc	13 25
25	163	W L Miller	Traveling expenses	15 06
25	164	Joseph Macfarland	do	11 38
25	165	W S Bayley	do	126 91
25	166	W H Weed	Field expenses	26 60
30	167	A P Davis	Services, Sept, 1894	163 00
30	168	W Lindgren	do	146 80
30	169	H W Turner	do	146 80
30	170	C Whitman Cross.	do	163 00
30	171	James Storrs	do	60 00
30	172	J L Hughes	do	40 00
30	173	A. W Lamson	do	50 00
30	174	Thomas W Vaughan	do	81 60
30	175	C W Purington	do	75 00
30	176	J E Spurr	do	81 60
30	177	T Nelson Dale	do	163 00
30	178	Louis M Prindle	do	34 00
30	179	Pay roll of employees	do	334 60
30	180	J W Maxwell	Services, Aug 26-31, 1894	8 70
30	181	C H Underwood	Services, Aug 30-31, 1894	2 25
30	182	Merrill Hackett	Services, Sept, 1894	146 80
30	183	Pay roll of employees	do	220 20
30	184	do	do	171 60
30	185	do	do	267 20
30	186	do	do	239 60
30	187	do	do	358 55
30	188	do	do	352 20
30	189	do	do	126 60
30	190	do	do	341 00
30	191	do	do	187 60
30	192	do	do	215 40
30	193	do	do	358 20
30	194	do	do	287 03
30	195	do	do	255 20
30	196	do	do	267 40
30	197	do	do	254 20
30	198	do	do	297 00
30	199	do	do	379 60
30	200	do	do	318 80
30	201	do	do	378 80
30	202	do	do	546 20
30	203	do	do	95 00
30	204	do	do	198 80
30	205	N H Darton	do	130 40
30	206	Joseph A Taff	do	97 80
30	207	T Nelson Dale	Traveling expenses	21 62
30	208	John H Renshawe	do	72 60
30	209	J W Thom	do	45 90
30	210	W H Lovell	do	61 50

Abstract of disbursements made by C D. Davis, special disbursing agent, United States Geological Survey, etc.—Continued.

SEPTEMBER, 1894—Continued

Date of payment	No of voucher	To whom paid	For what paid	Amount
Sept 30	211	R M Towson	Field expenses	$56 55
30	212	J F Ackerson	Hay	45 00
30	213	E T Perkins, jr	Field expenses	5 25
30	214	Pay roll of employees	Services, Sept, 1894.	335 40
30	215	do	do	308 40
30	216	do	do	114 20
30	217	do	do	811 40
30	218	do	do	790 80
30	219	Arnold Hague	do	326 00
30	220	W H Weed	do	146 80
30	221	S F Emmons	do	326 00
30	222	G F Becker	do	326 00
30	223	Gilbert Thompson	do	163 00
30	224	John H Renshawe	do	179 40
30	225	C D White	do	114 20
30	226	Pay roll of employees	do	204 20
30	227	do	do	212 00
30	228	do	do	238 80
30	229	James L Johnson	Traveling expenses	13 57
30	230	Bailey Willis	do	12 05
30	231	J S Diller	Services, Sept, 1894	195 60
30	232	W S Bayley	do	80 00
30	233	Ira B Weller	do	55 00
30	234	George O Smith	do	50 00
30	235	John Matthews	do	23 83
30	236	Pay roll of employees	do	343 00
30	237	do	do	300 20
30	238	do	do	222 80
30	239	S F Emmons	Traveling expenses	37 75
30	240	Charles F Urquhart	Field expenses	151 31
30	241	Arthur Keith	do	118 51
30	242	Bailey Willis	do	58 05
30	243	F C Schrader	Services, Sept, 1894	75 00
30	244	J B. Woodworth	do	50 00
		Total		24,036 25

OCTOBER, 1894

Date of payment	No of voucher	To whom paid	For what paid	Amount
Oct 8	1	R E Dodge	Traveling expenses	$46 41
8	2	T Nelson Dale	do	10 83
8	3	J E Wolff	do	51 90
8	4	do	Services, Sept, 1894.	105 00
8	5	Frederick Koch	Services, Aug, 1894.	70 00
8	6	A J Steele	do	60 00
8	7	William B Clark	Services, Sept, 1894.	100 00
8	8	Charles Harvey	do	50 00
8	9	W L Wilson	do	60 00
8	10	E B Mathews	do	75 00
8	11	Clarence W Lathrop	Services, Aug 23 to Sept 30, 1894	64 51
8	12	H Gibb	Services (job)	15 00
8	13	Lobban & Hine	Storage	6 30
8	14	S F. Emmons	Field expenses	132 65
8	15	M R Campbell	do	113 51
8	16	W H Weed	do	81 25
8	17	Spratlen & Anderson	Subsistence	22 60
8	18	A H Washburn	Pasturage	18 71
8	19	M P. Henderson & Son	Storage	16 00
8	20	James Hennessy	Hire of horse	90 00
8	21	Edward Denney & Co	Supplies	13 60
8	22	J F Barkley	Pasturage	13 90
8	23	E M Douglas	Traveling expenses	104 40
8	24	J H Jennings	Field expenses	101 10
8	25	A E Murlin	do	67 43
8	26	H L Baldwin, jr	do	76 85
8	27	G E Hyde	do	168 54
8	28	W M Beaman	do	34 83
8	29	Van H Manning	do	85 60
8	30	W T Griswold	do	42 53
8	31	Frank Tweedy	do	38 15
8	32	R U Goode	Traveling expenses	121 70
8	33	Pay roll of employees	Services, Sept, 1894.	256 50
8	34	do	do	312 46
8	35	do	do	293 00

Abstract of disbursements made by C D. Davis, special disbursing agent, United States Geological Survey, etc.—Continued.

OCTOBER, 1894—Continued

Date of payment	No of voucher	To whom paid	For what paid	Amount
Oct 1	36	George H Shields	Traveling expenses	$19 45
8	37	F P Gulliver	Services, Sept , 1894	75 00
8	38	George H Stone	do	50 00
8	39	Ben K Emerson	Services, Aug and Sept , 1894	115 00
8	40	do	Traveling expenses	67 06
8	41	do	Field expenses	5 70
8	42	C. W Cross	do	49 07
8	43	Wm J Park & Son	Supplies	15 70
8	44	W T McConnell & Son	Subsistence	25 40
8	45	Frank Sutton	Traveling expenses	279 96
8	46	J H Jennings	do	61 49
8	47	W H Lovell	Field expenses	98 70
8	48	H B Blair	do	180 25
8	49	Hersey Munroe	do	26 65
8	50	Charles H Kipp	Supplies	41 90
8	51	W D Johnson	Field expenses	136 94
8	52	John J Williams	Services	6 00
8	53	L C Fletcher	Field expenses	88 68
8	54	T. M Bannon	do	114 75
8	55	L Newmayer & Co	Supplies	74 91
8	56	W. J Peters	Field expenses	185 13
9	57	C W Cross	do	98 14
9	58	C K Leith	Services	11 00
9	59	J T McGhinnis	Storage	3 00
9	60	R O. Gordon	Field expenses	126 00
9	61	M P. Henderson & Son	Repairs	45 60
9	62	N S Shaler	Services, Sept , 1894	180 00
9	63	Joseph Goodman	Subsistence	23 28
9	64	Queen & Co	Repairs	12 00
9	65	T. Nelson Dale	Field expenses	6 83
9	66	C W Hayes	do	133 05
9	67	Robert T Hill	do	31 90
9	68	E T Perkins	do	67 55
9	69	A C. McKinney	do	207.09
9	70	O N Davis	Supplies	20 65
9	71	H K Ward	Subsistence	24 33
9	72	Isaac I Lewis	do	49 52
10	73	D C Hamson	Field expenses	135 25
10	74	W T. Griswold	do	57 20
10	75	do	do	23 95
10	76	W T. Turner	do	18 50
10	77	T McCauley	Boarding, etc	34 00
10	78	do	do	29 45
10	79	J L Labaree	Hire of wagon	16 00
10	80	Nat G. Van Doren	Traveling expenses	24 27
10	81	W Lindgren	Field expenses	158 48
10	82	H. W Turner	do	39 00
10	83	M Gleason & Son	Subsistence	41 40
10	84	T C Schrader	Services, Aug , 1894	21 77
10	85	E B Clark	Traveling expenses	46 16
11	86	G. F Becker	Field expenses	70 30
11	87	Bailey Willis	do	50 10
12	88	S F Emmons	do	314 96
12	89	Joseph Goodman	Subsistence	111 50
12	90	H B Blair	Field expenses	25 50
12	91	E M Douglas	do	69 96
12	92	Frank Tweedy	do	34 00
12	93	W. T Walker	Traveling expenses	24 20
12	94	Nat Tyler, jr	do	14 35
15	95	E C Barnard	Field expenses	111 60
15	96	Greer Machinery Co	Wagon	65 00
15	97	W. H Lovell	Field expenses	95 48
15	98	do	Traveling expenses	6 75
15	99	J B Woodworth	do	57 35
15	100	G K Gilbert.	Field expenses	154 37
15	101	Thoburn Gibson	Hire of transportation	27 00
15	102	John H Renshawe	Traveling expenses	90 02
17	103	John Cammack	Storage	6 61
18	104	Van H Manning	Traveling expenses	26 75
17	105	R M Towson	Field expenses	75 42
17	106	A. H Thompson	do	67 72
17	107	L C Fletcher	do	49 34
18	108	Ad Frese & Co	Instruments, etc	9 00
18	109	A H Washburn	Pasturage	10 00
17	110	T C Schrador	Traveling expenses.	49 73
18	111	H W Turner	do	37 05
18	112	Main & Winchester	Supplies	12 00

Abstract of disbursements made by C D. Davis, special disbursing agent, United States Geological Survey, etc —Continued.

OCTOBER, 1894—Continued

Date of payment	No of voucher	To whom paid	For what paid	Amount
Oct 18	113	Hersey Munroe	Field expenses	$42 15
18	114	F O Perry	Pasturage	13 32
18	115	Van H Manning	Field expenses	81 37
18	116	J H Jennings	do	86 00
18	117	H S. Wallace	do	131 65
18	118	Gilbert Thompson	do	31 10
18	119	M Hackett	do	170 75
18	120	R A F Penrose, jr	Services, Sept 3–24, 1894	190 00
20	121	W L Wilson	Services, Oct 1–20, 1894	38 70
20	122	Clarence W Lathrop	do	32 25
20	123	Charles Harvey	do	32 25
20	124	G K Gilbert	Field expenses	129 20
20	125	Al. Myers	Services, Sept 10–30, 1894	45 50
20	126	J A Edie	Services, Sept 11–30, 1894	40 00
20	127	Perkins & Wise	Supplies	43 39
20	128	H W Turner	Field expenses	100 17
20	129	G E Hyde	do	62 18
20	130	E C Barnard	do	69 50
20	131	Somers & Mears	Subsistence	45.40
22	132	R. W Goode	Field expenses	30 65
23	133	Young Bros	Supplies	48 87
23	134	H L Baldwin, jr	Field expenses	80 77
23	135	Willard D Johnson	do	88 40
24	136	Samuel Payne	Services, Sept 1 to Oct 23, 1894	87 10
24	137	Frank Tweedy	Field expenses	105 03
24	138	do	do	83 85
24	139	J. W Wadsworth	Hire of transportation	165 00
25	140	C C Bassett	Field expenses	62 69
25	141	Bailey Willis	do	104 75
25	142	H R Crocker	Subsistence	41 51
25	143	J F Ackerson	Hay	24 72
25	144	C Whitman Cross	Field expenses	80 98
31	145	do	Services, Oct, 1894	168 50
31	146	W H Weed	do	151 60
31	147	T Nelson Dale	do	168 60
31	148	W Lindgren	do	151 60
31	149	H W Turner	do	151 60
31	150	James Storrs	do	60 00
31	151	J L Hughes	do	40 00
31	152	J E Spurr	do	84 20
31	153	T. W. Vaughan	do	84 20
31	154	C. W Purington	do	75 00
31	155	A W Sampson	do	50 00
31	156	H L Baldwin, jr	do	151 60
31	157	M Hackett	do	151 60
31	158	William H Griffin	do	75 80
31	159	C W Goodlove	do	75 80
31	160	Pay roll of employees	do	174 20
31	161	do	do	176 90
31	162	do	do	245 60
31	163	do	do	696 07
31	164	do	do	263 50
31	165	do	do	315 80
31	166	do	do	325 60
31	167	R C McKinney	do	134 80
31	168	Paul Holman	do	84 20
31	169	Jeremiah Ahern	do	50 00
31	170	Mede Shortley	do	35 00
31	171	Pay roll of employees	do	129 20
31	172	do	do	219 80
31	173	do	do	347 90
31	174	do	do	349 50
31	175	do	do	361 40
31	176	do	do	365 90
31	177	John H Renshawe	do	185 30
31	178	Pay roll of employees	do	247 90
31	179	do	do	342 70
31	180	do	do	255.60
31	181	do	do	117 90
31	182	J B Woodworth	do	50 00
31	183	C D White	do	117 90
31	184	Poy roll of employees	do	455 60
31	185	do	do	234 68
31	186	do	do	276 73
31	187	do	do	339 80
31	188	do	do	205 60
31	189	R M Towson	Field expenses	60 20
31	190	J H Hagerty	Forage	14.17

Abstract of disbursements made by C. D. Davis, special disbursing agent, United States Geological Survey, etc.—Continued.

OCTOBER, 1894—Continued

Date of payment	No of voucher	To whom paid	For what paid	Amount
Oct 31	191	Frank Tweedy	Field expenses	$22.90
31	192	do	Traveling expenses	14 50
31	193	George O Glavis, jr	do	10 10
31	194	W T. Griswold	Field expenses	75 62
31	195	W H Lovell	do	98 43
31	196	G F Becker	Traveling expenses	46 33
31	197	F M Love	do	24 03
31	198	Pay roll of employees	Services, Oct, 1894	261 43
31	199	do	do	240.60
31	200	do	do	276 40
31	201	do	do	253 37
31	202	Arthur Keith	Traveling expenses	25 04
31	203	G. F Becker	Services Oct, 1894	337 00
31	204	S F Emmons	do	337 00
31	205	Gilbert Thompson	do	168 50
31	206	Pay roll of employees	do	1,154 10
31	207	do	do	1,173 80
31	208	G F Becker	Field expenses	87 60
31	209	Pay roll of employees	Services, Oct., 1894	219 00
31	210	C. W Hayes	Field expenses	172 49
		Total		24,296 32

NOVEMBER, 1894

Nov 10	1	D C Harrison	Field expenses	$101 28
10	2	do	Services, Oct, 1894	117 90
10	3	H S Wallace	Traveling expenses	20 75
10	4	do	Field expenses	20 25
10	5	Van H Manning	do	91 83
10	6	E T Perkins, jr	do	73 30
10	7	W S Post	do	107 75
10	8	W. D Johnson	do	43 40
10	9	R B Marshall	do	41 05
10	10	Frank Tweedy	do	35 60
10	11	R O Gordon	do	116 55
10	12	T M Bannon	do	227 66
10	13	R H McKee	do	26 80
10	14	do	do	22 85
10	15	do	do	8 20
10	16	do	do	30 75
10	17	R C McKinney	do	163 32
10	18	Pay roll of employees	Services, Oct, 1894	226 10
10	19	do	do	302.40
10	20	Spratlen & Anderson	Supplies	58 03
10	21	G O Glavis, jr	Traveling expenses	62 50
10	22	George Petrequin	Services, Oct, 1-13, 1894	20 97
10	23	J H Jennings	Traveling expenses	53 20
10	24	do	Field expenses	158 03
10	25	H L Baldwin, jr	do	91 70
10	26	W M Beaman	do	83 37
10	27	G E Hyde	do	169 53
10	28	S S Gannett	do	39 84
10	29	do	do	27 33
10	30	W. H Lovell	do	55 87
10	31	Frank Sutton	Traveling expenses	360 66
10	82	Fred Stewart	Hire of transportation	55 00
10	33	Horace Stewart	Board and lodging	92 62
10	34	F P Gulliver	Traveling expenses	63 60
10	35	do	do	4.80
10	36	William H Hobbs	do	8 22
10	37	C R. Van Hise	do	91 07
10	38	W H Weed	Field expenses	38 50
10	39	R T. Hill	do	66.79
10	40	J E Wolff	do	9 56
10	41	Samuel Storrow	Pasturage	11 50
10	42	do	do	11 50
10	43	Ira B Weller	Services, Oct, 1894	7 10
10	44	C K. Leith	do	34 37
10	45	T. E Morrow	do	25 00
10	46	W. S Bayley	do	80 00
10	47	R A F Penrose, jr	do	235 00
10	48	Frank Leverett	Services, July 1 to Oct 31, 1894	495 00
10	49	A. J. Steele	Services, Sept 1 to Oct. 27, 1894	112.15

Abstract of disbursements made by C. D. Davis, special disbursing agent, United States Geological Survey, etc.—Continued

NOVEMBER, 1894—Continued

Date of payment	No of voucher	To whom paid	For what paid	Amount
Nov 10	50	C R Van Hise	Services, July 1 to Oct 31, 1894	$450 00
10	51	F C Schrader	Services, Oct, 1894	75 00
10	52	Pay roll of employees	do	364 45
10	53	M Gleason & Son	Supplies	54 43
10	54	Rosette & Beaty	Field material	31 70
10	55	Joseph Goodman	Subsistence	52 10
10	56	do	Field material	84 91
10	57	Thoburn Gibson	Hire of transportation	6 75
10	58	Frank Lewis	do	31 00
10	59	F H Ainsworth	Traveling expenses	16 40
10	60	Bailey Willis	Field expenses	57 20
10	61	Gilbert Thompson	do	39 75
10	62	R H Chapman	do	148 40
10	63	H B Blair	do	206 30
10	64	L C Fletcher	do	145 12
10	65	E M Douglas	do	92 67
10	66	William J Peters	do	236 39
10	67	R U Goode	do	7 70
10	68	do	Traveling expenses	117 15
12	69	E M Douglas	do	141 10
12	70	Hersey Munroe	Field expenses	24 10
12	71	F C Schrader	Traveling expenses	57 50
12	72	J B Woodworth	do	20 01
12	73	A Irwin Oliver	Services, Oct, 1894	30 00
12	74	William B Clark	do	105 00
12	75	F P Gulliver	do	75 00
12	76	Isaac Munroe	Services, Nov 1-6, 1894	8 00
12	77	Robert P Mendenhall	do	8 00
12	78	N H Darton	Services, Oct, 1894	134 80
13	79	do	Traveling expenses	65 20
13	80	M R Campbell	Field expenses	142 05
13	81	S S Gannett	do	73 01
13	82	A E Murlin	do	76 57
13	83	E T Perkins, jr	do	67 92
13	84	Mrs S Koerner	Boarding	49 50
13	85	George H Eldridge	Field expenses	392 00
13	86	G F Becker	Traveling expenses	99 11
15	87	M R Campbell	do	43 70
15	88	Arthur Keith	do	68 53
15	89	H W Turner	Field expenses	67 50
15	90	Charles Perry	Services, Nov 1-8, 1894	16 00
15	91	Gust Johnson	do	10 66
15	92	Oscar J Weller	do	12 00
15	93	W. Murphy	do	11 00
15	94	W D Johnson	Field expenses	53 50
15	95	R H Chapman	do	102 02
15	96	do	Traveling expenses	39 23
16	97	Van H Manning	Field expenses	149 50
16	98	R M Towson	do	99 92
15	99	A M Walker	Traveling expenses	28 18
16	100	J W Wadsworth	Freight charges	28 45
16	101	Seaboard Air Line	do	25 83
16	102	Louis M Prindle	Services, Oct, 1894	60 00
16	103	do	Services, Nov, 1894	24 00
16	104	do	Traveling expenses	67 57
16	105	Ben K Emerson	do	44 12
16	106	do	Services, Oct., 1894	65 00
16	107	M P. Henderson & Son	Storage, Oct, 1894	16 00
16	108	W T Turner	Field expenses	27 00
16	109	R H Chapman	do	72 06
17	110	Pay roll of employees	Services, Oct, 1894	95 00
18	111	Goldberg, Bowen & Lebenbaum	Subsistence	24 60
18	112	Clarence W Lothrop	Services, Oct, 1894	17 74
18	113	W Lindgren	Field expenses	250 30
18	114	H L Baldwin, jr	do	56 38
18	115	Charles F Urquhart	do	154 34
19	116	R B Marshall	do	64 35
19	117	Louis F Garrard, jr	Traveling expenses	49 00
19	118	W H Lovell	Field expenses	99 37
20	119	Frank Perry	Services, Nov, 1894	20 00
20	120	W R Manning	do	22 50
20	121	Frank Tweedy	Field expenses	44 01
20	122	Adolph Lietz	Repairs	27 30
20	123	John T Braddock	Subsistence	36 46
20	124	Williams & Welty	Hire of horses	101 50
20	125	George H Barton	Traveling expenses	55 04
20	126	A H Brooks	do	35 60
20	127	Van H Manning	do	49 20

Abstract of disbursements made by C. D. Davis, special disbursing agent, United States Geological Survey, etc —Continued

NOVEMBER, 1894—Continued

Date of payment	No of voucher	To whom paid	For what paid	Amount
Nov 20	128	Robert A Farmer	Traveling expenses	$41.25
22	129	Charles H Stuver	Services, Nov 1-15, 1894	22 50
20	130	William M Smith, jr	do	22 50
21	131	John H Renshawe	Traveling expenses	212 96
21	132	J H Jennings	Field expenses	127 00
21	133	Nat G Van Doren	Traveling expenses	22 23
22	134	W T Griswold	Field expenses	66 45
22	135	E C Barnard	do	110 30
22	136	Gilbert Thompson	do	18.00
22	137	L H Baldwin, jr	do	101 50
22	138	do	do	27 25
22	139	L J Labareo	Hire of transportation	31 00
23	140	F H Ainsworth	Services, Nov 1-5, 1894	8 33
23	141	G E Hyde	Field expenses	78 83
23	142	R H Chapman	do	87 05
23	143	do	Traveling expenses	12 40
25	144	A M Walker	do	8 25
23	145	W V Inskeep	Feeding stock	48.72
23	146	D C Harrison	Traveling expenses	55 20
23	147	do	Field expenses	27 00
23	148	J A Taff	Traveling expenses	43 50
23	149	J Morgan Clements	do	236 76
24	150	W T Griswold	do	114 25
24	151	E C Barnard	do	113 25
26	152	do	Field expenses	77 46
26	153	W C Mendenhall	Services, Nov. 1-13, 1894	21 66
26	154	W C Cannon	Traveling expenses	28 77
30	155	B Peyton Legaré	Services, Nov, 1894	73 40
30	156	W T Walker	do	33 00
30	157	Pay roll of employees	do	109 46
30	158	do	do	215.40
30	159	do	do	443 80
30	160	Alex C Barclay	do	81 60
30	161	Pay roll of employees	do	213 70
30	162	do	do	258 03
30	163	do	do	318 80
30	164	M P Henderson & Son	Rent of storeroom	11 30
30	165	L C. Fletcher	Field expenses	93 24
30	166	Samuel Storrow	Pasturage	11 50
30	167	M Hackett	Services, Nov, 1894	146 80
30	168	William H Griffin	do	73 40
30	169	H L Baldwin, jr	do	146 80
30	170	C W Goodlove	do	73 40
30	171	Pay roll of employees	do	171 20
30	172	do	do	813 40
30	173	do	do	114 20
30	174	H W Turner	do	146 80
30	175	W Lindgren	do	146 80
30	176	C W Purington	do	75 00
30	177	Thomas Wayland Vaughan	do	81 60
30	178	J E Spurr	do	81 60
30	179	C Whitman Cross	do	163.00
30	180	J C Elliott	do	45 00
30	181	Walter H Weed	do	146 80
30	182	Robert T Hill	do	244 60
30	183	G F Becker	do	326 00
30	184	Pay roll of employees	do	2,164 72
30	185	do	do	1,116 80
30	186	John H Renshawe	do	179.40
30	187	Pay roll of employees	do	340 86
30	188	J J Fawbush	do	36.00
30	189	J G Gillum	do	24 00
30	190	W B Corse	do	81 60
30	191	do	Field expenses	13 70
30	192	William J Peters	do	218 18
30	193	do	Traveling expenses	17 50
30	194	Nat Tyler, jr	do	47 75
30	195	Duncan Hannegan	do	39 62
30	196	W B Corse	do	18 25
30	197	R C McKinney	do	89 50
30	198	W S Post	Field expenses	138 07
30	199	R B Marshall	do	54 35
30	200	W T Griswold	do	60 50
30	201	do	do	16 00
30	202	L W Estes	do	29 75
30	203	E A Goodnough	Rent of store room	70 00
30	204	E T. Perkins, jr	Services, Nov, 1894	130 40
30	205	R C McKinney	do	130 40

Abstract of disbursements made by C. D. Davis, special disbursing agent, United States Geological Survey, etc.—Continued.

NOVEMBER, 1894—Continued

Date of payment	No of voucher	To whom paid	For what paid	Amount
Nov 30	206	Paul Holman	Services, Nov, 1894	$81 60
30	207	Pay roll of employees	do	209 20
30	208	do	do	338.40
30	209	do	do	130 40
30	210	Joseph Macfarland	do	68 40
30	211	J W Thorn.	do	68 40
30	212	F P Johnson	Boarding stock	25 00
30	213	Gilbert Thompson	Traveling expenses	52 35
30	214	H B Blair	do	28 32
30	215	do	do	13 71
30	216	C Whitman Cross	Field expenses	51 45
30	217	T Nelson Dale	do	95
30	218	do	Services, Nov, 1894	157 61
30	219	James Storrs	do	60 00
30	220	J B Woodworth	do	50 00
30	221	Joseph Goodman	Supplies	73 01
30	222	G F Becker	Traveling expenses.	135 65
		Total		23,707 10

DECEMBER, 1894

Date of payment	No of voucher	To whom paid	For what paid	Amount
Dec 4	1	R C McKinney.	Field expenses	$125 98
6	2	B Peyton Legare	Traveling expenses.	65 38
6	3	George H Eldridge	do	68 30
8	4	George S Stose.	do	60 75
8	5	do	do	63 30
8	6	do	do	7 90
8	7	do	Services, Oct, 1894	50 00
8	8	do	Services, Nov, 1894	36 67
8	9	G K Gilbert	Field expenses	412 80
8	10	Robert T. Hill	do	76 70
8	11	Charles S Prosser	do	103 68
8	12	do	Traveling expenses	8 17
8	13	do	Services, Aug 16 to Sept 8, 1894	84 00
8	14	do	Services, Sept 17-20, 1894	16 00
8	15	C R Van Hise	Services, Nov, 1894	220 00
8	16	J Morgan Clements	do	86 00
8	17	W. S Bayley	do	80 00
8	18	C K Leith	do	43 25
8	19	S Weidman	do	52 00
8	20	Ben K Emerson	do	55 00
8	21	F C Schrader	do	75 00
8	22	F P Gulliver	Traveling expenses	68 50
8	23	Robert G Hill	do	63 85
8	24	T Wayland Vaughan	do	35 15
8	25	C Whitman Cross	do	79 85
8	26	do	Field expenses	34 00
8	27	H W Turner	do	31 32
8	28	Hersey Munroe	do	45 94
8	29	do	Traveling expenses	20 55
8	30	J W Thom	do	29 02
8	31	James L Johnson	do	8 75
8	32	W M Beaman	do	50 98
8	33	A E Murlin.	do	32 15
8	34	Joseph Macfarland	do	32 90
8	35	H L Baldwin, jr	do	85 85
8	36	do	Field expenses	43 65
8	37	J H Hagerty	Services, Nov, 1894	39 00
8	38	James L Carroll	Services, Dec, 1894	5 16
8	39	Pay roll of employees	Services, Nov, 1894	161 60
8	40	Frank Sutton	Traveling expenses	73 77
8	41	E. T Perkins, jr	do	62 70
8	42	Frank Tweedy	Field expenses	37.15
8	43	Willard D Johnson	do	89 75
8	44	Spratlen & Anderson	do	28 03
8	45	A H Washburn	Pasturage	14 60
8	46	O. E Harper	Services, Nov, 1894	50 00
8	47	A Irwin Oliver	do	23 00
8	48	Pay roll of employees	do	321 80
8	49	do	do	222 80
8	50	do	do	345 20
8	51	W H Herron	Services, Sept 1 to Oct 22, 1894	197 90
8	52	Duncan Hannegan	Traveling expenses	3.41

Abstract of disbursements made by C. D. Davis, special disbursing agent, United States Geological Survey, etc.—Continued.

DECEMBER, 1894—Continued

Date of payment	No. of voucher	To whom paid	For what paid	Amount
Dec 8	53	Basil Duke	Sept 1 to Oct 27, 1894	$35 00
8	54	E M Douglas	do	132 30
8	55	do	do	84 12
10	56	Robert Muldrow	do	7 33
8	57	J H Jennings	Field expenses	126 40
10	58	A. E Murlin	do	112 25
8	59	L C Fletcher	do	68 00
10	60	C F Edin	Forage, etc	25 66
8	61	William H Griffin	Traveling expenses	68.74
8	62	T E Morrow	Services, Nov , 1894	70 20
8	63	Peter Johnson	Services, Nov. 17–30, 1894	21 00
10	64	Frederick Koch	Services, Sept 1 to Nov 6, 1894	154 00
10	65	G K Gilbert	Traveling expenses	130 23
11	66	Frank Tweedy	do	68 55
11	67	Paul Holman	do	45 55
11	68	Joseph A Taff	do	7 82
11	69	G E Hyde	do	53 29
11	70	Nat G Van Doren	do	5 29
10	71	R H Chapman	Field expenses	44 64
10	72	H. B Blair	do	262 33
10	73	Clarence W Lothrop	Services, Nov 1–23, 1894	38 33
10	74	A W Lamson	Services, Nov , 1894	50 00
12	75	W M Beaman	Field expenses	49 76
12	76	Arthur Keith	Traveling expenses	35 06
12	77	R M Towson	Field expenses	70 25
12	78	Arthur Keith	do	56 63
12	79	J E Spurr	do	86 78
12	80	do	Traveling expenses	63 70
12	81	H L Baldwin, jr	Field expenses	121 82
12	82	W T Turner	do	75 81
13	83	C. C Bassett	do	68 98
13	84	Frank Sutton	do	397 00
13	85	R H McKee	do	24 50
13	86	do	do	50 48
13	87	do	Traveling expenses	105 75
14	88	James McCormick	do	20 29
14	89	R H Chapman	Field expenses	36 87
13	90	Charles F. Urquhart	Traveling expenses	76 50
14	91	J H Jennings	do	84 23
14	92	Samuel Storrow	Pasturage, etc	11 17
14	93	A Barafaldi & Co.	Boarding, etc	47 75
14	94	William B Clark	Services, Nov , 1894	95 00
15	95	C. C Bassett	Traveling expenses	23 00
15	96	do	Field expenses	54 24
15	97	T M Bannon	do	70 53
15	98	do	Traveling expenses	88 50
17	99	J H Jennings	do	40 43
17	100	do	Field expenses	20 05
17	101	W A Rogers	Boarding	18 85
19	102	Rosette & Beaty	Field transportation	3 00
19	103	H W. Turner	Field expenses	59 47
19	104	W H Lovell	do	60 79
19	105	Charles E Cooke	Traveling expenses	65 51
19	106	Frank Sutton	do	51 45
18	107	A H Thompson	do	80 25
19	108	J L Labaree	Hire of transportation	30 00
19	109	W Lindgren	Traveling expenses	132 45
20	110	Redick H McKee	Field expenses	44 90
20	111	A H Thompson	do	76 01
20	112	Willard D Johnson	do	79 36
20	113	W L Miller	Traveling expenses	31 89
20	114	R A F Penrose, jr	Field expenses	259 90
20	115	do	Services	200 00
21	116	W. Lindgren	Field expenses	116 65
21	117	E B Clark	Traveling expenses	6 75
20	118	C W Goodlove	do	36 86
21	119	W H Weed	Field expenses	40 00
26	120	Frank Tweedy	do	73 40
26	121	W H Leffingwell	Services	50 00
31	122	J J Fawbush	Care of animals	42 00
27	123	Charles B Green	Services, Aug , 1894	84.20
28	124	Albert Pike	Traveling expenses	43 40
28	125	William H Herron	do	56 85
28	126	H W Turner	do	153 50
28	127	Robert D Cummin	do	10 71
28	128	do	Field expenses	64 50
31	129	Pay roll of employees	Services, Dec , 1894	265.00

Abstract of disbursements made by C D. Davis, special disbursing agent, United States Geological Survey, etc —Continued

DECEMBER, 1894—Continued

Date of payment	No of voucher	To whom paid	For what paid	Amount
31	130	Pay roll of employees	Services, Dec , 1894	$361 40
31	131	do	do	1,154 10
31	132	do	do	3,638 76
31	133	T Nelson Dale	do	168 50
31	134	Robert D Cummin	do	134 80
31	135	Chester W Purington	do	75 00
		Total		15,391 53

JANUARY, 1895

Date of payment	No of voucher	To whom paid	For what paid	Amount
Jan 3	1	Ben K Emerson	Services, Dec , 1894	$50 00
3	2	J H Perry	Traveling expenses	5 31
3	3	do	Services	15 00
3	4	J B Woodworth	Services, Dec , 1894	50 00
3	5	James Storrs	do	16 00
3	6	Pay roll of employees	do	208 55
3	7	Charles B Green	Field expenses	15 65
3	8	W H Herron	do	21 00
3	9	Arthur Stiles	Traveling expenses	40 65
3	10	L C Fletcher	Field expenses	69 05
2	11	Charles T Urquhart	do	200 33
2	12	R O Gordon	do	181 04
2	13	G E Hyde	Traveling expenses	52 55
7	14	George W Stose	Services, Dec , 1894	50 00
7	15	P C Warman	do	48 91
7	16	Nat G Van Doren	Traveling expenses	7 50
7	17	A M Walker	do	8 79
8	18	W J Lloyd	do	57 75
8	19	J Bixby & Co	Pasturage	13 33
8	20	O E Harper	Services, Dec 1-10, 1894	16 13
8	21	Jeremiah Abern	Services, Dec 1-23, 1894	37 10
8	22	C F Edin	Pasturage	35 00
8	23	L W Estes	do	32 20
8	24	A F Ericsson	do	4 00
8	25	L A Ward	Feeding animals	3 35
8	26	W T Walker	Forage, etc	63 33
8	27	Fred Stiffler	Pasturage	35 66
8	28	O Parker	Rent of storeroom	15 00
8	29	Mrs C F Larsen	Boarding, etc	36 00
8	30	do	do	56 00
8	31	M P Henderson & Son	Storage	4 00
8	32	T N Miller	Hire of transportation	53 00
8	33	J H Hagerty	Care of animals	97 32
8	34	W V Inskeep	Hire of transportation	57 00
8	35	do	Boarding stock	19 66
8	36	J T Barkley	Pasturage, etc	15 00
8	37	F P Johnson	do	30 00
8	38	W S Bayley	Services, Dec , 1894	60 00
8	39	T E Morrow	do	81 00
8	40	C R Van Hise	do	210 00
8	41	J Morgan Clements	do	100 00
8	42	C K Leith	do	37 00
9	43	Frank Leverett	Services, Nov and Dec , 1894	250 00
9	44	R H Chapman	Traveling expenses	13 67
9	45	do	Field expenses	154 67
9	46	E T Perkins	do	200 70
9	47	L. C Fletcher	do	151 75
9	48	do	Services, Dec , 1894	151 60
10	49	do	Traveling expenses	233 60
10	50	W H Lovell	do	20 57
10	51	Harold B Goodrich	do	35 70
10	52	Charles E Cooke	Field expenses	1 50
10	53	F C Schrader	Services, Dec., 1894	75 00
10	54	do	Traveling expenses	43 24
10	55	Thomas G Gerdine	Services, Dec , 1894	75 80
12	56	R O Gordon	Traveling expenses	58.00
12	57	H W. Turner	Field expenses	83 27
12	58	E B Mathews	Traveling expenses.	64 00
12	59	W J Lloyd	Field expenses	5 60
14	60	J A Taff	Traveling expenses	33 32
16	61	W H Lovell	do	6 25
16	62	W. D Johnson	Field expenses	136 62
16	63	Don Hardy	Care of stock	144 00

Abstract of disbursements made by C D Davis, special disbursing agent, United States Geological Survey, etc.—Continued.

JANUARY, 1895—Continued

Date of payment		No of voucher	To whom paid	For what paid	Amount
Jan	16	64	A H Washburn	Care of stock	$35 00
	16	65	H G McCall	do	11 33
	16	66	Jasper Elliott	do	40 50
	16	67	A P Kelly	Storage	1 70
	16	68	R C. Hamilton	do	6 83
	16	69	R P Morgan	do	2 27
	16	70	J T. McGhinnis	do	3 00
	18	71	R. B Marshall	Field expenses	32 05
	18	72	do	Traveling expenses	109 25
	19	73	M Hackett	do	12 75
	19	74	do	Field expenses	305 98
	22	75	G W Bland	Services, Jan 1-4 1895	5 80
	22	76	R H Officer & Co	Assays, etc	85 25
	22	77	David A Porter	Services, Dec 1-5, 1894	8 06
	22	78	David A McNemar	Services, Jan 1-5, 1895	4 84
	22	79	J L Larabee	Hire of horse	31 00
	22	80	V L Hunter	Care of stock	23 33
	23	81	W S. Post	Traveling expenses	52 00
	26	82	Willard D Johnson	Field expenses	96 25
	26	83	W S. Post	Traveling expenses	276 83
	25	84	C M Harlan	Care of stock	60 85
	31	85	Pay roll of employees	Services, Jan, 1895	217 61
	31	86	R U Goode	Field expenses	8 00
	31	87	T Nelson Dale	Services, Jan, 1895	144 40
	31	88	Robert T Hill	do	258 30
	31	89	Pay roll of employees	do	3,659 37
	31	90	do	do	1,179 60
			Total		10,820 17

FEBRUARY, 1895

Date of payment		No of voucher	To whom paid	For what paid	Amount
Feb	2	1	J J Fairbush	Care of animals	$35 00
	2	2	W T Walker	do	50 00
	2	3	J Bixby & Co	do	44 45
	2	4	W Lindgren	Field expenses	32 00
	5	5	J H Hagerty	Care of animals, etc	83 50
	5	6	F P Johnson	do	30 00
	5	7	Ben K Emerson	Services, Jan, 1895	70 00
	5	8	Walter H Weed	Field expenses	117 51
	5	9	R H Chapman	do	20 00
	5	10	do	Traveling expenses	20 50
	5	11	W S Bayley	Services, Jan, 1895	60 00
	5	12	T E Morrow	do	66 00
	5	13	C K Leith	do	35 75
	5	14	J Morgan Clements	do	76 00
	5	15	George W Leatherman	Care of animals	43 55
	6	16	T M Alvord	do	22 66
	6	17	M P Henderson & Son	Storage	4 00
	8	18	J B Woodworth	Services Jan, 1895	50 00
	11	19	Fred Stiffler	Care of animals	16 50
	11	20	L W Estes	do	21 00
	11	21	A H Washburn	do	17 50
	11	22	Ad Freso & Co	Repairs to instruments	9 00
	11	23	C R Van Hise	Services, Jan, 1895	270 00
	12	24	Frank Leverett	do	130 00
	12	25	J C Merriam	Services, Nov 1 to Dec 31, 1894	14 00
	12	26	F C Ransome	do	20 00
	12	27	Andrew C. Lawson	do	25 00
	12	28	do	Field expenses	12 55
	12	29	William B. Clark	Services, Dec 1, 1894, to Jan 31, 1895	115 00
	12	30	Pay roll of employees	Services, Jan, 1895	59 19
	15	31	N S Shaler	do	180 00
	18	32	J B Carlisle	Storage	6 00
	18	33	V L Hunter	Care of animals	20 00
	18	34	J C Love	do	116 12
	19	35	A W Hyatt	Services	2 50
	19	36	California Warehouse Co	Storage	16 00
	20	37	N H Darton	Traveling expenses	51 58
	28	38	O A Ljungstedt	Services, Feb, 1895	108 80
	28	39	Pay roll of employees	do	3,559 40
	28	40	do	do	1,065 80
	28	41	T Nelson Dale	do	122 22
	28	42	F P Gulliver	Services, November, 1-22, 1894	55 00

Abstract of disbursements made by C D Davis, special disbursing agent, United States Geological Survey, etc.—Continued.

FEBRUARY, 1895—Continued

Date of payment	No of voucher	To whom paid	For what paid	Amount
Feb 28	43	Payot, Upham & Co	Map	$5 00
28	44	M P Henderson & Son	Storage	4 00
28	45	G D Kinnear	do	8 45
28	46	J W O Bannon	do	8 45
28	47	Henry Link	Care of animals	81 25
28	48	Fred Stiffler	do	16 50
28	49	T M Alvord	do	11 00
28	50	C F Edin	do	70 00
28	51	J J Fairbush	do	35 00
28	52	R L Rogers	do	7 14
28	53	J H Hagerty	do	83.50
28	54	V L Hunter	do	20 00
28	55	J B Woodworth	Services, Feb , 1895	50.00
28	56	J Bixby & Co	Care of animals	38.00
28	57	L W Estes	do	21 00
		Total		7,333 37

MARCH, 1895

Date of payment	No of voucher	To whom paid	For what paid	Amount
Mar 5	1	C R Van Hise	Services, Feb , 1895	$240 00
5	2	W S Bayley	do	75 00
5	3	J Morgan Clements	do	56 00
5	4	C K Leith	do	44 50
5	5	W Lindgren	Field expenses	66 10
5	6	California Warehouse Co	Storage	8 00
5	7	W T Walker	Care of animals	50 00
8	8	F P Johnson	do	30 00
11	9	A H Washburn	do	17 50
12	10	George W Leatherman	do	50 00
12	11	Frank Leverett	Services, Feb , 1895	120 00
14	12	Willard D Johnson	do	155 60
14	13	Ben K Emerson	do	60 00
18	14	N K Darton	Traveling expenses	46 62
18	15	J C Elliott	Care of animals	54 00
19	16	S F Emmons	Field expenses	25 40
19	17	F C Schrader	Services, Feb , 1895	75 00
19	18	H W Turner	Field expenses	7 05
23	19	H M Wilson	Traveling expenses	13 85
31	20	O Parker	Rent of storeroom	15 00
31	21	Mrs L C Brown	Care of stock	12 90
31	22	Weed & Rosengreen	Storage	22 50
31	23	J S Getchell	Care of stock	115 50
31	24	do	do	77 00
31	25	J B Woodworth	Traveling expenses	21 48
31	26	Louis V Pirsson	do	28 65
31	27	T Nelson Dale	Field expenses	1 49
31	28	do	Services, Mar , 1895	127 78
31	29	F E Morrow	Services, Feb , 1895	70 40
31	30	Pay roll of employees	Services, Mar , 1895	3,760 60
31	31	do	do	1,179 60
		Total		6,627 52

APRIL, 1895

Date of payment	No of voucher	To whom paid	For what paid	Amount
April 2	1	N. S Shaler	Services, Feb and Mar , 1895	$320 00
2	2	J B Woodworth	Services, Mar , 1895	50 00
2	3	Selden S Hooper	do	23 00
2	4	Mrs L C Brown	Care of stock	8 00
2	5	A G Ericsson	do	3 00
2	6	J. Bixby & Co	do	38 00
2	7	California Warehouse Co	Storage	8 00
2	8	M P Henderson & Son	do	4 00
2	9	Fred Stippler	Care of stock	16 50
2	10	L W. Estis	do	21 00
2	11	T. M Alvord	do	8 00
2	12	W T Walker	do	50 00
2	13	J J Fawbush	do	30 45
2	14	J E Elliott	do	27 00
4	15	C R Van Hise	Services, Mar , 1895	260 00

Abstract of disbursements made by C D. Davis, special disbursing agent, United States Geological Survey, etc.—Continued

APRIL, 1895—Continued

Date of payment	No of voucher	To whom paid	For what paid	Amount
April 4	16	W S Bailey	Services, Mar, 1895	$90 00
4	17	F C Schrader	do	75.00
4	18	Ben K Emerson	do	70 00
4	19	J Morgan Clements	do	52 00
4	20	F E. Morrow	do	38 40
4	21	C K Leith	do	10 75
4	22	George W Leatherman	Care of stock	50 00
4	23	F P Johnson	do	30 00
4	24	J F. Barkley	do	36 00
4	25	A H. Washburn	do	17 50
4	26	C F Edin	do	35 00
6	27	Walter H Weed	Traveling expenses	77 20
9	28	R. S. Rogers	Care of stock	8 00
9	29	J H. Hagerty	do	83 50
9	30	V L Hunter	do	20 00
9	31	Frank Leverett	Services, Mar 1–30, 1895	130 00
9	32	R A F Penrose, jr.	Services, Jan 24 to Mar 30, 1895.	570 00
9	33	N. H Darton	Traveling expenses	23 00
10	34	F C Schrader	do	1 55
10	35	do	do	5 46
13	36	A P Kelly	Storage	4 50
13	37	H. G McCall	Care of stock	30 00
13	38	R C Hamilton	do	15 00
13	39	N H Darton	Traveling expenses	8 93
16	40	R P Morgan	Storage	6 00
16	41	J T McGlinnis	do	3 00
16	42	Don Hardy	Pasturage, etc	72 00
16	43	Frederick Koch	Services, Nov 6 to Dec 31, 1894	52 00
16	44	do	Services, Jan, Feb, and Mar, 1895	90 00
16	45	do	Field expenses	4 65
16	46	do	Traveling expenses	37 55
22	47	John H Starch & Co	Boxes	8 75
22	48	Silbernagel & Dean	Pine specimen cases	22 00
23	49	W H Weed	Field expenses	48 40
23	50	C R Van Hise	do	16 97
23	51	do	Traveling expenses	32 17
23	52	T Nelson Dale	do	38 80
23	53	Don Hardy	Services	71 00
23	54	do	Pasturage	84 00
30	55	N H Darton	Traveling expenses	82 97
30	56	J E Wolff	do	28 65
30	57	Pay roll of employees	Services, Apr, 1895	3,668 35
30	58	do	do	1,129 15
30	59	A H Brooks	do	82 40
		Total		7,927 55

MAY, 1895

Date of payment	No of voucher	To whom paid	For what paid	Amount
May 1	1	W T Walker	Care of stock	$50 00
1	2	C F Edin	do	35 00
1	3	J J Weber	do	69 08
2	4	J. H Hagerty	do	83 50
1	5	C M Harlan	do	73 50
1	6	R C Hamilton	do	32 00
1	7	F P Johnson	do	20 00
1	8	J S Stone	do	31 60
3	9	T Nelson Dale	Services, Apr, 1895	142 86
2	10	William B Clark	Services, Feb 28 to Mar 31, 1895	185 00
2	11	J E Wolff	Services, April, 1895	70 00
1	12	J B. Woodruff	do	50 00
1	13	F C. Schrader	do	75 00
1	14	N S Shaler	do	210 00
1	15	Ben K Emerson	do	65 00
3	16	Bailey Willis	Traveling expenses	14 50
2	17	A H Brooks	do	16 25
1	18	W M Beaman	do	4 68
4	19	C. R Van Hise	Field expenses	9 06
4	20	do	Services, Apr, 1895	210 00
4	21	J Morgan Clements	do	98 00
4	22	F E Morrow	do	91 00
4	23	W S Bayley	do	75 00
4	24	C K Leith	do	44 25
4	25	J C Elliott	do	12 00
4	26	Frank Leverett	do	130 00

Abstract of disbursements made by C D Davis, special disbursing agent, United States Geological Survey, etc —Continued

MAY, 1895—Continued

Date of payment	No of voucher	To whom paid	For what paid	Amount
May 8	27	N H Darton	Traveling expenses	$56 20
8	28	T C Chamberlain	Services, Sept 1, 1894 to May 1, 1895	180 00
8	29	Geo W Leatherman	Care of stock	50 00
8	30	J Bixby & Co	do	38 00
8	31	L W Estes	do	21 00
8	32	T M Alvord	do	8 00
10	33	R L Rogers	do	10 00
10	34	M P Henderson & Son	Storage	4 00
10	35	California Warehouse Co	do	8 00
10	36	Baltimore and Ohio R R Co	Freight	49 70
13	37	V L Hunter	Care of stock	20 00
13	38	Mrs L C Brown	do	8 00
13	39	J C Love	do	108 00
13	40	Henry Link	do	120 00
13	41	A H Washburn	do	17 50
13	42	A H Brooks	Traveling expenses	13 35
13	43	C R Van Hise	do	76 60
13	44	T W Vaughan	do	18 05
13	45	J H Jennings	do	19 76
13	46	Frank Tweedy	do	33 30
13	47	A E Murlin	do	10 25
14	48	Arthur Keith	do	173 42
14	49	do	do	3 55
14	50	J W Thom	do	5 85
15	51	James McCormick	do	5 85
16	52	Hersey Munroo	do	26 39
17	53	M Hackett	do	10.55
18	54	R H McKee	Field expenses	110 70
18	55	H M Wilson	Traveling expenses	29 95
18	56	Albert Pike	do	9 35
18	57	C Bennett	One mule	125 00
18	58	H B Martin	Buckboard, etc	48 00
18	59	A E Murlin	Field expenses	77 12
18	60	M A Johnson	Care of stock	5 65
18	61	A H Brooks	Field expenses	15 75
18	62	Will Shay	Services	6 00
20	63	Charles E Cooke	Traveling expenses	23 15
20	64	T M. Bannon	do	20 55
20	65	W T Griswold	do	37 30
20	66	Weed & Rosengren	Storage	6 60
20	67	James Goodman	Field expenses	39 66
20	68	do	do	40 22
20	69	R Y Bandy	do	26 20
20	70	do	do	21 70
20	71	Rosette & Beaty	do	80 80
20	72	do	do	49 25
20	73	George A Brush	do	10 45
20	74	John A Webb & Bro	do	82 35
20	75	W L Wilson	Services May 8-17, 1895	19 36
20	76	Charles F Cooke	Field expenses	68 08
21	77	W T Turner & Co	Subsistence	48 77
22	78	Redick H McKee	Traveling expenses	25 15
23	79	N H Darton	do	39 30
23	80	G K Gilbert	do	24 00
23	81	do	do	54 33
23	82	M Hackett	Field expenses	36 45
23	83	Albert Pike	do	13 80
23	84	Hersey Munroo	do	70 81
27	85	William H Herron	do	39 70
27	86	do	Traveling expenses	21 50
27	87	E C Barnard	do	49 00
27	88	W J Lloyd	do	21 50
27	89	W H Otis	Field expenses	6 75
27	90	McKinney & Manning	Shoeing	27 00
27	91	C C Bassett	Traveling expenses	23 75
27	92	I M Long	Subsistence	34 80
27	93	do	Material	11 75
27	94	do	Field expenses	12 10
30	95	Redick H McKee	do	32 10
30	96	do	do	26 50
30	97	G E Hyde	Traveling expenses	77 80
30	98	Lydia H Atterbury	Board and Lodging	10 12
30	99	E M Douglas	Traveling expenses	61 50
31	100	Pay roll of employees	Services, May, 1895	223.86
31	101	do	do	182 02
31	102	do	do	70 16
31	103	W M Beaman	do	85 20

Abstract of disbursements made by C. D Davis, special disbursing agent, United States Geological Survey, etc.—Continued.

MAY, 1895—Continued

Date of payment	No of voucher	To whom paid	For what paid	Amount
May 31	104	J H Wheat	Traveling expenses	$6 75
31	105	Pay roll of employees	Services, May, 1895	213 29
31	106	do	do	189 42
31	107	do	do	262 74
31	108	do	do	183 38
31	109	do	do	219 17
31	110	do	do	109 55
31	111	T Nelson Dale	do	142 86
31	112	Pay roll of employees	do	142 29
31	113	do	do	1, 166 70
31	114	do	do	3, 236 50
31	115	do	do	151 80
31	116	do	do	232 24
31	117	do	do	169 10
31	118	do	do	210 16
31	119	Albert L Estes	do	20 65
31	120	Langley Hall	do	24 19
31	121	W T Griswold	do	170 40
31	122	Frank Tweedy	do	153 40
31	123	A H Sylvester	do	14 51
31	124	E T Perkins, jr	Traveling expenses	31 15
31	125	Mrs L C Brown	Pasturage	8 00
31	126	J Bixby & Co	do	38 00
31	127	California Warehouse Co	Storage	8 00
31	128	Ed Russell	Shoeing	30 00
31	129	M P Henderson & Son	Storage	4 00
31	130	Pay roll of employees	Services, May, 1895	165 23
31	131	do	do	206 05
31	132	do	do	185 23
31	133	do	do	71 60
31	134	Charles E Cooke	Field expenses	110 34
31	135	Redick H McKee	do	47 68
31	136	Hersey Munroe	do	43 67
31	137	W H Lovell	Traveling expenses	43 30
31	138	W S Winters	Supplies	41 45
31	139	Bradley & Goins	do	27 10
31	140	George W Leatherman	Pasturage	27 01
31	141	Pay roll of employees	Services, May, 1895	30 49
31	142	J B Woodworth	do	50 00
31	143	T C Chamberlin	Traveling expenses	66 80
31	144	do	do	124 45
		Total		13, 664 16

JUNE, 1895

June 3	1	Pay roll of employees	Services, May, 1895	$37 25
3	2	Humphris & Co	Pasturage	40 33
3	3	H Felitz	Field material	31 15
3	4	R B Marshall	Traveling expenses	33 75
3	5	Isaac I Lewis	Subsistence	107 70
3	6	J H Wheat	Field expenses	35 00
3	7	do	Traveling expenses	4 97
3	8	W L Miller	do	6 75
3	9	Nat G. Van Doren	do	13 60
3	10	Joseph A Taff	Field expenses	12 07
3	11	M R Campbell	Traveling expenses	6 05
3	12	N. S Shaler	Services, May, 1895	200 00
5	13	C R Van Hise	do	220 00
5	14	J Morgan Clements	do	104 00
5	15	T E Morrow	do	67 20
5	16	C K Leith	do	46 87
5	17	Oscar Rohn	do	25 00
5	18	Frank Leverett	do	135 00
5	19	F C. Schrader	do	75 00
5	20	do	Traveling expenses	8 21
5	21	T. Wayland Vaughan	Field expenses	27 85
5	22	W C Mendenhall	do	33 15
6	23	George O. Glavis, jr	Traveling expenses	25 50
6	24	Duncan Hannegan	do	24 50
6	25	Louis F Garrard, jr	do	24 25
6	26	W S Post	do	63 20
6	27	H. S Wallace	do	26 00
6	28	Van Vorhis & McNair	Material	32 30
6	29	F. E Jandt	1 horse	65 00

Abstract of disbursements made by C. D Davis, special disbursing agent, United States Geological Survey, etc —Continued

JUNE, 1895—Continued

Date of payment	No of voucher	To whom paid	For what paid	Amount
June 6	30	T, H Gorton	Subsistence	$30 23
6	31	W B Rogers	Boarding, etc	15 60
6	32	Baker & Hamilton	Road carts	50 00
6	33	J H Jennings	Traveling expenses	140 97
6	34	Robert Muldrow	do	26 20
6	35	E B Clark	do	62 15
6	36	W L Miller	Field expenses	28 25
6	37	W J Houston, jr	Services, May 27-31, 1895	8 06
6	38	C D White	Traveling expenses	34 25
6	39	M R Campbell	Field expenses	109 06
6	40	Ben K Emerson	Services, May, 1895	60 00
7	41	J B Woodworth	Field expenses	8 80
7	42	do	Traveling expenses	6 19
7	43	M Hackett	Field expenses	127 10
7	44	Charles E Cooke	do	89 14
7	45	A E Murlin	do	44 08
7	46	R H McKee	do	47 06
7	47	Fred Stiffler	Pasturage, etc	32 50
8	48	Frank Tweedy	Field expenses	147 07
7	49	G E Hyde	do	99 40
7	50	do	Traveling expenses	8 45
7	51	E T Perkins, jr	Field expenses	73 00
7	52	T M Bannon	do	126 46
7	53	H M Waterbury	Hire of team	23 75
7	54	Overpeck Bros	Shoeing etc	29 00
7	55	F C Schrader	Field expenses	26 57
7	56	do	do	11 20
7	57	do	Traveling expenses	9 11
8	58	H B Blair	do	26 00
8	59	do	do	85 12
8	60	J S Getchell	Pasturage, etc	38 50
8	61	do	do	22 75
8	62	C F Edin	do	60 00
8	63	J C Johnson & Co	Supplies	35 65
8	64	W G Rowland	Subsistence	51 49
8	65	W M Beaman	Traveling expenses	21 45
8	66	C D White	Field expenses	6.01
8	67	W M Beaman	do	163 03
8	68	W H Lovell	do	19 50
8	69	William H Herron	do	61 45
8	70	do	do	15 70
8	71	do	do	45 95
8	72	J. C Elliott	Pasturage	3 10
10	73	A H Brooks	Field expenses	24 30
10	74	do	Services May, 1895	85 20
10	75	W S Bayley	do	60 00
10	76	F Leslie Ransome	do	30 00
10	77	John C Merriam	do	44 00
10	78	Andrew C Lawson	do	60 00
10	79	do	Field expenses	15 20
10	80	Robert D Cummin	Traveling expenses	9 99
10	81	do	Field expenses	140 20
10	82	J H Wheat	Traveling expenses	6 50
10	83	A B Searle	do	36 80
10	84	R C McKinney	do	18 50
10	85	Nat Tyler, jr	do	39 15
10	86	William H Herron	Field expenses	65 20
10	87	do	do	41 80
10	88	O J King	Subsistence	49 30
10	89	C W Parks	do	26 65
10	90	E C Barnard	Field expenses	106 40
10	91	J W Thom	do	30 50
10	92	do	do	28 75
10	93	do	do	85 03
10	94	Frank Sutton	do	103 62
10	95	do	Traveling expenses	10 40
10	96	R H Chapman	do	106 68
10	97	W T Griswold	Field expenses	98 47
10	98	C C Bassett	do	201 03
11	99	E M Douglas	Traveling expenses	17 70
12	100	James McCormick	Field expenses	82 49
12	101	do	do	24 50
12	102	N B Dunn	Pasturage	175 50
13	103	Walter H Weed	Traveling expenses	36 55
14	104	A H Brooks	do	23 20
14	105	Joseph E Macfarland	do	10 00
14	106	R E Dodge	do	28 30
14	107	C W. Hayes	do	31.55

Abstract of disbursements made by C. D. Davis, special disbursing agent, United States Geological Survey, etc.—Continued.

JUNE, 1895—Continued

Date of payment	No of voucher	To whom paid.	For what paid	Amount
June 14	108	N Paige jr.	Traveling expenses	$14 35
14	109	do	do	4 35
18	110	H W Turner.	do	45 25
18	111	Charles E Peet	Services, May, 1895	60 00
20	112	Goldberg, Bowen & Lebenbaum.	Subsistence	15 85
20	113	J A Bishop	Hire of team	12 00
20	114	James Goodman	Supplies	27 92
21	115	R A. F Penrose, jr	Services, Apr, 1895	190 00
21	116	F C Schrader	Field expenses	44 49
21	117	do	Traveling expenses	15 14
21	118	Robert T. Hill	do	19 60
21	119	J E Wolff	do	13 80
21	120	do	do	18 00
22	121	A H Brooks	Field expenses	17 25
22	122	W J Elliott	Mules	200 00
24	123	T Wayland Vaughan	Field expenses	16 00
24	124	C W Hayes	do	151 56
24	125	Rosette & Beaty	Repairs	9 90
24	126	R Y Bandy	Harness	27 25
30	127	E M Douglas	Services, June, 1895	164 80
30	128	R W Goode	do	206.00
30	129	Pay roll of employees	do	404 65
30	130	H W Turner	do	148 30
30	131	G H Storrs.	do	41.66
30	132	Carl Rabe	do	28 00
24	133	B C Heald, jr	Services, May, 1895	18.00
24	134	do	Traveling expenses	9 75
24	135	T Nelson Dale	do	38 80
24	136	W T McConnell & Son	Subsistence	39 53
24	137	J T Barkley	Pasturage	12 00
30	138	T Nelson Dale	Services, June, 1895	148 35
30	139	F L Ransome	do	75 00
30	140	Pay roll of employees	do	332 80
30	141	A H Brooks	Traveling expenses	11 90
30	142	Pay roll of employees	Services, June, 1895	248 40
30	143	J S Diller	Field expenses	10 10
30	144	do	do	148 75
30	145	Pay roll of employees	Services, June, 1895	306 09
30	146	do	do	1,854 30
30	147	do	do	1,129 15
30	148	do	do	208 10
30	149	Paul Holman.	Traveling expenses	17 15
30	150	Charles E Cooke	do	20 80
30	151	do	Field expenses	87 87
30	152	Pay roll of employees	Services, June, 1895	100 50
30	153	do	do	271 30
		Total		12,599 22

Amount expended as per abstracts	$435,777 19
Bonded railroad accounts settled at United States Treasury	2,413 32
Total expenditures	438,190 51

DEPARTMENT OF THE INTERIOR, UNITED STATES GEOLOGICAL SURVEY.

PAPERS ACCOMPANYING THE ANNUAL REPORT

OF THE

DIRECTOR OF THE U. S. GEOLOGICAL SURVEY

FOR THE

FISCAL YEAR ENDING JUNE 30, 1895.

THE DINOSAURS OF NORTH AMERICA.

BY

OTHNIEL CHARLES MARSH.

CONTENTS.

Part II.—Jurassic dinosaurs—Continued.

Page

- Sauropoda—Continued.
  - Atlantosauridæ—Continued.

Part IV.—Conclusion—Continued.

ILLUSTRATIONS

THE DINOSAURS OF NORTH AMERICA.

By O. C. Marsh.

INTRODUCTION.

Among the many extinct animals that lived in this country in past ages, none were more remarkable than the dinosaurian reptiles which were so abundant during Mesozoic time. This group was then represented by many and various forms, including among them the largest land animals known, and some, also, very diminutive. In shape and structure, moreover, they showed great variety, and in many other respects they were among the most wonderful creatures yet discovered.

The true place of these reptiles in the animal kingdom has been a matter of much discussion among anatomists, but the best authorities now regard them as constituting a distinct subclass of the Reptilia. Some of the large, earlier forms are apparently related to the Crocodilia, while some of the later, small, specialized ones have various points of resemblance to birds. These diversified characters make it difficult to classify the dinosaurs among themselves, and have led some writers to assert that these reptiles do not form a natural group, but belong to divisions remotely connected and not derived from a common ancestry.

It is not within the province of the present article to discuss in detail the classification of this group, nor to treat fully the various questions relating to the genealogy of dinosaurs, about which little is really known. It may, however, be stated in few words that three great divisions of the Dinosauria are now generally recognized, which may be properly regarded as distinct orders. For these groups the writer has proposed the names *Theropoda*, for the one including the carnivorous forms, and *Sauropoda* and *Predentata*, for the two herbivorous groups, the last order being made up of three separate suborders; namely, the Stegosauria, the Ceratopsia, and the typical Ornithopoda. The first of these suborders contains large dinosaurs more or less protected by a dermal covering of bony plates; the second group includes the huge horned dinosaurs; and the third is made up of the forms that in shape and structure most nearly resemble birds.

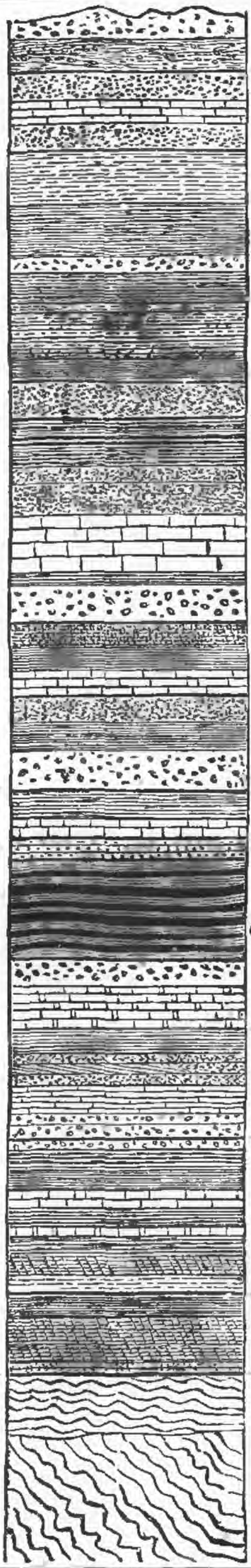
The nearer relations of these groups to one another and to allied forms will be treated more fully in the concluding portion of this article.

The geological range of the Dinosauria, so far as at present known, is confined entirely to the Mesozoic, or the Age of Reptiles. The first indications of the group are found in the lower Triassic, and during this period these reptiles increased in number and size. In Jurassic time they were especially abundant, and in size and diversity of form far surpassed all other forms of vertebrate life then existing. During the entire Cretaceous they were represented by many strange and highly specialized types, and at the close of this period all apparently became extinct.

The wide geographical extent of these reptiles is also of interest. While North America seems to have contained the greatest number of different types, some of the larger species are now known to have lived in the southern half of this continent. Europe stands next to America in variety and number of these reptiles, large and small. In Asia, Africa, and Australia, also, characteristic remains have been discovered, and doubtless many more will be found at no distant day. The geological horizons in which the dinosaurian remains of the Old World occur are essentially the same as those in which the corresponding types have been found in America.

The introduction and succession of the Dinosauria in North America form a most interesting chapter in the life-history of this continent, and one that has an important bearing on geology as well. As these reptiles were the dominant types of land animals during the whole of Mesozoic time, and the circumstances under which they lived were especially favorable to the preservation of their remains, the latter mark definite geological horizons, which have proved of great service in ascertaining the age of large series of strata containing few other characteristic fossils. In this way one important horizon in the Jurassic and another in the Cretaceous have been accurately determined by the remains of the gigantic dinosaurs entombed in them, while still other lines have been approximately drawn by less characteristic fossils from the same group of reptiles.

In describing briefly the various dinosaurs now known to have lived in North America, it will be most instructive to begin with the oldest, in the Triassic, and then treat of their successors as they left their remains in subsequent deposits of Jurassic and Cretaceous age. To make this succession clear to the reader, the diagram on page 145 (fig. 1) has been prepared. This diagram represents the principal geological horizons of vertebrate fossils in North America, as determined by the writer, and if carefully examined will be found in reality to be a synopsis of the whole subject. The first appearance, so far as known, of each important group of vertebrate animals may be ascertained, approximately, from the data given. Some of the more recent genera of each group are also recorded, with the period in which they lived.



CENOZOIC.	Recent. Quaternary.			Tapir, Peccary, Bison. *Bos, Equus, Tapirus, Dicotyles, Megatherium, Mylodon.*
	Tertiary.	Pliocene.	Equus Beds. Pliohippus Beds.	*Equus, Tapirus, Elephas.* *Pliohippus, Tapiravus, Mastodon, Procamelus.* *Aceratherium, Bos, Morotherium, Platygonus.*
		Miocene.	Miohippus Beds. Oreodon Beds. Brontotherium Beds	*Miohippus, Diceratherium, Thinohyus, Protoceras.* *Oreodon, Eporeodon, Hyænodon, Moropus, Ictops.* *Hyracodon, Agriochœrus, Colodon, Leptochœrus.* *Brontotherium, Brontops, Allops, Titanops, Titanotherium, Mesohippus, Ancodus, Entelodon.*
		Eocene.	Diplacodon Beds. Dinoceras Beds. Heliobatis Beds. Coryphodon Beds.	*Diplacodon, Epihippus, Amynodon, Eomeryx.* *Dinoceras, Tinoceras, Uintatherium, Palæosyops, Orohippus, Hyrachyus, Colonoceras, Homacodon.* *Heliobatis, Amia, Lepidosteus, Asineops, Clupea.* *Coryphodon, Eohippus, Eohyus, Hyracops. Parahyus.* Lemurs, Ungulates, Tillodonts, Rodents, Serpents.
MESOZOIC.	Cretaceous.		Ceratops Beds of Laramie Series.	*Ceratops, Triceratops, Claosaurus, Ornithomimus,* Mammals, *Cimolomys, Dipriodon, Selenacodon, Nanomyops, Stagodon.* Birds, *Cimolopteryx.*
			Fox Hills Group	
			Colorado Series, or Pteranodon Beds.	Birds with Teeth, *Hesperornis, Ichthyornis, Apatornis.* Mosasaurs, *Edestosaurus, Lestosaurus, Tylosaurus.* Pterodactyls, *Pteranodon.* Plesiosaurs, Turtles.
			Dakota Group.	
	Jurassic.		Atlantosaurus Beds. Baptanodon Beds. Hallopus Beds.	Dinosaurs, *Brontosaurus, Morosaurus. Diplodocus, Stegosaurus, Camptosaurus, Ceratosaurus.* Mammals, *Dryolestes, Stylacodon, Tinodon, Ctenacodon.*
	Triassic.		Otozoum, or Conn. River, Beds.	First Mammals, *Dromatherium.* First Dinosaurs, *Anchisaurus, Ammosaurus, Bathygnathus, Clepsysaurus.* Many footprints. Crocodiles, *Belodon.* Fishes, *Catopterus, Ischypterus, Ptycholepis.*
PALEOZOIC.	Permian.		Nothodon Beds.	Reptiles, *Nothodon, Eryops, Sphenacodon.*
	Carboniferous		Coal Measures, or Eosaurus Beds.	First Reptiles (?) *Eosaurus.* Amphibians, *Baphetes, Dendrerpeton, Hylonomus, Pelion.* Footprints, *Anthracopus, Allopus, Baropus, Dromopus, Hylopus, Limnopus, Nasopus.*
			Subcarboniferous, or Sauropus Beds.	First known Amphibians (Labyrinthodonts). Footprints, *Sauropus, Thenaropus.*
	Devonian.		Dinichthys Beds. Lower Devonian.	*Dinichthys, Acanthodes, Bothriolepis, Chirolepis, Cladodus, Dipterus, Titanichthys.*
	Silurian.		Upper Silurian. Lower Silurian.	First known Fishes.
	Cambrian.		Primordial.	No Vertebrates known.
	Archæan.		Huronian. Laurentian.	

FIG. 1.—GEOLOGICAL HORIZONS OF VERTEBRATE FOSSILS IN NORTH AMERICA.

PART I.

TRIASSIC DINOSAURS.

THEROPODA.

The remains of dinosaurs first discovered in this country were found in the Triassic sandstone of the Connecticut Valley, so famous for its fossil footprints, many of which were long supposed to have been made by birds. It is a remarkable fact that the first discovery in this sandstone was that of the skeleton of a true dinosaur, found in East Windsor, Conn., in 1818, many years before the first footprints were recorded. This discovery was announced in the American Journal of Science for November, 1820, and later numbers contain descriptions of the remains, some of which are now preserved in the museum of Yale University.

FIG. 2.—Slab of Connecticut River sandstone; showing footprints of two dinosaurs on a surface marked by raindrop impressions. One-tenth natural size. Triassic, Massachusetts.

When the footprints in the Connecticut sandstone first attracted attention, in 1835, many of these impressions resembled so closely those made by birds that they were from the first attributed to that class, and for many years it was not seriously questioned that all the three-toed impressions, even the most gigantic, were really the footprints of birds. The literature on this subject is very extensive, but its value to science has been seriously impaired by the discovery of dinosaurian remains in various parts of the world, which prove that many of these reptiles were remarkably bird-like and that their tracks could not be distinguished from those of birds.

It was also found that some of the most bird-like footprints of the Connecticut Valley were not made by birds, but by quadrupeds which usually walked on their hind feet, yet sometimes put their fore feet to the ground. Others occasionally sat down, and left an impression which proved that they, too, were not birds. Still others showed reptilian affinities in various ways; so that to day it may be stated that there is no evidence that any of these impressions in the Connecticut sandstone were made by birds. This is true, also, of similar bird-like footprints from strata of the same age in different portions of this country, and will likewise hold good for similar impressions from other parts of the world. It is quite probable that birds existed during the Triassic period, but at present there is no proof of it.

ANCHISAURIDÆ

A few bones of a dinosaur were found at Upper Milford, Lehigh County, Pa., in 1847, in strata regarded as Triassic. The animal was named *Clepsysaurus pennsylvanicus* by Dr. Isaac Lea, in the Proceedings of the Academy of Natural Sciences of Philadelphia, in 1851, and he subsequently described and figured the remains in the Journal of the Academy in 1853. They are now preserved in the museum of that society.

The next discovery of importance in this formation was reported from Prince Edward Island, Canada. The specimen was an upper jaw with teeth, in good preservation, indicating a true dinosaur of considerable size. This specimen was figured and described under the name *Bathygnathus borealis* by Dr. Leidy in the Journal of the Academy of Natural Sciences of Philadelphia for 1854, and is now in the museum of that institution.

The next important discovery of a Triassic dinosaur in this country was made in the Connecticut sandstone about 1856, at Springfield, Mass., and portions of the skeleton are now preserved at Amherst College. This animal was a true carnivorous dinosaur, very similar to the first one described, and from essentially the same horizon. This discovery was announced by Prof. Edward Hitchcock in 1858, in his Ichnology of New England, and the remains were described and figured by Edward Hitchcock, jr., in 1865, in a supplement to the above volume. The animal was then named *Megadactylus polyzelus*, and its affinities have since been discussed by various authors.

ANCHISAURUS.

A discovery of greater interest was made in 1884, near Manchester, Conn. The skeleton of another carnivorous dinosaur of larger size, but nearly allied to the one last mentioned, was found in a coarse conglomerate, in essentially the same horizon of the Connecticut River sandstone. This skeleton was probably complete and in position when discovered, but as its importance was not recognized at the time the posterior portion only was saved, which was secured later by the writer for the Yale University museum. This part consisted of the nearly entire pelvic arch, with both hind limbs essentially complete and in the position they were when the animal died. The remains preserved indicate an animal about 6 or 8 feet in length, which was named *Anchisaurus major* by the writer, in the American Journal of Science for April, 1889.[1] This generic title replaced Megadactylus, which was preoccupied. Subsequently, in 1891, this specimen was made the type of the genus Ammosaurus.

A still more important discovery of another small dinosaur was made later at the same locality, only a few feet distant from the spot where the fossil last mentioned was entombed. This reptile, named *Anchisaurus colurus* by the writer, is one of the most perfect dinosaurs yet discovered in the Triassic. The skull and limbs and most of the skeleton were in fair preservation, and in natural position, so that nearly all the important points of the osseous structure can be determined with certainty. Some of these are here placed on record as typical of the group.

THE SKULL

The skull was somewhat crushed and distorted, but its main features are preserved. In Pl. II, fig. 1, a side view of this skull is given, one-half natural size. One prominent feature shown in this view is the bird-like character of the skull. The nasal aperture is small and well forward. There is an antorbital opening and a very large orbit. The latter is elongated-oval in outline. It is bounded in front by the prefrontal, above by the same bone and a small extent of the frontal, and further back by the postfrontal. The postorbital completes the orbit behind and the jugal closes it below. The supratemporal fossa is large and somewhat triangular in outline. The infratemporal fossa is quite large and is bounded below by a slender quadratojugal. The quadrate is much inclined forward. The teeth are remarkable for the great number in use at one time. Those of the upper jaw are inclined forward, while those below are nearly vertical. The lower jaw has the same general features as this part in the typical Theropoda.

In Pl. III, figs. 1 and 2, the same skull is shown, also one-half natural size. The top of the skull, represented in fig. 1, is considerably broken, and this has made it difficult to trace the sutures, but the general form and proportions of the upper surface are fairly represented. In fig. 2 only the back portion of the cranium is shown. The foramen magnum is remarkably large, and the occipital condyle is small and oblique. The basipterygoid processes are unusually short.

The neck vertebræ of this skeleton are long and slender and very hollow. Their articular ends appear to be all plane or slightly concave. The trunk vertebræ are more robust, but their centra are quite long. The sacrals appear to be three in number.

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[1] The original descriptions of nearly all the other fossils discussed in the present paper may be found in the same journal

THE FORE LIMBS

The scapular arch is well preserved. The scapula, shown in Pl. II, fig, 2, *s*, is very long, with its upper end obliquely truncated. The coracoid is unusually small and imperforate. The sternum was of cartilage, some of which is preserved. The humerus is of the same length as the scapula and its shaft is very hollow. The radius and ulna also are both hollow, and are nearly equal in size.

There is but one carpal bone ossified in this specimen, and this is below the ulna. There were five digits in the manus, but only three of functional importance, the first, second, and third, all armed with sharp claws. The fifth was quite rudimentary. The fore foot of the type species of Anchisaurus is shown, one-half natural size, on Pl. III, fig. 5.

THE HIND LIMBS

The pelvic bones are shown in fig. 3 of Pl. II. The ilium is small, with a slender preacetabular process. The ischia are elongated, and their distal ends are slender and not expanded at the extremity. The pubes are also long, imperforate, and not coossified with each other. The anterior part is a plate of moderate width.

The femur is much curved and longer than the tibia. The latter is nearly straight, with a narrow shaft. The fibula when in position was not close to the tibia, but curved outward from it. All these bones have very thin walls. The astragalus is small, closely applied to the tibia, and has no ascending process. The calcaneum is of moderate size and free. There are only two tarsal bones in the second row.

The hind foot had four functional digits, all provided with claws. The fifth was represented only by a rudiment of the metatarsal. The first digit was so much shorter than either the second, third, or fourth, that this foot would have made a three-toed track very much like the supposed bird-tracks of the Connecticut River sandstone.

ANCHISAURUS SOLUS.

A fortunate discovery has recently brought to light almost the entire skeleton of still another diminutive dinosaur, which may be referred to Anchisaurus, but clearly belongs to a distinct species. It was found in nearly the same horizon as the remains above described, and in the immediate vicinity, so there can be little doubt that it was a contemporary. The skeleton is embedded in a very coarse matrix, so difficult to remove that the investigation is only in part completed. The portions uncovered show the animal to have been about 3 feet in length, and of very delicate proportions The bones of the skeleton are nearly all extremely light and hollow, but most of them are in a fair state of preservation.

The skull, so far as it can now be observed, resembles the one just described. The teeth are numerous, and inclined forward. The orbit is very large. The quadrate is inclined forward, and the lower jaw is robust. The entire skull is about 65^{mm} long, and the lower jaws are of the same length.

The neck was very long and slender, the first five cervicals measuring 80^{mm} in extent. The dorsals are also elongated, the last six covering a space of 135^{mm}. The number of vertebræ in the sacrum can not yet be determined. The caudal vertebræ are short, the first ten occupying a space of 140^{mm}.

The humerus has a very large radial crest, and is 66^{mm} in length. The rest of the fore limb, so far as made ont, is similar to that in the species described. The tibia is about 88^{mm} in length. There were five digits in the hind foot, but the fifth is represented only by the rudimentary metatarsal. The animal was about as large as a small fox.

AMMOSAURUS.

The genus Ammosaurus, represented by remains of larger size from the same strata, was also a typical carnivorous dinosaur, and apparently a near ally of Anchisaurus. So far as at present known, the footprints of the two reptiles would be very similar, differing mainly in size.

On Pl. III, fig. 6, is shown an entire hind foot of Ammosaurus, one-fourth natural size. In this foot the tarsus is more complete than in Anchisaurus. The astragalus has no true ascending process, the calcaneum is closely applied to the end of the fibula, and there are three well-developed bones in the second row. The fifth digit had only a single phalanx. The sacrum and ilia of the type species of Ammosaurus are shown in fig. 3, and the ischia of Anchisaurus in fig. 4.

RESTORATION OF ANCHISAURUS.

PLATE IV.

The Triassic dinosaurs known from eastern North America have now been briefly reviewed. Remains of seven individuals are sufficiently well preserved to indicate the main characters of the animals to which they pertained. These were all carnivorous forms of moderate size, and the known remains are from essentially the same geological horizon.

The genus Anchisaurus, one of the oldest known members of the Theropoda, is so well represented by parts of fonr skeletons from these deposits that a restoration of one species can now be made with considerable certainty. This has been attempted, and the result is given, one-twelfth natural size, in the accompanying Pl. IV. The animal was about 6 feet in length.

The skeleton chosen for this restoration is the type specimen of *Anchisaurus colurus*, described by the writer in the American Journal of Science in 1891 and 1893. This skeleton when discovered was entire, and apparently in the position in which the animal died. Portions of the neck and the tail vertebræ were unfortunately lost, but the skull and nearly all the rest of the skeleton were saved. The parts missing are fortunately preserved in a smaller specimen of an allied species (*Anchisaurus solus*) found at the same locality, and these have been used to complete the outline of the restoration. Portions of two other specimens, nearly allied, and from the same horizon, were also available, and furnished some suggestions of value.

The restoration, as shown on Pl. IV, indicates that *Anchisaurus colurus* was one of the most slender and delicate dinosaurs yet discovered, being surpassed in this respect only by some of the smaller bird-like forms of the Jurassic. The position chosen is one that must have been habitually assumed by the animal during life, but the comparatively large fore limbs suggest the possibility of locomotion on all four feet. The compressed terminal digits of the fore feet, however, must have been covered by very sharp claws, which were used mainly for prehension, and not for walking.

The small head and bird-like neck are especially noticeable. The ribs of the neck and trunk are very slender. The tail apparently differed from that of any other dinosaur hitherto described, as it was evidently quite slender and flexible. The short neural spines and the diminutive chevrons, directed backward, indicate a tail not compressed, but nearly round, and one usually carried free from the ground.

DINOSAURIAN FOOTPRINTS

The present restoration will tend to clear up one point long in doubt. The so-called "bird tracks" of the Connecticut River sandstone have been a fruitful subject of discussion for half a century or more. That some of these were not made by birds has already been demonstrated by finding with them the impressions of fore feet. Although no bones were found near them, others have been regarded as footprints of birds because it was supposed that birds alone could make such series of bipedal, three-toed tracks and leave no impression of a tail.

It is now evident, however, that a dinosaurian reptile like Anchisaurus and its near allies must have made footprints very similar to, if not identical with, the "bird tracks" of this horizon. On a firm but moist beach only three-toed impressions would have been left by the hind feet, and the tail could have been kept free from the ground. On a soft, muddy shore the claw of the first digit of the hind foot would have left its mark, and perhaps the tail also would have touched the ground. Such additional impressions the writer has observed in various series of typical "bird tracks" in the Connecticut sandstone, and all of them were probably made by dinosaurian reptiles. On Pl. V and also p. 146, fig. 2, are shown several series of Triassic footprints, which were probably all made by dinosaurs. No tracks of true birds are known in this horizon.

DISTRIBUTION OF TRIASSIC DINOSAURS

It is a remarkable fact that the seven skeletons of Triassic dinosaurs now known from the eastern part of this continent are all carnivorous forms and of moderate size. There is abundant evidence from footprints that large herbivorous dinosaurs lived here at the same time, but no bones nor teeth have yet been found. In the western part of this country a few fragments of a large dinosaur have been discovered in strata of supposed Triassic age, but with this possible exception osseous remains of these forms appear to be wanting in this horizon.

Fragmentary remains, also, of dinosaurs have been found in the Triassic deposits of Pennsylvania and North Carolina, but they throw little light on the animals they represent. Footprints, apparently made by dinosaurs, occur in New Jersey in the same horizon as those of the Connecticut Valley. Impressions of similar form have been discovered also in the Triassic sandstones of New Mexico. A few bones of a large dinosaurian were found by Prof. J. S. Newberry, in strata apparently of this age, in southeastern Utah. These remains were named by Professor Cope, *Dystrophæus viæmalæ*, in 1877, but their near affinities have not been determined. A single vertebra, apparently belonging to this group, had been previously found at Bathurst Island, Arctic America, and described by Prof. Leith Adams, in 1875, under the generic name Arctosaurus.

The European Triassic dinosaurs, with which the American forms may be compared, are mainly represented by the two genera Thecodontosaurus Riley and Stutchbury, from the upper Trias, or Rhætic, near Bristol, in England, and Plateosaurus (Zanclodon) von Meyer, from nearly the same horizon in Germany. The writer has investigated with care the type specimens and nearly all the other known remains of these genera found at these localities.

Remains of dinosaurs have been found in Triassic strata, also, in India, in South Africa, and in Australia, but the specimens discovered were mostly fragmentary, and apparently indicate no new types.

PART II.

JURASSIC DINOSAURS.

During the Jurassic period the dinosaurs of North America attained remarkable development, and, as a group, appear to have reached their culmination. The Theropoda, or carnivorous forms, which were so abundant, though of moderate size, in the Triassic, were represented in the Jurassic by many and various forms; some were very minute, but others were of gigantic size and dominated all living creatures during this age. The herbivorous dinosaurs, however, were the most remarkable of all, some far surpassing in bulk any known land animals; others, also of huge dimensions and clad in coats of mail, assumed the most bizarre appearance; while others still, diminutive in size and of light and graceful form, were so much like birds that only a comparative anatomist, with well-preserved skeletons of both before him, could tell one from the other. In this case, at least, a single tooth or bone would not suffice, though a Cuvier sat in judgment.

In the western part of this country, especially in the Rocky Mountain region, vast numbers of dinosaurs lived and flourished during all Jurassic time. Their remains are so abundant, and so perfectly preserved in many localities, that those already obtained have furnished the basis for a classification of the whole group. This classification, first proposed by the writer in the American Journal of Science in 1881, and subsequently emended, may be appropriately used here in considering the American dinosaurs from this formation. It will be discussed more fully in the concluding part of the present paper.

THEROPODA

Near the base of the Jurassic in the Rocky Mountain region an interesting geological horizon has been defined as the Hallopus beds, since here only remains of a remarkable dinosaurian, named by the writer *Hallopus victor*, have been found. The position of this horizon is shown in the diagram on page 145 (fig. 1). Another reptile, Nanosaurus, the most diminutive dinosaur known, occurs in the same strata. This horizon is believed to be lower than that of the Baptanodon beds, although the two have not been found together. The Hallopus beds now recognized are in Colorado, below the Atlantosaurus beds, but are apparently quite distinct from them.

HALLOPUS.

The type specimen of Hallopus, the only one known, is the greater part of the skeleton of an animal about the size of a rabbit. This was described by the writer in 1877, and referred to the Dinosauria. On further investigation it was found to be distinct from all the known members of that group, and in 1881 it was made the type of a new suborder, the Hallopoda. One of the most distinctive characters, which separated it widely from all known dinosaurs, was seen in the tarsus, which had the calcaneum much produced backward. This feature, in connection with the greatly elongated metatarsals, suggested the generic name Hallopus, or leaping foot.

The general structure of the pelvis, especially of the ilium and pubis, as well as the proportions of the entire hind limb, suggested an affinity with Compsognathus, from the Jurassic of Bavaria, and the writer, in his classification of the dinosaurs, in 1882, placed the Hallopoda next to the suborder Compsognatha, which belongs in the great group of carnivorous dinosaurs, the Theropoda.

The writer has since reexamined the type specimen and had various parts of it uncovered, so far as the hard matrix of red sandstone would permit. This has brought to light other portions of the skeleton, so that now many of the more important characters of the group can be determined with certainty.

FORE AND HIND LIMBS

In its present condition the specimen shows both the fore and hind limbs in good preservation, portions of the scapular arch, and apparently the entire pelvis and sacrum, various vertebræ, ribs, and other parts of the skeleton. It is doubtful if any portions of the skull are sufficiently well preserved for determination. On Pl. VI are given outline restorations of the fore and hind limbs of this specimen.

The scapula is of moderate length, and its upper portion broad and thin. The humerus is slender, with a strong radial crest. The shaft is very hollow, with thin walls, and the cavity extends almost to the distal end. The latter is but little expanded transversely. The radius and ulna are short, and were closely applied to each other. There were but four digits in the manus, the first being short and stout, and the others slender.

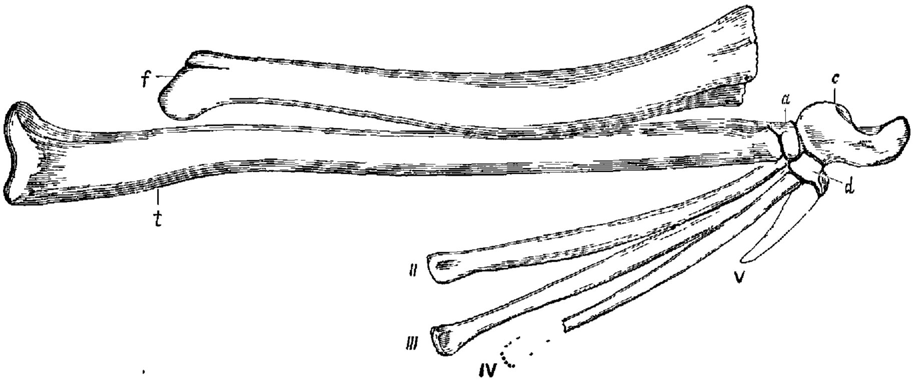

FIG 3—Left leg and foot of *Hallopus victor* Marsh, side view Natural size

a, astragalus, *c*, calcaneum, *d*, tarsal, *f*, femur, *t*, tibia, *II*, second metatarsal, *V*, remnant of fifth metatarsal

All three pelvic bones aided in forming the acetabulum, as in typical dinosaurs. The ilia are of the carnivorous type, and resemble in form those of Megalosaurus. The pubes are rod-like, and projected downward and forward. The distal ends are closely applied to each other, but not materially expanded, and in the present specimen are not coossified with each other. The ischia projected downward and backward, and their distal extremities are expanded, somewhat as in the Crocodilia.

The femur is comparatively short, with the shaft curved and very hollow. The tibia is nearly straight, much longer than the femur, and its shaft equally hollow. The fibula was slender and complete, but tapered much from above downward. Its position was not in front of the tibia, as in all known dinosaurs, but its lower extremity was outside, and apparently somewhat behind, the tibia.

The astragalus is large, and covered the entire end of the tibia, but was not coossified with it. The calcaneum is compressed transversely, and much produced backward. It was closely applied to the outside of the astragalus, and although agreeing in general form with that of a crocodile, strongly resembles the corresponding bone in some mammals. The tarsal joint was below the astragalus and calcaneum. There appears to be but a single bone in the second tarsal row, although this may be composed of two or more elements.

There were but three functional digits in the hind foot, and their metatarsals are greatly elongated. The first digit seems to be wanting, and the fifth is represented only by a remnant of the metatarsal. The posterior limbs, as a whole, were especially adapted for leaping, and are more slender than in almost any other known reptile.

The main characters of the posterior limb are shown in fig. 3, on the opposite page, which represents the bones of the left leg and foot, natural size, in the position in which they lay when uncovered. All the bones figured are still firmly embedded in the matrix.

There are but two vertebræ in the sacrum. The other vertebræ preserved have their articular faces biconcave. The chevrons are slender and very elongate.

Taken together, the known characters of Hallopus clearly indicate dinosaurian affinities rather than those of any other group of reptiles, and if the Dinosauria are considered a subclass the Hallopoda at present may be regarded as a group of dinosaurs standing further apart from typical forms than any other.

CŒLURUS.

In the horizon above, the Atlantosaurus beds of the upper Jurassic, the carnivorous dinosaurs are of larger size, and some of them were among the most powerful and ferocious reptiles known. The one nearest Hallopus in size and general characteristics is Cœlurus, described by the writer in 1879 and now known from several skeletons, although no good skull has yet been discovered.

The skull of Cœlurus is known only from fragments. The teeth are typical of the order Theropoda. One is shown on Pl. VII, fig. 1. The most marked feature in all the known remains of Cœlurus is the extreme lightness of the bones, the excavations in them being more extensive than in the skeleton of any other known vertebrate. In the vertebræ, for example, the cavities are proportionately larger than in either pterodactyls or birds, the amount of osseous tissue retained being mainly confined to their exterior walls. In Pl. VII cervical, dorsal, and caudal vertebræ are figured, with transverse sections of each to illustrate this point. Even the ribs of Cœlurus are hollow, with well-defined walls to their large cavities.

THE VERTEBRÆ

The vertebræ of Cœlurus now known are from various parts of the column, and most of them are in good condition. Three of these are represented, natural size, in Pl. VII. The cervicals are large and elon gate, and were locked together by strong zygapophyses. The first three or four behind the axis had the front articular face of the centrum somewhat convex, and the posterior one deeply concave. All the other cervicals were biconcave, as were also the vertebræ of the trunk and tail. The articular faces of the cervicals are inclined, showing that the neck was curved. The anterior cervical ribs were coossified with the centra, as in birds. Figs. 2, 2*a*, and 2*b*, Pl. VII, represent a cervical vertebra from near the middle of the neck. The cavities in the cervicals are connected with the outside by comparatively large pneumatic openings. The neural canal is very large, and traces of the neurocentral suture are distinct.

The dorsal vertebræ of Cœlurus are much shorter than the cervicals. The centra have a deep cup in front and a shallow concavity behind. These articular faces are nearly at right angles to the axis of the trunk. The neural spine is elevated and compressed. The transverse processes are elongate. The ribs preserved have undivided heads. A posterior dorsal is represented in Pl. VII, figs. 3, 3*a*, and 3*b*. The suture of the neural arch is distinct in this specimen. The foramina leading to the cavities in the dorsal vertebræ are quite small.

The caudal vertebræ are elongate and very numerous. They are all biconcave, and all appear to have been without chevron bones. An anterior caudal is figured in Pl. VII, fig. 4, and the accompanying section shows the inner structure. In most of the caudals, the neurocentral suture has entirely disappeared.

THE HIND LIMBS

The limb bones of Cœlurus are very hollow, and some of them appear pneumatic. The metatarsals are quite long and slender. The terminal phalanges of the hind feet are pointed, and in life were evidently covered with sharp claws. The ilium is of the Megalosaurus type. The pubes are slender, strongly coossified with each other, and terminated below by a large foot-like process, as shown in Pl. X, figs. 3 and 4.

The characters of Cœlurus are so distinctive that it appears to represent a separate family, which has been called by the writer the Cœluridæ. Several species of the genus are known in this country, all of moderate dimensions, varying in size from that of a fox to that of a wolf. Nearly all are from the Atlantosaurus beds of the West, but one small species has been found in the Potomac beds on the Atlantic Coast.

CERATOSAURUS.

The most interesting carnivorous dinosaur from the American Jurassic, and the one best known, is Ceratosaurus, which differs so widely from the typical forms that it has been regarded as representing a distinct suborder. The type specimen of Ceratosaurus, described by the writer in 1884, presented several characters not before seen in the Dinosauria. One of these is a horn core on the skull; another is a new type of vertebra as strange as it is unexpected; and a third is seen in the pelvis, which has the bones all coossified, as in existing birds. Among adult birds Archæopteryx alone has the pelvic bones separate, and this specimen of Ceratosaurus is the first dinosaur found with all the pelvic bones anchylosed. The metatarsal bones are also coossified, a feature characteristic of birds, but not known hitherto in any dinosaur.

THE SKULL.

The skull of *Ceratosaurus nasicornis* is very large in proportion to the rest of the skeleton. The posterior region is elevated, and moderately expanded transversely. The facial portion is elongate, and tapers gradually to the muzzle. Seen from above, the skull resembles in general outline that of an alligator. The nasal openings are separate and lateral, and are placed near the end of the snout, as shown in Pl. VIII.

Seen from the side, this skull appears lacertilian in type, the general structure being light and open. From this point of view one special feature of the skull is the elevated, trenchant horn core, situated on the nasals (Pl. VIII, fig. 1, *b*). Another feature is the large openings on the side of the skull, four in number. The first of these is the anterior nasal orifice; the second, the very large triangular antorbital foramen; the third, the large oval orbit; and the fourth, the still larger lower temporal opening. A fifth aperture, shown in the top view of the skull (Pl. VIII, fig. 3, *h*), is the supratemporal fossa. These openings are all characteristic of the Theropoda, and are found also in the Sauropoda, but the antorbital foramen is not known in any other Dinosauria.

The plane of the occiput, as bounded laterally by the quadrates, slopes backward. The quadrates are strongly inclined backward, thus forming a marked contrast to the corresponding bones in Diplodocus and other Sauropoda. The occipital condyle is hemispherical in general form, and is somewhat inclined downward, making a slight angle with the long axis of the skull. The basioccipital processes are short and stout. The paroccipital processes are elongate and flattened, and but little expanded at their extremities. They extend outward and downward, to join the head of the quadrate.

The hyoid bones appear to be four in number. They are elongate, rod-like bones, somewhat curved, and in the present specimen were found nearly in their original position.

The parietal bones are of moderate size, and there is no pineal foramen. The median suture between the parietals is obliterated, but that between these bones and the frontals is distinct.

The frontal bones are of moderate length, and are closely united on the median line, the suture being obliterated. Their union with the nasals is apparent on close inspection.

The nasal bones are more elongate than the frontals, and the suture uniting the two moieties is obsolete. These bones support entirely the large, compressed, elevated horn core on the median line. The lateral surface of this elevation is very rugose, and furrowed with vascular grooves. It evidently supported a high, trenchant horn, which must have formed a most powerful weapon for offense and defense. No similar weapon is known in any of the carnivorous Dinosauria, but it is not certain whether this feature pertained to all the members of this group or was only a sexual character.

The premaxillaries are separate, and each contained only three functional teeth. In the genera Compsognathus and Megalosaurus, of this order, each premaxillary contained four teeth, the same number found in the Sauropoda. In the genus Creosaurus, from the American Jurassic, the premaxillaries each contain five teeth, as shown in Pl. XII, fig. 1.

The maxillary bones in the present specimen are large and massive, as shown in Pl. VIII, fig. 1. They unite in front with the premaxillaries by an open suture; with the nasals, laterally, by a close union; and with the jugal behind, by squamosal suture. The maxillaries are each provided with fifteen functional teeth, which are large, powerful, and trenchant, indicating clearly the ferocious character of the animal. These teeth have the same general form as those of Megalosaurus, and the dental succession appears to be quite the same.

Above the antorbital foramen on either side is a high elevation composed of the prefrontal bones. These protuberances would be of service in protecting the orbit, which they partially overhang.

The orbit is of moderate size, oval in outline, with the apex below. It is bounded in front by the lachrymal, above this by the prefrontal, and at the summit the frontal forms for a short distance the orbital border. The postfrontal bounds the orbit behind, but the jugal completes the outline below.

The jugal bone is ⊥-shaped, the upper branch joining the postfrontal, the anterior branch uniting with the lachrymal above and with the maxillary below. The posterior branch passes beneath the quadratojugal, and with that bone completes the lower temporal arch, which is present in all known dinosaurs.

The quadratojugal is an L-shaped bone, and its anterior branch is united with the jugal by a close suture. The vertical branch is closely joined to the outer face of the quadrate.

The quadrate is very long and compressed antero-posteriorly. The head is of moderate size, and is inclosed in the squamosal. The lower extremity of the quadrate has a double articular face, as in some birds. One peculiar feature of the quadrate is a strong hook on the upper half of the outer surface. Into this hook a peculiar process of the quadratojugal is inserted, as shown in Pl. VIII, fig. 1.

The pterygoid bones are very large and extend well forward. The posterior extremity is applied closely to the inner side of the quadrate. The middle part forms a pocket, into which the lower extremity of the basipterygoid process is inserted. To the lower margin of the pterygoid is united the strong, curved transverse bone which projects downward below the border of the upper jaws, as shown in Pl. VIII, fig. 1, *t*.

There is a very short, thin columella, which below is closely united to the pterygoid by suture, and above fits into a small depression of the postfrontal.

The palatine bones are well developed, and after joining the pterygoids extend forward to the union with the vomers. The latter are apparently of moderate size.

The parasphenoid is well developed and has a long, pointed, anterior extremity.

The whole palate is remarkably open, and the principal bones composing it stand nearly vertical, as in the Sauropoda.

THE BRAIN

The brain in Ceratosaurus was of medium size, but comparatively much larger than in the herbivorous dinosaurs. It was quite elongate, and situated somewhat obliquely in the cranium, the posterior end being inclined downward. The position of the brain in the skull, and its relative size, are shown in Pl. VIII, fig. 3. A side view of the brain cast is shown in Pl. LXXVII, fig. 2.

The foramen magnum is small. The cerebellum was of moderate size. The optic lobes were well developed and proportionately larger than the hemispheres. The olfactory lobes were large and expanded. The pituitary body appears to have been of good size.

THE LOWER JAWS

The lower jaws of Ceratosaurus are large and powerful, especially in the posterior part. In front the rami are much compressed, and they were joined together by cartilage only, as in all dinosaurs. There is a large foramen in the jaw, similar to that in the crocodile, as shown in Pl. VIII, fig. 1, *f'*. The dentary bone extends back to the middle of this foramen. The splenial is large, extending from the foramen forward to the symphysial surface, and forming in this region a border to the upper margin of the dentary. There were fifteen teeth in each ramus, similar in form to those of the upper jaws.

THE VERTEBRÆ

The cervical vertebræ of Ceratosaurus differ in type from those in all other known reptiles. With the exception of the atlas, which is figured in Pl. IX, fig. 1, all are strongly cupped on the posterior end of each centrum. In place of an equally developed ball on the anterior end, there is a perfectly flat surface. The size of the latter is such that it can be inserted only a short distance in the adjoining cup, and this distance is accurately marked on the centrum by a narrow articular border, just back of the flat, anterior face. This peculiar articulation leaves more than three-fourths of the cup unoccupied by the succeeding vertebra, forming, apparently, a weak joint. This feature is shown in Pl. IX, figs. 2, 3, and 4.

The discovery of this new form of vertebra shows that the terms opisthocœlian and procœlian, in general use to describe the centra of vertebræ, are inadequate, since they relate to one end only, the other being supposed to correspond in form. The terms convexo-concave, concavo-convex, plano-concave, etc., would be more accurate and equally euphonious.

In Ceratosaurus, as in all the Theropoda except Cœlurus, the cervical ribs are articulated to the centra, not coossified with them, as in the Sauropoda. The latter order stands almost alone among dinosaurs in this respect, as all the Predentata—Stegosauria, Ceratopsia, and the Ornithopoda—have free ribs in the cervical region.

The dorsal and lumbar vertebræ are biconcave, with only moderate concavities. The sides and lower surface of the centra are deeply excavated, except at the ends, as shown in Pl. IX, fig. 5. These vertebræ show the diplosphenal articulation seen in Megalosaurus, and also in Creosaurus, as shown in Pl. XII, fig. 5.

All the presacral vertebræ are very hollow, and this is also true of the anterior caudals.

There are five well-coossified vertebræ in the sacrum in the present specimen of *Ceratosaurus nasicornis.* The transverse processes are very short, each supported by two vertebræ, and they do not meet at their distal ends.

The caudal vertebræ are biconcave. All the anterior caudals, except the first, supported very long chevrons, indicating a high, thin tail, well adapted to swimming (Pl. IX, fig. 6). The tail was quite long, and the distal caudals were very short.

THE SCAPULAR ARCH

The scapular arch of Ceratosaurus is of moderate size, but the fore limbs were very small. The humerus is short, with a strong radial crest. The radius and ulna are also very short, and nearly equal in size. The carpal bones were only imperfectly ossified. There were four digits in the fore foot, and all were armed with sharp claws. The second and third digits were much larger than the first and fourth, and the fifth was entirely wanting.

THE PELVIC ARCH

The pelvic bones in the Theropoda have been more generally misunderstood than any other portion of the skeleton in dinosaurs. The ilia, long considered as coracoids, have been usually reversed in position; the ischia have been regarded as pubes; while the pubes themselves have not been considered as part of the pelvic arch.

Fortunately, in the present specimen of Ceratosaurus, the ilium, ischium, and pubes are firmly coossified, so that their identification and relative positions can not be called in question. The ilia, moreover, were attached to the sacrum, which was in its natural place in the skeleton, and the latter was found nearly in the position in which the animal died. The pelves of Ceratosaurus and of Allosaurus are shown in Pl. X.

The ilium in Ceratosaurus has the same general form as in Megalosaurus. In most of the other Theropoda, also, this bone has essentially the same shape, and this type may be regarded as characteristic of the order, except in Triassic forms. In Creosaurus the anterior wing is more elevated, and the emargination below it wider, as shown in Pl. XII, fig. 2, but this may be due in part to the imperfection of the border.

The ischia in Ceratosaurus are comparatively slender. They project well backward, and for the last half of their length the two are in close apposition. The distal ends are coossified and expanded, as shown in Pl. X.

The pubes in Ceratosaurus have their distal ends coossified, as in all Jurassic Theropoda except Hallopus. They project downward and forward, and their position in the pelvis is shown in Pl. X. Seen from the front, they form a Y-shaped figure, which varies in form in different genera. The upper end joins the ilium by a large surface, and the ischium by a smaller attachment. The united distal ends are expanded into an elongate, massive foot, as shown in Pl. X, which is one of the most peculiar and characteristic parts of the skeleton. The pubes of Cœlurus are represented on the same plate.

The extreme narrowness of the pelvis is one of the most marked features in this entire group, being in striking contrast to its width in the herbivorous forms found with them. If the Theropoda were viviparous, which some known facts seem to indicate, one difficulty, naturally suggested in the case of a reptile, is removed.

Another interesting point is the use of the large foot at the lower end of the pubes, which is the most massive part of the skeleton. The only probable use is that it served to support the body in sitting down. That some Triassic dinosaurs sat down on their ischia is proved conclusively by the impressions in the Connecticut River sandstone. In such cases the leg was bent so as to bring the heel to the ground. The same action in the present group would bring the foot of the pubes to the ground, nearly or quite under the center of gravity of the animal. The legs and ischia would then naturally aid in keeping the body balanced. Possibly this position was assumed habitually by these ferocious biped reptiles while lying in wait for prey.

The femur is much curved, and the shaft very hollow. The tibia is shorter than the femur, nearly straight, and has a large cnemial crest. The astragalus is not coosified with the femur, and has a strong ascending process. The fibula is well developed, and nearly straight, its distal end fitting into the calcaneum. The tarsals of the second row are very thin, and united to the metatarsals below them.

THE METATARSALS.

One of the most interesting features in the extremities of Ceratosaurus is seen in the metatarsal bones, which are completely anchylosed, as were the bones of the pelvis. There are only three metatarsal elements in the foot, the first and fifth having apparently disappeared entirely. The three metatarsals remaining, which are the second, third, and fourth, are proportionately shorter and more robust than in the other known members of the order Theropoda, and, being firmly united to each other, they furnish the basis for a very strong hind foot.

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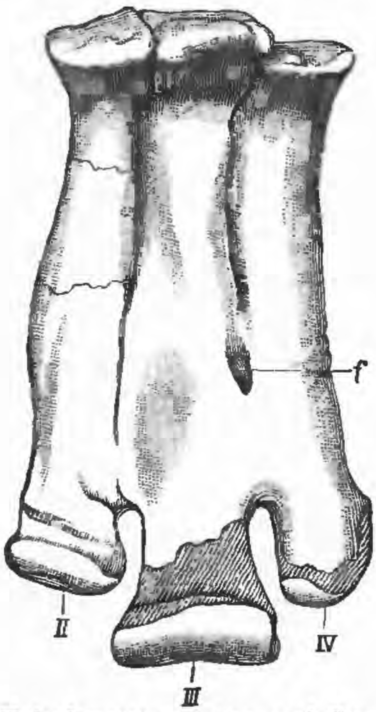

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FIG. 4.—United metatarsal bones of *Ceratosaurus nasicornis* Marsh; left foot; front view. One-fourth natural size.

FIG. 5.—United metatarsal bones of great Penguin (*Aptenodytes Pennantii* G. R. Gr.); left foot; front view. Natural size.

f, foramen: *II*, *III*, *IV*, second, third, and fourth metatarsals.

In fig. 4, above, these coosified metatarsals of Ceratosaurus are represented, and in fig. 5 the corresponding bone of a penguin is given for comparison.

In comparing these two figures, it will be seen that the three metatarsal elements of the dinosaur are quite as closely united as those of the bird. To the anatomist familiar with the tarsometatarsal bones of existing birds the specimen represented in fig. 4 will appear even more like this part in the typical birds than the one shown in fig. 5.

The position of the foramen, as seen in fig. 4, *f*, is especially characteristic of recent birds, and, as a whole, the hind foot of this Jurassic dinosaur was evidently similar to that of a typical bird.

All known adult birds, living and extinct, with possibly the single exception of Archæopteryx, have the metatarsal bones firmly united, while all the Dinosauria, except Ceratosaurus, have these bones separate. The exception in each case brings the two classes near together at this point, and their close affinity has now been clearly demonstrated.

RESTORATION OF CERATOSAURUS.

PLATE XIV

The restoration of Ceratosaurus on Pl. XIV represents the reptile one-thirtieth natural size, and in a position it must have frequently assumed.

ALLOSAURUS.

Of the other carnivorous dinosaurs of the American Jurassic, three genera, Allosaurus, Creosaurus, and Labrosaurus, are especially worthy of notice. All were represented by species of large size, the natural enemies of the gigantic herbivorous forms that were so abundant in the same period. All had powerful jaws, sharp, cutting teeth, and a flexible neck. The fore limbs were quite small, and the feet were armed with strong claws for seizing living prey. The hind limbs were large and strong, and the animals used them alone in ordinary locomotion. These three genera may be separated by distinctive characters, and it is probable that they were not all contemporaneous.

The genus Allosaurus contains the largest carnivorous dinosaurs known. It may be readily distinguished from Ceratosaurus by the vertebræ and the pelvis, or the feet.[1] The cervicals are opisthocœlian instead of plano-concave, and the pelvic bones and metatarsals are free, as shown in Pls. X and XI. In Creosaurus, a smaller allied form, the teeth in the premaxillaries are more numerous, while the sacrum contains fewer vertebræ (Pl. XII). Labrosaurus is evidently a quite different type, for the dentary bone is edentulous in front, as shown in Pl. XIII.

EUROPEAN THEROPODA.

From the Jurassic of Europe the best-known carnivorous form is Megalosaurus, so named by Buckland, in 1824, the type specimen having been found in England, near Oxford. Although the first genus of dinosaurs described, but little has been made out in regard to the structure of the skull, and many portions of the skeleton remain to be determined. Its nearest American representative is probably Allosaurus, and both genera include species of large size.

The most interesting member of the Theropoda known in Europe is the diminutive specimen described by Wagner, in 1861, as *Compsognathus longipes*. The type specimen, the only one known, is from the lithographic slates of Solenhofen, Bavaria, and is now preserved in the museum in Munich. Fortunately, the skull and nearly all the skeleton are preserved, and as the specimen has been studied by many anatomists its more important characters have been made out. It is regarded as representing a distinct suborder, and no nearly related forms are known in Europe. A restoration in outline of this interesting dinosaur has been prepared by the writer, and will be found on Pl. LXXXII.

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[1] The skull of *Allosaurus ferox* Marsh has an aperture in the maxillary in front of the antorbital opening This aperture is not present in Ceratosaurus

SAUROPODA.

The herbivorous dinosaurs of the American Jurassic are of special interest. To begin with the order Sauropoda, which includes the most primitive and gigantic forms, it is an interesting fact that the first specimen found in this country was one of the rarest of the group, and one of the most diminutive. A few teeth and bones only were obtained by Prof. P. T. Tyson, about 1858, near Bladensburg, Md. The teeth were named Astrodon by Dr. Christopher Johnston, in 1859, and in 1865 were described and figured by Dr. Leidy. The type specimens are now in the Yale museum, and one tooth is represented below in fig. 6. The strata containing these remains are known as the Potomac beds, but their exact age is a matter of doubt. They have been referred by some geologists to the Jurassic, and by others to the Cretaceous.

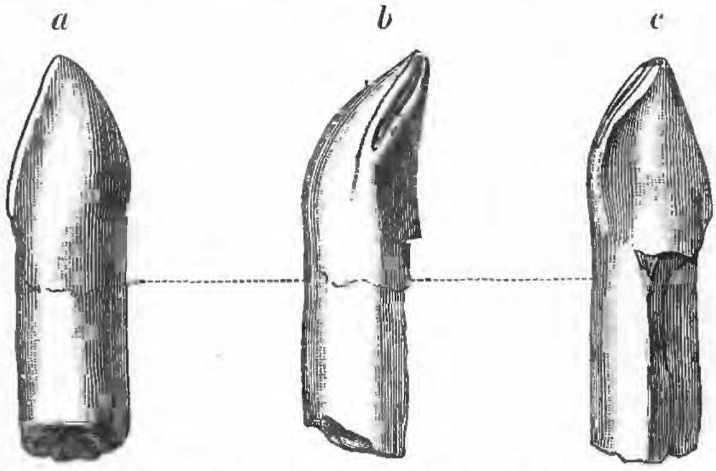

FIG. 6.—Tooth of *Astrodon Johnstoni* Leidy. Natural size. Potomac, Maryland. *a*, outer view; *b*, end view; *c*, inner view.

ATLANTOSAURUS BEDS.

The first known specimen of Sauropoda from the West was secured by the writer in August, 1868, near Lake Como, in Wyoming Territory. This fossil, an imperfect vertebra belonging to the genus since named Morosaurus, was found in the upper Jurassic clays, in the horizon now known as the Atlantosaurus beds. The section on page 145 will show the position of these beds in the geological scale, and their relation to other deposits in which Dinosauria have been found. This locality has since become one of the most famous in the entire Rocky Mountain region, and the writer has secured from it remains of several hundred dinosaurs, among which are many of the type specimens here described.

Remains of an enormous dinosaurian were found in 1877, near Morrison, Colo., by Prof. Arthur Lakes and Capt. H. C. Beckwith, U. S. N., and this was the beginning of a series of similar discoveries. These remains, described by the writer in the American Journal of Science for July of that year, proved to be those of a dinosaur far surpassing in size any previously known, and having characters that indicated a new order of these reptiles.

When first found these fossils were supposed to be from the Dakota group, but their upper Jurassic age was soon after determined by the writer from evidence that placed the horizon beyond dispute. The name *Titanosaurus montanus* was given by the writer to this reptile when first described, but as the generic designation proved to be preoccupied, Atlantosaurus was substituted.

A third Rocky Mountain locality which proved to be especially prolific in dinosaurs was found the following year, by Mr. M. P. Felch, a few miles north of Canyon, Colo., and in essentially the same horizon as the last-mentioned locality. Here were found the type specimens of some of the most interesting dinosaurs yet discovered in this country, all of them in fine preservation, and not infrequently in the exact position in which they died. Other localities of interest have been found in the same region.

Another locality of Sauropoda, more recently explored by the writer, is in South Dakota, on the eastern slope of the Black Hills. This is the most northern limit now known of the Atlantosaurus beds, which form a distinct horizon along the eastern flanks of the Rocky Mountains, marked at many points by the bones of gigantic dinosaurs, for nearly 500 miles. The strata are mainly shales or sandstones of fresh-water or estuary origin. They usually rest unconformably upon the red Triassic series, and have above them the characteristic Dakota sandstones.

On the western slope of the Rocky Mountains the Atlantosaurus beds are also well developed, especially in Wyoming, but here they have immediately below them a series of marine strata, which the writer has named the Baptanodon beds, from the largest reptile found in them. This horizon, also of Jurassic age, is shown in the section on page 145. One of the best exposures of the entire Jurassic series may be seen near Lake Como, Wyoming.

Besides the dinosaurs, which are especially abundant, the Atlantosaurus beds also contain numerous remains of extinct crocodiles, tortoises, and fishes, and with them have been found a small pterodactyl and a single bird. Many small mammals, also, have been described by the writer from the same beds.

FAMILIES OF SAUROPODA.

The Sauropoda of the American Jurassic are worthy of special attention, and so far as now known they may be divided into four families: the Atlantosauridæ, which include the largest forms; the Diplodocidæ and Morosauridæ, both represented by gigantic species; and the small Pleurocœlidæ, which were apparently the last survivors of the order in this country. Remains of the first three families are abundant in the Atlantosaurus beds of the West, but it is not certain that all were contemporaneous. The Pleurocœlidæ are especially characteristic of the Potomac beds on the Atlantic coast.

All the known members of these families were quadrupedal, with the fore and hind limbs nearly equal in length. The head was very small and the neck long, with its vertebræ opisthocœlian and lightened by inner cavities, thus allowing free motion.

The limb bones of all were solid, and the feet plantigrade, with five toes on each. The tail was especially long and massive. The general form and proportions of these reptiles are indicated in Pl. XLII, which represents the skeleton of a species of Brontosaurus, one of the typical genera of the Atlantosauridæ.

ATLANTOSAURIDÆ

ATLANTOSAURUS.

The present family was named by the writer in 1877, the type genus being Atlantosaurus. The type specimen of the first species described, *Atlantosaurus montanus*, is the sacrum represented in fig. 1, Pl. XVII, which shows characteristic features of the sacrum of the entire group Sauropoda, and thus distinguishes it from that of the other known dinosaurs. A second and larger species, *Atlantosaurus immanis*, was described by the writer in the following year, and on Pl. XVI are represented two pelvic bones and a femur, which belong to the type specimen, and give an idea of its gigantic size. The femur is over 6 feet long, and this, with other portions of the skeleton, indicates an animal about 70 or 80 feet in length. The pubis and ischium, represented in position in fig. 1, are especially characteristic of the family, as will be seen by comparing them with the corresponding parts of other allied genera, as shown in Pl. XXXVI.

At the same locality where these remains were found, portions of a skull were discovered, one of which is figured on Pl. XV. This specimen, which is the posterior part of the skull, is of much interest, and shows characters which separate it from all other corresponding remains of dinosaurs. The most marked feature is a distinct pituitary canal leading from the brain cavity down through the base of the skull, as shown in fig. 2 of Pl. XV. This canal appears to be a marked character of the family Atlantosauridæ. Other points of interest in these remains will be discussed later in the present paper.

APATOSAURUS.

Another genus of the present family is Apatosaurus, also described by the writer in 1877, and from the same geological horizon in Colorado. The sacrum represented in fig. 2, Pl. XVII, may be regarded as the type specimen. It has the same general features as the sacrum of Atlantosaurus, shown on that plate, but it has only three coossified vertebræ instead of four.

THE SACRAL CAVITY.

The neural canal in this sacrum, and indeed in all the sacra of the Sauropoda, is much enlarged, being especially expanded above each vertebral centrum, thus leaving a vaulted chamber in the united neural arches of the sacral vertebræ. A cast of this cavity in the type specimen of Apatosaurus is shown in fig. 3, Pl. XVIII.

This enlargement of the neural cord in the sacral region exists to some degree in reptiles and birds now living, but does not approach that found in the Sauropoda, or especially that in the Stegosauria, where, as will be shown later in the present article, this expansion reaches its maximum, and its functional importance must make it a dominant factor in the movements of the reptiles in which it is so highly developed. This great development has been found only in extinct reptiles in which the brain was especially diminutive, and the relation of the two nervous centers to each other offers a most interesting problem to physiologists.

THE VERTEBRÆ.

In Pl. XVIII, fig. 1, is shown a posterior cervical vertebra of Apatosaurus, and in fig. 2 of the same plate a dorsal vertebra is also represented, both being typical of the family Atlantosauridæ. The cervical

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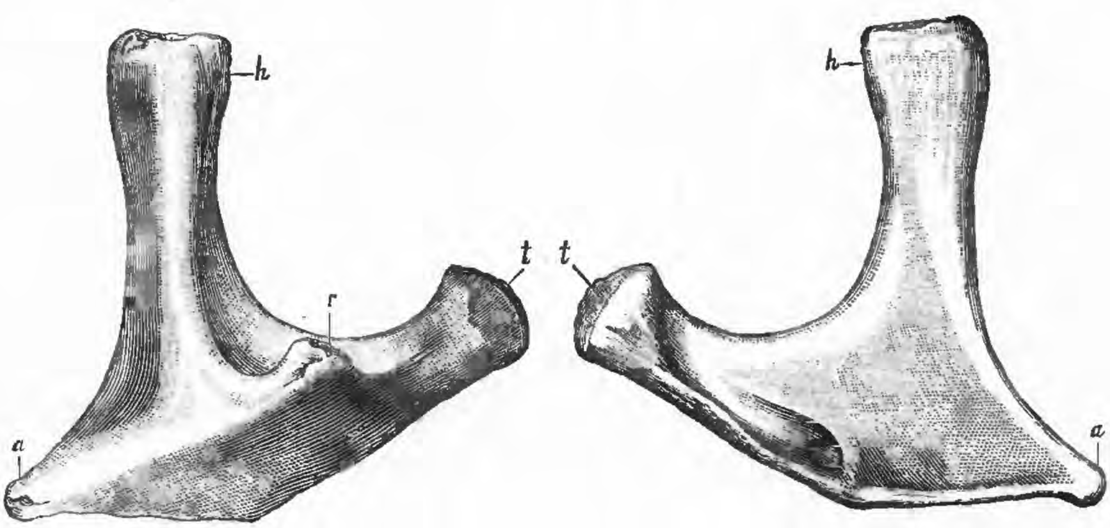

FIG. 7.—Cervical rib of *Apatosaurus ajax* Marsh; outer view.
FIG. 8.—The same rib; inner view.
Both figures are one-eighth natural size. *a*, anterior extremity; *h*, head; *r*, posterior process; *t*, tubercle.

vertebra, seen from behind, shows the deep, transverse cup of the posterior articular end of the centrum, as well as the coossified cervical ribs, both typical of the Sauropoda. A cervical rib of one species is shown in figs. 7 and 8.

The dorsal vertebra, seen from in front, presents the convex anterior ball of the centrum, and also the massive neural arch of the vertebra, with its elevated metapophyses, constituting a neural spine. The expanded diapophyses, or transverse processes, are especially noteworthy, as they aid in supporting the massive ribs, their extremities articulating with the tubercle of the rib, while the head is supported at the base of the arch by a sessile facet representing the parapophysis of the cervicals. The small neural canal in each vertebra is also an interesting feature, especially when contrasted with the expanded cavity in the sacrum shown in fig. 3 of the same plate.

The scapula and coracoid of Apatosaurus, shown in Pl. XIX, fig. 1, are also characteristic features of the family they represent. The shaft of the scapula is not expanded above in any of the genera of the Atlantosauridæ, although this expansion is characteristic of the genus Morosaurus and the family Morosauridæ, as shown in the same plate, fig. 2. Another important difference is indicated on this plate, in the coracoids, that of Apatosaurus being nearly square in outline, while in Morosaurus and its allies the contour of the coracoid is subovate.

BRONTOSAURUS.

The best-known genus of the Atlantosauridæ is Brontosaurus, described by the writer in 1879, the type specimen being a nearly entire skeleton, by far the most complete of any of the Sauropoda yet discovered. It was found in the Atlantosaurus beds, near Lake Como, Wyoming, and the remains were nearly in the position in which they were left at the death of the animal. This fortunate discovery has done much to clear up many doubtful points in the structure of the whole group Sauropoda, and the species *Brontosaurus excelsus* may be taken as a typical form, especially of the family Atlantosauridæ. The animal was about 60 feet in length. A second species, equally gigantic, has since been found in the same region

In Pl. XX, fig. 1, a characteristic tooth of Brontosaurus is shown, which may also be regarded as typical for the family. In fig. 2 of the same plate the dentary bone is shown, with the teeth in outline. This bone is one of the most characteristic of the whole skeleton, as will be seen by comparing it with the corresponding parts of other Sauropoda represented in the following plates.

The genus Brontosaurus may be readily distinguished from all the other Sauropoda by the sacrum, which is composed of five anchylosed vertebræ, none of the other genera in this group having more than four. The sternum, moreover, consists of two separate bones, which are parial, and were united to each other on the median line apparently by cartilage only. In several other respects the genus resembles Morosaurus.

The present species, aside from its immense size, is distinguished by the peculiar lightness of its vertebral column, the cervical, dorsal, and sacral vertebræ all having very large cavities in their centra. The first three caudals, also, are lightened by excavations in their sides, a feature first seen in this genus, and one not observed in the other families of this group.

THE SCAPULAR ARCH.

The scapular arch in the present species is, fortunately, better known than that of any other member of the present order. In Pl. XXII the various bones are represented in position, and in fig. 2 of the same plate a sternal bone is shown separately. The scapula resembles in general form the corresponding bone in Apatosaurus, but the shaft is longer and the upper end somewhat wider.

The coracoid approaches more nearly that of Apatosaurus, which is subquadrate in outline. In Pl. XXII the scapula and coracoid of the present species are placed nearly in the same plane, and the space between them probably represents about the amount of cartilage which originally separated them. Both scapulæ were found in apposition with their respective coracoids.

The two sternal bones lay side by side between the two coracoids, and in this plate they are represented nearly as found. They are suboval in outline, concave above, and convex below. They are parial, and when in position nearly or quite meet on the median line. Each bone is considerably thickened in front, and shows a distinct facet for union with the coracoid. The posterior end is thin and irregular. The sternal ribs represented in figs. 12–15, p. 171, were found near the sternal bones. The sternum of a young ostrich is shown for comparison on Pl. XXII, fig. 3.

THE CERVICAL VERTEBRÆ

The cervical vertebræ of the present species are quite numerous, thirteen at least belonging in this part of the column. All are strongly opisthocœlian. The anterior cervicals are very small in comparison with those near the dorsal region. From the third vertebra to the middle of the neck the centra increase in length and especially in bulk, but the posterior cervicals gradually become shorter. In Pl. XX, figs. 3 and 4, the sixth cervical is represented, and this is typical for the anterior half of the neck. All the anterior cervicals have coossified ribs, as in birds. In the posterior cervicals the ribs occasionally become free (Pl. XXI, fig. 1). The articular facet for the head of the rib rises gradually on the side of the centrum, the tubercular articulation remaining on the diapophysis. None of the cervicals have a neural spine. The neural canal is comparatively small. The centra of all the cervicals have deep excavations in the sides, and the transverse processes are more or less cavernous. The posterior cervicals which bear free ribs are remarkable for the great size of the zygapophyses, which are here much larger than elsewhere in the series. The anterior cervicals have several lateral cavities, while those farther back have only one large foramen in each side of the centrum, as in the dorsals.

THE DORSAL VERTEBRÆ

The dorsal vertebræ of this species have short centra, more or less opisthocœlian. There is a very large cavity in each side, which is separated from the one opposite by a thin vertical partition. The neural canal is much larger than in the cervicals. The anterior dorsals are distinctly opisthocœlian. The neural spine has no prominence in this region, but rises rapidly farther back. In Pl. XXI, figs. 2 and 3, a posterior dorsal is represented, which shows the peculiar character of the vertebræ in this part of the series. The neural spine is greatly developed and has its summit transversely expanded. The vertebræ in this region, as in all the known Sauropoda, have the peculiar diplosphenal articulation. This is shown in fig. 3. In the vertebra figured, at the base of the neural spine, there is a strong anterior projection, which was inserted into the cavity between and above the posterior zygapophyses of the vertebra in front. There appear to be no true lumbar vertebræ, as those near the sacrum supported free ribs of moderate size. The vertebræ in this region have both faces of the centrum nearly flat or biconcave. An anterior dorsal rib is shown below.

THE SACRUM.

The sacrum in the present species consists of five well-coossified vertebræ, and in the type specimen the centrum of the last lumbar is firmly united with it, as shown in Pl. XXIII. The striking feature

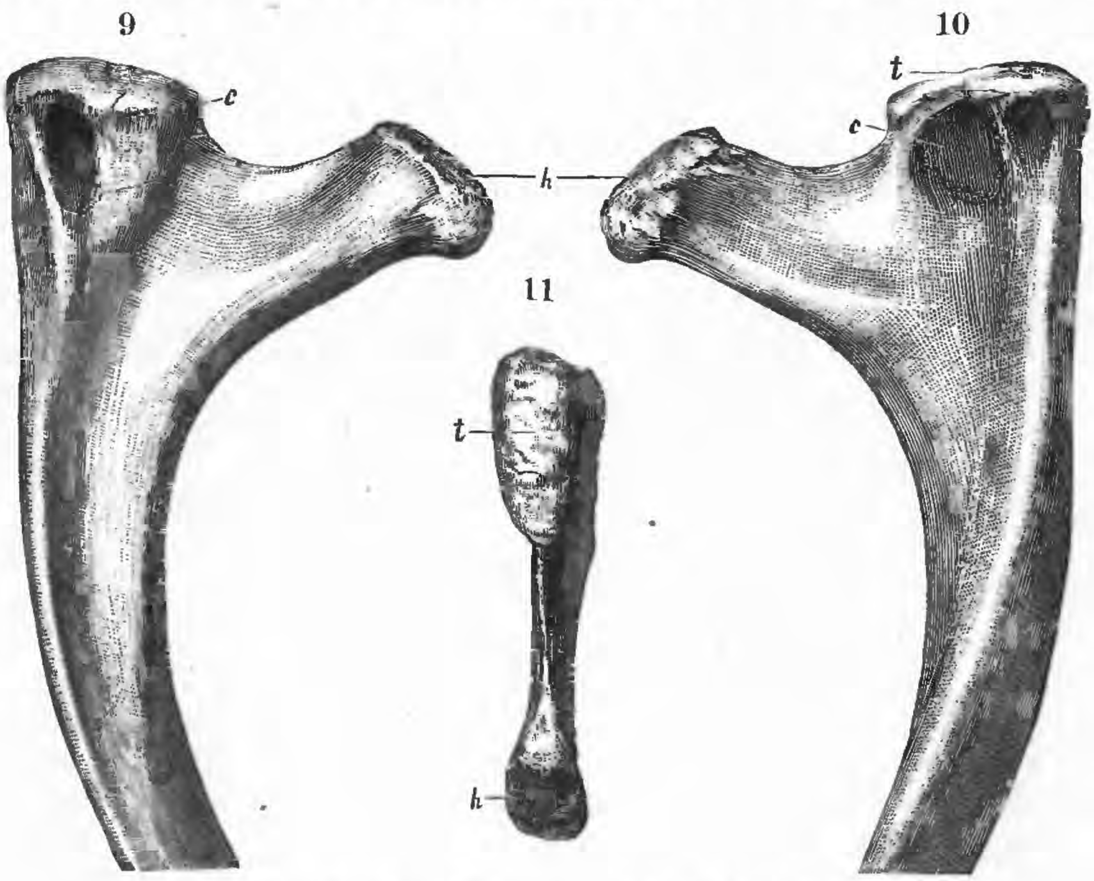

FIG. 9.—Proximal end of rib of *Brontosaurus excelsus* Marsh; front view.
FIG. 10.—The same bone; back view.
FIG. 11.—The same; superior view.
All the figures are one-eighth natural size. *c*, cavity; *h*, head; *t*, tubercle.

about this sacrum is the large general cavity it contained. This was divided in part by a median longitudinal partition, as shown in Pl. XXIII, fig. 2. The septum, however, was not continuous the whole length of the sacrum, so that the two lateral cavities were virtually one. This extended even into the lateral processes. The transverse partitions formed by the ends of the respective centra were also perforate, so that the sacrum proper was essentially a hollow cylinder. The cavernous character of the sacrum is one of the peculiar features of the suborder Sauropoda, and was described by the writer when the first species of this group was discovered in this country. The statement that any of the species has the sacrum solid is evidently based on erroneous observation.

Another peculiar character of the sacrum in the present genus is its lofty neural spine. This is a thin, vertical plate of bone with a thick massive summit, evidently formed by the union of the spines of several vertebræ. In front it shows rugosities for the ligament uniting it to the adjoining vertebra, and its posterior margin likewise indicates a similar union with the first caudal. In this genus, as in all the Sauropoda, each vertebra of the sacrum supports its own transverse processes. As shown in Pl. XXIII, the articulation for the ilium is formed by the coossification of the distal ends of the transverse processes. The neural canal is much enlarged in the sacrum, but less proportionally than in Stegosaurus.

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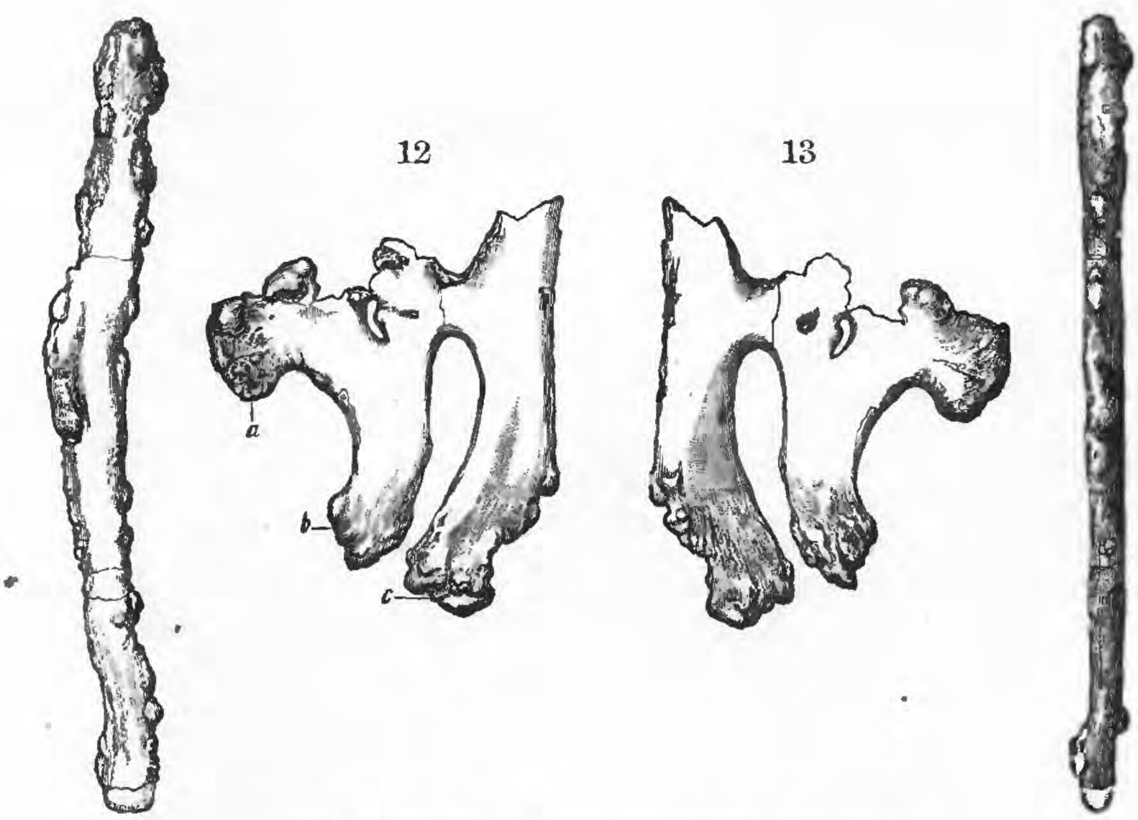

FIG. 12.—Sternal ribs of *Brontosaurus excelsus*; outer view.
FIG. 13.—The same specimen; inner view.
FIG. 14.—Sternal rib of same individual; outer view.
FIG. 15.—The same rib; inner view.
All the figures are one-eighth natural size.

THE CAUDAL VERTEBRÆ.

In the present species the three vertebræ next behind the sacrum have moderate-sized cavities between the base of the neural arch and the transverse processes. These shallow pockets extend into the base of the processes, but the centra proper are solid. All the other caudals have the centra, processes, and spines composed of dense bone. The fourth caudal vertebra, represented in Pl. XXIV, figs. 2 and 3, is solid throughout, and the same is true of the chevron, figs. 4 and 5. The neural spines of the anterior caudal vertebræ are elevated and massive. The summit is cruciform in outline, due to the four strong buttresses which unite to form it.

The median caudals all have low, weak spines, and no transverse processes. The posterior caudals are elongate and without spines or zygapophyses.

THE PELVIC ARCH.

The pelvic bones in the present species are shown in fig. 16. The ilium represented is not quite perfect on its upper margin. Its anterior process for the support of the pubis is much larger than the poste-

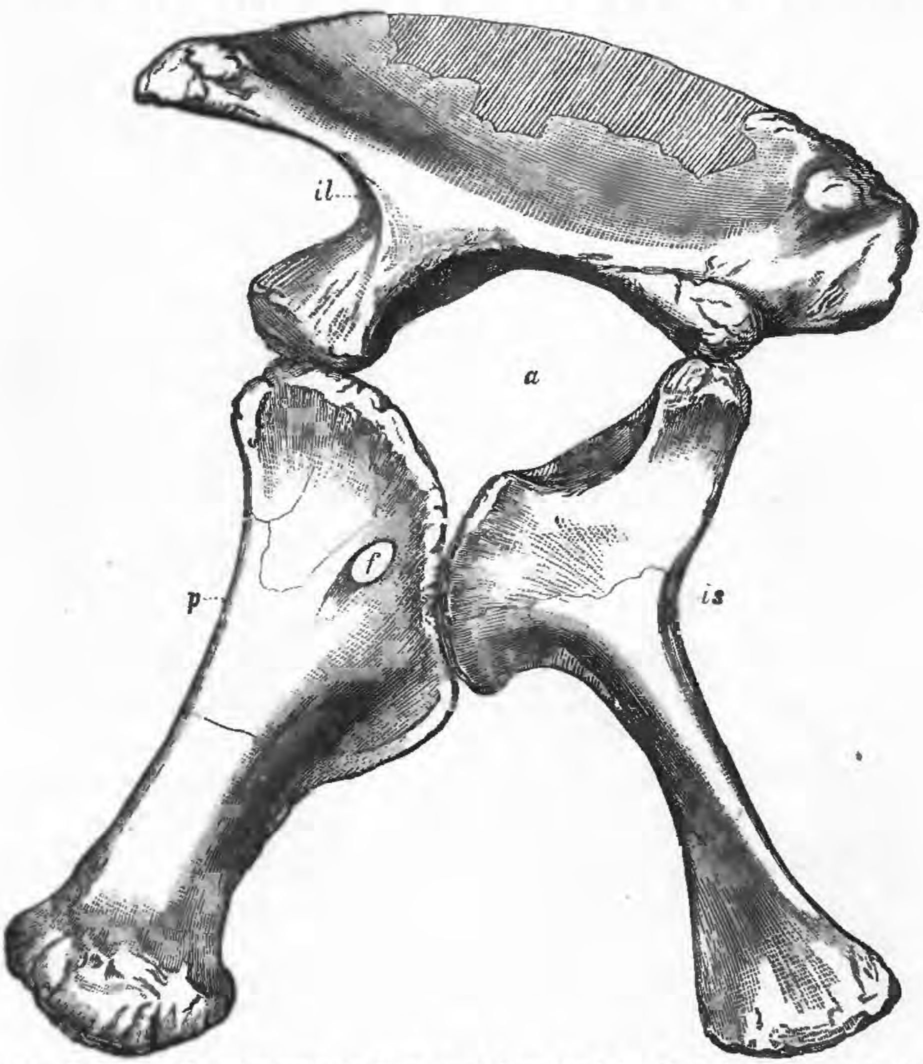

FIG. 16.—Pelvis of *Brontosaurus excelsus;* seen from the left. One-sixteenth natural size. *a*, acetabulum; *f*, foramen in pubis; *il*, ilium; *is*, ischium; *p*, pubis.

rior one which meets the ischium. The pubis is elongate and massive. It sends down a strong wing for union with the ischium, and has in front of this the usual foramen. The distal end is expanded, and has on the inner surface a rugose facet for union with its fellow by cartilage. The ischium is more slender than the pubis, and has its lower end expanded for symphysial union with the one on the other side (Pl. XXIV, figs. 1 and 1*a*). This pelvis is more like that of Atlantosaurus than any other of the known genera of the Sauropoda. The three bones shown in fig. 16 were found nearly in the position represented.

THE FORE LIMBS.

The fore limbs of Brontosaurus, as in most of the Sauropoda, were of large size and of massive proportions. The limb bones are all solid, and those of the feet are quite robust. There were five well-developed digits in the manus, and the metacarpals were all moderately elongate. A characteristic example is shown in figs. 17–20, below.

17 19 18

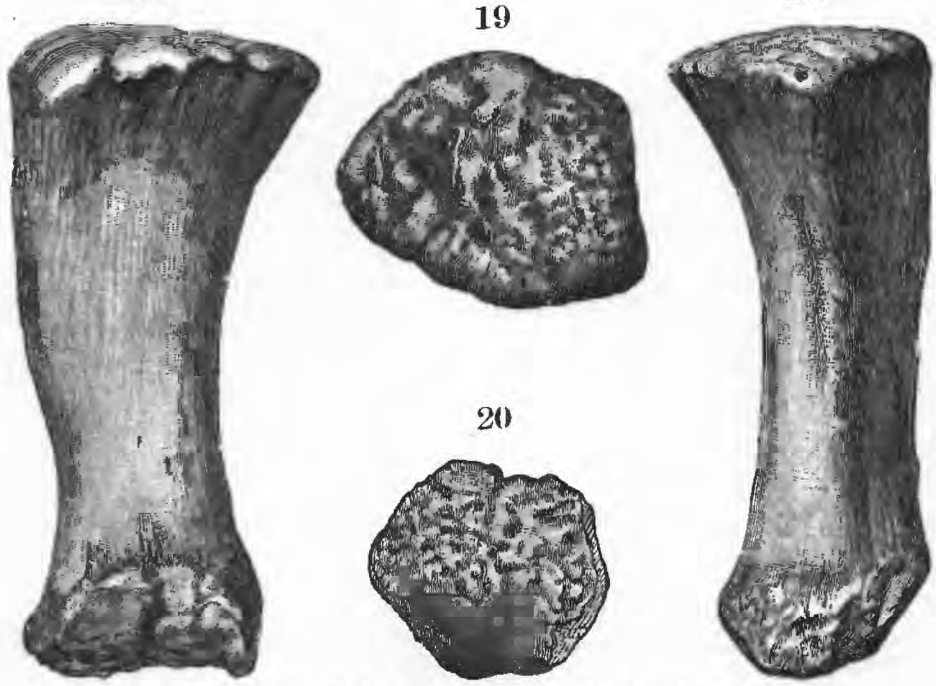

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FIG. 17.—First metacarpal of *Brontosaurus amplus* Marsh; front view.
FIG. 18.—The same bone; side view.
FIG. 19.—Proximal end of same.
FIG. 20.—Distal end of same.
All the figures are one-fourth natural size.

THE HIND LIMBS.

The hind limbs of Brontosaurus were larger than those in front, and the bones were all solid, thus being in remarkable contrast to the elements of the vertebral column. The hind feet were plantigrade, and had five powerful digits. The first was very stout, and its terminal phalanx, shown in figs. 21–23, supported a powerful claw.

RESTORATION OF BRONTOSAURUS.

PLATE XLII.

Nearly all the bones represented in this restoration belonged to a single individual, which when alive was nearly or quite 60 feet in length. The position here given was mainly determined by a careful adjustment of these remains. That the animal at times assumed a position more erect than here represented is probable, but locomotion on the posterior limbs alone was hardly possible.

The head was remarkably small. The neck was long and flexible, and, considering its proportions, was the lightest portion of the vertebral column. The body was short, and the abdominal cavity of moderate size. The legs and feet were massive and the bones all solid. The feet were plantigrade, and each footprint must have been about a square yard in extent. The tail was large and nearly all the bones are solid.

The diminutive head will first attract attention, as it is smaller in proportion to the body than in any vertebrate hitherto known. The entire skull is less in diameter or actual weight than the fourth or fifth cervical vertebra.

A careful estimate of the size of Brontosanrus, as here restored, shows that when living the animal must have weighed more than 20 tons. The very small head and brain, and the slender neural cord, indicate a stupid, slow-moving reptile. The beast was wholly without offensive or defensive weapons or dermal armatnre.

21 22 23

FIG. 21.—Terminal phalanx of *Brontosaurus excelsus;* outer view.
FIG. 22.—The same bone; front view.
FIG. 23.—The same; inner view.
All the figures are one-fourth natural size.

In habits Brontosaurus was more or less amphibious, and its food was probably aquatic plants or other succulent vegetation. The remains are usually found in localities where the animals seem to have been mired. The type specimen was discovered by W. H. Reed, near Lake Como, Wyoming.

BAROSAURUS.

Another genus of the Sauropoda is indicated by various remains of a gigantic reptile described in 1890 by the writer. The most characteristic portions examined are the caudal vertebræ, which in general form resemble those of Diplodocus. They are concave below, as in the caudals of that genus, but the sides of the centra are also deeply excavated.

In the anterior caudals this excavation extends nearly or quite through the centra, a thin septum usually remaining. In the median caudals a deep cavity on each side exists, as shown in figs. 24–26, below.

On the distal caudals the lateral cavity has nearly or quite disappeared. All the caudal vertebræ are proportionally shorter than in Diplodocus, and their chevrons have no anterior projection, as in that genus.

The remains on which the present description is based are from the Atlantosaurus beds of South Dakota, about 200 miles farther north than this well-marked horizon has hitherto been recognized.[1]

24 25 26

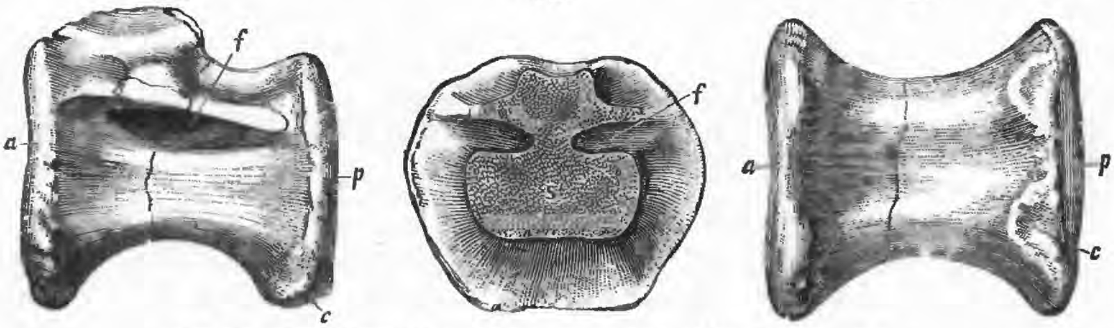

FIG. 24.—Caudal vertebra of *Barosaurus lentus* Marsh; side view.
FIG. 25.—The same vertebra, in section; front view.
FIG. 26.—The same vertebra; bottom view.
All the figures are one-eighth natural size. *a*, anterior end; *c*, face for chevron; *f*, lateral cavity; *p*, posterior end; *s*, section.

DIPLODOCIDÆ.

DIPLODOCUS.[2]

THE SKULL.

The skull of Diplodocus is of moderate size. The posterior region is elevated and narrow. The facial portion is elongate and the anterior part expanded transversely. The nasal opening is at the apex of the cranium, which from this point slopes backward to the occiput. In front of this aperture the elongated face slopes gradually downward to the end of the muzzle, as represented in Pl. XXV, fig. 1.

Seen from the side the skull of Diplodocus shows five openings: a small oval aperture in front, a large antorbital vacuity, the nasal aperture, the orbit, and the lower temporal opening. The first of these has not been seen in any other Sauropoda; the large antorbital vacuity is characteristic of the Theropoda also; while the other three openings are present in all the known Dinosauria.

On the median line, directly over the cerebral cavity of the brain, the type specimen of Diplodocus has also a fontanelle in the parietals. This, however, may be merely an individual peculiarity.

The plane of the occiput is of moderate size, and forms an obtuse angle with the frontoparietal surface.

The occipital condyle is hemispherical in form, and seen from behind is slightly subtrilobate in outline. It is placed nearly at right angles

[1]Strata that may represent this horizon have been observed still farther north, especially in Montana, but have not yet been identified by characteristic fossils.

[2]American Journal of Science, 1878–1884.

to the long axis of the skull. It is formed almost wholly of the basioccipital, the exoccipitals entering but slightly or not at all into its composition. The basioccipital processes are large and rugose. The paroccipital processes are stout and somewhat expanded at their extremities, for union with the quadrates.

The parietal bones are small and composed mainly of the arched processes which join the squamosals. There is no true pineal foramen, but in the skull here figured (Pl. XXV) there is the small unossified tract mentioned above. In one specimen of Morosaurus a similar opening has been observed, but in other Sauropoda the parietal bones, even if thin, are complete. The suture between the parietals and frontal bones is obliterated in the present skull, and the union is firm in all the specimens observed.

The frontal bones in Diplodocus are more expanded transversely than in the other Sauropoda. They are thin along the median portion, but quite thick over the orbits.

The nasal bones are short and wide and the suture between them and the frontals is distinct. They form the posterior boundary of the large nasal opening, and also send forward a process to meet the ascending branch of the maxillary, thus taking part in the lateral border of the same aperture.

The nasal opening is very large, subcordate in outline, and is partially divided in front by slender posterior processes of the premaxillaries. It is situated at the apex of the skull, between the orbits, and very near the cavity for the olfactory lobes of the brain.

The premaxillaries are narrow below, and with the ascending processes very slender and elongate. Along the median line these processes form an obtuse ridge, and above they project into the nasal opening. Each premaxillary contains four functional teeth.

The maxillaries are very largely developed, more so than in most other known reptiles. The dentigerous portion is very high and slopes inward. The ascending process is very long, thin, and flattened, inclosing near its base an oval foramen, and leaving a large unossified space posteriorly. Above, it meets the nasal and prefrontal bones. Along its inner border for nearly its whole length it unites with the ascending process of the premaxillary. Each maxillary contains nine teeth, all situated in the anterior part of the bone (Pl. XXV, fig. 1).

Along their upper margin, on the inner surface, the maxillaries send off a thickened ridge, or process, which meets its fellow, thus excluding the premaxillaries from the palate, as shown in fig. 27, opposite. Above this, for a large part of their length, the ascending processes of the maxillaries underlap the ascending processes of the premaxillaries and join each other on the median line.

The orbits are situated posteriorly in the skull, being nearly over the articulation of the lower jaw. They are of medium size, nearly circular in outline, their plane looking outward and slightly backward. No indications of sclerotic plates have been found either in Diplodocus or in the other genera of Sauropoda.

The supratemporal fossa is small, oval in outline, and directed upward and outward. The lateral temporal fossa is elongated, and oblique in position, bounded, both above and below, by rather slender temporal bars.

The prefrontal and lachrymal bones are both small; the suture connecting them, and also that uniting the latter with the jugal, can not be determined with certainty.

The postfrontals are triradiate bones. The longest and most slender branch is that descending downward and forward for connection with the jugal; the shortest is the triangular projection directed backward and fitting into a groove of the squamosal; the anterior branch, which is thickened and rugose, forms part of the orbital border above.

The squamosal lies upon the upper border of the paroccipital process. The lower portion is thin and closely fitted over the head of the quadrate bone.

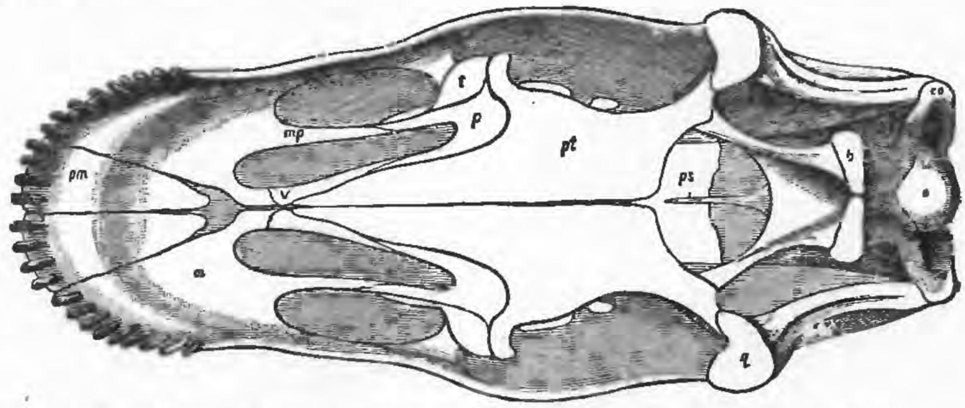

FIG. 27.—Skull of *Diplodocus longus* Marsh; seen from below. One-sixth natural size.
b, basioccipital process; *eo*, exoccipital; *m*, maxillary; *mp*, maxillary plate; *o*, occipital condyle; *p*, palatine; *pm*, premaxillary; *pt*, pterygoid; *ps*, parasphenoid; *q*, quadrate; *t*, transverse bone; *v*, vomer.

The quadrate is elongated and slender, with its lower end projecting very much forward. In front it has a thin plate extending inward and overlapping the posterior end of the pterygoid.

The quadratojugal is an elongate bone, firmly attached posteriorly to the quadrate by its expanded portion. In front of the quadrate it forms for a short distance a slender bar, which is the lower temporal arcade.

The palate is very high and roof-like, and composed chiefly of the pterygoids, as shown above in fig. 27. The basipterygoid processes are elongate, much more so than in the other genera of Sauropoda.

The pterygoids have a shallow cavity for the reception of these processes, but no distinct impression for a columella. Immediately in front of this cavity the pterygoids begin to expand, and soon form a broad, flat plate, which stands nearly vertical. Its upper border is thin, nearly straight, and extends far forward. The anterior end is acute and unites along its inferior border with the vomer. A little in front of the middle a process extends downward and outward, for union with the transverse bone. In front of this process, uniting with it and with the transverse bone, is the palatine.

The palatine is a small semioval bone fitting into the concave anterior border of the pterygoid, and sending forward a slender process for union with the small palatine process of the maxillary.

The vomer is a slender, triangular bone, united in front by its base to a stout process of the maxillary, which underlaps the ascending process of the premaxillary. Along its upper and inner border it unites with the pterygoid, except at the end, where for a short distance it joins a slender process from the palatine. Its lower border is wholly free.

THE BRAIN.

The brain of Diplodocus was very small, as in all dinosaurs from the Jurassic. It differed from the brain of the other members of the Sauropoda, and from that of all other known reptiles, in its position, which was not parallel with the longer axis of the skull, as is usually the case, but inclined to it, the front being much elevated, as in the ruminant mammals (Pl. LXXVI, fig. 4). Another peculiar feature of

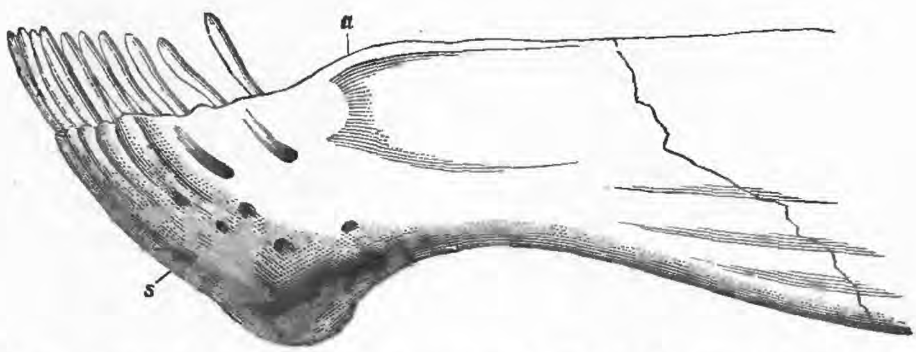

FIG. 28.—Dentary bone of *Diplodocus longus;* seen from the left. One-third natural size. *a*, edentulous border; *s*, symphysis.

the brain of Diplodocus was its very large pituitary body, inclosed in a capacious fossa below the main brain case. This character separates Diplodocus at once from the Atlantosauridæ, which have a wide pituitary canal connecting the brain cavity with the throat. In the Morosauridæ the pituitary fossa is quite small.

The posterior portion of the brain of Diplodocus was diminutive. The hemispheres were short and wide and more elevated than the optic region. The olfactory lobes were well developed, and separated in front by a vertical osseous septum. The very close proximity of the external nasal opening is a new feature in dinosaurs, and appears to be peculiar to the Sauropoda.

THE LOWER JAWS.

The lower jaws of Diplodocus are more slender than in any of the other Sauropoda. The dentary especially lacks the massive character seen in Morosaurus, and is much less robust than the corresponding bone in Brontosaurus. The short dentigerous portion in front is decurved (Pl. XXV, fig. 1), and its greatest depth is at the symphysis, as shown in fig. 28 above. The articular, angular, and surangular bones are well developed, but the coronary and splenial appear to be small.

THE TEETH.

The dentition of Diplodocus is the weakest seen in any of the known Dinosauria, and strongly suggests the probability that some of the more specialized members of this great group were edentulous. The teeth are entirely confined to the front of the jaws (Pl. XXV, fig. 1), and those in use were inserted in such shallow sockets that they were readily detached. Specimens in the Yale museum show that entire series of upper or lower teeth could be separated from the bones supporting them without losing their relative position. In Pl. XXVI, fig. 1, a number of these detached teeth are shown.

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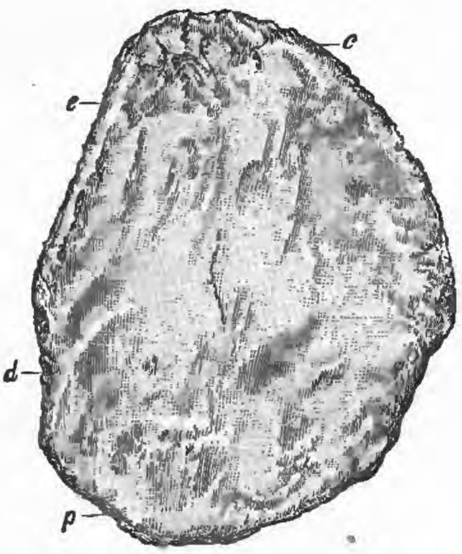

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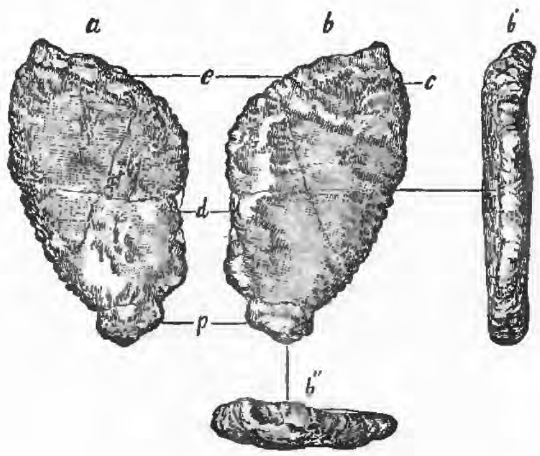

FIG. 29.—Sternal plate of *Brontosaurus amplus*; top view.
FIG. 30.—Sternal plate of *Morosaurus grandis* Marsh.
Both figures are one-eighth natural size. *a*, bottom view; *b*, top view; *b′*, side view; b″, end view; *c*, face for coracoid; *d*, margin next to median line; *e*, inner front margin; *p*, posterior end.

The teeth of Diplodocus are cylindrical in form and quite slender. The crowns are more or less compressed transversely and are covered with thin enamel, irregularly striated. The roots are long and slender and the pulp cavity is continued nearly or quite to the crown. In the type specimen of Diplodocus there are four teeth, the largest of the series, in each premaxillary; nine in each maxillary, and ten in each dentary of the lower jaws. There are no palatine teeth.

The jaws contain only a single row of teeth in actual use. These are rapidly replaced, as they wear out or are lost, by a series of successional teeth, more numerous than is usual in these reptiles. Pl. XXVI, fig. 2, represents a transverse section through the maxillary, just behind the fourth tooth. The latter is shown in place, and below it is a series of five immature teeth, in various stages of development, preparing to take its place. These successional teeth are lodged in a large cavity, which extends through the whole dental portion of the maxillary. The succession is also similar in the premaxillary teeth and in those of the lower jaws.

THE VERTEBRÆ

The vertebral column of Diplodocus, so far as at present known, may be readily distinguished from that of the other Sauropoda by both the centra and chevrons of the caudals. The former are elongated and deeply excavated below, as shown in Pl. XXVI, figs. 4 and 5. The chevrons are especially characteristic, and to their peculiar form the generic name Diplodocus refers. They are double, having both anterior and posterior branches, and the typical forms are represented in figs. 6 and 7 of the above plate.

The cervical and dorsal vertebræ of Diplodocus are represented by typical examples on Pl. XXVI, fig. 3, and Pl. XXVII, and the sacrum with ilium attached is shown on Pl. XXVIII.

THE STERNAL BONES.

The sternal bones in Diplodocus are especially large, and in form resemble those in *Brontosaurus excelsus*. Those in *Brontosaurus amplus* are less robust, and are somewhat similar in shape to those of Morosaurus, as shown in figs. 29 and 30.

THE PELVIC GIRDLE

A most characteristic bone of the two families of Sauropoda first described is the ischium. In the Atlantosauridæ the ischia are massive and directed downward, with their expanded extremities meeting on the median line. In the Morosauridæ the ischia are slender, with the shaft twisted about 90°, directed backward, and the sides meeting on the median line, thus approaching this part in the more specialized dinosaurs. The ischia referred to the genus Diplodocus (Pl. XXVIII, fig. 3) are intermediate in form and position between those above mentioned. The shaft is not expanded distally, nor twisted, but was directed downward and backward, with the sides meeting on the median line.

The feet of Diplodocus are shown in Pls. XXVIII and XXIX.

SIZE AND HABITS.

The type specimen of Diplodocus, to which the skull here figured belongs, indicates an animal intermediate in size between Atlantosaurus and Morosaurus, probably 40 or 50 feet in length when alive. The teeth show that it was herbivorous, and the food was probably succulent vegetation. The position of the external nares would seem to indicate in some measure an aquatic life.

MOROSAURIDÆ.

MOROSAURUS.

The genus Morosaurus, the type of the family, was described by the writer in 1878, in the American Journal of Science, which contains most of the original descriptions of Sauropoda found in this country.

THE SKULL.

The head in this genus was very small. The posterior part of the skull resembled that in Diplodocus, but the front was much more massive. The lower jaw was especially powerful, as shown by the dentary bone figured in Pl. XXX, fig. 3. This figure also shows the size and position of the teeth, one of which is figured in Pl. XXXI, figs. 1 and 2.

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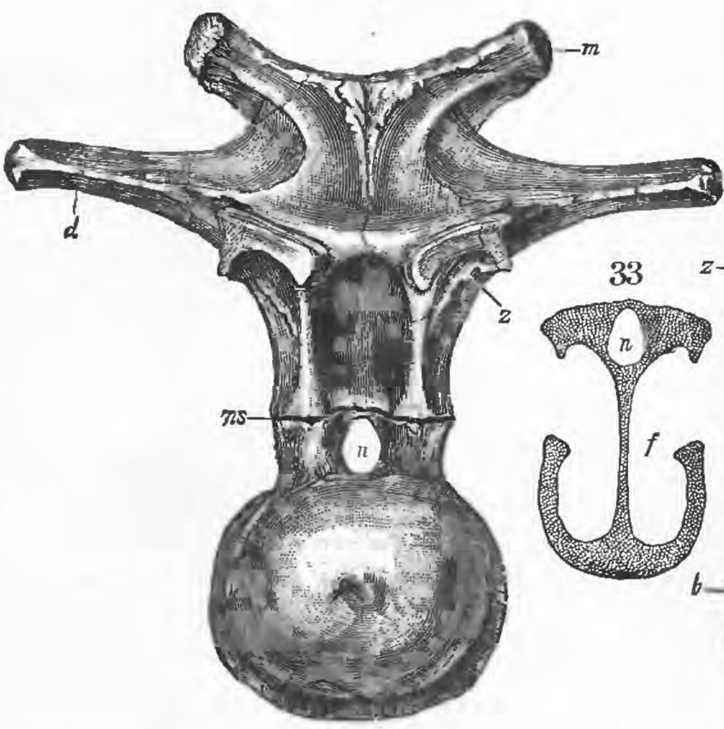

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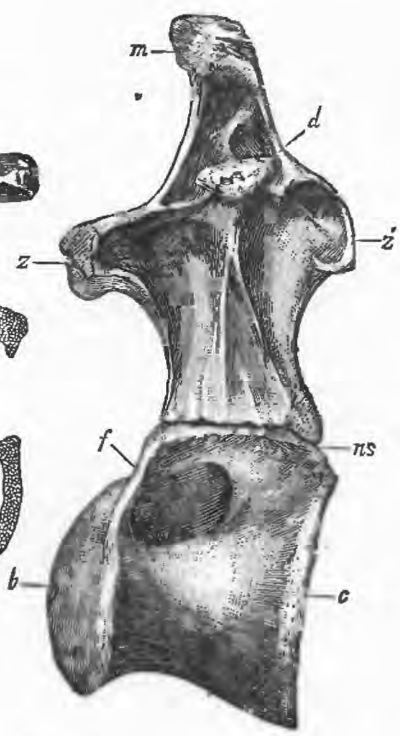

FIG. 31.—Anterior dorsal vertebra of *Morosaurus grandis;* front view.
FIG. 32.—The same vertebra; side view.
FIG. 33.—Transverse section through centrum of same.
All the figures are one-eighth natural size. *b*, ball ; *c*, cup ; *d*, diapophysis ; *f*, cavity in centrum; *m*, metapophysis ; *n*, neural canal ; *ns*, neural suture ; *z*, anterior zygapophysis ; *z'*, posterior zygapophysis.

The brain was very small. Its form and position in the skull are shown in fig. 2 of Pl. XXX. At the back of the skull there are two peculiar bones, called by the writer the postoccipital bones, which are shown in Pl. XXX, fig. 1.

THE VERTEBRÆ.

The neck was elongated, and except the atlas all the cervical vertebræ have deep cavities in the sides of the centra, similar to those in birds of flight. They are also strongly opisthocœlous. The atlas and axis are not anchylosed together, and the elements of the atlas are separate (Pl. XXXI).

The dorsal vertebræ are distinctly opisthocœlous. The posterior dorsals have elongated transverse neural spines, and have deep cavities in the sides. An anterior dorsal is shown in figs. 31–33, p. 181. There are four vertebræ in the sacrum, all with cavities in the centra. Their transverse processes, or sacral ribs, are vertical plates with expanded ends. The anterior caudal vertebræ are plano-concave, and nearly or quite solid. The tail was elongated, and the chevrons are similar to those in crocodiles (Pl. XXXIX). The vertebræ of Morosaurus are represented on Pls. XXXI–XXXIV.

THE FORE LIMBS.

The scapula is elongated and very large, and the shaft has a prominent anterior projection. The coracoid is small, suboval in outline, and has the usual foramen near its upper border. These two bones are well represented in Pl. XIX, nearly in the relative position in which they were found. The humerus is very large and massive, and its radial crest prominent. This bone is nearly solid, and its ends were rough and well covered with cartilage. This is true, also, of all

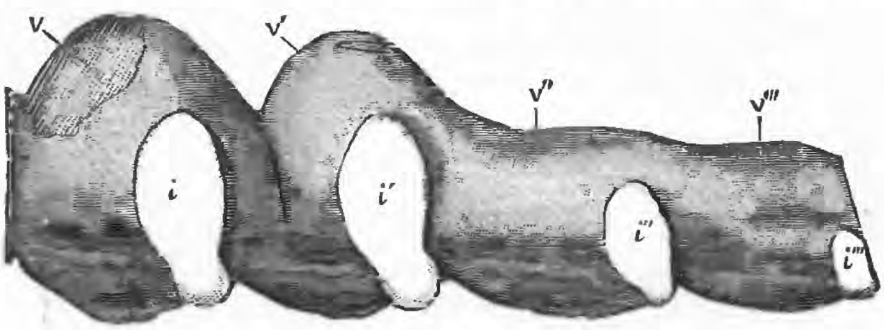

FIG. 34.—Cast of neural cavity in sacrum of *Morosaurus lentus* Marsh; side view. One-fourth natural size.
i, *i'*, *i''*, *i'''*, intervertebral foramina; *v*, *v'*, *v''*, *v'''*, cavities in first, second, third, and fourth sacral vertebræ.

the large limb bones in this genus. The radius and ulna are nearly equal in size. The carpal bones are separate and quite short. The five metacarpals are elongated, and the first is the stoutest. The toes were thick, and the ungual phalanges were evidently covered with hoofs. In Pl. XXXVIII, fig. 1, the restoration of the scapular arch and entire fore limb of one species of Morosaurus well illustrates this part of the skeleton.

THE PELVIS.

The pelvic bones are distinct from each other and from the sacrum. The ilium is short and massive, and shows on its inner side only slight indications of its attachment to the sacrum. More than half the acetabulum is formed by the ilium, which sends down in front a strong process for union with the pubis, and a smaller one behind to join the ischium (Pl. XXXV, fig. 1, *a* and *b*). The acetabulum is completed below by the pubis and ischium. The pubis is large and stout, and projects forward and downward, uniting with its fellow on the median line in a strong ventral symphysis. Its upper posterior margin meets the ischium and contains a large foramen. The ischium projects downward and backward, and its distal end is not expanded. The relative position and general form of the three pelvic bones in this genus are shown in Pl. XXXVI, fig. 1, and the entire pelvic arch in Pl. XXXI. The ischia of two species are shown on Pl. XXXV. The sacrum of one species of Morosaurus is shown on Pl. XXXI, and that of another on Pl. XXXIII. A cast of the sacral cavity of the latter is represented in fig. 34, p. 182.

THE HIND LIMBS

The femur is long and massive, and without a true third trochanter, although a rugosity marks its position. The great trochanter is obtuse and is placed below the head. The ridge which plays between the tibia and fibula is distinct. The tibia is shorter than the femur. It is without a spine or fibular ridge, and its distal end shows that the astragalus was separated from it by a cushion of cartilage. The fibula is stout, its two extremities nearly equal, and its distal end supports the calcaneum. The tarsal elements of the second row are unossified. The five well-developed digits are similar to those in the manus. The first metatarsal is much the largest (Pl. XXIX, fig. 2). The feet are also shown on Pls. XXXVII and XXXVIII.

PLEUROCŒLIDÆ.

PLEUROCŒLUS.[1]

THE SKULL.

The genus Pleurocœlus includes the smallest individuals of the Sauropoda found in this country, most of them not being larger than existing crocodiles, and some even smaller. The skull is quite small, and resembles in its structure that of Morosaurus, but has points of similarity also with that of Brontosaurus. The teeth resemble those of Diplodocus most nearly, but have shorter roots and are much more numerous, the entire upper and lower jaws being furnished with teeth. The dentary bone is similar in shape and proportions to that of Brontosaurus, differing widely from that of Diplodocus and Morosaurus. It is slender and rounded at the symphysis, instead of having the massive, deep extremity seen in Morosaurus. The maxillary also is much less robust. The supraoccipital agrees closely in shape with that of Morosaurus, and forms the upper border of the foramen magnum, as in that genus. In Pl. XL, fig. 1, is shown the dentary of Pleurocœlus, with the teeth in outline, and beside it are typical examples of the teeth.

THE VERTEBRÆ

The cervical vertebræ are very elongate and strongly opisthocœlous. The deep cavities in the sides of the centrum are separated only by a thin septum of bone, as shown in fig. 3 of the same plate. The dorsal

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[1] American Journal of Science, 1888

vertebræ are much longer than the corresponding vertebræ of Morosaurus, and have a very long, deep cavity in each side of the centrum, to which the generic name refers. All the trunk vertebræ hitherto found are proportionately nearly double the length of the corresponding centra of Morosaurus, and the lateral cavity is still more elongate. These points are shown in the posterior dorsal vertebra represented in figs. 4 and 5 of Pl. XL. The neural arch in this region is lightened by cavities, and is connected with that of the adjoining vertebræ by the diplosphenal articulation. A dorsal centrum of another species is shown below in figs. 35–37.

The sacral vertebræ in Pleurocœlus are more solid than in Morosaurus, but more elongate. The surface for the rib, or process which abuts against the ilium, is well in front, more so than in any of the known

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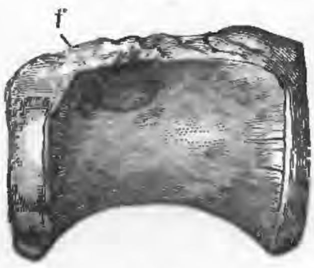

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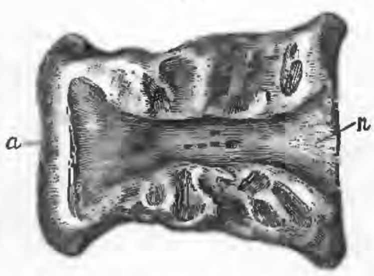

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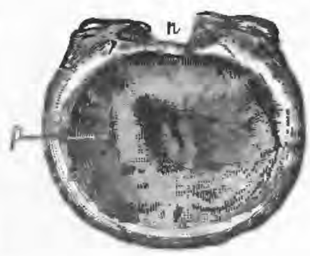

FIG. 35.—Dorsal vertebra of *Pleurocœlus montanus* Marsh; side view.
FIG. 36.—The same vertebra; top view.
FIG. 37.—The same; back view.

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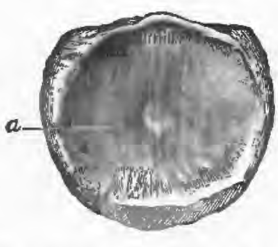

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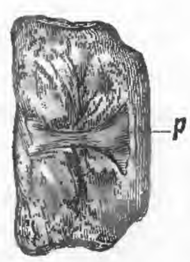

FIG. 38.—Caudal vertebra of same individual; front view.
FIG. 39.—The same vertebra; side view.
FIG. 40.—The same; back view.
FIG. 41.—The same; top view.
All the figures are one-half natural size. *a*, anterior end; *f*, cavity in centrum; *n*, neural canal; *p*, posterior end.

Sauropoda. Behind this articular surface is a deep pit, which somewhat lightens the centrum. These characters are seen in the sacral vertebra represented in figs. 6 and 7 of Pl. XL.

The first caudal vertebra has the centrum very short, and its two articular faces nearly flat, instead of having the anterior surface deeply concave, as in the other known Sauropoda. An anterior caudal is shown in figs. 38–41, above. The neural spines in this region are compressed transversely. The middle and distal caudals are comparatively short and the former have the neural arch on the front half of the centrum, as shown in figs. 8 to 11 of Pl. XL.

The bones of the limbs and feet preserved agree in general with those of the smaller species of Morosaurus, but indicate an animal of slighter and more graceful build. The metapodials are much more slender and the phalanges are less robust than in the other members of the order, as shown in Pl. XLI.

DISTRIBUTION OF THE SAUROPODA.

In the preceding pages the most important forms of the Sauropoda now known from North America have been briefly described and illustrated. The only remains known from other parts of America are a few fragmentary specimens recently found in Patagonia, and described by Lydekker, under the generic names Argyrosaurus and Titanosaurus, in the Anales del Museo de La Plata, 1893. The specimens now known, although in poor preservation, show distinctive characters of the order Sauropoda, and indicate reptiles of gigantic size. The discovery is interesting and will doubtless soon be followed by others of more importance.

In England remains of Sauropoda have long been known, and the first generic name given was Cardiodon, proposed by Owen, in 1841, and based on teeth alone. A number of other generic names have since been proposed, and several are still in use. Among these are Cetiosaurus and Bothriospondylus Owen, Pelorosaurus Mantell, Æpysaurus and Hoplosaurus Gervais, Ornithopsis Seeley, and Eucamerotus Hulke. The absence of the skull, and the fact that most of the type specimens pertain to different parts of the skeleton, render it difficult, if not impossible, to determine the forms described, and especially their relations to one another.

COMPARISON WITH EUROPEAN FORMS

In examining the European Sauropoda with much care the writer was impressed by three prominent features in the specimens investigated:

(1) The apparent absence of any characteristic remains of the Atlantosauridæ, which embrace the most gigantic of the American forms.

(2) The comparative abundance of another family, Cardiodontidæ, nearly allied to the Morosauridæ, but, as a rule, less specialized.

(3) The absence, apparently, of all remains of the Diplodocidæ.

A number of isolated teeth and a few vertebræ of one immature individual appear to be closely related to the Pleurocœlidæ, but this, for the present, must be left in doubt.

A striking difference between the Cardiodontidæ and the allied American forms is that in the former the fore and hind limbs appear to be more nearly of the same length, indicating a more primitive or generalized type. Nearly all the American Sauropoda, indeed, show a higher degree of specialization than those of Europe, both in this feature and in some other respects.

The identity of any of the generic forms of European Sauropoda with those of America is at present doubtful. In one or two instances it is impossible, from the remains now known, to separate closely allied forms from the two countries. Portions of one Wealden animal, referred by Mantell to Pelorosaurus, are certainly very similar to some of the smaller forms of Morosaurus, especially in the proportions of the fore limbs, which are unusually short. This fact would distinguish them at once from Pelorosaurus, and until the skull and more of the skeleton are known they can not be separated from Morosaurus.

The only Sauropoda reported from other parts of the world are some fragmentary remains from India, referred by Lydekker to the genus Titanosaurus, and more recently other remains from Madagascar, which the same author has placed in the genus Bothriospondylus. The wide distribution of the forms already known indicates that many future discoveries may be expected

PREDENTATA

The third order of the Dinosauria, according to the system of classification here adopted, is the one named by the writer the Predentata, a name derived from the fact that all the members of the group have a predentary bone, which is wanting in all other dinosaurs, and in fact in all other vertebrates, living and extinct. This order includes three suborders. the Stegosauria (plated lizards), the Ceratopsia (horned lizards), and the Ornithopoda (bird-footed). These are all herbivorous forms. and most of them contain species of very large size. The Stegosauria were mainly confined to the Jurassic, the Ceratopsia entirely to the Cretaceous, while the Ornithopoda were abundant in each of these periods. Of the Jurassic forms the Stegosauria will be first discussed, especially the typical family Stegosauridæ, which contains the American forms.

STEGOSAURIDÆ

The genus Stegosaurus, the type of the family, was described by the writer in 1877 from a specimen found in the Atlantosaurus beds of Colorado. Subsequently other remains were discovered and described by the writer, the more important being from near Lake Como, Wyo., and Canyon, Colo , localities which have furnished so many type specimens of the Sauropoda and other dinosaurs.

STEGOSAURUS.

THE SKULL.

The skull of Stegosaurus is long and slender, the facial portion being especially produced. Seen from the side, with the lower jaw in position, it is wedge-shaped, with the point formed by the premaxillary, which projects well beyond the mandible, as shown in fig. 1, Pl. XLIII. The anterior nares are large and situated far in front. The orbit is very large and placed well back. The lower temporal fossa is somewhat smaller. All these openings are oval in outline and are on a line nearly parallel with the top of the skull. In this view the lower jaw covers the teeth entirely.

Seen from above, as shown in fig. 3, Pl. XLIII, the wedge-shaped form of the skull is still apparent. The only openings visible are the supratemporal fossæ. The premaxillary bones are short above, but send back a long process below the narial orifice. The nasal bones are very large and elongate. They are separated in front by the premaxillaries, and behind by anterior projections from the frontal bones. The prefrontals are large, and are placed between the nasals and the prominent, rugose supraorbitals. The frontals are short, and externally join the postfrontals. The parietals are small and closely coossified with each other.

Viewed from in front, the skull and mandible present a nearly quadrate outline (Pl. XLIII, fig. 2), and the mutual relations of the facial bones are well shown. In this view is seen, also, the predentary bone, a characteristic feature of the mandible in this genus The lateral aspect of this bone is shown in fig. 1 of the same plate.

The teeth in this genus are entirely confined to the maxillary and dentary bones, and are not visible in any of the figures here given. They are small, with compressed, fluted crowns, which are separated from the roots by a more or less distinct neck. The premaxillary and the predentary bones are edentulous. A typical tooth of Stegosaurus, and one of an allied genus, Priconodon, are represented on Pl. XLIV, figs. 1 and 2.

The present skull belongs to the type specimen of a very distinct species, *Stegosaurus stenops*. The skull and nearly complete skeleton of this specimen, with most of the dermal armor in place, were found almost in the position in which the animal died.

This reptile was much smaller than those representing the other species of this genus. Its remains were found by Mr. M. P. Felch in the Atlantosaurus beds of the Upper Jurassic, in southern Colorado. In this geological horizon all known American forms of Stegosaurus have been discovered.

THE BRAIN

Little has been known hitherto of the brain in dinosaurs, but fortunately one specimen of Stegosaurus has the brain case well preserved and apparently without distortion. Figs. 3 and 4 of Pl. XLIV show the form and general characters of this brain cavity. The brain of this reptile was much elongated, and its most striking features were the large size of the optic lobes and the small cerebral hemispheres. The latter had a transverse diameter only slightly in excess of the medulla. The cerebellum was quite small. The optic nerve corresponded in size with the optic lobes. The olfactory lobes were of large size. As a whole, this brain was lacertilian rather than avian. A brain cast of a young alligator is given on Pl. LXXVII for comparison.

The contrast in the development of the cerebral region is marked, but in some other respects the correspondence is noteworthy.

In comparing the proportionate size of the brain of this living reptile with that of Stegosaurus, as given on the same plate, the result proves of special interest. The absolute size of the two brain casts is approximately as 1 to 10, while the bulk of the entire bodies, estimated from corresponding portions of each skeleton, was as 1 to 1,000. It follows that the brain of Stegosaurus was only $\frac{1}{100}$ that of the alligator, if the weight of the entire animal is brought into the comparison. If the cerebral *regions only of the two brains were compared the contrast* would be still more striking. This comparison gives, of course, only approximate results, and some allowance should be made for the proportionally larger brain in small animals.

The brain of *Stegosaurus ungulatus* is clearly of a lower type than that of Morosaurus, which, as the writer has shown, was several times smaller in diameter than the neural canal in its own sacrum. In the latter genus the brain was proportionally shorter, and the cerebral region better developed, as shown in the plate cited. The absolute size of this brain as compared with that of Stegosaurus is about 16 to 10, the brain of the alligator figured being regarded as 1. Taking again the body of the alligator as the unit, and Stegosaurus as 1,000, that of Morosaurus would be about 1,500. Stegosaurus had thus one of the smallest brains of any known land vertebrate. These facts agree fully with the general law of brain growth in extinct mammals and birds as made out by the writer.[1]

THE ANTERIOR VERTEBRÆ.

The vertebræ of Stegosaurus preserved all have the articular faces of their centra concave, although in some the depression is slight. They are all, moreover, without pneumatic or medullary cavities. On Pl. XLV a selection from the vertebral series of one skeleton is given, which shows the principal forms. Figs. 1 and 2 represent a median cervical. The other neck vertebræ have their centra of similar length, but the diameter increases from the axis to the last of the series. Some of the anterior cervicals have a small tubercle in the center of each end of the centra, a feature seen also in some of the caudals. All the cervicals supported short ribs.

The dorsal vertebræ have their centra rather longer and more or less compressed. The neural arch is especially elevated. The neural canal is much higher than wide. The head of the rib fits into a pit on the side of the neural arch. Figs. 3 and 4 of Pl. XLV represent a posterior dorsal with characteristic features. The ribs are massive, and are strengthened by their form, which is T-shaped in transverse section.

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[1] Odontornithes, a monograph on the extinct toothed birds of North America U S Geol Expl Fortieth Par, Vol VII, pp 8, 121, 1880 Dinocerata, a monograph of an extinct order of gigantic mammals Mon U S Geol Survey, Vol X, Author's Edition, pp 57-59, 1884

THE SACRUM

The true sacrum of Stegosaurus is composed of four well-coossified vertebræ. In fully adult animals the pelvic arch may be strengthened by the addition of one or more lumbar vertebræ, as in the specimen figured in Pl. XLVI, fig. 5, where two are firmly consolidated with the sacrum. The centra of the sacral vertebræ are solid, like the others in the column. Their neural arches are especially massive, and the spines have high and expanded summits. The transverse processes of the sacral vertebræ are stout vertical plates, which curve downward below and unite to meet the ilia. Each vertebra supports its own process, although there is a tendency to overlap in front. There is a gradual increase in size from the first to the last sacral vertebra, and the first caudal is larger than the last sacral. The neural cavity of the sacrum is described below.

THE CAUDAL VERTEBRÆ

The caudal vertebræ present the greatest diversity, both in size and form. The anterior caudals are the largest in the whole vertebral series, and are highly modified to support a portion of the massive dermal armor. The articular faces of their centra are nearly plane and very rugose. The neural spine has an enormous development, and its summit is expanded into a bifurcate rugose head. These caudals are very short, and their neural spines nearly or quite in apposition above. Their centra have no distinct faces for chevrons. The transverse processes are expanded vertically, and their extremities curve downward. Farther back the same general characters are retained, but the centra are more deeply cupped and the spines less massive. Figs. 5, 6, and 7 of Pl. XLV show anterior caudal vertebræ. The chevrons here have their articular ends separate and rest upon two vertebræ, as shown on the same plate.

In the median caudals, figs. 8 and 9, the spine has greatly diminished in height, and the faces for chevrons are placed on prominent tubercles on the postero-inferior surface. The lower margin of the front articular face is sharp and the chevrons do not meet it. In the more distal caudals the neural spine and zygapophyses are reduced to mere remnants, but the chevron facets remain distinct. These vertebræ, as well as those farther back, have their centra much compressed. The caudal vertebræ are remarkably uniform in length throughout most of the series.

THE SACRAL CAVITY.

During an investigation of one skeleton of this genus the writer found a very large chamber in the sacrum, formed by an enlargement of the spinal canal. This chamber was ovate in form, and strongly resembled the brain case in the skull, although very much larger, being at least twenty times the size of the cavity which contained the brain. This remarkable feature led to the examination of the sacra of several other individuals of Stegosaurus, and it was found that all had a similar large chamber in the same position. The form and proportions of this cavity are indicated in Pl. XLVI, figs. 2 and 3, which represent a cast of the entire neural canal inclosed in the sacrum. The large vaulted chamber, it will be observed, is contained mainly in the first and second sacral vertebræ, although the canal is considerably enlarged behind this cavity. The sections represented in fig. 4 are in each case made where the transverse diameters are greatest.

The remarkable feature about this posterior brain case, if so it may be called, is its size in comparison with that of the true brain of the animal, which is also indicated in the same plate, and in this respect it is entirely without a parallel. A perceptible swelling in the spinal cord of various recent animals has indeed been observed in the pectoral and pelvic regions, where the nerves are given off for the anterior and posterior limbs; and in extinct forms some very noticeable cases are recorded, especially in dinosaurs, but nothing that approaches the sacral enlargement in Stegosaurus has hitherto been known. The explanation may doubtless in part be found in the great development of the posterior limbs in this genus; but in some allied forms—Camptosaurus, for example, where the disproportion between the fore and hind limbs is quite as marked—the sacral enlargement of the spinal cord is not one-fourth as great as in Stegosaurus.

It is an interesting fact that in young individuals of Stegosaurus the sacral cavity is proportionately larger than in adults, which corresponds to a well-known law of brain growth.

The physiological effect of a posterior nervous center so many times larger than the brain itself is a suggestive subject which need not here be discussed It is evident, however, that in an animal so endowed the posterior part was dominant.

THE PELVIS

The ilium in Stegosaurus is a very peculiar bone, unlike any hitherto known in the reptiles. Its most prominent feature is its great anterior extension in front of the acetabulum. Another striking character is seen in its superior crest, which curves inward, and firmly unites with the neural arches of the sacrum, thus roofing over the cavities between the transverse processes. The acetabular portion of the ilium is large and shallow (Pl. XLVI, fig. 5). The face for union with the ischium is large and rugose, but that for the pubis is much less distinct. The postacetabular part of the ilium is very short, scarcely one-third as long as the anterior projection.

The ischium of *Stegosaurus ungulatus* is short and robust, and has a prominent elevation on the upper margin of the shaft (Pl. XLVIII, fig. 2). Its larger articular face meets a postacetabular process of the ilium, and a smaller articulation joins the pubis. The shaft of the ischium is twisted so that it resembles somewhat the corresponding bone of Morosaurus. The pelvis of *Stegosaurus stenops* is shown in the same plate, fig. 3.

The pubic element of the pelvis of *Stegosaurus ungulatus* is in general form somewhat like that of Camptosaurus. The prepubis consists of a strong spatulate process, projecting forward nearly horizontally. Its proximal end articulates with the preacetabular process of the ilium. The postpubic branch extends backward and downward, nearly to the end of the ischium. The two bones fit closely together in this region. The usual pubic foramen is in this species replaced by a notch, opening into the acetabular cavity. In a smaller species, *Stegosaurus affinis*, the postpubic bone is slender and more rod-like, not flattened as in the specimen here figured.

THE FORE LIMBS

On Pl. XLVII some of the bones of the scapular arch and anterior limbs of Stegosaurus are figured. The scapula and coracoid are of the true dinosaurian type. The former has its upper portion rather short and moderately expanded. The coracoid was closely united to the scapula by cartilage. It is perforated by the usual foramen, which in some cases may become a notch.

The humerus (fig. 3) is short and massive. It has a distinct head and a strong radial crest. The shaft is constricted medially, and is without any medullary cavity. The ulna (fig. 4) is also massive, and has a very large olecranal process. Its distal end is comparatively small. The radius is smaller than the ulna. The fore limb, as a whole, was very powerful and adapted to varied movements. There were five well-developed digits in the fore foot, as shown on Pl. XLVIII, fig. 1.

THE HIND LIMBS

The femur of Stegosaurus (Pl. XLVII, fig. 1) is by far the largest bone in the skeleton. It is remarkably long and slender. There is no distinct head, and the great trochanter is nearly or quite obsolete. The shaft is of nearly uniform width and very straight. There is no evidence of a third trochanter. The distal end of the femur is peculiar in having very flat condyles, with only a shallow depression between them. The external one has only a rudiment of the ridge which passes between the heads of the tibia and fibula, and is very characteristic of true dinosaurs and birds.

The tibia (fig. 2) is very much shorter than the femur. Its superior end is unusually flat, indicating that it met the condyles of the femur so as to bring the two bones at times nearly or quite into the same line. The shaft of the tibia is constricted medially, leaving a wide space between it and the fibula. The distal end of the tibia is blended entirely with the convex astragalus, so as to resemble strongly the corresponding part in birds.

The fibula (fig. 2) is slender, and has its smaller end above. This extremity is applied closely to the head of the tibia by a rugose suture, so as to unite readily with it. Its upper articular surface is nearly or quite on a level with that of the tibia. The distal end of the fibula is expanded, and in the specimen figured is firmly coossified with the calcaneum. The two coalesce with the tibia and astragalus, and form a smooth convex articulation for the ankle joint. There were only three functional digits in the hind feet, as shown on Pl. XLVIII, fig. 2.

THE DERMAL ARMOR

The most remarkable feature about Stegosaurus is the series of ossifications which formed its offensive and defensive armor. These consist of numerous spines, some of great size and power, and many bony plates of various sizes and shapes, well fitted for protecting the animal against assaults. Some of these plates are a meter, or more than 3 feet, in diameter.

The spines were of different forms and varied much in size. Four of these are represented on Pl. L. All of those preserved are unsymmetrical, and most of them are in pairs. One of the largest is shown in fig. 2, which gives the more usual form and proportions. This specimen is over 2 feet in length.

The osseous dermal covering of the Stegosauria was first described by the writer from specimens found associated with several skeletons, but not in place, and hence the position of the various parts was a matter of considerable doubt. Subsequent discoveries have shown the general arrangement of the plates, spines, and ossicles, and it is now evident that, while all the group were apparently well protected by offensive and defensive armor, the various species, and perhaps the sexes, differed more or less in the form, size, and number of portions of their dermal covering. This was especially true of the spines, which are quite characteristic in some members of the group, if not in all.

The skull was evidently covered above with a comparatively soft integument. The throat and neck below were well protected by small, rounded and flattened ossicles having a regular arrangement in the thick skin. One of these ossicles is shown in Pl. XLIX, fig. 1. The upper portion of the neck, back of the skull, was protected by plates, arranged in pairs on either side. These plates increased in size farther back, and thus the trunk was shielded from injury. From the pelvic region backward a series of huge plates stood upright along the median line, gradually diminishing in size to about the middle of the tail. One of these is shown in Pl. XLIX, fig. 4. Some of the species, at least, had somewhat similar plates below the base of the tail, and one of these bones is represented in fig. 3 of the same plate.

The offensive weapons of this group were a series of huge spines arranged in pairs along the top of the distal portion of the tail, which was elongate and flexible, thus giving effective service to the spines, as in the genus Myliobatis.

In *Stegosaurus ungulatus* there were four pairs of these spines, diminishing in size backward. Two of the larger of these are shown on Pl. L, figs. 2 and 3. In some other forms there were three pairs, and in *S. stenops* but two pairs have been found.

In one large species, *Stegosaurus sulcatus*, there is at present evidence of only one pair of spines. These are the most massive of any yet found, and have two deep grooves on the inner face, which distinguish them at once from all others known. One of these grooved spines is represented on Pl. L, figs. 4, 5, and 6.

The position of these caudal spines with reference to the tail is indicated in the specimen figured on Pl. LI, which shows the vertebræ, spines, and plate as found.

DIRACODON.

The American genera of the Stegosauria are Stegosaurus and Diracodon. Of the former there are several well-marked species besides *S armatus*, the type. Of the latter genus but one is known at present, *Diracodon laticeps*, the remains of which have hitherto been found at a single locality only, where several individuals referred to this species have been discovered. Aside from the form of the skull, these specimens have in the fore foot the intermedian and ulnar bones separate, while in Stegosaurus these carpals are firmly coossified.

All the American Stegosauridæ have the second row of carpals unossified and five digits in the manus. In the hind foot the astragalus is always coossified with the tibia, even in very young specimens, while the calcaneum is sometimes free. The second row of tarsals is not ossified in any of the known specimens. Only four digits in the hind foot are known with certainty, and one of these is quite small. All forms have at least three well-developed metatarsals, which are short and massive, but longer and much larger than the metacarpals.

In one large specimen, of which the posterior half of the skeleton was secured, no trace of dermal armor of any kind was found. If present during life, as indicated by the massive spines of the vertebræ, it is difficult to account for its absence when the remains were found, unless, indeed, the dermal covering had been removed after the death of the animal and previous to the entombment of the skeleton where found. In this animal the ilia were firmly coossified with the sacrum, thus forming a strong bony roof over the pelvic region, as in birds.

This specimen represents a distinct species, *Stegosaurus duplex.* It was originally referred by the writer to *S. ungulatus.* In the sacrum of this species each vertebra supports its own transverse process, or rib, as in the Sauropoda, while in *S. ungulatus* the sacral ribs have shifted somewhat forward, so that they touch, also, the vertebra in front, thus showing an approach to some of the Ornithopoda.

CHARACTERS OF STEGOSAURIA.

The large number of specimens of the Stegosauria now known from the American Jurassic, and the fine preservation of some of the remains, aid in forming a more accurate estimate of the relations of the group to the other dinosaurs than has hitherto been possible. The presence of a predentary bone, and the well developed postpubis, are important characters that point to the Ornithopoda as near allies, with a common ancestry. These positive characters are supplemented by some points in the structure of the skull and the form of the teeth.

There are, however, a large number of characters in which the Stegosauria differ from the Ornithopoda, and among these are the following:

(1) All the bones of the skeleton are solid.
(2) The vertebræ are all biconcave.
(3) All the known forms have a strong dermal armor.
(4) The second row of carpals and tarsals are unossified.
(5) The astragalus is coossified with the tibia
(6) The spinal cord was greatly enlarged in the sacral region.

RESTORATION OF STEGOSAURUS.

PLATE LII

In this restoration the animal is represented as walking, and the position is adapted to that motion. The head and neck, the massive fore limbs, and, in fact, the whole skeleton, indicate slow locomotion on all four feet. The longer hind limbs and the powerful tail show, however, that the animal could thus support itself, as on a tripod, and this position could perhaps have been easily assumed in consequence of the massive hind quarters.

In the restoration as here presented the dermal armor is the most striking feature, but the skeleton is almost as remarkable, and its high specialization was evidently acquired gradually as the armor itself was developed. Without the latter many points in the skeleton would be inexplicable, and there are still a number that need explanation.

The small, elongated head was covered in front by a horny beak. The teeth are confined to the maxillary and dentary bones, and are not visible in the figure here given. They are quite small, with compressed, fluted crowns, and indicate that the food of this animal was soft, succulent vegetation. The vertebræ are solid, and the articular faces of the centra are biconcave or nearly flat. The ribs of the trunk are massive and placed high above the centra, only the tubercle being supported on the elevated diapophysis. The neural spines, especially those of the sacrum and anterior caudals, have their summits expanded to aid in supporting the massive dermal armor above them. The limb bones are solid, and this is true of every other part of the skeleton. The feet were short and massive, and the terminal phalanges of the functional toes were covered by strong hoofs. There were five well-developed digits in the fore foot, and only three in the hind foot, the first toe being rudimentary and the fifth entirely wanting.

In life the animal was protected by a powerful dermal armor, which served both for defense and offense. The throat was covered by a thick skin, in which were embedded a large number of rounded ossicles, as shown in the plate. The gular portion represented was found beneath the skull, so that its position in life may be regarded as definitely settled. The series of vertical plates which extended above the neck, along the back, and over two thirds of the tail, is a most remarkable feature, which could not have been anticipated and would hardly have been credited had not the plates themselves been found in position. The four pairs of massive spines characteristic of the present species, which were situated above the lower third of the tail, are apparently the only part of this peculiar armor used for offense. In addition to the portions of armor above mentioned there was a pair of small plates just behind the skull, which served to protect this part of the neck. There were also, in the present species, four flat spines, which were probably in place below the tail, but as their position is somewhat in doubt they are not represented in the present restoration

All these plates and spines, massive and powerful as they now are, were in life protected by a thick, horny covering, which must have greatly increased their size and weight. This covering is clearly indicated by the vascular grooves and impressions which mark the surface of both plates and spines, except their bases, which were evidently implanted in the thick skin.

The peculiar group of extinct reptiles named by the writer the Stegosauria, of which a typical example is represented in the present restoration, is now nearly as well known as any other dinosaurs. They are evidently a highly specialized suborder of the Predentata, which have the Ornithopoda as their most characteristic members, and all doubtless had a common ancestry.

Another highly specialized branch of the same great order is seen in the gigantic Ceratopsia of the Cretaceous, which the writer has recently investigated and made known. The skeleton of the latter group presents many interesting points of resemblance to that of the Stegosauria, which can hardly be the result of adaptation alone, but the wide difference in the skull and in some parts of the skeleton indicates that their affinities are remote. A comparison of the present restoration with that of Triceratops on Pl. LXXI will make the contrast between the two forms clearly evident.

DISTRIBUTION OF STEGOSAURIA.

All the typical members of the Stegosauria are from the Jurassic formation, and the type specimen used in the present restoration was found in Wyoming, in the Atlantosaurus beds of the upper Jurassic. Diracodon, a genus nearly allied to Stegosaurus, occurs in the same horizon. Palæoscincus Leidy, 1856, from the Cretaceous, and Priconodon of the writer, 1888, from the Potomac formation, are perhaps allied forms of the Stegosauria, but until additional remains are found their exact affinities can not be determined. Apparently the oldest known member of this group in America is the Dystrophæus Cope, 1877, from the Triassic of Utah.

One of the best-preserved specimens of the Stegosauria in Europe was described by Owen, in 1875, as *Omosaurus armatus*, and the type specimen is in the British Museum. It is from the Kimmeridge clay (Upper Jurassic) of Swindon, England The skull is wanting, but the more important parts of the skeleton are preserved. Various portions of the skeleton of several other individuals have also been found in England, but the skull and teeth still remain unknown.

Another genus of the Stegosauria, representing a distinct family, is Scelidosaurus, established by Owen in 1859, from the Lias of England. The greater part of the skeleton is known. A restoration in outline, made by the writer for comparison with that of Stegosaurus, is shown on Pl. LXXXIII. The Euskelesaurus of Huxley, 1867, from the Trias of South Africa, is apparently a member of this group.

CAMPTOSAURIDÆ.

Another important family of Jurassic Dinosaurs is the Camptosauridæ, so named from the type genus Camptosaurus, described by the writer in 1879, the type specimen being from the Atlantosaurus beds of Wyoming. This genus includes several species of herbivorous dinosaurs, which belong to the true Ornithopoda, or bird-footed forms. The species were all bipedal, with the fore limbs much smaller than those behind, and all the limb bones light and hollow. The head was comparatively small, the neck of moderate length and quite flexible, and in life the animals were evidently agile and graceful in movement. Some of the smaller species were quite bird-like in form and structure. The three American genera, Camptosaurus, Dryosaurus, and Laosaurus, are all from the same general horizon.

CAMPTOSAURUS.

The large dinosaur described by the writer as *Camptosaurus dispar*, of which a restoration is given on Pl. LVI, is now so well known that it may be taken as a form typical of the group. It is exceeded in size by *Camptosaurus amplus* Marsh, but there are at least two smaller species of the genus (*C. medius* and *C. nanus*). So far as at present known these species are found in successive deposits of the same general horizon, the smallest below and the largest above.

Camptosaurus amplus is represented by remains which show that this reptile when alive was about 30 feet in length. The type specimen of *C. dispar* was about 20 feet in length and 10 feet in height. *C. medius* was about 15 feet long. The smallest species of the genus, *C. nanus*, was not more than 10 feet in length, and perhaps 6 feet in height when standing at rest. One of the striking features of this diminutive species is its long sigmoid scapula, shown in fig. 2, Pl. LV. This is in strong contrast with the short, straight scapula of *C. dispar*, seen on Pl. LIV, fig. 1. The limb bones of all the species of this genus are very hollow.

The skull, brain, and teeth of *C. medius* are shown on Pl. LIII. The peculiar peg-and-notch articulation in the sacral vertebræ of this genus, already described elsewhere, is indicated on Pl. LIV, figs. 3 and 4, and a summary of the principal characters of the genus, and of the nearest allied genera, will be found on p. 201.

RESTORATION OF CAMPTOSAURUS.

PLATE LVI

The restoration here given is based upon the type specimen of *Camptosaurus dispar*, one of the most characteristic forms of the great group Ornithopoda, or bird-footed dinosaurs. The reptile is represented on Pl. LVI, one-thirtieth natural size. The position chosen was determined after a careful study not only of the type specimen, but of several others in excellent preservation, belonging to the same species or to others nearly allied. It is therefore believed to be a position frequently assumed by the animal during life, and thus, in some measure, characteristic of the genus Camptosaurus. The type specimen of the present species, when alive, was about 20 feet in length, and 10 feet high in the position here represented.

The genus Camptosaurus is a near ally of Iguanodon of Europe, and may be considered its American representative. Camptosaurus, however, is a more generalized type, as might be expected from its lower geological horizon. It resembles more nearly some of the Jurassic forms in England generally referred to Iguanodon, but as these are known only from fragmentary specimens their generic relations with Camptosaurus can not now be determined with certainty.

In comparing Camptosaurus, as here restored, with a very perfect skeleton of Iguanodon from Belgium, as described and figured, various points of difference as well as of resemblance may be noticed. The skull of Camptosaurus had a sharp, pointed beak, evidently encased during life in a horny sheath. This was met below by a similar covering, which inclosed the predentary bone. The entire front of the upper and lower jaws was thus edentulous, as in Iguanodon, but of different shape. The teeth of the two genera are of similar form, and were implanted in like manner in the maxillary and dentary bones. In Camptosaurus there is over each orbit a single supraorbital bone, curving outward and backward, with a free extremity, as in the existing monitor, a feature not before observed in any other dinosaur except Laosaurus, an allied genus, also from the Jurassic of America. Other portions of the skull of Camptosaurus, as well as the hyoid bones, appear to agree in general with those of Iguanodon.

The vertebræ of Camptosaurus are similar in many respects to those of Iguanodon, but differ in some important features In the posterior dorsal region the transverse processes support both the head and tubercle of the rib, the head resting on a step, as in existing crocodiles. The five sacral vertebræ, moreover, are not coossified even in adult forms, and to this character the name Camptonotus, first given to the genus by the writer in 1879, especially refers. Another notable feature of the sacral vertebræ of the type specimen should be mentioned. The vertebræ of the sacrum, especially the posterior four, are joined to each other by a peculiar peg and-notch articulation. The floor of the neural canal of each vertebra is extended forward into a pointed process (somewhat like an odontoid process), which fits into a corresponding cavity of the centrum in front. This arrangement, while permitting some motion between the individual vertebræ, helps to hold them in place, thus compensating in a measure for absence of anchylosis. A similar method of articulation is seen in the dermal scales of some ganoid fishes, but so far as the writer is aware nothing of the kind has been observed before in the union of vertebræ.

In Camptosaurus the sternum was entirely unossified, and no trace of clavicles has been found. The pelvis of Camptosaurus differs especially from that of Iguanodon in the pubis, the postpubic branch being even longer than the ischium, while in Iguanodon this element is much shortened.

In the fore foot of Camptosaurus there were five functional digits, the first being flexible and nearly parallel with the second, thus differing from the divergent, stiff thumb of Iguanodon. The hind feet had each three functional digits only, the first being rudimentary and the fifth entirely wanting, as shown in Pl. LVI. The entire skeleton of Camptosaurus was proportionately more slender and delicately formed than that of Iguanodon, although the habits and mode of life of these two herbivorous dinosaurs were doubtless very similar.

The type specimen of *Camptosaurus dispar*, used as the basis of the present restoration, is from the Atlantosaurus beds of the Upper Jurassic of Wyoming. This species and other allied forms will be described in full in an illustrated memoir now in preparation by the writer for the United States Geological Survey. The present restoration is reduced from a large drawing made for that volume.

LAOSAURIDÆ.

DRYOSAURUS.

Another genus of Jurassic dinosaurs, allied to Camptosaurus, but differing from it in many important respects, is Dryosaurus. The type was described by the writer in 1878 under the name *Laosaurus altus*, and a tooth, the pelvis, and a hind leg were also figured. Additional material since received shows that this genus is quite distinct from Laosaurus, to which it was at first referred, and is intermediate between Camptosaurus and that genus, as is shown in a summary of the characters of these genera given later in the present article.

The only species of Dryosaurus at present known is the type first described, and this form is now called *Dryosaurus altus* (Pl. LV, fig. 4). Several specimens of this dinosaur are preserved in the Yale museum, and they show it to have been in life about 10 or 12 feet long, and one of the most slender and graceful members of the group. The known remains are all from the Atlantosaurus beds of Colorado and Wyoming.

LAOSAURUS.

The present genus includes several species of diminutive dinosaurs, all much smaller than those above described, and possessing many features now seen only in existing birds, especially in those of the ostrich family. The two species of the genus first described by the writer (*Laosaurus celer*, the type, and *Laosaurus gracilis*) show these avian features best of all, and it would be difficult to tell many of the isolated remains from those of birds. A larger species, which has been called *Laosaurus consors*, is known by several skeletons nearly complete. The type specimen, here figured in part on Pl. LV, figs. 1 and 3, is the most perfect of all, and this was collected by the writer in 1879. The animal when alive was about 8 or 10 feet in length. The known remains are from the Atlantosaurus beds of Wyoming.

One of the distinctive features of this genus, which separates it at once from those above described, is the pubis. The prepubis, or anterior branch of this bone, which was very large and broad in Camptosaurus, still long and spatulate in Dryosaurus, is here reduced to a pointed process not much larger than in some birds. These differences are shown in Pl. LIV and in Pl. LV, figs. 3 and 4.

The European representative of Laosaurus is Hypsilophodon Huxley, from the Wealden of England. That genus, however, differs from the nearest allied forms of this country in several well-marked characters. Among these the presence of teeth in the premaxillary bones and a well-ossified sternum are features not seen in American Jurassic forms. The fifth digit of the manus, moreover, in Hypsilophodon is almost at right angles to the others, and not nearly parallel with them, as in Dryosaurus. It agrees with the latter genus in having the tibia longer than the femur. An outline restoration of Hypsilophodon, made by the writer for comparison with allied American forms, is given on Pl. LXXXIV

NANOSAURIDÆ.

NANOSAURUS.

The smallest known dinosaur, representing the type species of the present genus, was described by the writer in 1877, under the name *Nanosaurus agilis*. The type specimen consists of the greater portion of the skull and skeleton of one individual, with the bones more or less displaced and all entombed in a slab of very hard quartzite. The whole skeleton was probably thus preserved in place, but before its discovery a part of the slab had been split off and lost. The remaining portion shows on the split surface many important parts of the skeleton, and these have been further exposed by cutting away the matrix, so that the main characters of the animal can be determined with considerable certainty.

A study of these remains shows that the reptile they represent was one of the typical Ornithopoda, and one of the most bird-like yet discovered. A dentary bone in fair preservation (fig. 42) indicates that the animal was herbivorous, and the single row of pointed and compressed teeth, thirteen in number and small in size, forms a more regular and uniform series than in any other member of the group. The ilium, also, shown in fig. 43, is characteristic of the Ornithopoda, having a slender, pointed process in front, but one much shorter than in any of

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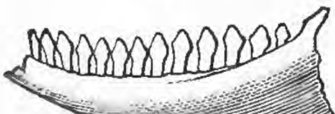

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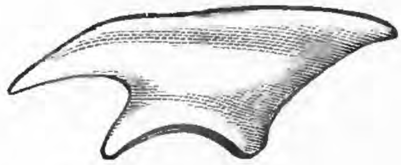

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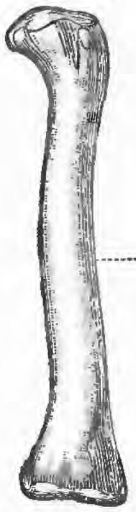

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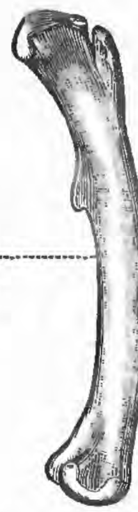

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FIG. 42.—Dentary bone of *Nanosaurus agilis* Marsh; seen from the left.
FIG. 43.—Ilium of same individual; left side.
Both figures are natural size.
FIG. 44.—Left femur of *Nanosaurus rex* Marsh; front view.
FIG. 45.—Proximal end of same.
FIG. 46.—The same bone; side view.
FIG. 47.—The same; back view.
FIG. 48.—Distal end of same.
All five figures are one-half natural size.

the larger forms. The posterior end is also of moderate size. All the bones of the limbs and feet are extremely hollow, strongly resembling in this respect those of birds. The femur was shorter than the tibia. The metatarsals are greatly elongated and very slender, and there were probably but three functional toes in the hind foot.

A second form referred by the writer to this genus, under the name *Nanosaurus rex*, may perhaps belong to the genus Laosaurus. The femur is shown in figs. 44 to 48, above. The animal thus represented was considerably larger than the present type species and from a somewhat higher horizon in the Atlantosaurus beds.

The type specimen here described, which pertained to an animal about half as large as a domestic fowl, was found in Colorado. This reptile was a contemporary of the carnivorous Hallopus, likewise one of the most diminutive of dinosaurs, and one of the most remarkable.

DETERMINATION OF GENERA

The various dinosaurs thus briefly referred to under their respective genera have many other points of interest that can not be here discussed, but their resemblance to birds is worthy of some notice. This is apparent in all of them, but in the diminutive forms the similarity becomes more striking. In all the latter the tibia is longer than the femur, a strong avian character, and one seen in dinosaurs only in the small bird-like forms.[1] In Nanosaurus nearly all, if not all, the bones preserved might have pertained to a bird, and the teeth are no evidence against this idea. In the absence of feathers an anatomist could hardly state positively whether this was a bird-like reptile or a reptilian bird.

The main characters of the four genera above discussed are as follows:

CAMPTOSAURUS.

Premaxillaries edentulous, with horny beak. Teeth large, irregular, and few in number. A supraorbital fossa. Cervical vertebræ long and opisthocœlous. Lumbars present. Five vertebræ in sacrum, with peg-and-notch articulation. Sternum unossified. Limb bones hollow. Fore limbs small. Five functional digits in manus. Prepubis long and broad; postpubis elongated. Femur longer than tibia. Metatarsals short. Three functional digits in pes, the first rudimentary and the fifth wanting.

DRYOSAURUS.

Premaxillaries edentulous, with horny beak. Teeth of moderate size. A supraorbital fossa. Cervicals long and biconcave. No lumbars. Six coossified vertebræ in sacrum, without peg-and-notch articulation. Sternum unossified. Limb bones hollow. Fore limbs very small. Five digits in manus. Prepubis long and narrow; postpubis elongate and slender. Posterior limbs very long. Femur shorter than tibia. Metatarsals long and hollow. First digit in pes complete; fifth metatarsal represented by short splint only.

LAOSAURUS.

Premaxillaries edentulous. Teeth small and irregular. Cervicals short and flat. Six coossified vertebræ in sacrum; no peg-and-notch articulation. Sternum unossified. Fore limbs small. Limb and foot bones hollow. Prepubis very short and pointed; postpubis slender. Femur shorter than tibia. Metatarsals elongate. First digit in pes functional; fifth rudimentary.

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[1] Besides the genera here mentioned, Cœlurus, Compsognathus and Hallopus also possess this character

NANOSAURUS.

Teeth compressed and pointed, and in a single uniform row. Cervical and dorsal vertebræ short and biconcave. Sacral vertebræ three (?). Anterior caudals short. Ilium with very short, pointed front and narrow posterior end. Fore limbs of moderate size. Limb bones and others very hollow. Femur curved and shorter than tibia. Fibula pointed below. Metatarsals very long and slender.

The genera thus defined contain all the known forms of the typical Ornithopoda from the American Jurassic. They are, moreover, the earliest representatives of this group known in this country from osseous remains, as such fossils have not yet been found in the Triassic, where the oldest dinosaurs occur. Some of the bird-like footprints in the Connecticut River sandstone may indeed have been made by dinosaurs of this group, but there is no positive evidence on this point. The American Cretaceous forms of the typical Ornithopoda, so far as at present known, are all of large size and highly specialized, and this appears to be true also of the Old World species.

RESTORATION OF LAOSAURUS.

PLATE LVII.

The present restoration in outline of *Laosaurus consors*, one-tenth natural size, will serve to show the form and proportions of one of the most bird-like of the smaller Jurassic Ornithopoda and its contrast with the more massive Camptosaurus from the same horizon. A comparison of this restoration with that of Hypsilophodon from the English Wealden (Pl. LXXXIV) is especially instructive, as the two animals were near allies, although from different geological horizons.

The position here chosen for the restoration of Laosaurus is one which would seem to have been natural to the animal when standing at rest. This would mean a height of about 4 feet, with 8 feet in length. That the animal was bipedal in its usual locomotion on land is assumed in this case from the general structure, especially the very small and weak fore limbs, and the large size and strong articulations of the posterior limbs. When walking upright, as here represented, it seems probable that the animal would touch the ground with its tail; but this is by no means certain. That reptiles of similar structure and proportions could walk on their hind feet without leaving a mark of the tail is clearly indicated by many long series of bipedal footprints left in the sandstone of the Connecticut Valley, some of which have already been described and figured in this paper. In the present species the tail was powerful and more or less compressed, thus suggesting its use in swimming.

PART III.

CRETACEOUS DINOSAURS.

During Cretaceous time in North America the dinosaurs were still abundant, and most of them were much more specialized than those that lived in the preceding periods. Some of the Cretaceous forms were the strangest of the whole group, of gigantic size and bizarre appearance. Others were diminutive in size and so bird-like in form and structure that their remains can be distinguished with difficulty, if at all, from those of birds.

Of the carnivorous dinosaurs known from Cretaceous deposits the family Dryptosauridæ is especially conspicuous, on account of the large size and ferocious nature of all its representatives. In the later Cretaceous a second family, the Ornithomimidæ, was also abundant, and among its members were some of the most minute and bird-like of dinosaurs hitherto discovered. Of the herbivorous forms the huge, horned Ceratopsidæ, the most remarkable of all dinosaurs, were for a limited period the dominant reptiles in western North America. Living at the same time with these were the Claosauridæ, large bipedal dinosaurs, of sluggish disposition, that dwelt along the shores of the lakes and rivers of that time. Besides these were still others related to the Jurassic Stegosaurus, among them the Nodosauridæ, quadrupedal forms with heavy dermal armor. All these became extinct at the close of the Cretaceous, and no remains of dinosaurs have been found in place in any later deposits.

THEROPODA

DRYPTOSAURIDÆ.

This family is well represented throughout the Cretaceous in North America, but up to the present time only fragmentary remains have been found, so that little is known about the skull, pelvis, and feet, the most characteristic portions of the skeleton. So far as now determined they appear to be nearly allied to Megalosaurus of Europe and include Allosaurus from the Jurassic of this country.

Remains of the genus Dryptosaurus (Lælaps) have been found at various localities on the Atlantic Coast, especially in the marl region of New Jersey. Many of these fossils have been described by Prof. Cope.[1]

ORNITHOMIMIDÆ.

This family can be separated sharply from all other dinosaurs by the hind feet, which contain three functional metatarsals, the middle one, or third, of which has its proximal end much diminished in size and crowded backward behind the second and fourth, as in many existing birds.

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[1] Extinct Batrachia, Reptilia, and Aves of North America, p 100, 1870

Another important character, seen also in the genus Ceratosaurus of the Jurassic, is found in the pelvis, the bones of which are firmly coossified with each other and with the sacrum.

ORNITHOMIMUS.

The most marked characters of the genus Ornithomimus already determined are manifest in the limbs and feet, and these have been selected for description in the present article. A typical example is shown on Pl. LVIII, figs. 1-4, which is the type specimen, the species being *Ornithomimus velox* Marsh.

On the distal part of the tibia represented in fig. 1 the astragalus is seen in place, with a very large ascending process, larger than in any dinosaur hitherto known. The calcaneum is also shown in position, but the slender fibula is absent. This bone was complete, but of little functional value. The tibia and all the larger limb bones were hollow, with thin walls, as indicated in the section, fig. 1, *c*.

In fig. 5 the corresponding parts of a young ostrich are shown for comparison. The slender, incomplete fibula is in place beside the tibia. The astragalus with its ascending process, and the distinct calcaneum, are also shown in position. The almost exact correspondence of these different parts in the bird and reptile will be manifest to every anatomist.

THE METATARSALS

The most striking feature of the foot belonging with the reptilian tibia is shown in the metatarsals represented in fig. 2, *A*. These are three in number, and are in the same position as in life. They are the three functional metatarsals of the typical Ornithopoda and of birds. The distal ends of these bones correspond in size and relative position in the two groups, but here, in the present specimen, the reptilian features cease, and those of typical birds replace them. In all the reptiles known hitherto, and especially in dinosaurs, the second, third, and fourth metatarsals are prominent in front, at their proximal ends, and the third is usually the largest and strongest. In birds the place of the third is taken above by the second and fourth, the third being crowded backward and very much diminished in size.

This character is well shown in fig. 6, which represents the second, third, and fourth metatarsals of a young turkey, with the tarsal bones absent. In the reptilian metatarsals seen in fig. 2 the same arrangement is shown, with the tarsals in place. The second and fourth metatarsals have increased much in size in the upper portion, and meet each other in front.

The third metatarsal, usually the largest and the most robust throughout, here diminishes in size upward, and takes a subordinate, posterior position, as in birds. The correspondence between the metatarsals of the bird and reptile are here as strongly marked as in the tibiæ and their accompanying elements, above described.

In fig. 3 of the plate the three phalanges represented belong with the second metatarsal, and were found together in place.

The three metacarpals represented in fig. 4 were found together in position, near the remains of the hind limb here described. Their very small size is remarkable, and they may possibly belong to a smaller individual, but with this exception there is no reason why they do not pertain to the same specimen as the hind foot. The remains of this species were found by George L. Cannon, jr., in the Ceratops beds of Colorado.

THE PELVIC ARCH.

A larger species from the same horizon, *Ornithomimus sedens*, more recently described by the writer, is based upon the nearly complete

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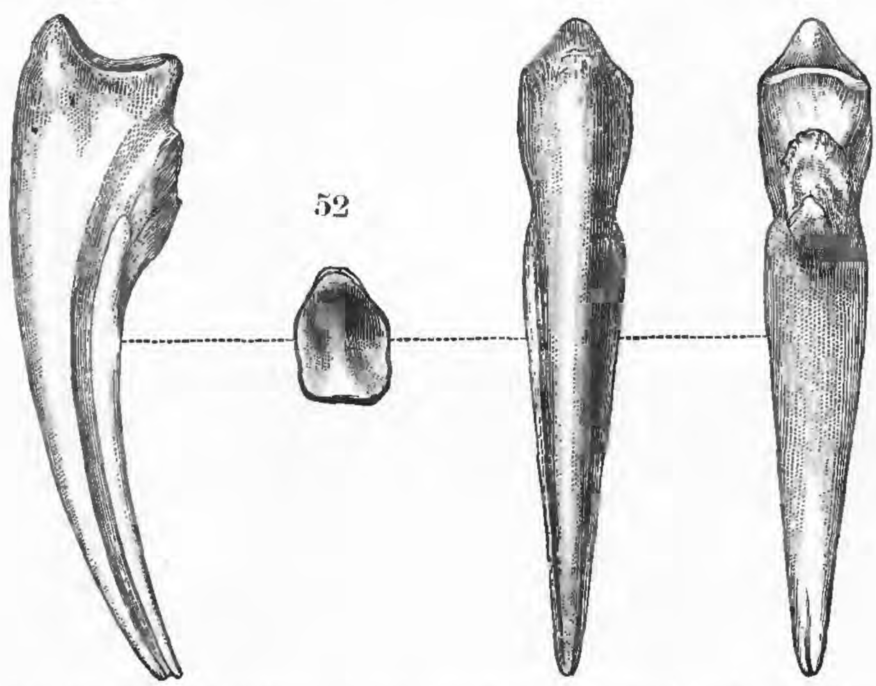

FIG. 49.—Terminal phalanx, manus of *Ornithomimus sedens* Marsh; side view.
FIG. 50.—The same phalanx; front view.
FIG. 51.—The same; back view.
FIG. 52.—Proximal end of same.
All the figures are one-half natural size.

pelvis, with various vertebræ, and some other parts of the skeleton. The most striking feature of the pelvis is the fact that the ilium, ischium, and pubis are firmly coossified with one another, as in recent birds. This character has been observed hitherto among dinosaurs only in the genus Ceratosaurus, described by the writer from the Jurassic of Wyoming. The present pelvis resembles that of Ceratosaurus in its general features, but there is no foramen in the pubis.

There are five vertebræ in the sacrum, firmly coossified with one another, as are also the sacral spines. The sacral vertebræ are grooved below, with the sides of the centra excavated. The caudals have the diplosphenal articulation, and the first caudal bears a chevron. All the bones preserved are very delicate, and some of them, at least, are apparently pneumatic. The sacrum measures 15 inches in length, and the twelve caudals following occupy a space of 31 inches. The known remains indicate a reptile about 8 or 10 feet in length. A terminal phalanx of the fore foot is represented on page 205.

In the same horizon occur the remains of a very minute species, which agrees in all its characters, so far as determined, with the members of this genus. The most characteristic portions secured are the metatarsal bones, and these show the same features exhibited in the type species of the genus, *O velox.* They are, however, so much smaller as to suggest that they may pertain to a bird. Various portions of the second, third, and fourth metatarsals are known, and the distinctive feature is seen in the third, which has the upper part of the shaft so attenuated that it may not reach to the tarsus. The second and fourth metatarsals are very long and slender. This unique animal was about the size of the common fowl. The species has been called *Ornithomimus minutus.*

The large species described by the writer as *Ornithomimus grandis* belongs in essentially the same horizon. Portions of two other skeletons have since been obtained, which apparently pertain to this species. In one of these the femur, tibia, and fibula are in good preservation, and they clearly demonstrate that this reptile was one of the largest of the Theropoda The femur and tibia have each a very large cavity in the shaft, with well-defined walls. Even the fibula has a cavity in its upper portion. In the other specimen the second metatarsal is in fair preservation and shows the same form as in the type of the genus.

There is much probability that this gigantic carnivore was one of the most destructive enemies of the herbivorous Ceratopsidæ, next to be described.

PREDENTATA

CERATOPSIDÆ

The huge horned dinosaurs, from the Cretaceous, recently described by the writer,[1] have now been investigated very carefully, and much additional light has been thrown upon their structure and affinities. A large amount of new material has been secured, including several skulls, nearly complete, as well as various portions of the skeleton.

CERATOPS BEDS.

The geological deposits, also, in which their remains are found have been carefully explored during the last few years, and the known localities of importance examined by the writer, to ascertain what other fossils occur in them and what were the special conditions which preserved so many relics of this unique fauna. The definite horizon in which these strange reptiles occur has been called by the writer the Ceratops beds, from the type genus Ceratops, and its position is shown in the section on page 145.

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[1] *American Journal of Science,* 1888-1894

This geological horizon is a distinct one in the upper Cretaceous, and is indicated for more than 800 miles along the eastern flank of the Rocky Mountains. It is marked at nearly every outcrop by remains of these reptiles, and hence the strata containing them have been called the Ceratops beds. They are fresh-water or brackish deposits which form a part of the so-called Laramie, but are below the uppermost beds referred to that group. In some places, at least, they rest upon marine beds, which contain invertebrate fossils characteristic of the Fox Hills deposits. The most important localities in the Ceratops beds are in Wyoming, especially in Converse County.

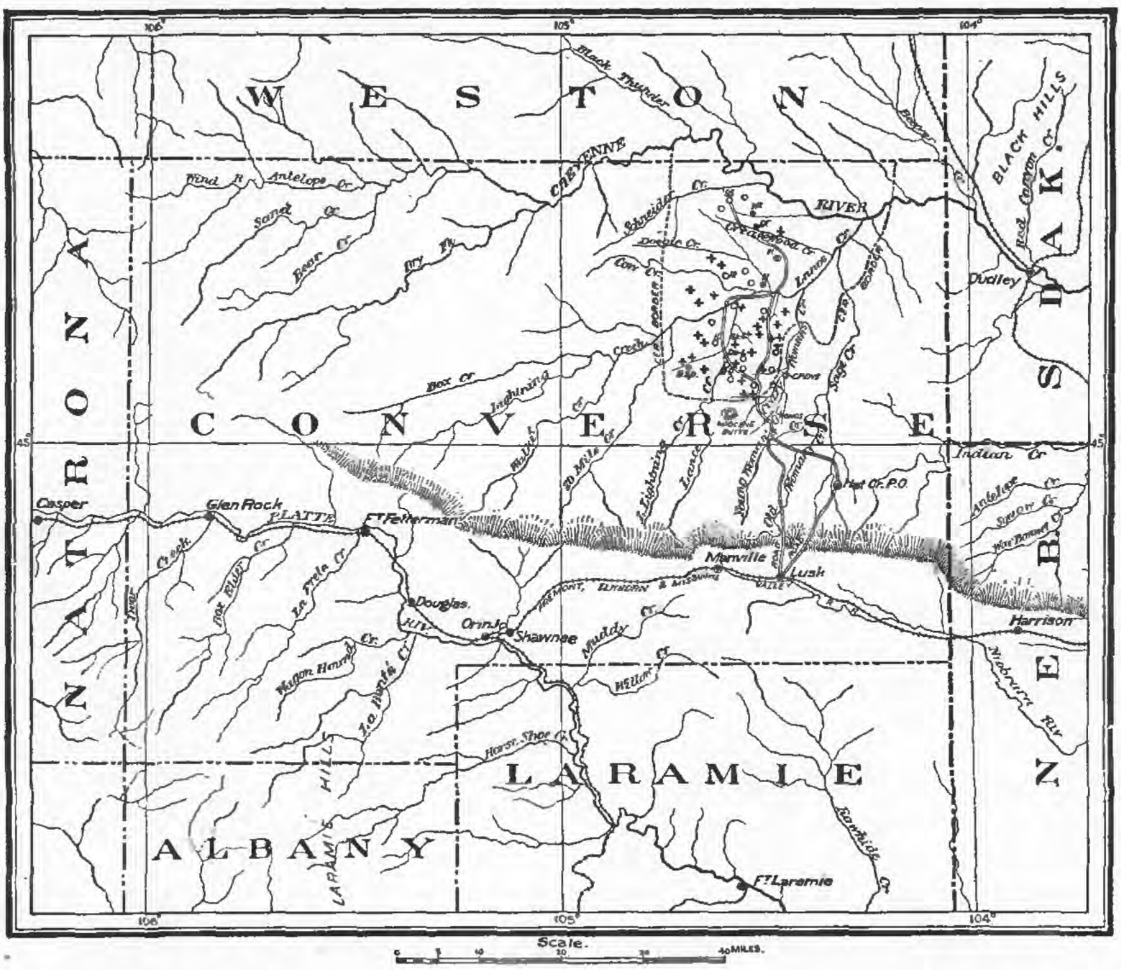

FIG. 53.—Map of Converse County, Wyoming; showing localities where skulls of the Ceratopsidæ have been discovered.

The position of each skull is indicated by a cross (+), and more than thirty of these specimens were found within the area bounded by the Cheyenne River and the dotted line. The localities given are based upon field notes made by Mr. J. B. Hatcher.

The fossils associated with the Ceratopsidæ are mainly dinosaurs, representing one or two orders and several families. Plesiosaurs, crocodiles, and turtles, of Cretaceous types, and many smaller reptiles, have left their remains in the same deposits. Numerous small mammals, also of ancient types, a few birds, and many fishes, are likewise entombed in this formation. Invertebrate fossils and plants are not uncommon in the same horizon.

TRICERATOPS.

THE SKULL

The skull of Triceratops, the best-known genus of the family, has many remarkable features. First of all, its size, in the largest individuals, exceeds that of any land animal hitherto discovered, living or extinct, and is surpassed only by that of some of the cetaceans. The skull represented (one-ninth natural size) on Pl. LIX is one of the most perfect yet discovered. Those shown on Pl. LX, figs. 1-3, are both of comparatively young animals, but are about 6 feet in length. The type specimen of *Triceratops horridus* was an old individual, and the head, when complete, must have been 7 or 8 feet long. Two other skulls, nearly perfect, from the same horizon, have equal or still greater dimensions

Another striking feature of the skull is its armature. This consisted of a sharp, cutting beak in front, a strong horn on the nose, a pair of very large pointed horns on the top of the head, and a row of sharp projections around the margin of the posterior crest. All these had a horny covering of great strength and power. For offense and defense they formed together an armor for the head as complete as any known. This armature dominated the skull, and in a great measure determined its form and structure. In some forms the armature extended over portions of the body.

The skull itself is wedge-shaped in form, especially when seen from above. The facial portion is very narrow, and much prolonged in front. In the frontal region the skull is massive and greatly strengthened, to support the large and lofty horn cores which formed the central feature of the armature. The huge, expanded, posterior crest, which overshadowed the back of the skull and neck, was evidently of secondary growth, a practical necessity for the attachment of the powerful ligaments and muscles that supported the head (Pl. LX, figs. 2 and 4).

THE ROSTRAL BONE.

The front part of the skull shows a very high degree of specialization, and the lower jaws have been modified in connection with it. In front of the premaxillaries there is a large, massive bone not before seen in any vertebrate, which the writer has named the rostral bone (*os rostrale*). It covers the anterior margin of the premaxillaries, and its sharp inferior edge is continuous with their lower border. This bone is much compressed, and its surface is very rugose, showing that it was covered with a strong, horny beak. It is a cartilage ossification, and corresponds to the predentary bone below.

The latter in Triceratops is also sharp and rugose, and likewise was protected by a strong, horny covering. The two together closely resemble the beak of some turtles, and as a whole must have formed a most powerful weapon of offense.

In one skull figured (Pl. LX, fig. 1) the rostral bone was free, and was not obtained. This was also true of the predentary bone and the nasal horn core. Hence these parts are represented in outline, taken from another specimen in which they are all present and in good preservation. In another skull represented (Pl. LIX, and Pl. LXI, figs. 1-3), the rostral bone and nasal horn core are in position and firmly coossified with the adjoining elements.

The premaxillary bones are large and much compressed transversely. Their inner surfaces are flat and meet each other closely on the median line. In old specimens they are firmly coossified with each other and with the rostral bone. Each sends upward a strong process to support the massive nasals. Another process, long and slender, extends upward and backward, forming a suture with the maxillary behind, and uniting in front with a descending branch of the nasal. The premaxillaries are much excavated externally for the narial aperture, and form its lower margin. They are entirely edentulous.

The maxillaries are thick, massive bones of moderate size, and subtriangular in outline when seen from the side. Their front margin is bounded mainly by the premaxillaries. They meet the prefrontal and lachrymal above, and also the jugal. The alveolar border is narrow and the teeth are small, with only a single row in use at the same time.

The nasal bones are large and massive, and greatly thickened anteriorly to support the nasal horn core. In two of the skulls figured these bones are separate, but in older individuals they are firmly coossified with each other and with the frontals. The nasal horn core ossifies from a separate center, but in adult animals it unites closely with the nasals, all traces of the connection being lost. It varies much in form in different species.

THE HORN CORES

The frontal bones are quite short and early unite with each other and with the adjoining elements, especially those behind them. The frontal or central region of the skull is thus greatly strengthened to support the enormous horn cores which tower above. These elevations rest mainly on the postfrontal bones, but the supraorbitals and the postorbitals are also absorbed to form a solid foundation for the horn cores.

These horn cores are hollow at the base (Pl. LX, fig. 3), and in general form, position, and external texture agree with the corresponding parts of the Bovidæ. They vary much in shape and size in different species. They were evidently covered with massive, pointed horns, forming most powerful and effective weapons.

The orbit is at the base of the horn core, and is surrounded, especially above, by a very thick margin. It is oval in outline and of moderate size.

The postfrontal bones are very large, and meet each other on the median line. Posteriorly they join the squamosals and the parietals. At their union with the latter there is a median foramen (Pl. LX, fig. 3, *x*), which may correspond to the so-called "parietal foramen." In old individuals it is nearly or quite closed. When open it leads into a large sinus, extending above the brain case into the cavities of the horn cores. This foramen has not before been observed in dinosaurs.

THE POSTERIOR CREST

The enormous posterior crest is formed mainly by the parietals, which meet the postfrontals immediately behind the horn cores. The posterior margin is protected by a series of special ossifications, which in life had a thick horny covering. These peculiar ossicles, which extend around the whole crest, the writer has called the epoccipital bones (Pl. LX, figs 1–3, *e*, and Pl. LXI, fig. 8, *e*). In old animals they are firmly coossified with the bones on which they rest.

The lateral portions of the crest are formed by the squamosals, which meet the parietals in an open suture. Anteriorly they join the postfrontal elements, which form the base of the horn core, and laterally they unite with the jugals. The supratemporal fossæ lie between the squamosals and the parietals.

BASE OF SKULL

The base of the skull has been modified in conformity with its upper surface The basioccipital is especially massive, and strong at every point. The occipital condyle is very large, and its articular face nearly spherical, indicating great freedom of motion. The basioccipital processes are short and stout. The basipterygoid processes are longer and less robust.

The foramen magnum is very small, scarcely one-half the diameter of the occipital condyle. The brain cavity is especially diminutive, smaller in proportion to the skull than in any other known reptile.

The exoccipitals are also robust, and firmly coossified with the basioccipitals They form about three-fourths of the occipital condyle, as in some of the chameleons. The supraoccipital is very small, and its external surface is excavated into deep cavities. It is coossified late with the parietals above and with the exoccipitals on the sides (Pl LX, fig. 2).

The quadrate is robust and its head much compressed. The latter is held firmly in a deep groove of the squamosal. The anterior wing of the quadrate is large and thin, and closely united with the broad blade of the pterygoid.

The quadratojugal is a solid, compressed bone, uniting the quadrate with the large, descending process of the jugal. In the genus Triceratops the quadratojugal does not unite with the squamosal. In Ceratops, which includes some of the smaller, less specialized forms of the family, the squamosal is firmly united to the quadratojugal by suture.

The quadratojugal arch in this group is strong and curves upward, the jugal uniting with the maxillary, not at its posterior extremity, but at its upper surface (Pl. LX, fig. 1). This greatly strengthens the center of the skull, which supports the horn cores, and also tends to modify materially the elements of the palate below. The pterygoids, in addition to their strong union with the quadrate, send outward a branch, which curves around the end of the maxillary.

The palatine bones are much smaller than the pterygoids. They are vertical, curved plates, outside and in front of the pterygoids, and uniting firmly with the maxillaries. The vomers join the pterygoids in front, where they appear as thin bones, closely applied to each other.

The transverse bones give some support to the maxillaries, which are further strengthened by close union with the pterygoids. They meet the pterygoids behind and the palatines in front.

THE LOWER JAWS.

The lower jaws show no specialization of great importance, with the exception of the predentary bone already described (Pl. LXI, figs. 4-6). There is, however, a very massive coronoid process rising from the posterior part of the dentary (Pl. LX, fig. 1). The articular, angular, and surangular bones are all short and strong, but the splenial is very long and slender, extending to the predentary. The angle of the lower jaw projects but little behind the quadrate.

The skull shown on Pl. LIX was discovered in the Ceratops beds of Wyoming by the writer's able assistant, Mr. J. B. Hatcher, who also found many other remains of dinosaurs.

THE BRAIN.

The brain of Triceratops appears to have been smaller in proportion to the entire skull than in any known vertebrate. Its relative size is shown on Pl. LXXVI, fig. 1.

The position of the brain in the skull does not correspond to the axis of the latter, the front being elevated at an angle of about 30° (Pl. LXI, fig. 7).

The brain case is well ossified in front, and in old animals there is a strong septum separating the olfactory lobes.

THE TEETH.

The teeth of Triceratops and its near allies are very remarkable in having two distinct roots. This is true of both the upper and lower series. These roots are placed transversely in the jaw, and there is a separate cavity, more or less distinct, for each of them. One of these teeth from the upper jaw, represented by several figures (Pl. LXI, figs. 9 and 10, and Pl. LXXVIII, fig. 4), is typical of the group.

The teeth form a single series only in each jaw. The upper and lower teeth are similar, but the grinding face is reversed, being on the inner side of the upper series and on the outer side of the lower series. The sculptured surface in each series is on the opposite side from that in use.

The teeth are not displaced vertically by their successors, but from the side. The crown of the young tooth, also with two strong roots, cuts its way between the alveolar margin and the adjacent root of the old tooth, but sometimes, as might be expected, advances between the two roots.

The teeth in this family are entirely confined to the maxillary and dentary bones. The rostral bone, the premaxillaries, and the predentary are entirely edentulous.

CERVICAL AND DORSAL VERTEBRÆ.

The atlas and axis of Triceratops are coossified with each other, and at least one other vertebra is firmly united with them. These form a solid mass, well adapted to support the enormous head (Pl. LXIV, fig. 1). The cup for the occipital condyle is nearly round and very deep. The rib of the second vertebra is coossified with it, but the third is usually free. The centrum of the fourth vertebra is free, and the remaining cervicals are of the same general form, all having their articular faces nearly flat.

The anterior dorsal vertebræ have very short centra, with flat articular ends, and resemble somewhat those of Stegosaurus, especially in the neural arch. This is shown in Pl LXIV, figs. 3 and 4.

The posterior trunk vertebræ have also short, flat centra, but the diapophyses have faces for both the head and tubercle of the ribs, as in crocodiles, a feature but recently seen in dinosaurs.

THE SACRUM

The sacrum was strengthened by union of several vertebræ, ten being coossified in one specimen of Triceratops (Pl. LXV). The middle or true sacral vertebræ have double transverse processes, diapophyses being present and aiding in supporting the ilium. This character has been seen hitherto in the Dinosauria only in Ceratosaurus and some other Theropoda.

The main support of the pelvis was borne by four vertebræ, which evidently constituted the original sacrum. In front of these, two others have only simple processes, and apparently were once dorsals or lumbars. Three vertebræ next behind the true sacrum have also single processes, and the fourth, or last of the series, has the rib process weak, and not reaching the ilium (Pl. LXV). Seen from the side the sacrum is much arched upward, and the neural spines of the true sacrum are firmly coossified. In the median region the sacral vertebræ have their centra much compressed, but the last of the series are widely expanded transversely. The whole appearance of the sacrum is remarkably avian. The neural canal of the sacral vertebræ has no special enlargement, thus differing widely from that in Stegosaurus.

THE CAUDAL VERTEBRÆ

The caudal vertebræ are short and the tail was of moderate length. The first caudal has the anterior face of the centrum concave vertically, but flat transversely, and a short, massive neural spine with expanded summit (Pl. LXIV, figs. 5-7). In the median caudals the centra have biconcave articular faces and weak neural spines. The distal caudals are longer than wide, with the ends concave and nearly round.

THE SCAPULAR ARCH AND FORE LIMBS.

The scapula is massive, especially below. The shaft is long and narrow, with a thin edge in front and a thick posterior margin above the glenoid fossa. The distal portion has a median external ridge and a thick end (Pl. LXVI, fig. 1, *sc*).

The coracoid is rather small, and in old individuals may become united to the scapula. It is subrhombic in outline, and is perforated by a large and well-defined foramen. No indications of a sternum have yet been found in this group.

The humerus is large and robust and similar in form to that of Stegosaurus. In one individual it is nearly as long as the femur, proving that the animal walked on all four feet. The radius and ulna are comparatively short and stout, and the latter has a very large olecranon process, as shown in Pl. LXVI, fig. 3.

There were five well developed digits in the manus. The metacarpals are short and stout, with rugose extremities. The distal phalanges are broad and hoof-like, showing that the fore feet were distinctly ungulate (Pl. LXIX).

THE PELVIS.

The pelvis in this group is very characteristic, and the three bones, ilium, ischium, and pubis, all take a prominent part in forming the acetabulum. The relative size and position of these are shown in Pl. LXVII, fig. 1, which represents the pelvic elements as nearly in the same plane as their form will allow, while retaining essentially their relative position in life.

The ilium is much elongated, and differs widely from that in any of the known groups of the Dinosauria. The portion in front of the acetabulum forms a broad, horizontal plate, which is continued backward over the acetabulum, and narrowed in the elongated, posterior extension. Seen from above, the ilium, as a whole, appears as a nearly horizontal, sigmoid plate. From the outside, as shown in the figure, the edge of this broad plate is seen.

The protuberance for the support of the pubis is comparatively small and elongated. The face for the ischium is much larger, and but little produced. The acetabular face of the ilium is quite narrow.

The pubis is massive, much compressed transversely, with its distal end widely expanded, as shown in the figures (Pl. LXVII). There is no true postpubis, but only a small postpubic process. The pubis itself projects forward, outward, and downward. Its union with the ilium is not a strong one, and is similar to that seen in the pubis of Stegosaurus.

The ischium is smaller than the pubis, but more elongate. Its shaft is much curved downward and inward, and in this respect it resembles somewhat the corresponding part of the pubis of the ostrich. There is no indication that the two ischia met closely at their distal ends, and they were probably united only by cartilage.

A comparison of this pelvis with that of Stegosaurus (Pl. LXXXI) shows some points of resemblance, but a wide difference in each of the elements. The pubis corresponds in its essential features to the prepubis of Stegosaurus, but the postpubis is represented only by a short process.

THE POSTERIOR LIMBS

The femur is short, with the great trochanter well developed. The shaft is comparatively slender, and the distal end much expanded. The third trochanter is wanting, or represented only by a rugosity (Pl. LXVIII, fig. 1).

The tibia is of moderate length, and resembles that of Stegosaurus. The shaft is slender, but the ends are much expanded. The fibula is very slender, and the distal end was closely applied to the front of the tibia (Pl. LXVIII, fig. 2). In adult individuals the astragalus is firmly coossified with the distal end of the tibia, as in Stegosaurus.

The metatarsal bones which were functional are rather long, but massive. Their phalanges are stout, and the distal ones broad and rugose, indicating that the digits were terminated by very strong hoofs (Pl. LXIX, figs. 7–12).

All the limb bones and vertebræ in Triceratops and the nearly allied genera are solid.

THE DERMAL ARMOR

Besides the armature of the skull, the body also in Triceratops was protected (Pl. LXX). The nature and position of the defensive parts in the different forms can not be determined with certainty, but various spines, bosses, and plates have been found that clearly pertain to the dermal covering of Triceratops, or nearly allied genera. Several of these ossifications were probably placed on the back, behind the crest of the skull, and some of the smaller ones may have defended the throat, as in Stegosaurus.

TOROSAURUS.

In the type specimen on which this genus was based the greater portion of the skull is preserved, and this presents so many points of interest that a figure of it, one-twentieth natural size, is here given in Pl. LXII, fig. 1. The second species is represented also by the skull, which, although not complete, supplements the type in several important respects, and figures of its posterior portions are likewise given in the same plate and in fig. 54, on the opposite page. Both specimens are of gigantic size, one skull measuring 5½ feet across the parietal crest, and the other is nearly as large. They differ widely, moreover, from the huge horned dinosaurs hitherto found in the same general horizon, and in the skull present characters of much interest.

THE SKULL

In *Torosaurus latus*, the species first described, the skull appears wedge-shaped when seen from above, as shown in Pl. LXII. The facial portion is very short and pointed, and somewhat sulline in form. The nasal horn core is compressed, with a sharp apex directed forward. The frontal horn cores are large and strongly inclined to the front, extending apparently in advance of the nasal protuberance. The long, slender squamosals diverge rapidly as they extend backward, their outer margins being nearly on a line with the facial borders in the maxillary region.

The parietal forms more than half of the upper surface of the skull, and is the most characteristic element in its structure. In the posterior part are two very large apertures, oval in outline, with their outer margin at one point formed by the squamosal. The rest of the border is thin and somewhat irregular, showing that the openings are true

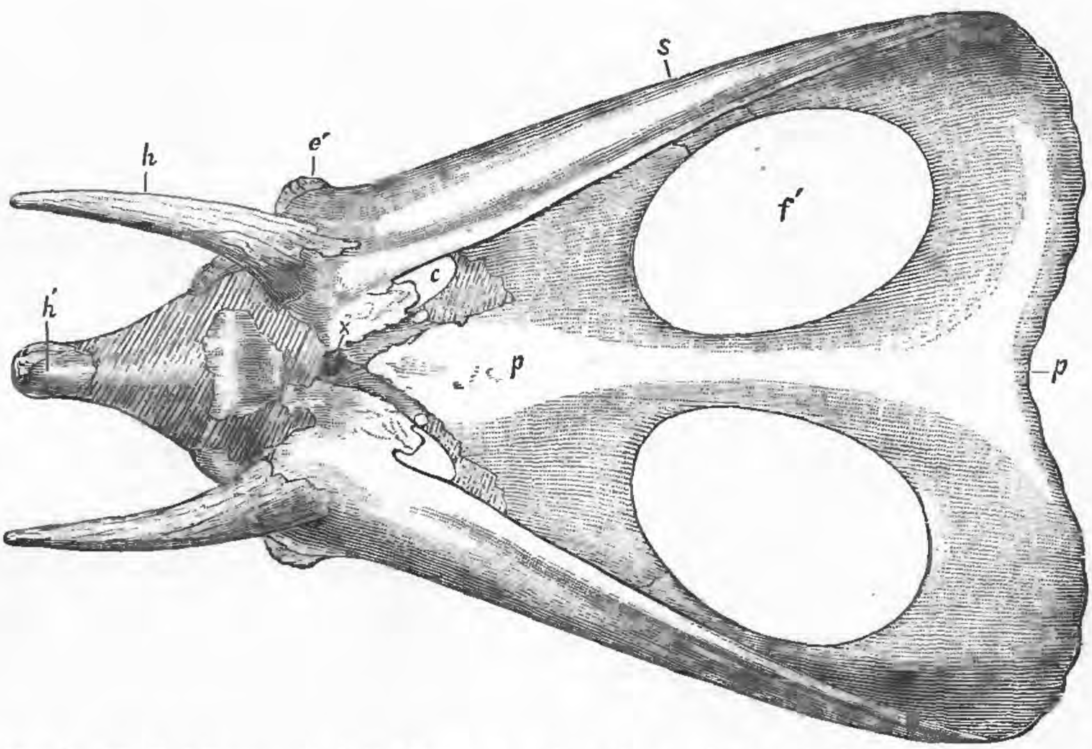

FIG. 54.—Skull of *Torosaurus gladius* Marsh; seen from above. One-twentieth natural size. *c*, supratemporal fossa; *e'*, epijugal bone; *f'*, parietal fontanelle; *h*, horn core; *h'*, nasal horn core; *p*, parietal; *s*, squamosal; *x*, pineal foramen (?).

fontanelles. This is still better seen in the second species represented in the same plate, fig. 2, and in fig. 54, above. In the latter specimen, however, these vacuities are entirely in the parietal, a thin strip of bone separating them on either side from the squamosal. A second pair of openings, much smaller, apparently the true supratemporal fossæ, are shown in the type specimen. These are situated mainly between the parietal and squamosal, directly behind the bases of the large horn cores (Pl. LXII, fig. 1, *c*). The same apertures are represented in the genus Triceratops by oblique openings, as in the skull shown on Pl. LX, fig. 3, *c*, where the front border of each is formed by the postfrontal.

Between these openings, in the type of Torosaurus, is a third pair of apertures (Pl. LXII, fig. 1, *c'*). These are quite small, nearly circular in outline, and entirely in the parietal, although probably connected originally with the supratemporal fossæ. Another pair of still smaller foramina may be seen in the same skull, close to the median line, and separated from each other by the anterior projection of the parietal. A deep groove leads forward to each of these foramina, along the suture between the parietal and the postfrontal. The position and direction of these perforations suggest that they may correspond to the foramen seen in Triceratops, and shown on Pl. LX, fig. 3, *x*. The same foramen is shown above in fig. 54.

The extreme lightness and great expanse of the posterior crest in Torosaurus make it probable that it was encased in the integuments of the head, and that no part of it was free. The outer borders of both the parietal and the squamosals show no marginal ossifications, as in the other known genera of the group, but the presence of a large, separate, epijugal bone in one specimen suggests that epoccipitals may yet be found.

The open perforations in the parietal, which have suggested the name Torosaurus, readily separate this genus from all the gigantic species hitherto known in the Ceratopsidæ, but may perhaps be found in some of the smaller and less specialized forms, from lower horizons of the same formation.

CERATOPS.

The genus Ceratops so far as at present known is represented by individuals of smaller size than those of Triceratops, and in some instances, at least, of quite different proportions. The type specimen is shown in Pl. LXIII. A third genus, Sterrholophus, can be readily distinguished from the other two by the parietal crest, which had its entire posterior surface covered with the ligaments and muscles supporting the head. In Ceratops and Triceratops a wide margin of this surface was free, and protected by a thick, horny covering. There is some evidence that still other forms, quite distinct, left their remains in essentially the same horizon, but their true relation to the above genera can not be settled without further discoveries.

STERRHOLOPHUS.

With the successive changes in the parietal in the Ceratopsidæ, there were corresponding variations in the squamosals, and these bones also will serve to distinguish the principal genera from one another. In Pl. LXIII the squamosals of three genera of this group are shown, and the wide difference between them, when seen from the inside, is especially noticeable. In fig. 4 of this plate, the long, slender, right squamosal of Torosaurus, with its smooth outer border, is well represented. In fig. 5 is seen the same bone of Sterrholophus, with a serrate outer margin and smooth inner surface, also shown in fig. 1 of Pl. LX. Next, in fig. 6 is the small, short squamosal of Ceratops, nearly bisected by its deep quadrate groove. The free sculptured border of both the parietal and squamosals of Triceratops is clearly shown in Pl. LX, fig. 4, where the contrast with the corresponding parts in fig. 2 is noteworthy.

AGATHAUMAS.

Three other generic names have been applied by Cope to remains of Ceratopsidæ found in this country, namely, Agathaumas, Polyonax, and Monoclonius. The first of these was based on part of a skeleton, without the skull, found in Wyoming. The second name was given to various fragments from Colorado, including parts of horn cores, regarded as ischia, but all these may be the same generically as the preceding specimen. The third name, Monoclonius, was used for a skeleton from Montana, with parts of the skull and teeth preserved. This animal was one of the smallest of the group, while the other remains pertained to reptiles of larger size, but not of the gigantic proportions of those more recently described. So far as can be judged from the descriptions and figures of the type specimens, the three generic names just cited can not be used for any of those previously mentioned in this article. A comparison of the principal characters will place this beyond reasonable doubt.

In the type of Agathaumas the remains best preserved are from the pelvic region, which, according to Cope,[1] possesses the following features: The ilium has no facet nor suture for the pubis at the front of the acetabulum, and the base of the ischium is coossified with the ilium. There are eight, or perhaps nine, sacral vertebræ, with the neural spines of the first five mere tuberosities. The diapophyses are in pairs, and the last sacral vertebra is reduced and elongate. These characters, and some others found in the description cited, are certainly distinctive, but do not apply to any of the allied fossils described by the writer. Portions of the type specimen, moreover, are in the Yale museum, as well as other remains from near the same locality. The fossils described as Polyonax, and other similar specimens collected in the same region, afford at present no evidence for separation from Agathaumas.

MONOCLONIUS.

The small dinosaur for which the name Monoclonius was proposed is perhaps generically distinct from Agathaumas, but no conclusive evidence of this has yet been presented. The description given makes the teeth, dorsal vertebræ, and pelvis different from those of any of the larger forms, and the T-shaped parietal (figured first by Cope as an episternal bone) is especially distinctive. None of the other known Ceratopsidæ have the parietal fontanelles except Torosaurus, one of the most gigantic forms discovered, and this genus differs from Monoclonius, as described, in various important points. The very long frontal horn cores, directed forward, the narrow, elongate squamosals, the absence of a median crest on the parietal, as well as the form and anterior connections of this bone, all serve to distinguish clearly the former from the latter.

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[1] Vertebrata of the Cretaceous formations of the West, p 53, 1875

RESTORATION OF TRICERATOPS.

PLATE LXXI

The abundant material now available for examination makes it possible to attempt a restoration of one characteristic form of this group, and the result is given in Pl. LXXI. This figure, about one fortieth natural size, is reduced from a large outline plate of a memoir now in preparation by the writer for the United States Geological Survey.

This restoration is based mainly on two specimens. One of these is the type of *Triceratops prorsus* Marsh, in which the skull, lower jaw, and cervical vertebræ are in remarkable preservation. The other specimen, although somewhat larger, is referred to the same species. It consists of parts of the skull, of vertebræ, the pelvic arch, and nearly all the important limb bones. The remaining portions are taken mostly from other remains found in the same horizon and localities, and at present are not distinguishable specifically from the two specimens above mentioned. The skull as here represented corresponds in scale to the skeleton of the larger individual.

In this restoration the animal is represented as walking, and the enormous head is in a position adapted to that motion. The massive fore limbs, proportionally the largest in any known dinosaur, correspond with the head, and indicate slow locomotion on all four feet.

The skull is, of course, without its strong horny covering on the beak, horn cores, and posterior crest, and hence appears much smaller than in life. The neck seems short, but the first six cervical vertebræ are entirely concealed by the crest of the skull, which in its complete armature would extend over one or two vertebræ more. The posterior dorsals with their double-headed ribs continue back to the sacrum itself, there being no true lumbars, although two vertebræ, apparently once lumbars, are now sacrals, as their transverse processes meet the ilia, and their centra are coossified with the true sacrum. The four original sacral vertebræ have their neural spines fused into a single plate, while the posterior sacrals, once caudals, have separate spines directed backward.

No attempt is made in this restoration to represent the dermal armor of the body, although in life the latter was more or less protected. Various spines, bosses, and plates, indicating such dermal armature, have been found with remains of this group, but the exact position of these specimens can be, at present, only a matter of conjecture.

This restoration gives a correct idea of the general proportions of the entire skeleton in the genus Triceratops. The size, in life, would be about 25 feet in length and 10 feet in height

DISTINCTIVE CHARACTERS OF GROUP.

This group so far as at present investigated is very distinct from all other known dinosaurs, and whether it should be regarded as a family, Ceratopsidæ, as first described by the writer, or as a suborder, Ceratopsia, as later defined by him, will depend upon the interpretation and value of the peculiar characters manifested in its typical forms.

The main characters which separate the group from other families of the Dinosauria are as follows:

(1) A rostral bone, forming a sharp, cutting beak.
(2) The skull surmounted by massive horn cores.
(3) The expanded parietal crest, with its marginal armature.
(4) A pineal foramen (?).
(5) The teeth with two distinct roots.
(6) The anterior cervical vertebræ coossified with each other.
(7) The dorsal vertebræ supporting, on the diapophysis, both the head and tubercle of the rib.
(8) The lumbar vertebræ wanting.

The animals of this group were all herbivorous, and their food was probably the soft, succulent vegetation that flourished during the Cretaceous period. The remains here figured are from the Ceratops beds of the upper Laramie, on the eastern slope of the Rocky Mountains.

The only known European member of this group is the Struthiosaurus Bunzel, 1871, apparently identical with Cratæomus Seeley, 1881. It is from the Gosau formation of Austria, and the locality was visited by the writer in 1864. Although only fragments, mostly of the skeleton and dermal armor, are known, some of these are very characteristic. One specimen figured by Seeley, and regarded as a dermal plate bearing a horn-like spine, is certainly part of the skull. It is very similar in form to some of the horn cores of the smaller species of Ceratops.

CLAOSAURIDÆ

The next most important family of herbivorous dinosaurs from the Cretaceous of North America is the Claosauridæ, and of these the type genus is Claosaurus, described by the writer in 1890, from a specimen found by him in Kansas in 1872. Several fortunate discoveries since made have rendered this genus one of the best known of American forms, and hence the principal characters of the skull and skeleton are here given in detail.

CLAOSAURUS.

THE SKULL

The skull of Claosaurus is long and narrow, with the facial portion especially produced. The anterior part is only moderately expanded transversely. Seen from the side (Pl. LXXII, fig. 1), the skull shows a blunt, rugose muzzle, formed above by the premaxillary and below by the predentary, both probably covered in life with a thick, corneous integument.

Behind the upper part of this muzzle is an enormous lateral cavity, which includes the narial orifice, but was evidently occupied in life mainly by a nasal gland, somewhat like that in the existing monitor, and seen also in some birds. This cavity is bounded externally by the nasal bone and the premaxillary. The median septum between the two narial orifices was only in part ossified, the large oval opening now present in the skull probably having been closed in life by cartilage.

The orbit is very large and subtriangular in outline. It is formed above by the prefrontal, frontal, and postfrontal, and below mainly by the jugal. There are no supraorbital bones. A distinct lachrymal forms a portion of the anterior border. The infratemporal fossa is large, and is bounded above by the postfrontal and squamosal, and below by the jugal. The quadrate forms a small portion of the posterior border.

Seen from in front (Pl. LXXII, fig. 2), the skull of Claosaurus is subovate in outline, with the narrow portion above. The premaxillaries and the predentary bone forming the rugose muzzle are especially massive and prominent, and the powerful lower jaws seem out of proportion to the more delicate bones of the cranium.

Seen from above (Pl. LXXII, fig. 3), the structure of the skull itself is shown to the best advantage. In front are the large premaxillaries, deeply excavated for the nasal openings. These bones are separate, and each sends back a long, slender process inside the anterior projection of the nasal, and a still longer process forming the lower border of the narial orifice, and extending to the lachrymal. The front of the premaxillaries is especially massive, and its surface rugose, indicating that it had been covered with a horny beak. The lower border is sharp, conforming to the corresponding surface of the predentary bone, which was doubtless also inclosed in a horny covering. The premaxillaries were entirely without teeth.

The nasal bones are long and slender, and especially produced in front, where they embrace the posterior median extensions of the premaxillaries. They also meet the lateral processes of the premaxillaries behind the nasal openings, and likewise touch the lachrymals. Farther back they meet the prefrontals and closely unite with the frontals, as shown in Pl. LXXII.

The frontal bones are quite short, and nearly as wide as long. They are united to each other by a well-marked suture. Their upper surface is smooth, and there is a slight depression on either side, posterior to the suture with the prefrontals. Each frontal bone forms a portion of the upper border of the orbit, and behind this meets the postfrontal. Posteriorly the frontals form the anterior border of the supratemporal fossæ, and between these unite by suture with the coossified parietals.

The latter bones are quite small, and appear on the upper surface of the skull mainly as a narrow ridge separating the supratemporal fossæ, and ending behind in a point, between the median processes of the squamosals. The parietals expand below, where they cover the posterior portion of the brain cavity.

The squamosal bones are robust, and their position and connections are well shown on Pl. LXXII, figs. 1 and 3. On the median line above they meet the narrow extension of the parietals, and exterior to this they form the posterior borders of the supratemporal fossæ. In front they unite by a strong process with the posterior branch of the post frontals. Their posterior border is joined mainly to the exoccipitals. On the outer surface of each squamosal there is a deep pit to receive the head of the quadrate, and in front of this a short, narrow process extends down the quadrate, forming a part of the border of the infratemporal fossa.

The quadrate bone and its main connections are shown on Pl. LXXII, figs. 1–3. It is firmly supported above by the squamosal, but its distinct, rounded head indicates the possibility of some motion. On the outer surface in front it joins by open suture the strong jugal bone, and below this unites with the small, discoid quadratojugal. Its inner margin extends forward into a broad, thin wing for union with the pterygoid. The lower extremity is massive, and moderately expanded transversely for articulation with the lower jaw.

The jugal is one of the most characteristic parts of the skull, as may be seen from the figures on Pl. LXXII. Its main portion is robust, much compressed, and convex externally. On its upper margin it forms the lower border of the orbit and of the infratemporal fossa, sending up a strong process between them, which extends inside and in front of the postorbital branch of the postfrontal. In front it is strongly united to the maxillary, and above joins by suture with the lachrymal.

The maxillary bone in Claosaurus is of moderate dimensions, and seen from the outside is overshadowed by the premaxillary and jugal, as shown in the same plate, fig. 1. Its lower dentary border is thickly studded with a regular series of teeth, which slightly overlap those of the lower jaw. From above only a small portion of the maxillary is visible, as seen in Pl. LXXII, fig. 3.

The lower jaws are long and massive. The predentary bone is robust, and especially fitted for meeting the strong beak above. The dentary bones are large and powerful, with elevated coronoid processes. The angular and surangular bones are, however, quite short and not especially strong.

THE TEETH

The teeth of Claosaurus are confined entirely to the maxillary and dentary bones. In each the teeth are very numerous, and are arranged in vertical series, so that they succeed each other as the functional teeth are worn away. This is seen in Pl. LXXVIII, fig. 2, which shows the form of the teeth and their relations to each other in the same series. The number of teeth in each depends upon the position, the series near the middle of the jaw having the greatest number, sometimes six or more The teeth of the upper jaw have the external face of the crown covered with enamel and ridged. In the lower jaw this is reversed, the ridged face of the crown being on the inside. This arrangement greatly increased the cutting power of the jaws. The food was probably soft vegetation.

THE BRAIN

The brain of Claosaurus was very small, its size in proportion to the skull being represented in Pl. LXXVI, fig. 2, which also shows the exact position of the brain in the cranium. A cast of the brain cavity is shown in Pl. LXXVII, fig. 3, one-fourth natural size. The brain as a whole was considerably elongated, especially the posterior half. The olfactory lobes were well developed, and not separated by an osseous septum. The cerebral hemispheres were comparatively large, forming nearly or quite half the entire brain. The optic lobes were narrow, but considerably elevated. The cerebellum was rather small, and also much compressed. The medulla was of good size, and nearly circular in transverse outline. The pituitary body was quite large. The interpretation of some of the more minute features of the brain is a matter of difficulty, and will be more fully discussed elsewhere.

THE VERTEBRÆ

The main characters of the vertebral column of Claosaurus are well shown in the restoration (Pl. LXXIV). There are thirty vertebræ between the skull and sacrum, nine in the sacrum, and about sixty in the tail. The whole vertebral column was found in position except the terminal caudals, which are here represented in outline. The cervical vertebræ are strongly opisthocœlian, and the first eleven have short ribs. The dorsals are also opisthocœlian. There are no true lumbar vertebræ, as the last of those in front of the sacrum support free ribs. The anterior caudals are opisthocœlian. The first and second have no chevrons. Behind these the chevron bones are very long, indicating a powerful, compressed tail, well adapted for swimming.

In the median dorsal region, between the ribs and the neural spines, are numerous rod-like ossified tendons, which increase in number in the sacral region and along the base of the tail, and then gradually diminish in number and size, ending at about the thirty-fifth caudal. These ossified tendons are well shown in the restoration, and are of much interest. They are not unlike those in Iguanodon described by Dollo, but as a rule are more elongate, and appear to lack the definite arrangement in rhomboidal figures observed in that genus

THE FORE AND HIND LIMBS

The fore limbs are unusually small in comparison with the posterior, and the relative size of the two is shown on Pl. LXXIII. The scapular arch presents many points of interest. The scapula is large, and so much curved that its shaft is nearly at right angles to the articular faces of its lower extremity (Pl. LXXIII, fig. 1, *s*). On the anterior margin, above the articulation for the coracoid, is a strong protuberance, with a well-defined facet, adapted to the support of the clavicle, if such a bone were present. The coracoid is very small, and is perforated by a large foramen. The two peculiar bones now generally regarded as belonging to the sternum were separate, as shown in Pl. LXXV, fig. 4.

The humerus is comparatively short, and has a prominent radial crest. The radius and ulna are much elongated, the latter being longer than the humerus, and the radius about the same length. The ulna has a prominent olecranon process, and is a stouter bone than the radius. The carpal bones were quite short, and appear to have been only imperfectly ossified. The fore foot, or manus, was very long, and contained three functional digits only. The first digit was rudimentary, the second and third were nearly equal in length, the fourth was shorter and less developed, and the fifth entirely wanting, as shown in Pl. LXXIII, fig. 1.

In the functional digits (II, III, IV) the phalanges are elongate, thus materially lengthening the fore foot. The terminal phalanges of these digits are broad and flat, showing that they were covered with hoofs, and not with claws. The limb as a whole was thus adapted to locomotion or support, and not at all for prehension, although this might have been expected from its small size and position.

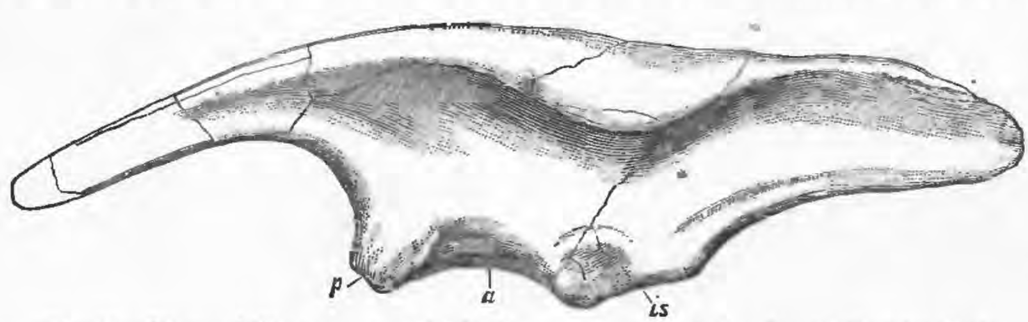

FIG. 55.—Ilium of *Claosaurus agilis* Marsh; seen from the left. One-sixth natural size *a*, acetabular border; *is*, face for ischium; *p*, face for pubis.

The elongation of the forearm and manus is a peculiar feature, especially when taken in connection with the ungulate phalanges. It may, perhaps, be explained by supposing that the animal gradually assumed a more erect position until it became essentially a biped, while the fore limbs retained in a measure their primitive function, and did not become prehensile as in some allied forms.

The pelvis is shown in Pl. LXXIII, figs. 2 and 3, and has been fully described by the writer. Its most notable features are seen in the pubis and ischium, the former having a very large expanded prepubis, with the postpubis rudimentary, while the shaft of the ischium is greatly elongated. The ilium of the type species is shown in fig. 55.

The femur is long, and the shaft nearly straight. The great trochanter is well developed, while the third trochanter is large and near the middle of the shaft, as shown in Pl. LXXIII, fig. 2. The external condyle of the distal end is projected well backward, indicating great freedom of motion at the knee

The tibia is shorter than the femur and has a prominent cnemial crest. The distal end is much flattened, and the astragalus is closely adapted to it. The fibula is very straight, with its lower end flattened and closely applied to the front of the tibia. The calcaneum is large, with its concave upper surface closely fitted to the end of the fibula. Of the second row of tarsals only a single one appears to be ossified, and that is very small and thin, and placed between the calcaneum and the fourth metatarsal, nearly or quite out of sight.

The hind foot, or pes, had but three digits, the second, third, and fourth, all well developed and massive. The terminal phalanges were covered with broad hoofs. The first and fifth digits were entirely wanting.

A comparison of the limbs and feet of Claosaurus, as here described and figured, with those of three allied forms from the Jurassic, Stegosaurus, Laosaurus, and Camptosaurus, as shown on Pls. XLVIII, LIV, and LV, is especially instructive. These three genera have already been quite fully described and figured by the writer, but new points of interest have been made out by the recent investigation of more perfect material The present figures will show more accurately some of the mutual relations of these early herbivorous dinosaurs to one another, as well as to their successors in Cretaceous time. The gradual changes that can be traced from one to the other will be discussed in a later communication.

All the limb bones in Claosaurus are solid, thus distinguishing it from Trachodon (Hadrosaurus). The separate ischium not coossified with the pubis, the absence of a fourth digit in the hind foot, and other marked characters, also make the genus distinct from Pteropelyx, the skull of which is not known.

RESTORATION OF CLAOSAURUS.

Plate LXXIV

The reptile here restored was nearly 30 feet in length when alive, and about 15 feet in height in the position represented in Pl. LXXIV. The remains were obtained in the Ceratops beds of the Laramie, in Wyoming. Among the associated fossils are the gigantic Triceratops and Torosaurus, which were also herbivorous dinosaurs, and with them were found the diminutive Cretaceous mammals recently described by the writer.

TRACHODONTIDÆ

The genus Trachodon of Leidy, which has been admirably described under the name Hadrosaurus by that author,[1] is a near ally of Claosaurus, but quite distinct. The generic name Diclonius Cope should be regarded as a synonym of Trachodon. The teeth of one species of this genus are shown in Pl. LXXV, figs. 1 and 2.

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[1] Cretaceous Reptiles of the United States, p 76, 1865

PALÆOSCINCUS.

A new reptilian genus and species, *Palæoscincus costatus*, was proposed by Dr. Leidy, in 1856, for a single tooth found by Dr. Hayden in the Judith Basin. This tooth was more fully described and figured by Leidy in 1859. The specimen showed well-marked characters, and many similar teeth have since been found, both in the Judith Basin and in various other localities of the same horizon.

A smaller species, apparently of the same genus, is not uncommon in the Ceratops beds of Wyoming, and a characteristic tooth is shown on Pl. LXXV, fig. 3. This is the type specimen of the species *Palæoscincus latus*. The crown of the tooth in this species is broader and the apex more pointed than in the first species described, and this is clearly shown in comparing the present figures on Pl. LXXV with those given by Leidy.

NODOSAURIDÆ

NODOSAURUS.

Another genus of Stegosauria, from a lower horizon in the Cretaceous, was discovered several years since, in Wyoming, and the type specimen is now in the Yale museum. This genus, Nodosaurus, was described by the writer in 1889. The skull is not known, but various portions of the skeleton were secured. One characteristic feature in this genus is the dermal armor, which appears to have been more complete than in any of the American forms hitherto found. This armor covered the sides closely, and was supported by the ribs, which were especially strengthened to maintain it. In the present specimen portions of it were found in position. It was regularly arranged in a series of rounded knobs in rows, and these protuberances have suggested the generic name.

Near the head the dermal ossifications were quite small, and those preserved are quadrangular in form, and arranged in rows. The external surface is peculiarly marked by a texture that appears interwoven, like a coarse cloth. This has suggested the specific name, and is well shown in Pl. LXXV, fig. 5.

The fore limbs are especially massive and powerful, and are much like those of the Jurassic Stegosaurus. There were five well-developed digits in the manus, and their terminal phalanges are more narrow than usual in this group. The ribs are T-shaped in transverse section, and thus especially adapted to support the armor over them. The caudal vertebræ are more elongate than those of Stegosaurus, and the middle caudals have a median groove on the lower surface of the centrum.

The animal when alive was about 30 feet in length. The known remains are from the middle Cretaceous of Wyoming.

DISTRIBUTION OF ORNITHOPODA

The great group which the author has called the Ornithopoda is well represented in Europe by Iguanodon and its allies. The remarkable discoveries in the Wealden of Belgium of a score or more skeletons of Iguanodon have furnished material for an accurate study of the genus which they represent, and, indirectly, of the family. The genus Iguanodon, founded by Mantell in 1824, is now the best known of European forms, while Hypsilophodon Huxley, 1870, also from the Wealden, is well represented, and its most important characters are fully determined. For comparison with American forms, restorations of both Hypsilophodon and Iguanodon are given on Pls. LXXXIII and LXXXIV. The other genera of this group, among which are Mochlodon Bunzel, 1871, Vectisaurus Hulke, 1879, and Sphenospondylus Seeley, 1883, are described from less perfect material, and further discoveries must decide their distinctive characters.

None of these genera are known from America, but allied forms are not wanting. A distinct family, the Trachodontidæ, is especially abundant in the Cretaceous, and another, the Camptosauridæ, includes most of the Jurassic species. The latter are the American representatives of the Iguanodontidæ. The nearest allied genera are, apparently, Iguanodon and Camptosaurus for the larger forms, and Hypsilophodon and Laosaurus for those of small size. A few isolated teeth from each country suggest that forms more nearly related may at any time be brought to light.

Many generic names have been proposed for members of this group found in America and in Europe, but in most cases they are based on fragmentary, detached specimens, which must await future discoveries before they can be assigned to their true place in the order.

In conclusion, it may be said that the three great groups of Dinosauria are each well represented in Europe as well as in America. Some of the families, also, of each order have representatives in the two regions, and future discoveries will doubtless prove that others occur in both.

No genera common to the two continents are known with certainty, although a few are so closely allied that they can not be distinguished from one another by the fragmentary specimens that now represent them.

From Asia and Africa, also, a few remains of dinosaurs have been described, and the latter continent promises to yield many interesting forms. Characteristic specimens, representing two genera, one apparently belonging to the Stegosauria, and one to the Theropoda, are already known from South Africa, from the region so rich in other extinct Reptilia.

From Australia no Dinosauria, except a single specimen, have as yet been recorded, but many more will undoubtedly be found there, as reptiles of this great group were the dominant land animals of the earth during all Mesozoic time.

PART IV.

CONCLUSION.

The brief review of North American Dinosaurs given in the preceding pages, in connection with the accompanying illustrations, will make the reader acquainted with the more important type specimens of this interesting group of reptiles, as now known from this continent. To discover and bring together these remains, representing several hundred individuals, from widely separated localities and various geological horizons, has been a long and laborious undertaking, attended with much hardship, and often with danger, but not without the pleasure that exploration in new fields brings to its votaries. These researches, especially in the West, have been continued by the writer more than a score of years, and have led him across the Rocky Mountains a still greater number of times. The field work thus prosecuted has been of great service in the subsequent study of the specimens secured, especially in determining the natural position in life of each animal investigated.

In comparing the type specimens of these various animals, one with another, as they were found and as they appeared when removed from the vesture of their entombment, many questions have suggested themselves that can not be answered in the present limited paper. Resemblances and differences are striking, both in structure and form, in these ancient reptiles, but the true meaning of such features is a difficult problem to solve. On the interpretation of characters thus exhibited in these animals depend both the laws of their classification and theories of their origin.

COMPARISON OF CHARACTERS

In the concluding part of the present paper a number of plates (LXXVI–LXXXI) have been given with a view to illustrate especially the corresponding parts of various animals of different orders, showing the wide divergence in some points of nearly allied forms, and the approach in particular features of types clearly distinct.

In Pl. LXXVI four skulls of as many typical genera of herbivorous dinosaurs (Triceratops, Claosaurus, Camptosaurus, and Diplodocus) are represented, with a cast of the brain cavity of each in position. All are so drawn that they can be readily compared, thus exhibiting in a striking manner both the diminutive size of the brain in each in proportion to that of the skull, and also the form of the brain cavity, when seen from above. In the next plate (LXXVII) the brain casts alone of several dinosaurs, as seen from the side, are exhibited, and with them for comparison the corresponding cast of a young alligator. The special features of the dinosaur brain are well shown in these two plates.

Pl. LXXVIII will make clear the wide divergence of forms of teeth in four different families of predentate dinosaurs. The typical genera, Camptosaurus, Claosaurus, Stegosaurus, and Triceratops, each have teeth of a distinct type, yet it seems possible to trace the gradation of one to the other through different intermediate forms. In Triceratops the teeth have two distinct roots, a feature unknown in any other reptiles, living or extinct, but characteristic of mammals.

The series of pubic bones of herbivorous dinosaurs shown on Pl. LXXIX is especially instructive, as they indicate how the anterior and posterior elements of the pubis may vary in the Predentata, and thus afford good characters for classification. The same is true, but in a less degree, of the ischia represented on Pl. LXXX, which all pertain to one group of dinosaurs. The comparison may even be carried much further, as in the two other orders (the Theropoda and Sauropoda) some families have ischia of the type here represented, as shown on Pls. XXVIII and XXXV.

The pelves represented on Pl. LXXXI, pertaining to the three predentate genera, Camptosaurus, Triceratops, and Stegosaurus, will supplement the facts presented on the two preceding plates. The series might be much further extended, and prove equally instructive. This will be done by the writer in the monographs now in preparation, as in these the whole subject of dinosaurian reptiles will receive careful consideration.

RESTORATIONS OF EUROPEAN DINOSAURS.

The remaining restorations of dinosaurs in this paper are four in number, and represent some of the best-known European forms, types of the genera Compsognathus, Scelidosaurus, Hypsilophodon, and Iguanodon. These outline restorations have been prepared by the writer mainly for comparison with the corresponding American forms, but in part to insure, so far as the present opportunity will allow, a more comprehensive review of the whole group. The specimens restored are all of great interest in themselves, and of special importance when compared with their nearest American allies.

COMPSOGNATHUS.

PLATE LXXXII.

The first restoration, that of *Compsognathus longipes* Wagner, 1861, shown one-fourth natural size on Pl. LXXXII, is believed to represent fairly well the general form and natural position, when alive, of this diminutive carnivorous dinosaur that lived during the Jurassic period. The basis for this restoration is (1) a careful study of the type specimen itself, made by the writer in Munich in 1881; (2) an accurate cast of this specimen, sent to him by Professor von Zittel; and (3) a careful drawing of the original, made by Krapf in 1887. The original description and figure of Wagner (Bavarian Academy of Sciences, 1861), and those of later authors, have also been used for some of the details.

No restoration of the skeleton of this unique dinosaur has hitherto been attempted.[1]

Compsognathus has been studied by so many anatomists of repute since its discovery that any attempt to restore the skeleton to a natural position will be scrutinized from various points of view. Interest in this unique specimen led the writer long ago to examine it with care, and he has since made a minute study of it, as related elsewhere, not merely to ascertain its anatomy, but also to learn, if possible, what its relations are to another diminutive form, Hallopus, from a lower horizon in America, which has been asserted to be a near ally. Both are carnivorous dinosaurs, probably, but certainly on quite different lines of descent.

The only previous attempt to restore this remarkable dinosaur was by Huxley when in America in 1876. He made a rapid sketch from the Wagner figure, and this was enlarged for his New York lecture. This sketch represents the animal sitting down, a position which such dinosaurs occasionally assumed, as shown by the footprints in the Connecticut Valley, which Huxley examined in place at several localities with great interest.

In the present restoration of Compsognathus (Pl. LXXXII) the writer has tried to represent the animal as walking in a characteristic lifelike position.

SCELIDOSAURUS.

PLATE LXXXIII.

The second of these restorations is that of *Scelidosaurus Harrisonii* of Owen, shown one-eighteenth natural size on Pl. LXXXIII. This reptile was an herbivorous dinosaur of moderate size, related to Stegosaurus, and was its predecessor from a lower geological horizon in England. This restoration is essentially based upon the original description and figures of Owen (Palæontographical Society, 1861). These have been supplemented by the writer's own notes and sketches, made during examinations of the type specimen now in the British Museum.

Scelidosaurus is a near relative, as it were, of one of the American forms, Stegosaurus, now represented by so many specimens that the skull, skeleton, and dermal armor are known with much certainty. The English form usually called Omosaurus is still more nearly allied to Stegosaurus, perhaps identical with it.[2]

A restoration of the skeleton of Scelidosaurus by Dr. Henry Woodward will be found in the British Museum Guide to Geology and Palæontology, 1890, p. 19. The missing parts are restored from Iguanodon, and the animal is represented as bipedal, as in that genus.

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[1] The remains of the embryo within the skeleton of Compsognathus, first detected by the writer in 1881 while examining the type specimen, is not represented in the present restoration. This unique fossil affords the only conclusive evidence that dinosaurs were viviparous.

[2] The generic name Omosaurus was preoccupied by Leidy in 1856.

In the present outline restoration of Scelidosaurus the writer has endeavored merely to place on record his idea of the form and position of the skeleton when the animal was alive, based on the remains he has himself examined. In case of doubt, as, for example, in regard to the front of the skull, which is wanting in the type specimen, a dotted outline is used, based on the nearest allied form. Of the dermal armor, only the row of plates best known is indicated. The position chosen in this figure (Pl. LXXXIII) is one that would be assumed by the animal in walking on all four feet, and this is believed to have been its natural mode of progression.

HYPSILOPHODON.

PLATE LXXXIV

The third of these restorations, that of *Hypsilophodon Foxii* Huxley, 1870, given in outline one-eighth natural size on Pl. LXXXIV, has been made with much care, partly from the type specimen, and in part from other material mostly now in the British Museum. The figures and description by the late Dr. Hulke[1] were of special value, although the conclusions of the writer as to the natural position of the animal when alive do not coincide with those of his honored friend, who did so much to make this genus of dinosaurs, and others, known to science. The restoration by Dr. Hulke represented the animal as quadrupedal.

In the case of Hypsilophodon a number of specimens are available instead of only one. This makes the problem of its restoration a simpler matter than in Scelidosaurus. Moreover, there is in America a closely allied form, Laosaurus, of which several species are known. A study of the genus Laosaurus, and the restoration of one species given on Pl. LVII, will clear up several points long in doubt.

Huxley and Hulke both shed much light on this interesting genus, Hypsilophodon; indeed, on many of the Dinosauria. The mystery of the dinosaurian pelvis, which baffled Cuvier, Mantell, and Owen, was mainly solved by them, the ilium and ischium by Huxley, and the pubis by Hulke. The more perfect American specimens have demonstrated the correctness of nearly all their conclusions.

IGUANODON.

PLATE LXXXV

The fourth restoration here given, that of *Iguanodon Bernissartensis* Boulenger, 1881, one-fortieth natural size, has been made in outline for comparison with American forms. It is based mainly on photographs of the well-known Belgian specimens, the originals of which the writer has studied with considerable care during several visits to Brussels. The descriptions and figures of Dollo[2] have also been used in the preparation of this restoration. A few changes only have been introduced in

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[1] Philosophical Transactions, 1882

[2] Bulletin Royal Museum of Belgium, 1882–88

the accompanying plate, based mainly upon a study of the original specimens.

Besides the four genera here represented, no other European dinosaurs at present known are sufficiently well preserved to admit of accurate restorations of the skeleton. This is true, moreover, of the dinosaurian remains from other parts of the world outside of North America.

AFFINITIES OF DINOSAURS.

The extinct reptiles known as dinosaurs were for a long time regarded as a peculiar order, having, indeed, certain relations to birds, but without being closely allied to any of the groups of known reptiles. Megalosaurus and Iguanodon, the first dinosaurian genera described, were justly considered as representing two distinct families, one including the carnivores, and the other the herbivorous forms.

With the discovery and investigation of Cardiodon (Cetiosaurus) and its allies in Europe, and especially of the gigantic forms with similar characters in America, it became evident that these reptiles could not be placed in the same families with Megalosaurus or Iguanodon, but constituted a well-marked group by themselves. It was this new order, the Sauropoda, as the writer has named them, that first showed definite

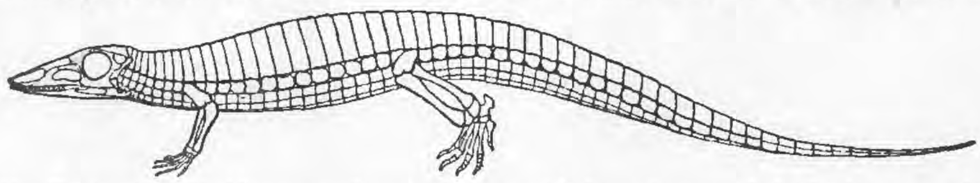

FIG. 56.—Restoration of *Aëtosaurus ferratus* Fraas; with dermal armor of the limbs removed. One-eighth natural size.

characters allying them with other known groups of reptiles. In 1878 he pointed out that the Sauropoda were the least specialized of the dinosaurs, and gave a list of characters in which they showed such an approach to the Mesozoic crocodiles as to suggest a common ancestry at no very remote period.[1]

AFFINITIES WITH AËTOSAURIA.

Again, in 1884, the writer called attention to the same point, and also to the relationship of dinosaurs with the Aëtosauria, as he has named them, a group of small reptiles from the Triassic of Germany showing strong affinities with crocodilians.[2] A restoration of one of these small animals is shown in fig. 56. In the same communication he compared with dinosaurs another allied group, the Hallopoda, which he described from the lower Jurassic of America, but had not then fully investigated. Subsequent researches proved the latter group to be of the first importance in estimating the affinities of dinosaurs, and in figs. 59 and 60 are restorations of the fore and hind limbs of the type species (*Hallopus victor*).

[1] American Journal of Science, Vol. XVI, p. 412, November, 1878.
[2] Report British Association, Montreal Meeting, 1884, p. 765.

AFFINITIES WITH BELODONTIA.

Another group of extinct reptiles, which may be termed the Belodontia, were considered in the same paper as allies of the Dinosauria. They are known from the Trias of Europe and America, and the type genus, Belodon, has been investigated by many anatomists, who all appear to have regarded it as a crocodilian, an opinion that in the light of our present knowledge may fairly be questioned.

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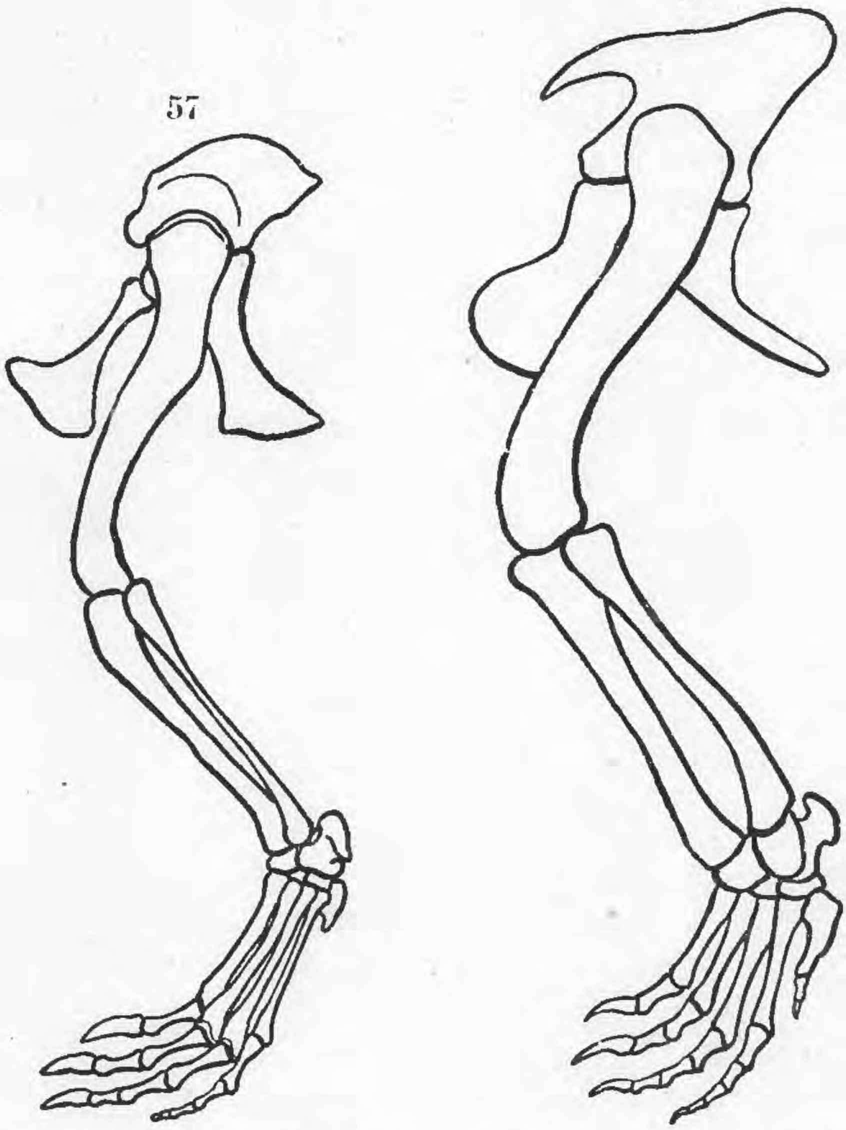

FIG. 57.—Diagram of left hind limb of *Alligator mississippiensis* Gray; seen from the left; in position for comparison with dinosaurs. One-fourth natural size.
FIG. 58.—Diagram of left hind limb of *Aëtosaurus ferratus;* in same position. One-half natural size.

AFFINITIES WITH CROCODILIA.

The relations of these various groups to the true crocodiles on the one hand and to dinosaurs on the other is much too broad a subject to be introduced here, but attention may at least be called to some points of resemblance between the dinosaurs and these supposed crocodilian forms that seem to indicate genetic affinities.

If some of the characteristic parts of the skeletons of these groups are compared, e. g., of the true Crocodilia as existing to-day, the Belodontia, the Aëtosauria, and the Hallopoda, and all with the corresponding portions of the more typical dinosaurs, the result may indicate in some measure the relationship between them. Taking first the pelvis and hind limb, as being especially characteristic. it will be seen in

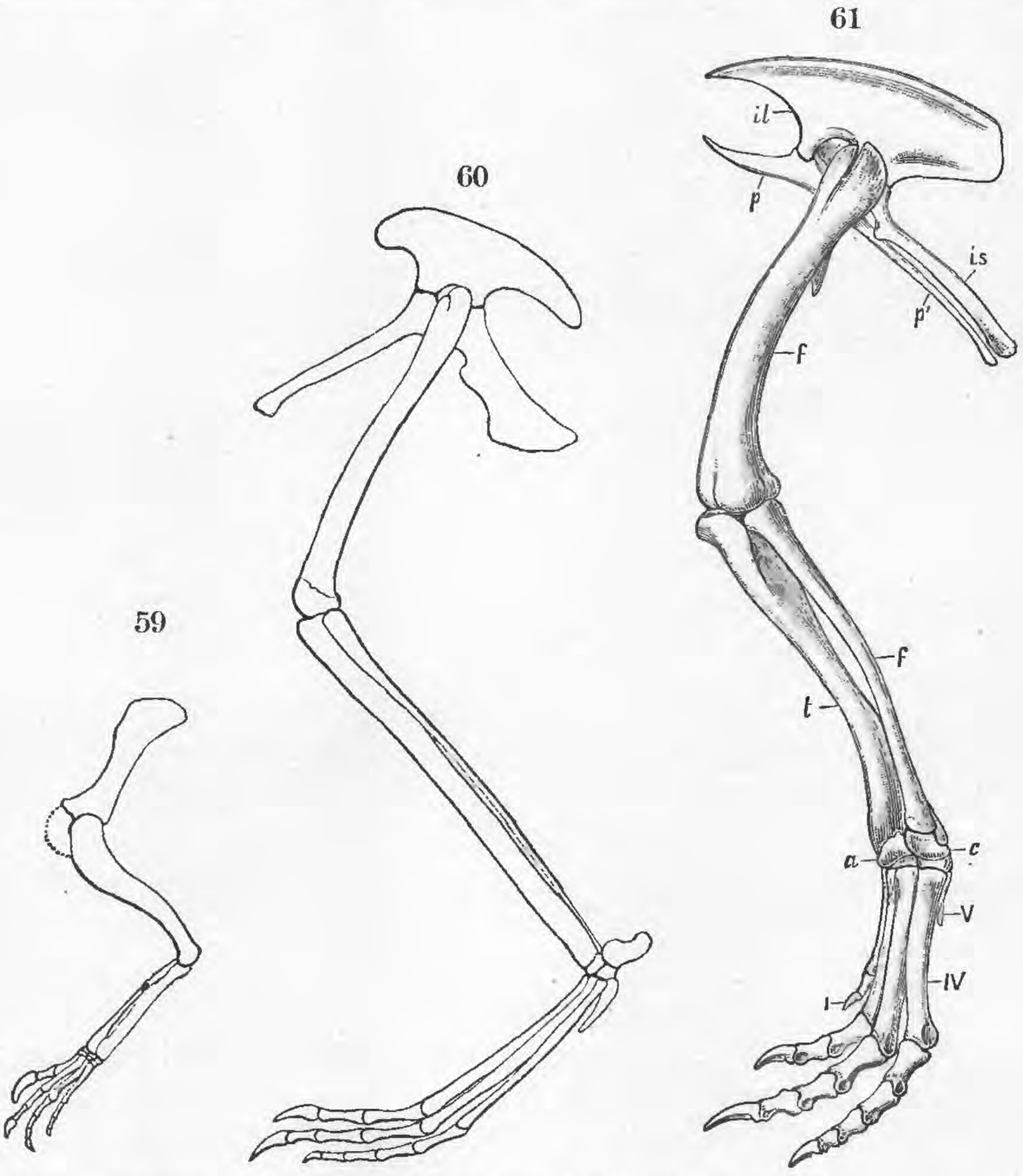

FIG. 59.—Diagram of left fore limb of *Hallopus victor* Marsh; seen from the left.
FIG. 60.—Diagram of left hind limb of same individual. Both figures are one-half natural size.
FIG. 61.—Left hind leg of *Laosaurus consors* Marsh; outside view. One-sixth natural size.
a, astragalus; *c*, calcaneum; *f*, femur; *f'*, fibula; *il*, ilium· *is*, ischium; *p*, pubis; *p'*, postpubis; *t*, tibia; *I*, *IV*, *V*, first, fourth, and fifth digits.

the existing alligator, as represented in fig. 57, that the pubic bone is excluded from the acetabulum, articulating with the ischium only, and not at all with the ilium. The calcaneum, moreover, has a posterior extension. In Aëtosaurus, as shown in fig. 58, the pubic bone forms part of the acetabulum, as in dinosaurs and birds, and this is a noteworthy difference from all the existing crocodiles. The hind foot, however, is of the crocodilian type, with the calcaneum showing a posterior projection.

In Belodon, only the pelvis of which is here represented (fig. 62), the pubis contributes a very important part to the formation of the acetabulum, and to the entire pelvic arch. The latter differs from the pelvis of a typical dinosaur mainly in the absence of an open acetabulum, but a moderate enlargement of the fontanelle at the junction of the three pelvic elements would practically remove this difference. A more erect position of the limb, leading to a more distinct head on the femur, might possibly bring about such a result. The feet and limbs of Belodon are crocodilian in type.

Bearing these facts in mind, the diagram representing the restored fore and hind limbs of the diminutive Hallopus (figs. 59–60) shows first

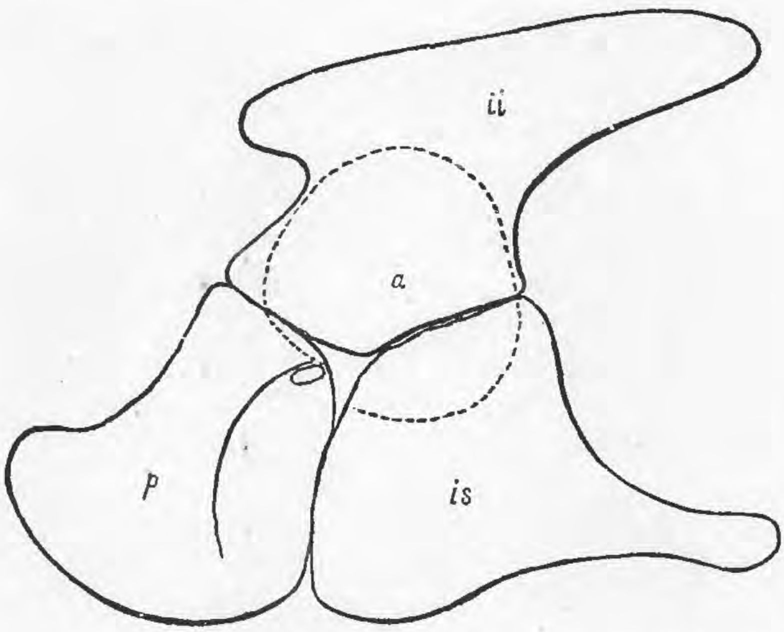

FIG. 62.—Diagram of pelvis of *Belodon Kapffi* von Meyer; seen from the left. One-fourth natural size.

a, acetabular surface within dotted line; *il*, ilium; *is*, ischium; *p*, pubis.

of all the true dinosaurian pelvis, with the pubic bone taking part in the open acetabulum, and forming an important and distinctive element of the pelvic arch. The delicate posterior limb and foot, evidently adapted mainly for leaping, as the generic name suggests, are quite unique among the Reptilia, but the tarsus, especially the calcaneum, recalls strongly the same region in the orders already passed in review.

Just what this posterior extension of the calcaneum signifies in this case it is difficult to decide from the evidence now known. It may be merely an adaptive character, as Hallopus appears in nearly every other respect to be a true carnivorous dinosaur. It may, however, be an inheritance from a crocodilian ancestry, preserved by a peculiar mode of life. Whatever its origin may have been, it was certainly, during the life of the animal, an essential part of the remarkable leaping foot to which it belonged, and in which it has since kept its position undisturbed. The presence of such an element in the foot of this diminutive dinosaur certainly suggests that the group Hallopoda, which the writer has here considered a suborder, stands somewhat apart from the typical Theropoda, but not far enough away to be excluded from the subclass Dinosauria, as defined in the present paper.

The genus Plateosaurus (Zanclodon), which is from essentially the

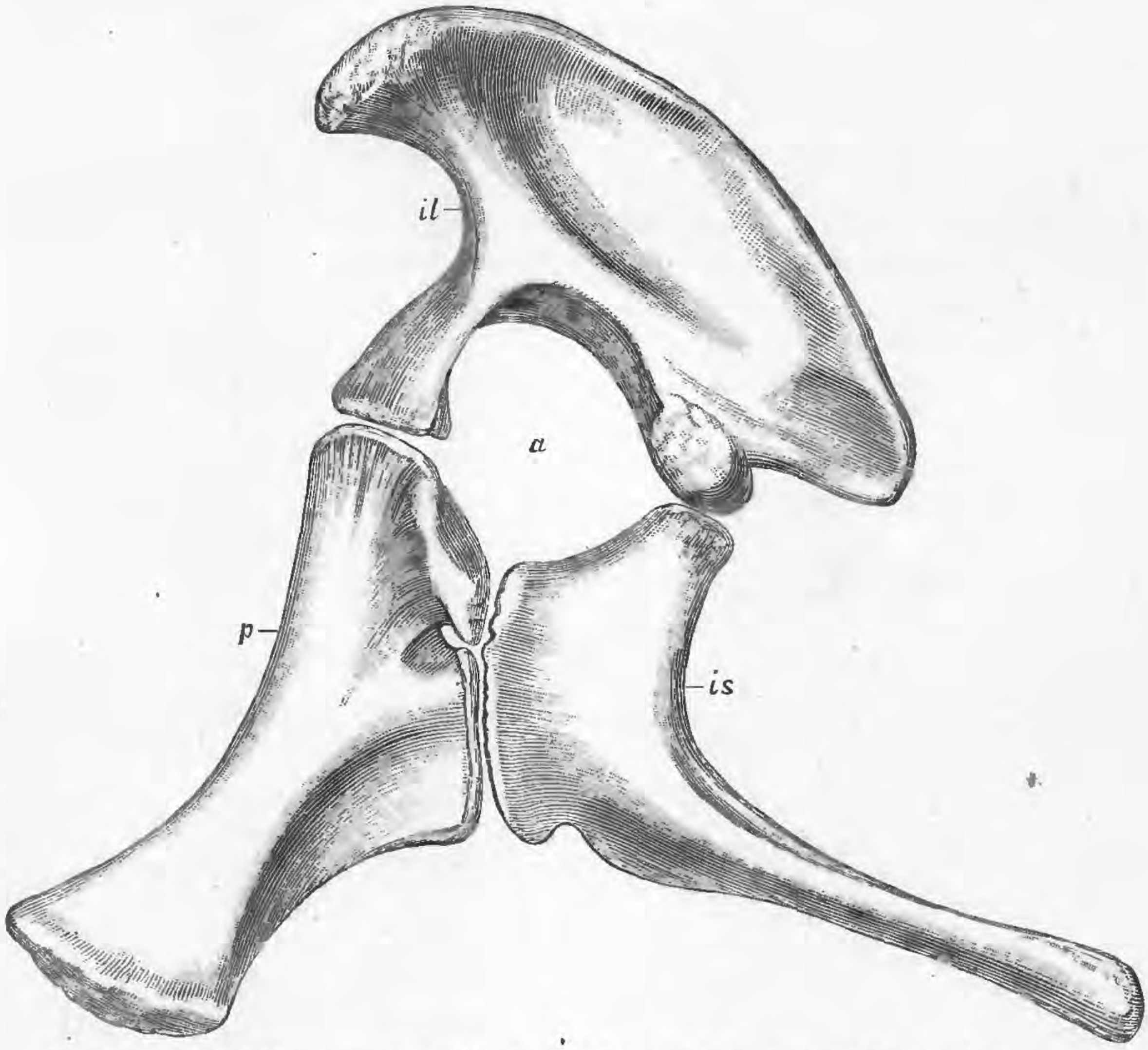

FIG. 63.—Pelvis of *Morosaurus lentus* Marsh; seen from the left. One-eighth natural size. *a*, acetabular opening; other letters as in fig. 62.

same geological horizon in Germany as Aëtosaurus and Belodon, is one of the oldest true dinosaurs known, and a typical member of the order Theropoda. In the pelvic arch of this reptile the ilium and ischium are in type quite characteristic of the group to which it belongs, but the pubic elements are unique. They consist of a pair of broad, thin plates united together so as to form an apron-like shield in front, quite unlike anything known in other dinosaurs. The wide pubic bones of Belodon, and the corresponding plates in some of the Sauropoda (Morosaurus, fig. 63), indicate that this feature of the reptilian pelvis may have been derived from some common ancestor of a generalized primitive type. The known transformations of this same pelvic element in one other order of dinosaurs (the Predentata) show that the modifications here suggested are well within the limits of probability. The hind limb of one genus of this order is shown in fig. 61 (p. 233).

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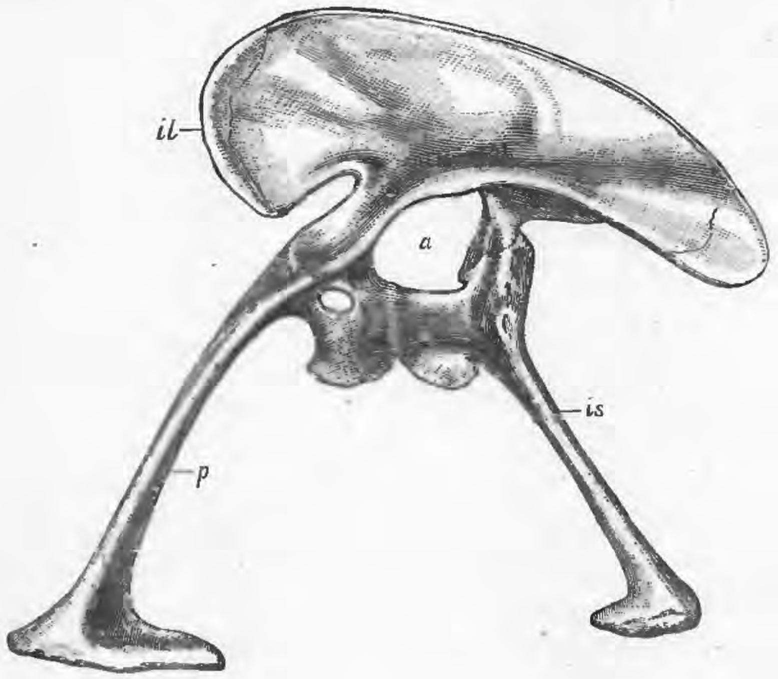

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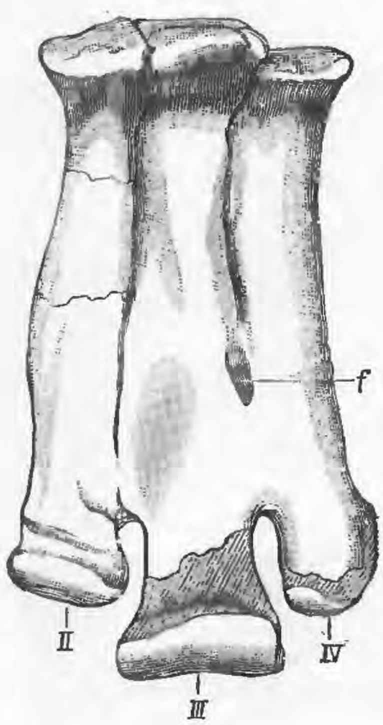

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FIG. 64.—Pelvis of *Ceratosaurus nasicornis* Marsh; seen from the left. One-twelfth natural size. Letters as in fig. 63.

FIG. 65.—United metatarsal bones of *Ceratosaurus nasicornis;* left foot; front view. One-fourth natural size.

FIG. 66.—United metatarsal bones of great penguin (*Aptenodytes Pennantii* G. R. Gr.); left foot, front view. Natural size.

The skulls of Aetosaurus and Belodon both show features characteristic of some of the dinosaurs, especially of the Sauropoda, but these features need not be discussed here.

AFFINITIES WITH BIRDS.

The relation of dinosaurs to birds, a subject of importance, must also be postponed for another occasion. One point, however, may be mentioned in this connection. The pelvic bones of all known birds, living and extinct, except the genus Archæopteryx, are coossified, while in all the known dinosaurs they are separate, excepting Ceratosaurus (fig. 64) and Ornithomimus. Again, all known adult birds, living and extinct, with possibly the single exception of Archæopteryx, have the metatarsal bones firmly united (fig. 66), while all the Dinosauria, except Ceratosaurus (fig. 65), have these bones separate. The exception in each case brings the two classes near together at this point, and their close affinity is thus rendered more than probable.

These few facts will throw some light on the affinities of the reptiles known as the Dinosauria. The problem is certainly one of much difficulty, and the writer hopes soon to discuss it more fully elsewhere.

PART V.

CLASSIFICATION OF DINOSAURIA.

In the present review of the dinosaurs the writer has confined himself mainly to the type specimens which he has described, but has included with them other important remains where these were available for investigation. The extensive collections in the museum of Yale University contain so many of the important type specimens now known from America that they alone furnish an admirable basis for classification, and it was mainly upon these that he first established the present system, which has since been found to hold equally good for the dinosaurs discovered elsewhere. In the further study of these reptiles it was also necessary to examine both the European forms and those from other parts of the world, and he has now studied nearly every known specimen of importance. These investigations have enabled him to make this classification more complete, and to bring it down to the present time.

Many attempts have been made to classify the dinosaurs, the first being that of Hermann von Meyer in 1830. The name Dinosauria, proposed for the group by Owen in 1839, has been generally accepted, although not without opposition. Hæckel, Cope, and Huxley followed, the last in 1869 proposing the name Ornithoscelida for the order, and giving an admirable synopsis of what was then known of these strange reptiles and their affinities. Since then, Hulke, Seeley, Lydekker, Gaudry, Dollo, Baur, and others have added much to our knowledge of these interesting animals.

The remarkable discoveries in North America, however, have changed the whole subject, and in place of fragmentary specimens many entire skeletons of dinosaurian reptiles have been brought to light, and thus definite information has replaced uncertainty and rendered a comprehensive classification for the first time possible.

The system of classification first proposed by the writer in 1881 has been very generally approved, but a few modifications have been suggested by others that will doubtless be adopted. This will hardly be the case with several radical changes recently advocated, based mainly upon certain theories of the origin of dinosaurs. At present these theories are not supported by a sufficient number of facts to entitle them to the serious consideration of those who have made a careful study of these reptiles, especially the wonderful variety of forms recently made known from America.

Further discoveries may in time solve the problem of the origin of all the reptiles now called dinosaurs, but the arguments hitherto advanced against their being a natural group are far from conclusive. The idea that the Dinosauria belong to two or more distinct groups, each of independent origin, can at present only claim equal probability with a similar suggestion recently made in regard to mammals. This subject of the origin of the dinosaurs and the relation of their divisions to each other will be more fully treated by the writer elsewhere.

A classification of any series of extinct animals is of necessity, as the writer has previously said, merely a temporary convenience, like the bookshelves in a library, for the arrangement of present knowledge. In view of this fact and of the very limited information in regard to so many dinosaurs known only from fragmentary remains, it will suffice for the present, or until further evidence is forthcoming, to still consider the Dinosauria as a subclass of the great group of Reptilia.

Regarding, then, the dinosaurs as a subclass of the Reptilia, the forms best known at present may be classified as follows·

Subclass DINOSAURIA Owen.

Premaxillary bones separate; upper and lower temporal arches; no teeth on palate; rami of lower jaw united in front by cartilage only. Neural arches of vertebræ joined to centra by suture; cervical and thoracic ribs double headed; ribs without uncinate processes; sacral vertebræ united; caudal vertebræ numerous; chevrons articulated intervertebrally. Scapula elongate; no precoracoid; clavicles wanting. Ilium prolonged in front of the acetabulum; acetabulum formed in part by pubis; ischia meet distally on median line. Fore and hind limbs present, the latter ambulatory, and larger than those in front; head of femur at right angles to condyles; tibia with procnemial crest; fibula complete; first row of tarsals composed of astragalus and calcaneum only, which together form the upper portion of ankle joint; reduction in number of digits begins with the fifth.

Order THEROPODA (Beast foot). Carnivorous.

Skull with external narial openings lateral; large antorbital vacuity; brain case incompletely ossified; no pineal foramen; premaxillaries with teeth; no predentary bone; dentary without coronoid process; teeth with smooth compressed crowns and crenulated edges. Vertebræ more or less cavernous; posterior trunk vertebræ united by diplosphenal articulation. Neural canal in sacrum of moderate size. Each sacral rib supported by two vertebræ; diapophyses distinct from sacral ribs. Sternum unossified. Pubes projecting downward, and united distally; no postpubis. Fore limbs small; limb bones hollow; astragalus closely applied to tibia; feet digitigrade; digits with prehensile claws; locomotion mainly bipedal.

(1) Family Megalosauridæ. Lower jaws with teeth in front. Anterior vertebræ convexo-concave; remaining vertebræ biconcave; five sacral vertebræ. Abdominal ribs. Ilium expanded in front of acetabulum; pubes slender, and distally coossified Femur longer than tibia; astragalus with ascending process; five digits in manus and four in pes.

Genus Megalosaurus (Poikilopleuron). Jurassic and Cretaceous. Known forms, European.

(2) Family Dryptosauridæ. Lower jaws with teeth in front. Cervical vertebræ opisthocœlian; remaining vertebræ biconcave, sacral vertebræ less than five. Ilium expanded in front of acetabulum; distal ends of pubes coossified and much expanded; an interpubic bone. Femur longer than tibia; astragalus with ascending process; fore limbs very small, with compressed prehensile claws. (Pls. X-XII.)

Genera Dryptosaurus (Lælaps), Allosaurus, Cœlosaurus, Creosaurus. Jurassic and Cretaceous. All from North America.

(3) Family Labrosauridæ. Lower jaws edentulous in front. Cervical and dorsal vertebræ convexo-concave; centra cavernous or hollow. Pubes robust, with anterior margins united; an interpubic bone. Femur longer than tibia; astragalus with ascending process. (Pl. XIII.)

Genus Labrosaurus. Jurassic, North America.

(4) Family Plateosauridæ (Zanclodontidæ). Vertebræ biconcave; two sacral vertebræ. Ilium expanded behind acetabulum; pubes broad, elongate plates, with anterior margins united; no interpubic bone; ischia united at distal ends. Femur longer than tibia; astragalus without ascending process; five digits in manus and pes.

Genera Plateosaurus (Zanclodon), Teratosaurus (?), Dimodosaurus. Triassic. Known forms, European.

(5) Family Anchisauridæ. Skull light in structure, with recurved, cutting teeth. Vertebræ plane or biconcave. Bones hollow. Ilium expanded behind acetabulum; pubes rod-like and not coossified distally; no interpubic bone. Fore limbs well developed; femur longer than tibia; astragalus without ascending process; five digits in manus and in pes. (Pls. II-IV.)

Genera Anchisaurus (Megadactylus), Ammosaurus, Arctosaurus (?), Bathygnathus, and Clepsysaurus, in North America; and in Europe, Palæosaurus, Thecodontosaurus. All known forms, Triassic.

Suborder CŒLURIA (Hollow tail).

(6) Family Cœluridæ. Teeth much compressed. Vertebræ and bones of skeleton very hollow or pneumatic; neural canal much expanded; anterior cervical vertebræ convexo-concave; remaining vertebræ biconcave; anterior cervical ribs coossified with vertebræ; pubes slender and distally coossified; an interpubic bone. Femur shorter than tibia; metatarsals very long and slender. (Pl. VII.)

Genera Cœlurus in North America, and Aristosuchus in Europe. Jurassic.

Suborder COMPSOGNATHA.

(7) Family Compsognathidæ. Skull elongate, with slender jaws and pointed teeth. Cervical vertebræ convexo-concave, with free ribs; remaining vertebræ biconcave. Ischia with long symphysis on median line. Bones very hollow; femur shorter than tibia; astragalus with long ascending process; three functional digits in manus and in pes. (Pl. LXXXII.)

Genus Compsognathus. Jurassic. Only known specimen, European.

Suborder CERATOSAURIA (Horned saurians).

(8) Family Ceratosauridæ. Horn on skull; teeth large and trenchant. Cervical vertebræ plano-concave; remaining vertebræ biconcave. Ribs free. Pelvic bones coossified; ilium expanded in front of acetabulum; pubes slender; an interpubic bone; sacral vertebræ five; ischia slender, with distal ends coossified. Limb bones hollow; manus with four digits; femur longer than tibia; astragalus with ascending process; metatarsals coossified; three digits only in pes. Osseous dermal plates. (Pls. VIII-X, XIV.)

Genus Ceratosaurus. Jurassic, North America.

(9) Family Ornithomimidæ. Pelvic bones coossified with each other and with sacrum; ilium expanded in front of acetabulum. Limb bones very hollow; fore limbs very small; digits with very long, pointed claws; hind limbs of true avian type; femur longer than tibia; astragalus with long ascending process; feet with three functional digits, digitigrade and unguiculate. (Pl. LVIII.)

Genus Ornithomimus. Cretaceous, North America.

Suborder HALLOPODA (Leaping foot).

(10) Family Hallopidæ. Vertebræ and limb bones hollow; vertebræ biconcave; two vertebræ in sacrum. Acetabulum formed by ilium, pubis, and ischium; pubes rod-like, projecting downward, but not coossified distally; no postpubis; ischia with distal ends expanded, meeting below on median line. Fore limbs very small, with four digits in

manus; femur shorter than tibia; hind limbs very long, with three functional digits in pes, and metatarsals greatly elongated; astragalus without ascending process; calcaneum much produced backward; feet digitigrade, unguiculate. (Pl. VI.)

Genus Hallopus. Jurassic, North America.

Order SAUROPODA (Lizard foot). Herbivorous.

External nares at apex of skull; premaxillary bones with teeth; teeth with rugose crowns more or less spoon-shaped; large antorbital openings; no pineal foramen; alisphenoid bones; brain case ossified; no columellæ; postoccipital bones; no predentary bone; dentary without coronoid process. Cervical ribs coossified with vertebræ; anterior vertebræ opisthocœlian, with neural spines bifid; posterior trunk vertebræ united by diplosphenal articulation; presacral vertebræ hollow; each sacral vertebra supports it own transverse process, or sacral rib; no diapophyses on sacral vertebræ; neural canal much expanded in sacrum; first caudal vertebræ procœlian. Sternal bones parial; sternal ribs ossified. Ilium expanded in front of acetabulum; pubes projecting in front, and united distally by cartilage; no postpubis. Limb bones solid; fore and hind limbs nearly equal; metacarpals longer than metatarsals; femur longer than tibia; astragalus not fitted to end of tibia; feet plantigrade, ungulate; five digits in manus and pes; second row of carpal and tarsal bones unossified; locomotion quadrupedal.

(1) Family Atlantosauridæ. A pituitary canal; large fossa for nasal gland. Distal end of scapula not expanded. Sacrum hollow; ischia directed downward, with expanded extremities meeting on median line. Anterior caudal vertebræ with lateral cavities; remaining caudals solid. (Pls. XV-XXIV, and XLII.)

Genera Atlantosaurus, Apatosaurus, Barosaurus, Brontosaurus. Include the largest known land animals. Jurassic, North America.

(2) Family Diplodocidæ. External nares superior; no depression for nasal gland; two antorbital openings; large pituitary fossa; dentition weak, and in front of jaws only; brain inclined backward; dentary bone narrow in front. Ischia with shaft not expanded distally, directed downward and backward, with sides meeting on median lines. Sacrum hollow, with three vertebræ. Caudal vertebræ deeply excavated below; chevrons with both anterior and posterior branches. (Pls. XXV-XXIX.)

Genus Diplodocus. Jurassic, North America.

(3) Family Morosauridæ. External nares lateral; large fossa for nasal gland; small pituitary fossa; dentary bone massive in front; teeth very large. Shaft of scapula expanded at distal end. Sacral vertebræ four in number, and nearly solid; ischia slender, with twisted shaft directed backward, and sides meeting on median line. Anterior caudals solid. (Pls. XXIX-XXXVIII.)

Genera Morosaurus, Camarasaurus (?) (Amphicœlias). Jurassic, North America.

(4) Family Pleurocœlidæ. Dentition weak; teeth resembling those of Diplodocus. Cervical vertebræ elongated; centrum hollow, with large lateral openings; sacral vertebræ solid, with lateral depressions in centra; caudal vertebræ solid; anterior caudals with flat articular faces and transversely compressed neural spines; middle caudal vertebræ with neural arch on front half of centrum. Ischia with compressed distal ends, meeting on median line. (Pls. XL and XLI.)

Genera Pleurocœlus, Astrodon (?). Potomac, North America.

(5) Family Titanosauridæ. Fore limbs elongate; coracoid quadrilateral. Presacral vertebræ opisthocœlian; first caudal vertebra biconvex; remaining caudals procœlian; chevrons open above.

Genera Titanosaurus and Argyrosaurus. Cretaceous (?), India and Patagonia.

(6) Family Cardiodontidæ. Teeth of moderate size. Upper end of scapula expanded; humerus elongate; fore limbs near equaling hind limbs in length. Sacrum solid; ischia with wide distal ends meeting on median line. Caudal vertebræ biconcave.

Genera Cardiodon (Cetiosaurus), Bothriospondylus, Ornithopsis, and Pelorosaurus. European, and probably all Jurassic.[1]

Order PREDENTATA. Herbivorous.

Narial opening lateral; no antorbital foramen; brain case ossified; supraorbital bones; teeth with sculptured crowns; maxillary teeth with crowns grooved on outside; lower teeth with grooves on inside of crown; a predentary bone; dentary with coronoid process. Cervical ribs articulating with vertebræ; each sacral rib supported by two vertebræ. Ilium elongated in front of acetabulum; prepubic bones free in front; postpubic bones present; ischia slender, directed backward, with distal ends meeting side to side. Astragalus without ascending process.

Suborder STEGOSAURIA (Plated lizard).

Skull without horns; no teeth in premaxillaries; teeth with distinct compressed crowns and serrated edges. Vertebræ and limb bones solid. Pubes projecting free in front; postpubis present. Fore limbs small; femur longer than tibia; feet plantigrade, ungulate; five digits in manus and four in pes; second row of carpals and tarsals unossified; locomotion mainly quadrupedal. Osseous dermal armor.

(1) Family Stegosauridæ. Vertebræ biconcave. Neural canal in sacrum expanded into large chamber; ischia directed backward, with sides meeting on median line. Dorsal ribs T-shaped in cross section. Astragalus coossified with tibia; metapodials very short. Back surmounted by a crest of vertical plates; tail armed with large spines. (Pls. XLIII–LII.)

Genera Stegosaurus (Hypsirhophus), Diracodon, Palæoscincus, Priconodon, all from North America; and in Europe, Omosaurus, Owen. Jurassic and Cretaceous.

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[1] The Wealden is here regarded as upper Jurassic, and not Cretaceous See American Journal of Science, Vol L, p 412, November, 1895

(2) Family Scelidosauridæ. Neural canal narrow; diapophyses of dorsal vertebræ supporting head and tubercle of ribs. Astragalus not coossified with tibia; metatarsals elongated; three functional digits in pes.

Genera Scelidosaurus, Acanthopholis, Hylæosaurus, Polacanthus. Jurassic and Cretaceous. Known forms, all European. (Pl. LXXXIII.)

(3) Family Nodosauridæ. Heavy dermal armor. Bones solid. Fore limbs large; five digits in manus; feet ungulate.

Genus Nodosaurus. Cretaceous, North America.

Suborder CERATOPSIA (Horned face).

Premaxillaries edentulous; teeth with two distinct roots; skull surmounted by massive horn cores; a rostral bone, forming a sharp, cutting beak; expanded parietal crest, with marginal armature; a pineal foramen (?). Vertebræ and limb bones solid; fore limbs large; femur longer than tibia; feet ungulate; locomotion quadrupedal. Dermal armor.

(4) Family Ceratopsidæ. Anterior cervical vertebræ coossified with each other; posterior dorsal vertebræ supporting on the diapophysis both the head and tubercle of the rib; lumbar vertebræ wanting; sacral vertebræ with both diapophyses and ribs. Neural canal in sacrum without marked enlargement. Pubes projecting in front, with distal end expanded; postpubic bone rudimentary or wanting. (Pls. LIX-LXXI.)

Genera Ceratops, Agathaumas, Monoclonius, Polyonax, Sterrholophus, Torosaurus, Triceratops, in North America; and in Europe, Struthiosaurus (Cratæomus). All are Cretaceous.

Suborder ORNITHOPODA (Bird foot).

Skull without horns; premaxillaries edentulous in front. Vertebræ solid. Fore limbs small. Pubes projecting free in front; postpubis present. Astragalus closely fitting to end of tibia; feet digitigrade; three to five functional digits in manus and three to four in pes; locomotion mainly bipedal. No dermal armor.

(5) Family Camptosauridæ (Camptonotidæ). Premaxillaries edentulous; teeth in single row; a supraorbital fossa. Anterior vertebræ opisthocœlian; sacral vertebræ five, not coossified, with peg-and-notch articulation. Sternum unossified. Limb bones hollow; fore limbs small; five digits in manus. Postpubis reaching to the distal end of ischium. Femur longer than tibia, and with pendent fourth trochanter; hind feet with three functional digits. (Pls. LIII-LVI.)

Genus Camptosaurus (Camptonotus). Jurassic, North America.

(6) Family Laosauridæ. Premaxillaries edentulous; teeth in single row. Anterior vertebræ with plane articular faces; sacral vertebræ coossified. Sternum unossified. Postpubis reaching to distal end of ischium. Limb and foot bones hollow; fore limbs very small; five digits in manus; femur shorter than tibia; metatarsals elongate; four digits in pes. (Pls. LV and LVII.)

Genera Laosaurus and Dryosaurus. Jurassic, North America.

(7) Family Hypsilophodontidæ. Premaxillaries with teeth; teeth in single row; sclerotic bony plates. Anterior vertebræ opisthocœlian; sacral vertebræ coossified. Sternum ossified. Postpubis extending to end of ischium. Limb bones hollow; five digits in manus; femur shorter than tibia; hind feet with four digits. (Pl. LXXXIV.)

Genus Hypsilophodon. Wealden, England.

(8) Family Iguanodontidæ. Premaxillaries edentulous; teeth in single row. Anterior vertebræ opisthocœlian. Manus with five digits; pollex spine-like. Sternal bones ossified. Postpubis incomplete. Femur longer than tibia; three functional digits in pes. (Pl. LXXXV.)

Genera Iguanodon, Vectisaurus. Jurassic and Cretaceous. Known forms, all European.

(9) Family Trachodontidæ (Hadrosauridæ). Premaxillaries edentulous; teeth in several rows, forming with use a tessellated grinding surface. Cervical vertebræ opisthocœlian. Limb bones hollow; fore limbs small; femur longer than tibia.

Genera Trachodon (Hadrosaurus, Diclonius), Cionodon, and Ornithotarsus. Cretaceous, North America.

(10) Family Claosauridæ. Premaxillaries edentulous; teeth in several rows, but a single row only in use. Cervical vertebræ opisthocœlian. Limb bones solid; fore limbs small. Sternal bones parial. Postpubis incomplete. Sacral vertebræ nine. Femur longer than tibia; feet ungulate; three functional digits in manus and pes. (Pls. LXXII–LXXIV.)

Genus Claosaurus. Cretaceous, North America.

(11) Family Nanosauridæ. Teeth compressed and pointed, and in a single uniform row. Cervical and dorsal vertebræ short and biconcave; sacral vertebræ three. Ilium with very short pointed front and narrow posterior end. Limb bones and others very hollow; fore limbs of moderate size; humerus with strong radial crest; femur curved, and shorter than tibia; fibula pointed below; metatarsals very long and slender. Anterior caudals short.

Genus Nanosaurus. Jurassic, North America. Includes the most diminutive of known dinosaurs.

POSTSCRIPT.

The accompanying plates, as well as the figures in the text, are all from original drawings made to illustrate the writer's investigations on the early vertebrate life of North America. Many of these illustrations were designed especially for the monographs on dinosaurian reptiles now in preparation for the United States Geological Survey, and are here used, with the approval of the Director, to give the general reader a clear idea of some of the type specimens of one great group of extinct animals that were long the dominant forms of life on this continent.

YALE UNIVERSITY, *June 15, 1895.*

PLATES.

PLATE II.

PLATE II.

TRIASSIC DINOSAURS.—THEROPODA.

ANCHISAURIDÆ.

Page.

FIG. 1. Skull of *Anchisaurus colurus* Marsh; side view; one-half natural size. 148

a, nasal opening; *b*, antorbital opening; *c*, lower temporal fossa; *d*, upper temporal fossa; *o*, orbit; *q*, quadrate.

FIG. 2. Bones of left fore leg of same individual; outside view; one-fourth natural size 149

c, coracoid; *h*, humerus; *r*, radius; *s*, scapula; *u*, ulna; *I*, first digit; *V*, fifth digit.

FIG. 3. Bones of left hind leg of same individual, outside view; one-fourth natural size.. 149

a, astragalus, *c*, calcaneum; *f*, femur, *f'*, fibula; *il*, ilium; *is*, ischium; *p*, pubis, *t*, tibia, *I*, first digit; *V*, fifth digit.

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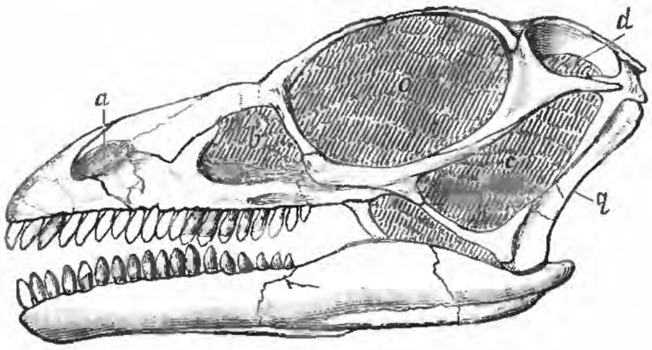

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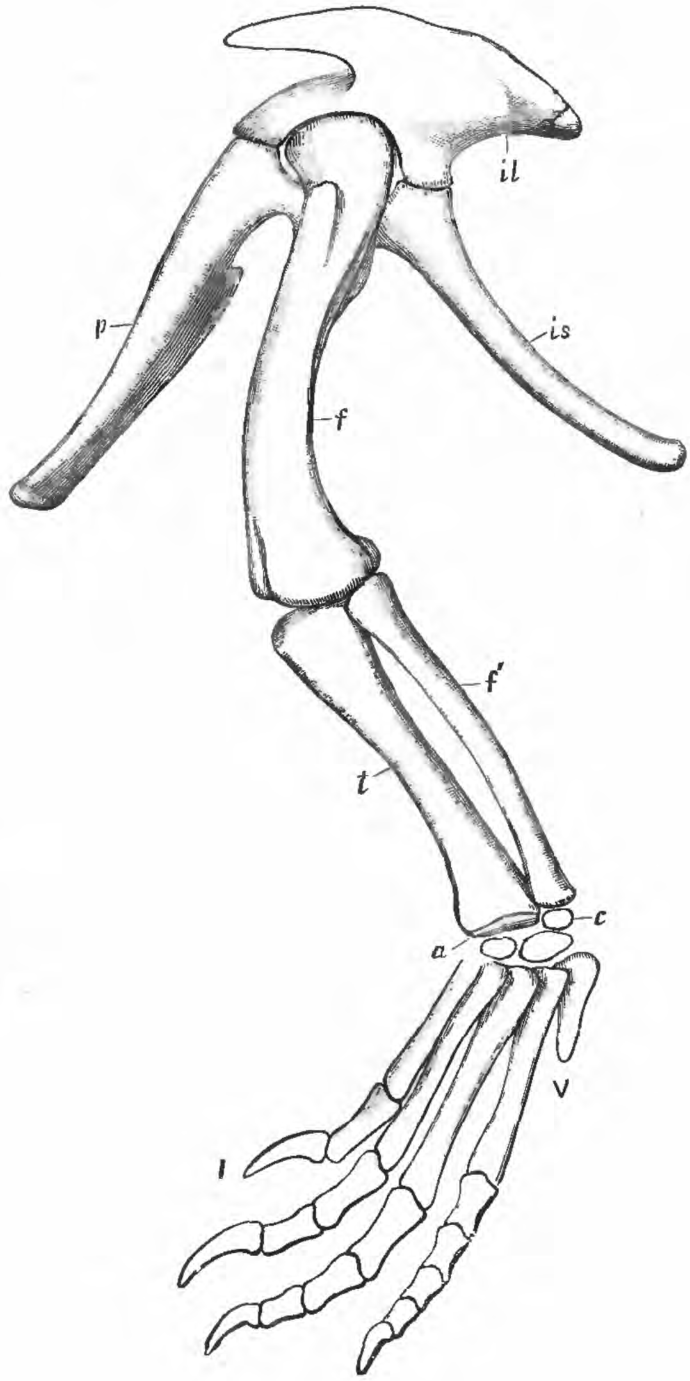

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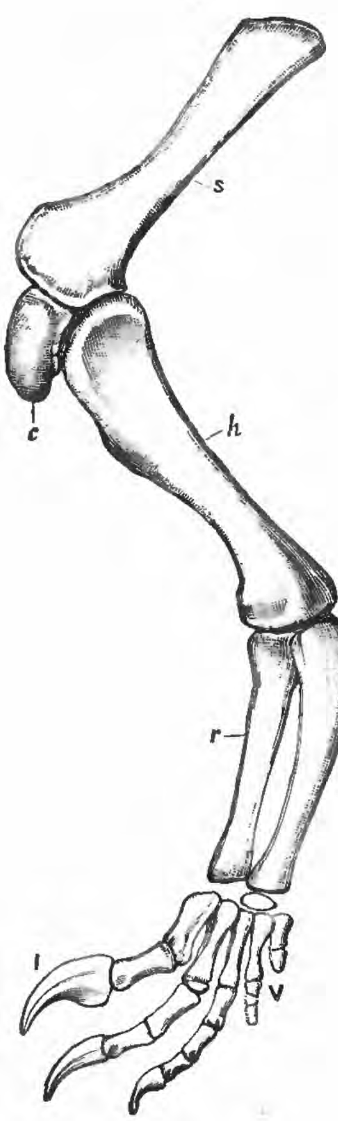


ANCHISAURUS COLURUS Marsh.

Triassic.

PLATE III.

PLATE III.

TRIASSIC DINOSAURS.—THEROPODA.

ANCHISAURIDÆ.

Page

FIG. 1. Skull of *Anchisaurus colurus* Marsh; top view; one-half natural size.. 148

FIG. 2. Base of same skull; back view; one-half natural size................ 148

a, nasal opening; *bp*, bas pterygoid process; *d*, upper temporal fossa, *f*, frontal; *j*, jugal; *n*, nasal; *o*, orbit; *oc*, occipital condyle; *p*, parietal; *p′*, paroccipital process; *pf*, prefrontal; *pm*, premaxillary.

FIG. 3. Sacrum and ilia of *Ammosaurus major* Marsh; seen from below; one-fourth natural size.. 150

FIG. 4 Ischia of *Anchisaurus polyzelus* Hitchcock, sp., seen from above; one-half natural size.. 150

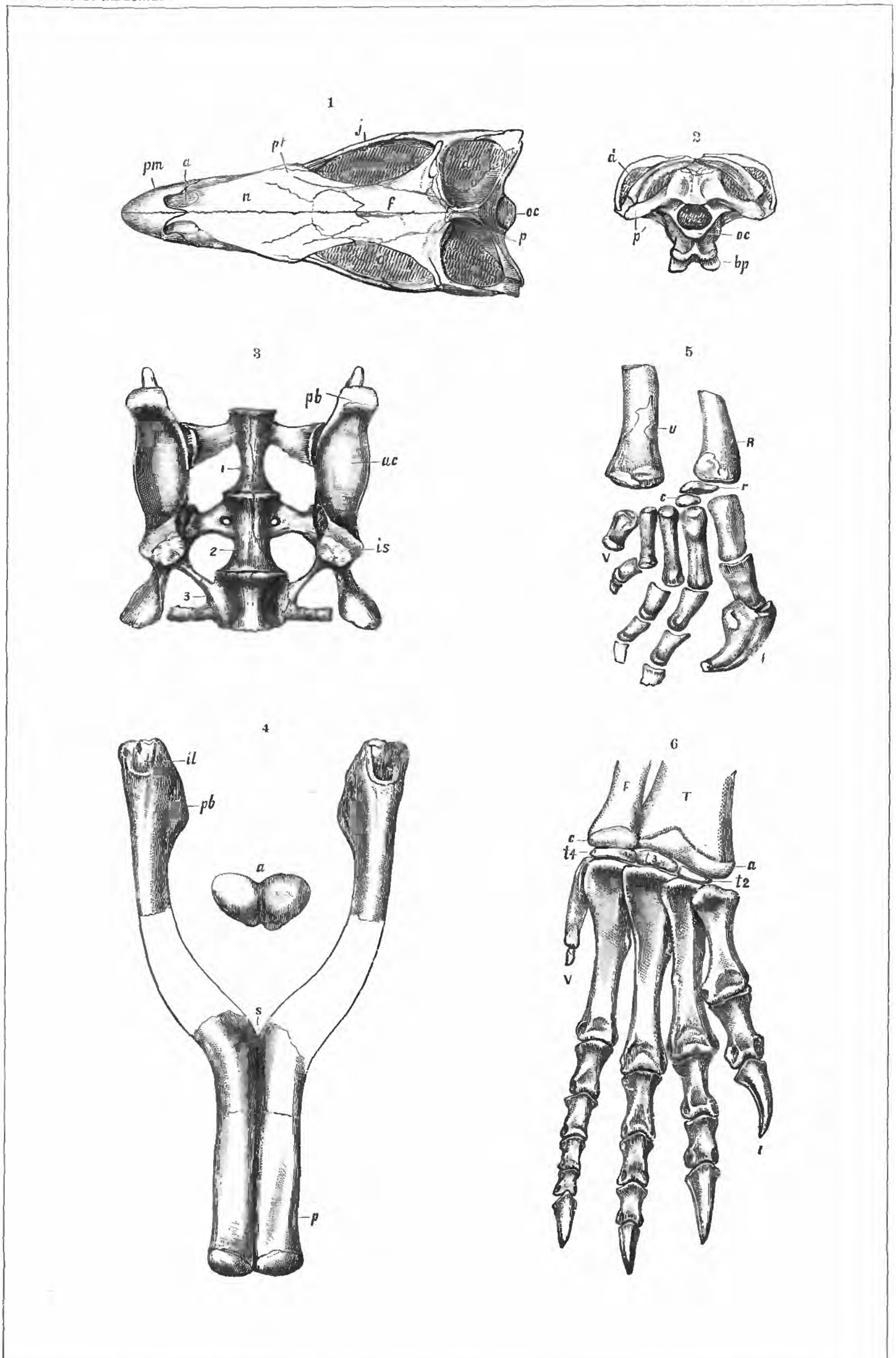
a, posterior view of distal ends; *ac*, acetabular surface; *il*, face for ilium; *is*, face for ischium, *p*, distal end; *pb*, face for pubis; *s*, symphysis; *1*, *2*, *3*, sacral vertebræ

FIG 5. Left fore foot of *Anchisaurus polyzelus;* back view; one-half natural size.. 149

c, centrale, *r*, radiale; *R*, radius; *U*, ulna; *I*, first digit; *V*, fifth digit

FIG. 6 Right hind foot of *Ammosaurus major;* front view; one-fourth natural size.. 150

a, astragalus; *c*, calcaneum; *F*, fibula, *T*, tibia; *t2*, *t3*, *t4*, tarsal bones, *I*, first digit; *V*, fifth digit.



ANCHISAURUS AND AMMOSAURUS.

Triassic.

PLATE IV.

PLATE IV.

TRIASSIC DINOSAURS.—THEROPODA.

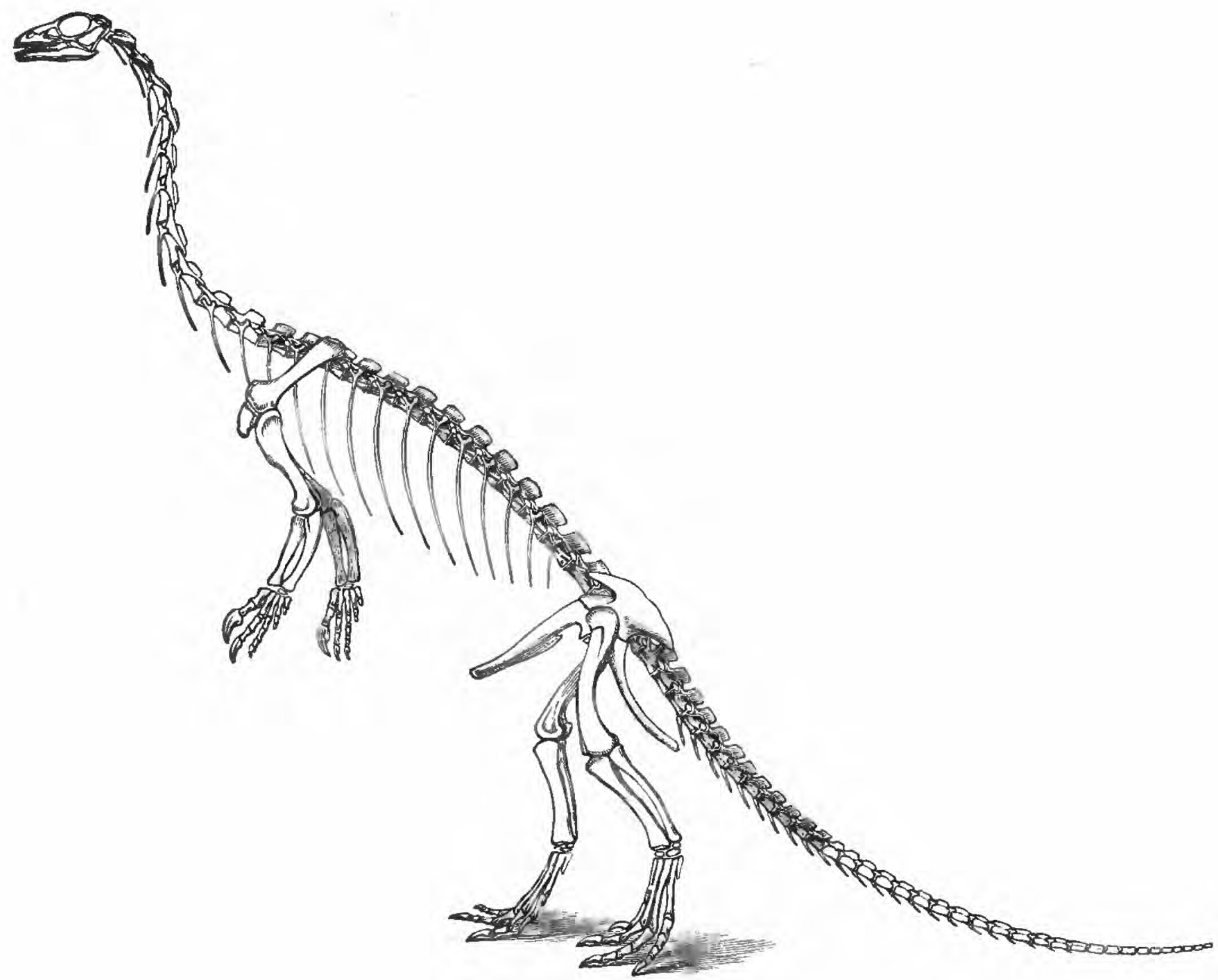
ANCHISAURIDÆ.

Page

Restoration of *Anchisaurus colurus* Marsh 150

One-twelfth natural size

Connecticut River sandstone, Connecticut.



RESTORATION OF ANCHISAURUS COLURUS Marsh.

One-twelfth natural size. Triassic, Connecticut.

PLATE V.

PLATE V.

TRIASSIC DINOSAURS.—FOOTPRINTS.

Page

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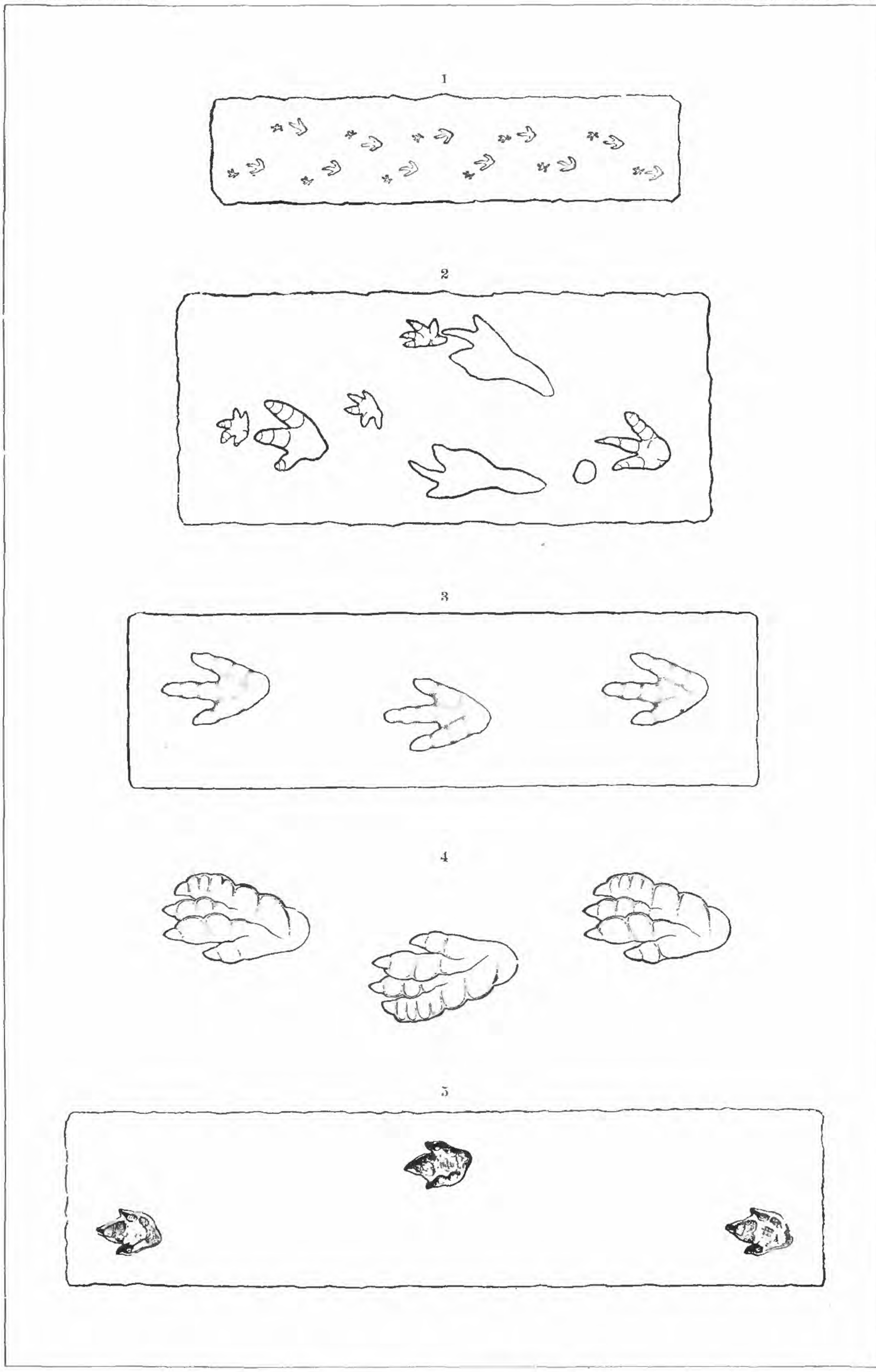
FIG. 2. Footprints of bipedal dinosaur (Anomœpus); showing where the animal sat down; one-twelfth natural size 151

FIG 3. Footprints of large bipedal dinosaur (Brontozoum), one-twentieth natural size.. 151

FIG 4 Footprints of large dinosaur (Otozoum), showing impressions of hind feet alone, one-twentieth natural size............................ 151

FIG 5 Footprints of bipedal dinosaur; one-twelfth natural size.............. 151

The specimens represented in figs 1–4 are from the Connecticut River sandstone of Massachusetts, and the one shown in fig 5 is from nearly the same horizon in Arizona.



FOOTPRINTS OF TRIASSIC DINOSAURS.

PLATE VI.

PLATE VI.

JURASSIC DINOSAURS.—THEROPODA.

HALLOPIDÆ.

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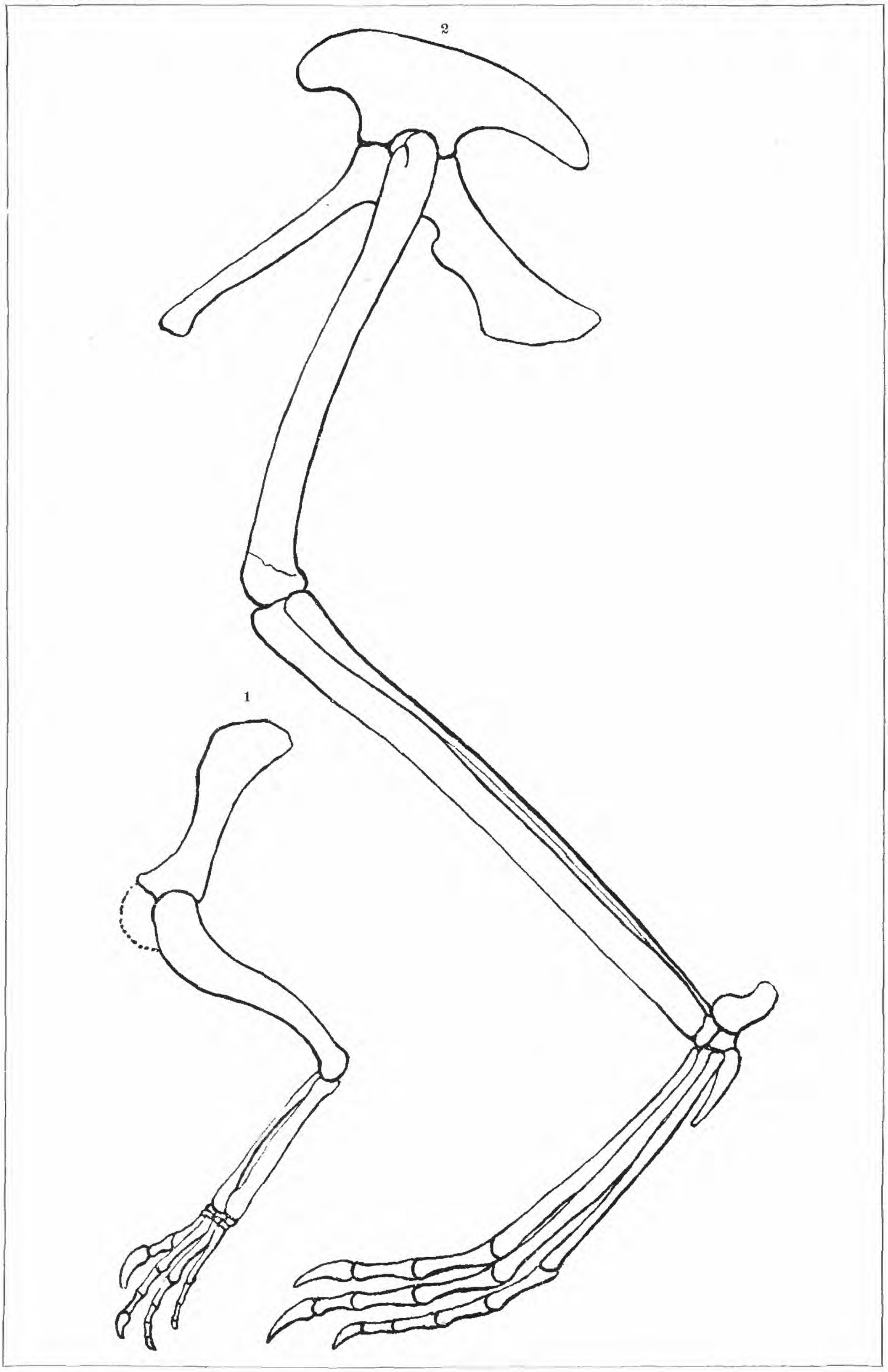
FIG 2. Outline restoration of left hind leg of same individual, outer view...	154

Both figures are natural size



HALLOPUS VICTOR Marsh.

Jurassic.

PLATE VII.

PLATE VII.

JURASSIC DINOSAURS.—THEROPODA.

CŒLURIDÆ.

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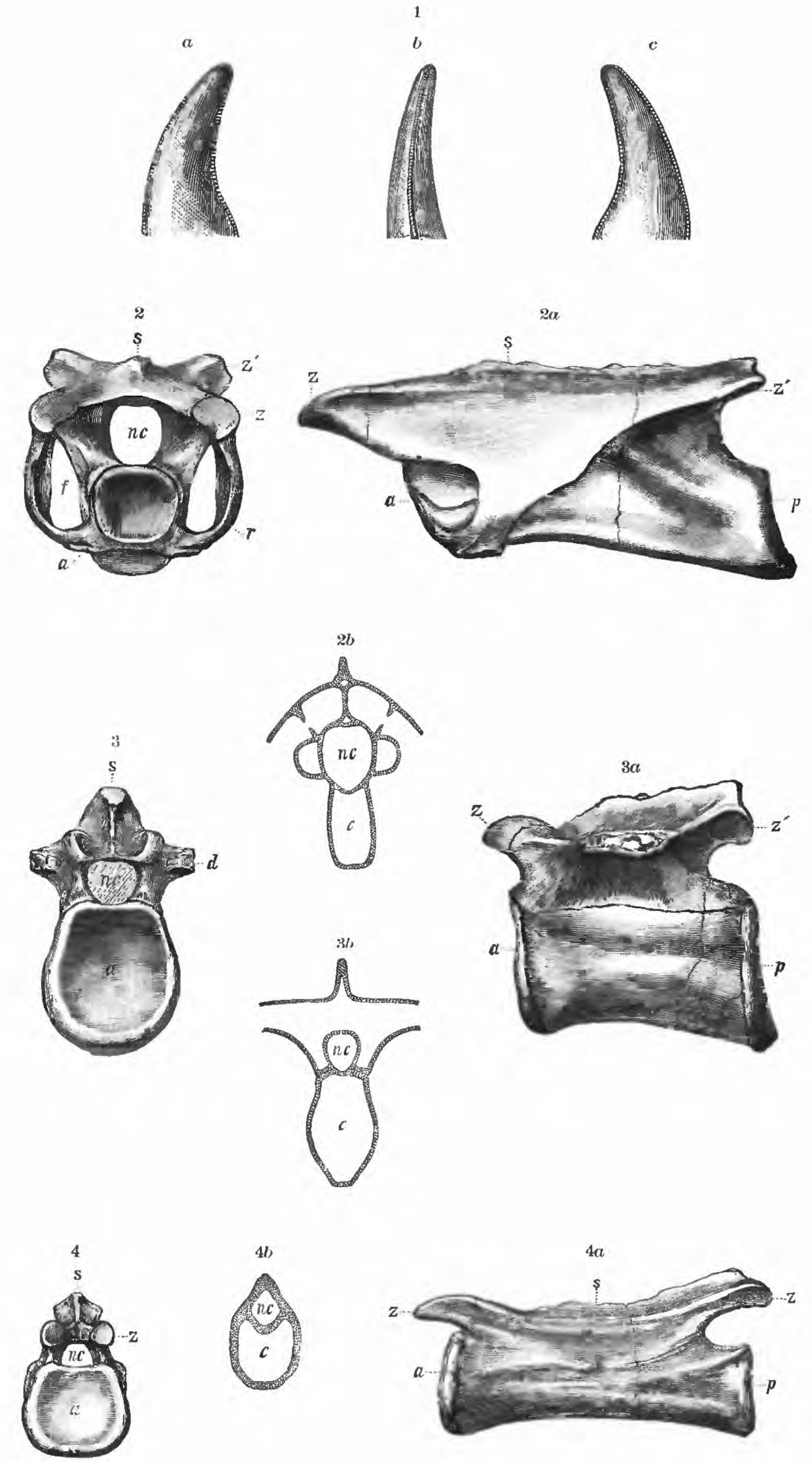
a, anterior end; *c*, cavity; *d*, diapophysis, *f*, lateral foramen; *nc*, neural canal; *p*, posterior end, *r*, coossified rib; *s*, neural spine, *z*, anterior zygapophysis; *z′*, posterior zygapophysis.

All the figures of vertebræ are natural size



CŒLURUS FRAGILIS Marsh.

Jurassic.

PLATE VIII.

PLATE VIII.

JURASSIC DINOSAURS.—THEROPODA.

CERATOSAURIDÆ.

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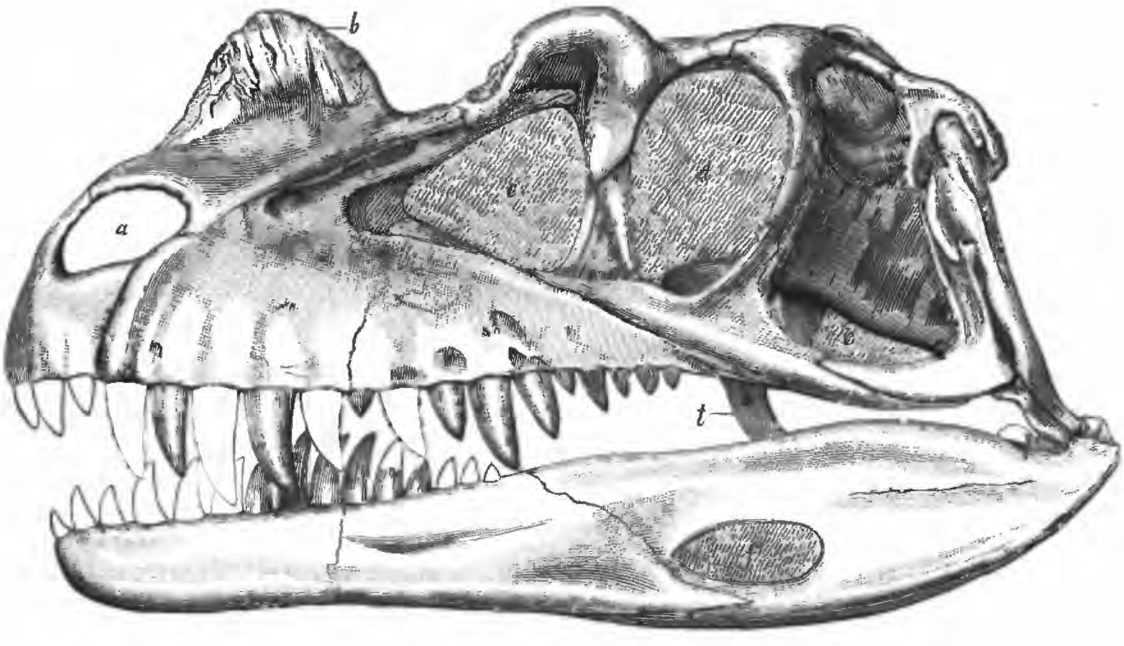
a, nasal opening, *b*, horn core; *c*, antorbital opening; *c′*, cerebral hemispheres; *d*, orbit; *e*, lower temporal fossa; *f*, frontal bone; *f′*, foramen in lower jaw, *h*, supratemporal fossa, *j*, jugal, *m*, maxillary bone; *m′*, medulla, *n*, nasal bone, *oc*, occipital condyle; *ol*, olfactory lobes; *pf*, prefrontal bone, *pm*, premaxillary bone, *q*, quadrate bone; *qj*, quadratojugal bone; *t*, transverse bone

All the figures are one-sixth natural size

1



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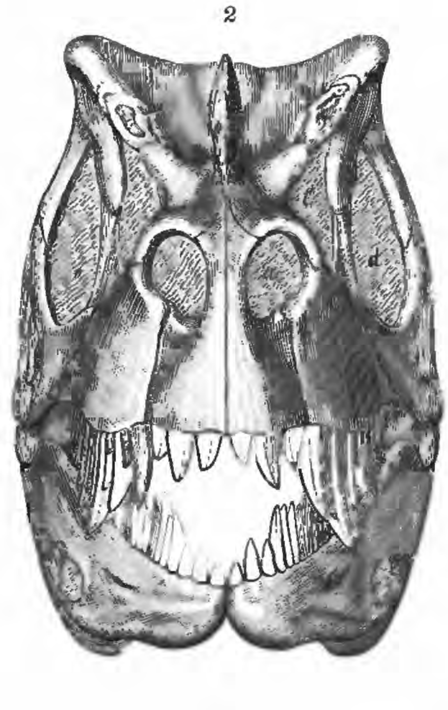

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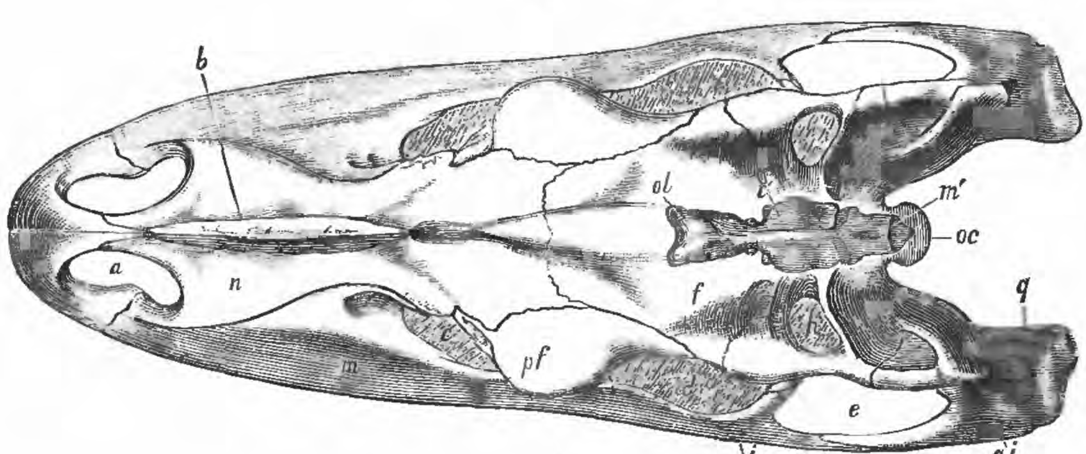

CERATOSAURUS NASICORNIS Marsh.
Jurassic.

PLATE IX.

PLATE IX.

JURASSIC DINOSAURS.—THEROPODA.

CERATOSAURIDÆ

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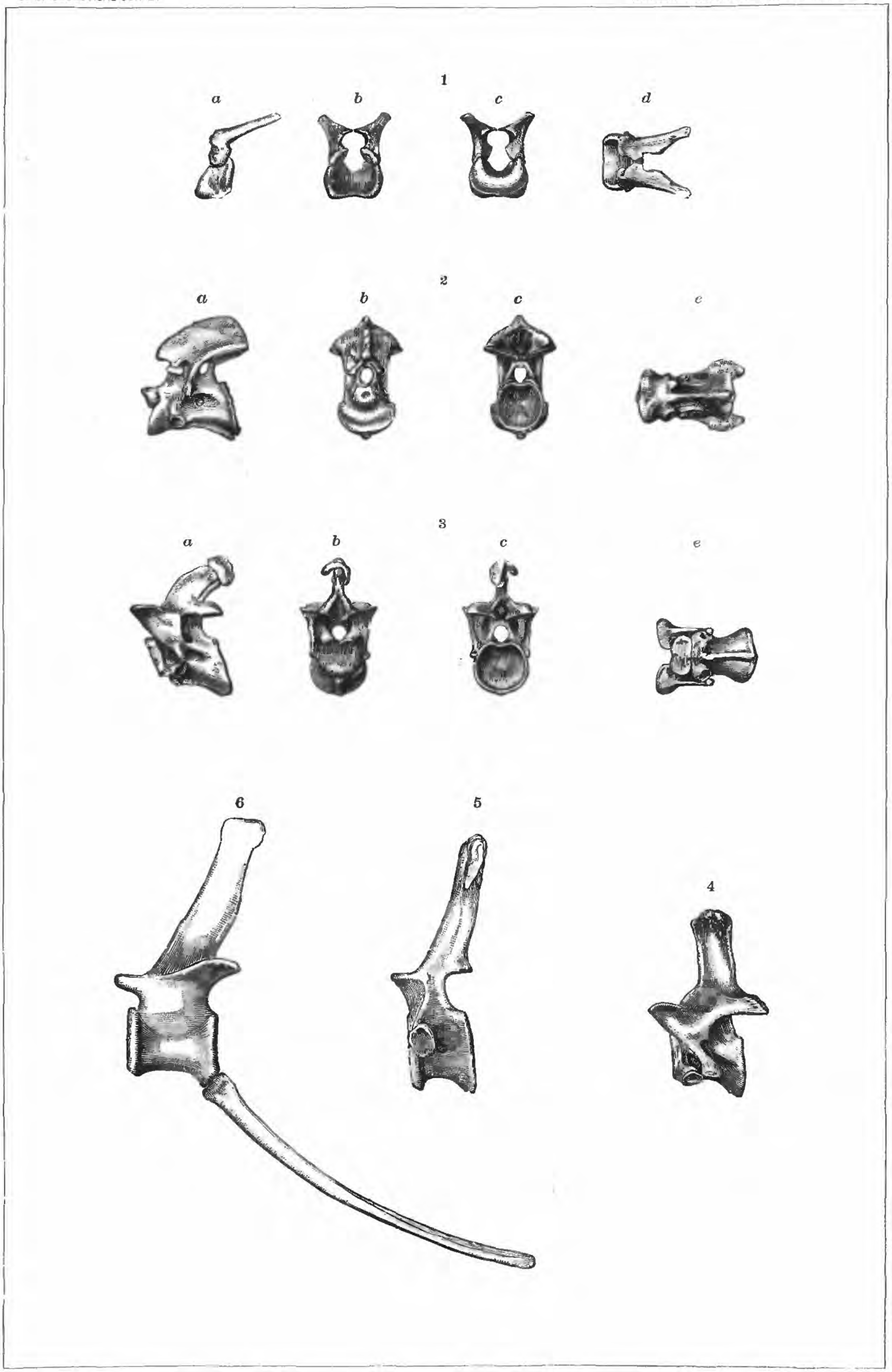
All the figures are one-sixth natural size.



CERATOSAURUS NASICORNIS,

Jurassic,

PLATE X.

PLATE X.

JURASSIC DINOSAURS.—THEROPODA.

CERATOSAURIDÆ, DRYPTOSAURIDÆ, AND CŒLURIDÆ

Page

FIG. 1. Pelvis of *Ceratosaurus nasicornis* Marsh, side view; seen from the left; one-twelfth natural size 161

The three pelvic bones are coossified

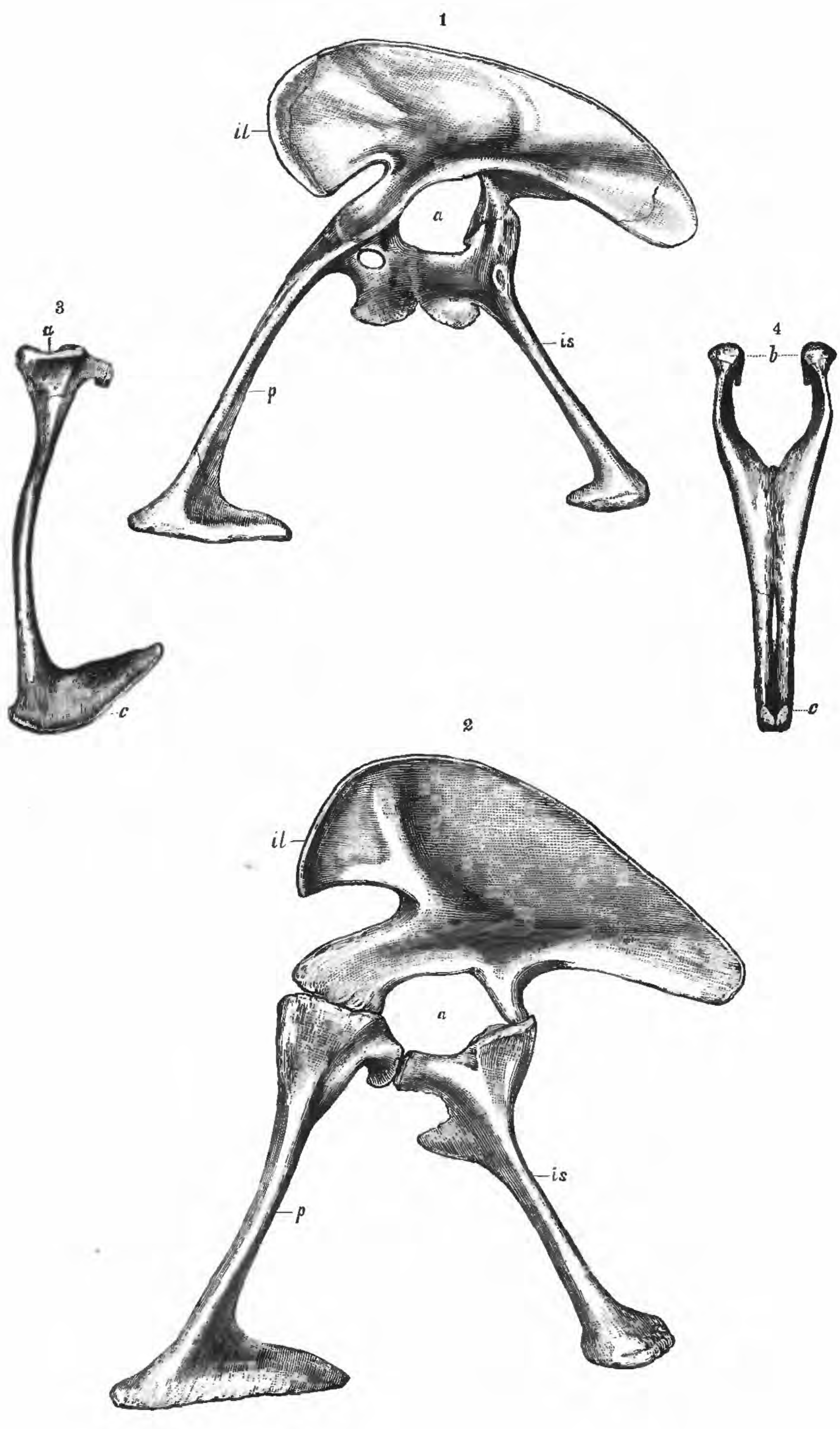
FIG. 2. Pelvis of *Allosaurus fragilis* Marsh; the same view; one-twelfth natural size 163

a, acetabulum; *il*, ilium; *is*, ischium; *p*, pubis.

FIG. 3. Pubes of *Cœlurus agilis* Marsh; one-fourth natural size 156

FIG. 4. The same bones, one-fourth natural size 156

a, side view; *b*, front view, *c*, foot, or distal end.



CERATOSAURUS, ALLOSAURUS, AND CŒLURUS.

Jurassic.

PLATE XI.

PLATE XI.

JURASSIC DINOSAURS.—THEROPODA.

DRYPTOSAURIDÆ.

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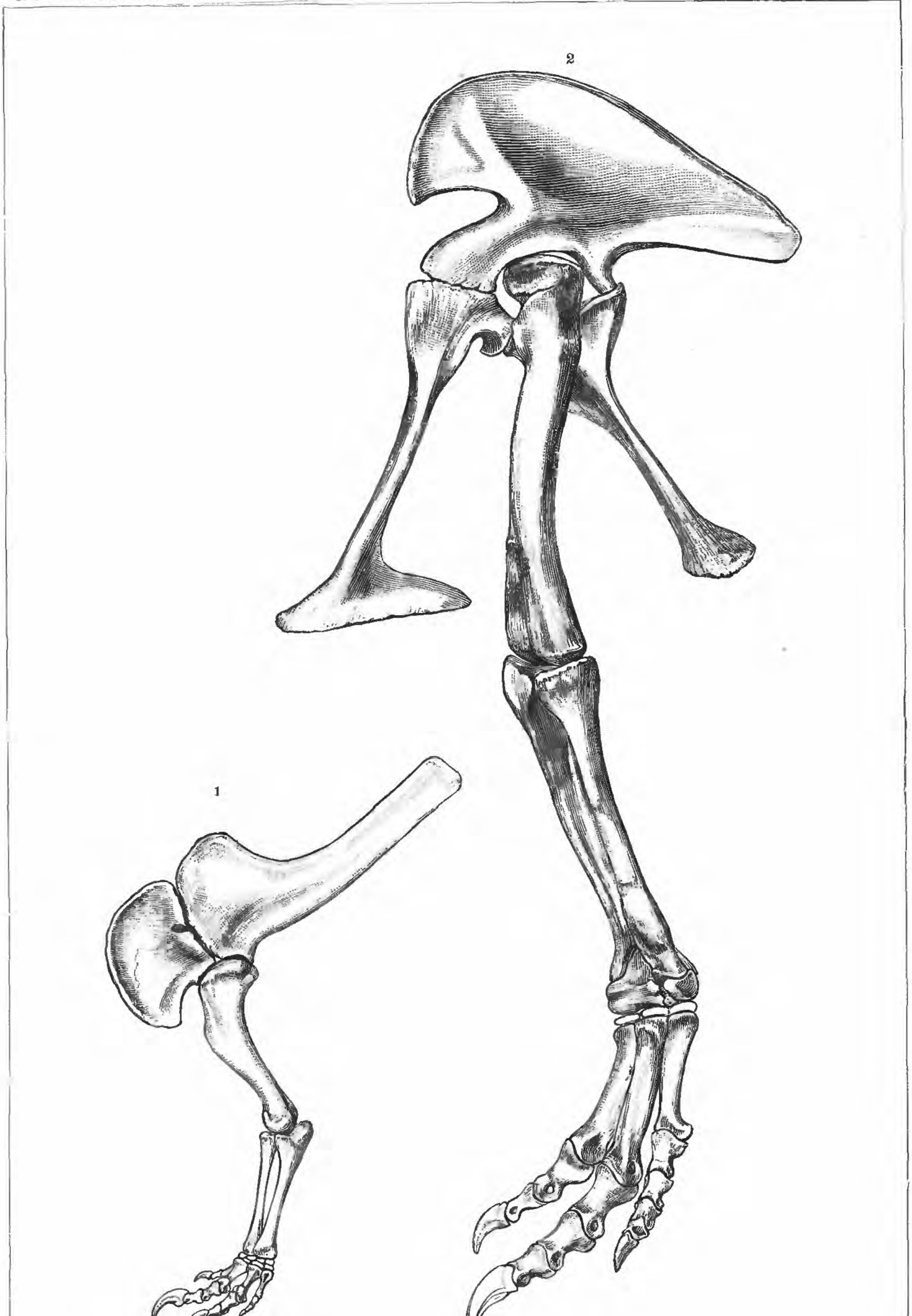
FIG. 2. Bones of left hind leg of *Allosaurus fragilis;* outer view	163

Both figures are one-twelfth natural size.



ALLOSAURUS FRAGILIS Marsh.

Jurassic.

PLATE XII.

PLATE XII.

JURASSIC DINOSAURS.—THEROPODA.

DRYPTOSAURIDÆ

Page

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a, front view; *b*, lateral view, showing outer side; *c*, lateral view, showing inner surface.

Fig 2. Left ilium of *Creosaurus atrox;* seen from the left; one-tenth natural size 161

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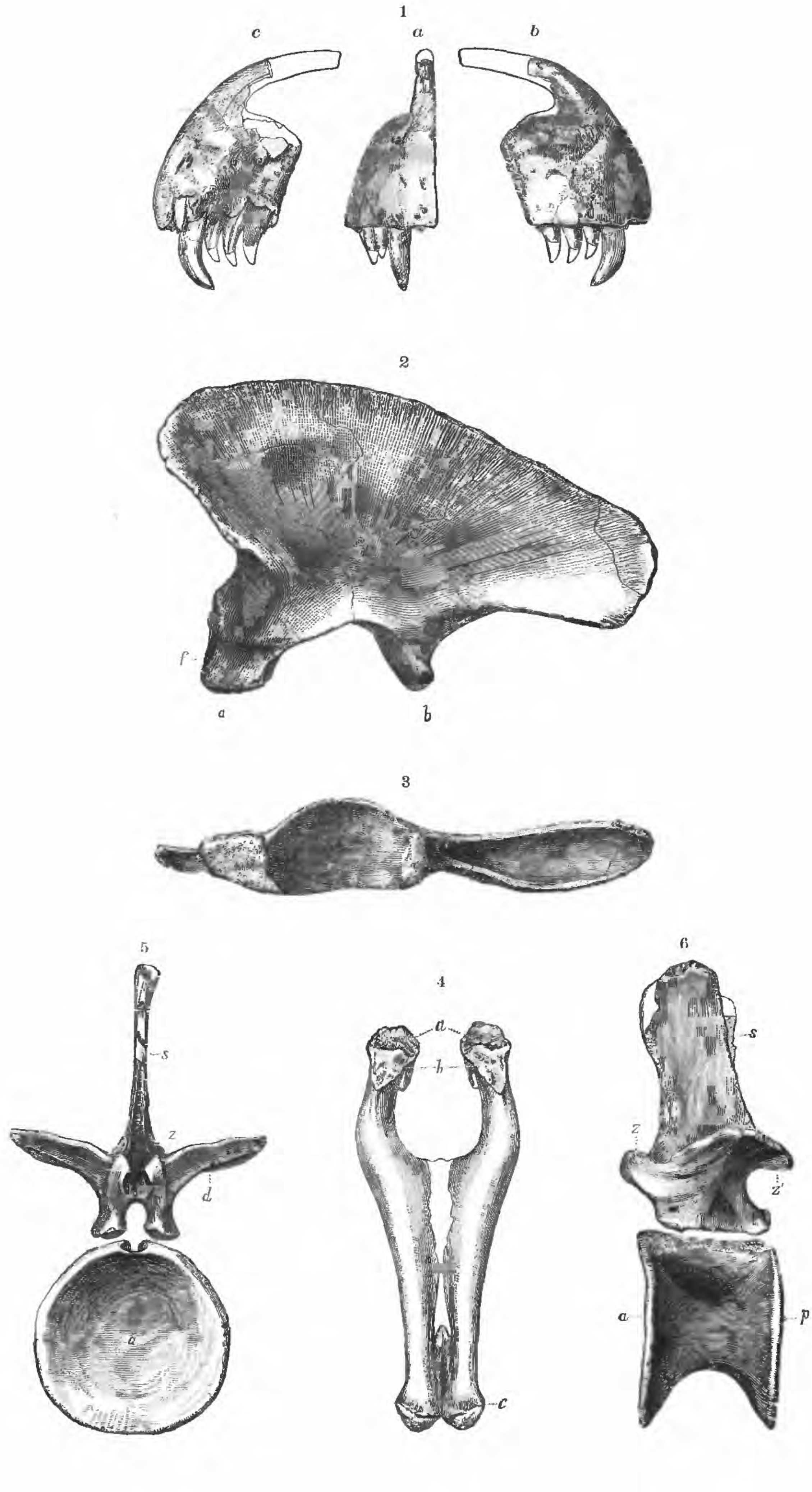
a, anterior, or pubic, articulation; *b*, posterior, or ischiadic, articulation.

Fig 4 Pubes of *Creosaurus atrox;* front view; one-twelfth natural size...... 163
a, acetabular surface; *b*, face for ilium; *c*, distal end.

Fig 5 Lumbar vertebra of *Creosaurus atrox;* front view; one-sixth natural size 160

Fig. 6 The same, side view; seen from the left, one-sixth natural size...... 160
a, anterior articular face; *d*, diapophysis; *p*, posterior articular face, *s*, neural spine; *z*, anterior zygapophysis, *z′*, posterior zygapophysis.



CREOSAURUS ATROX Marsh.

Jurassic.

PLATE XIII.

PLATE XIII.

JURASSIC DINOSAURS.—THEROPODA.

LABROSAURIDÆ.

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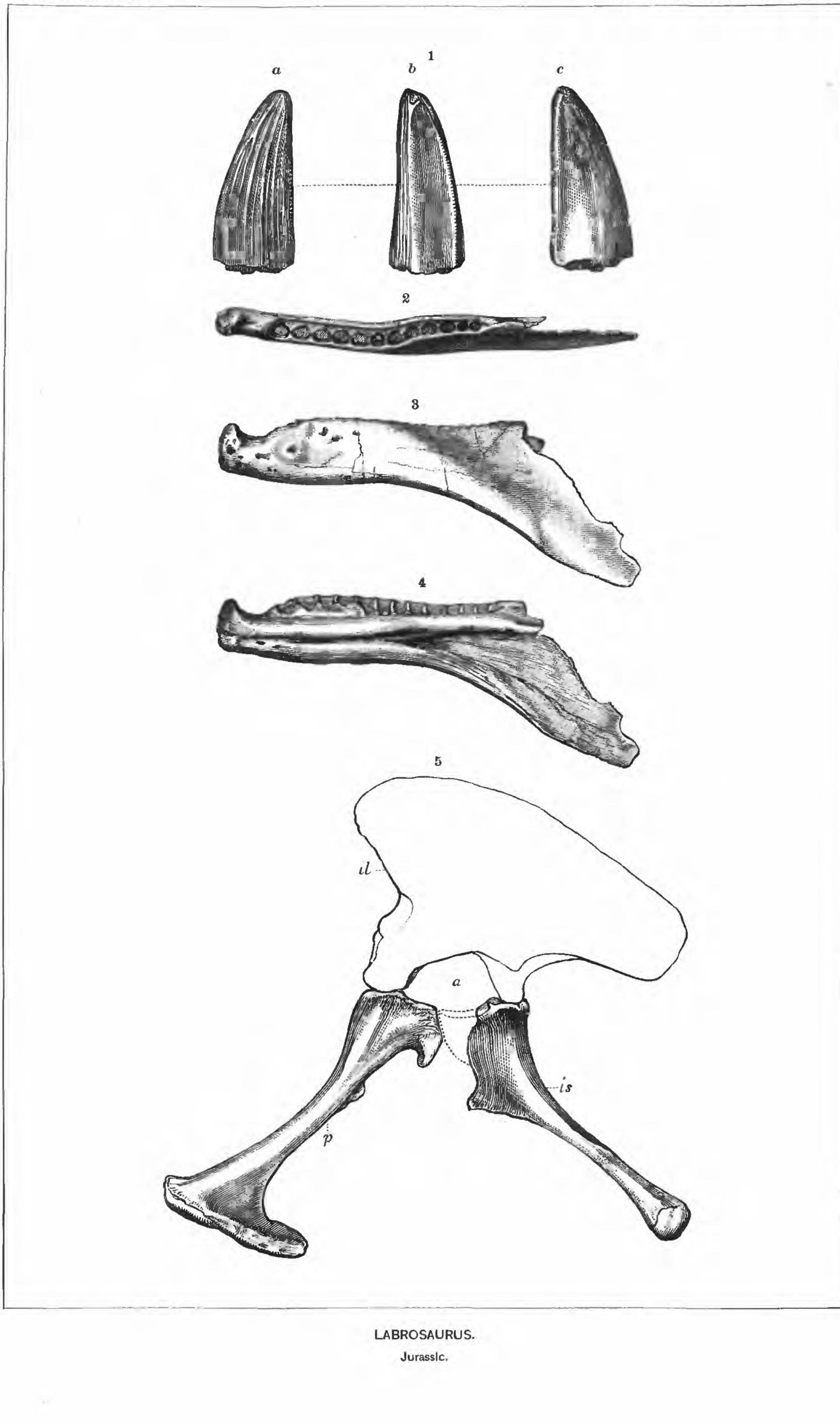
a, acetabulum, *il*, ilium, *is*, ischium, *p*, pubis	



LABROSAURUS.

Jurassic.

PLATE XIV.

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JURASSIC DINOSAURS.—THEROPODA.

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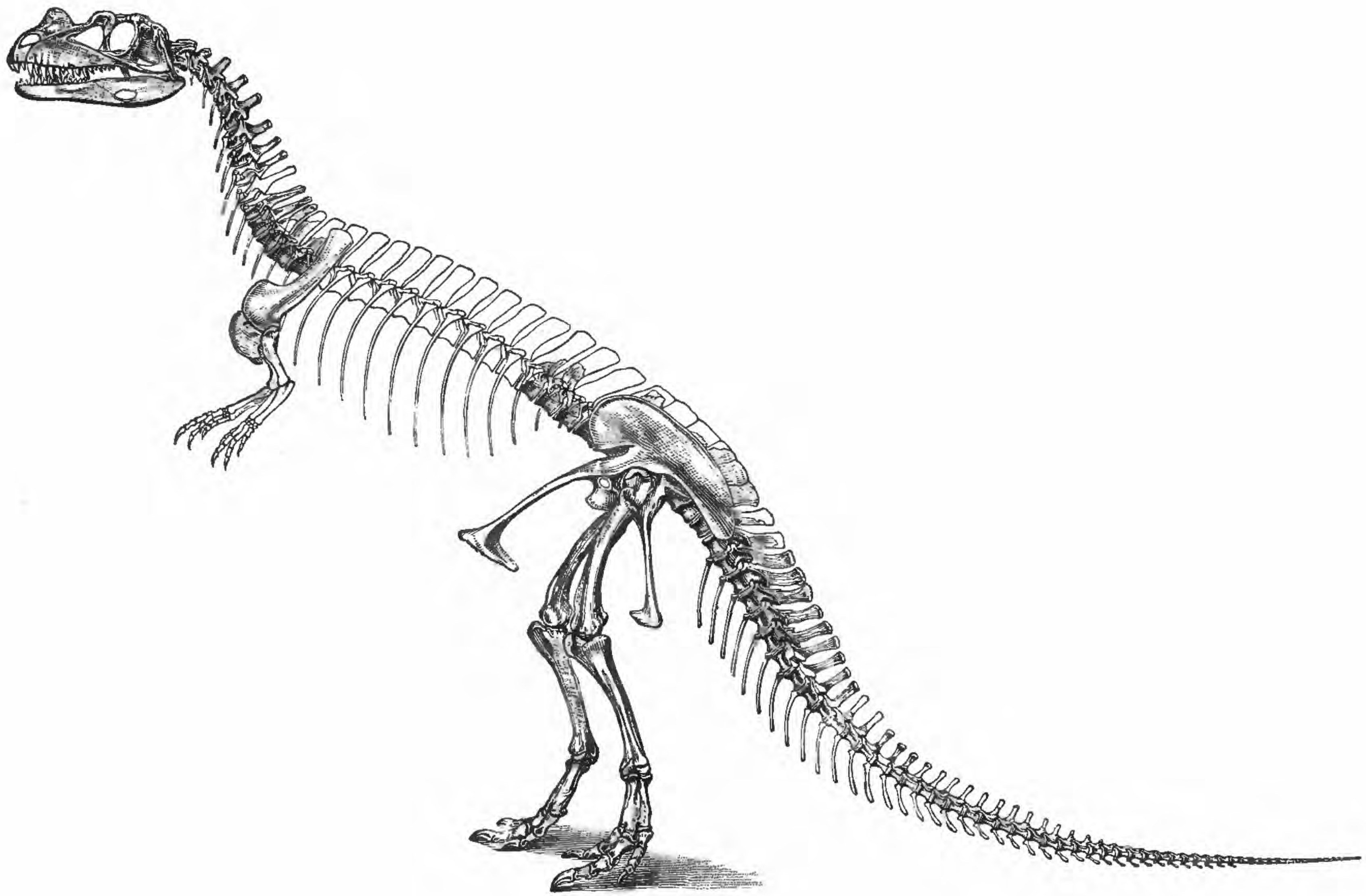
Restoration of *Ceratosaurus nasicornis* Marsh	163

One-thirtieth natural size.
Jurassic, Colorado.



RESTORATION OF CERATOSAURUS NASICORNIS Marsh.

One-thirtieth natural size. Jurassic, Colorado.

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ATLANTOSAURIDÆ.

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Both figures are one-half natural size

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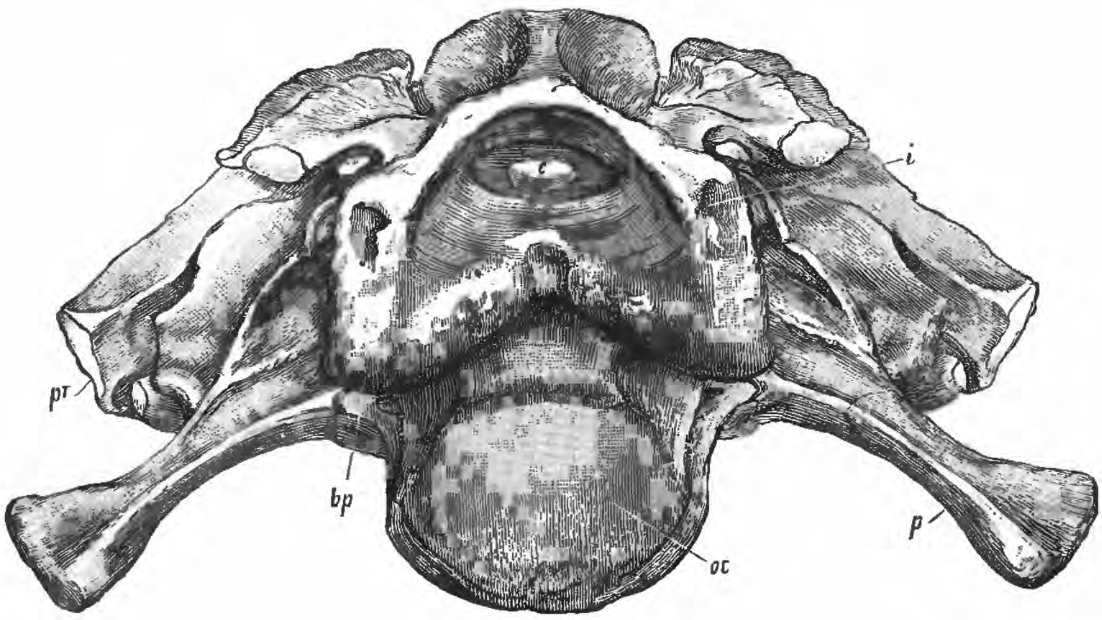

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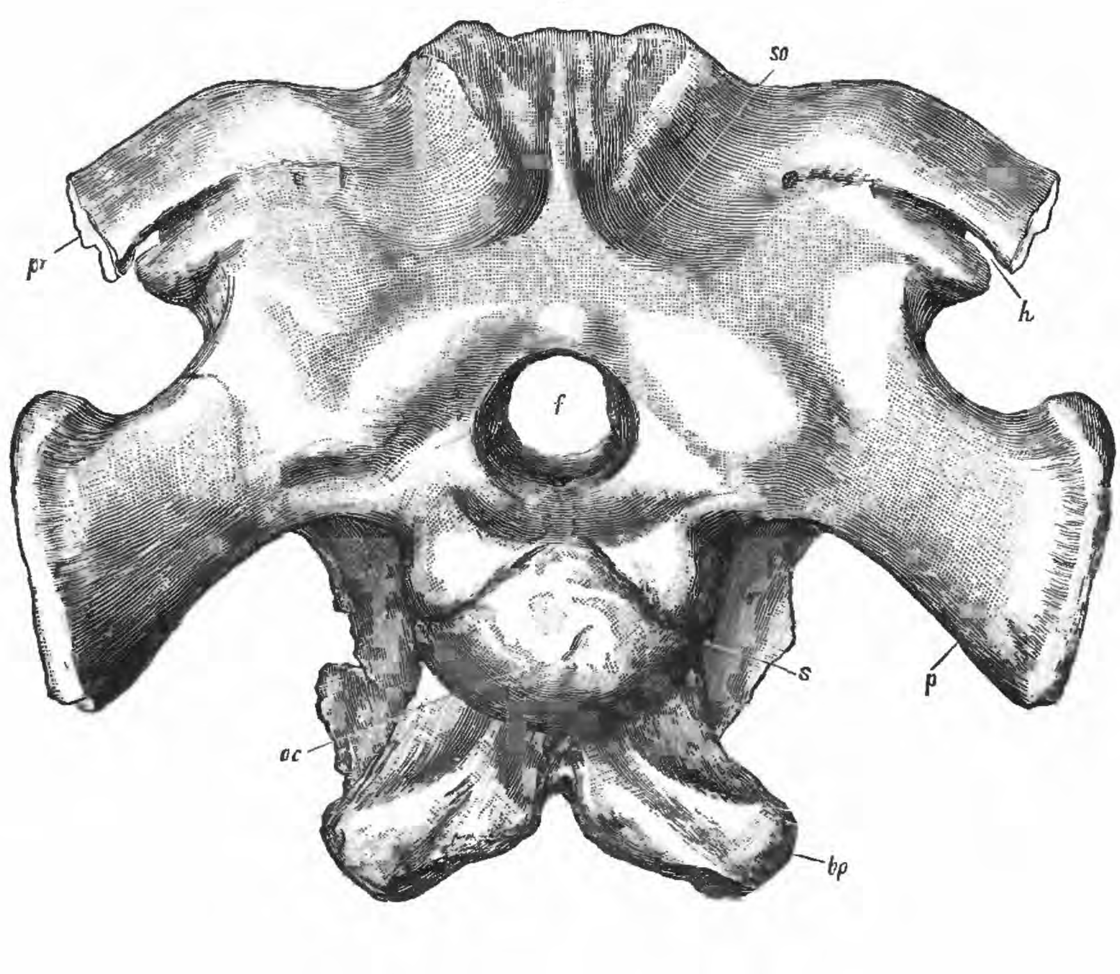

ATLANTOSAURUS MONTANUS Marsh.

Jurassic.

PLATE XVI.

PLATE XVI.

JURASSIC DINOSAURS.—SAUROPODA.

ATLANTOSAURIDÆ.

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2*a*, proximal end

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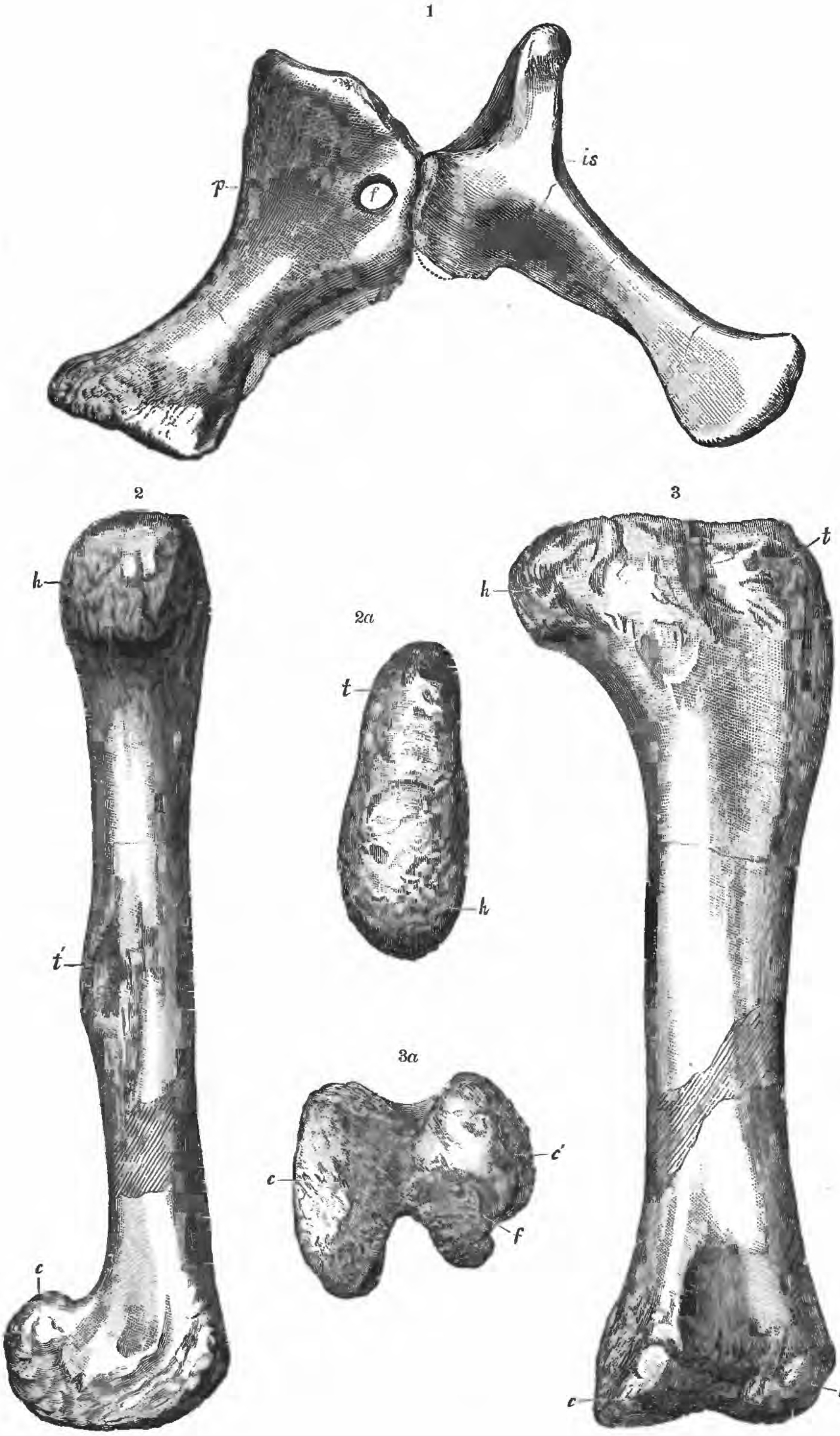
3*a*, distal end.

c, inner condyle; *c'*, outer condyle; *f*, groove for fibula; *h*, head, *t*, trochanter; *t'*, inner trochanter.



ATLANTOSAURUS IMMANIS Marsh.

Jurassic.

PLATE XVII.

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Both figures are one-tenth natural size.

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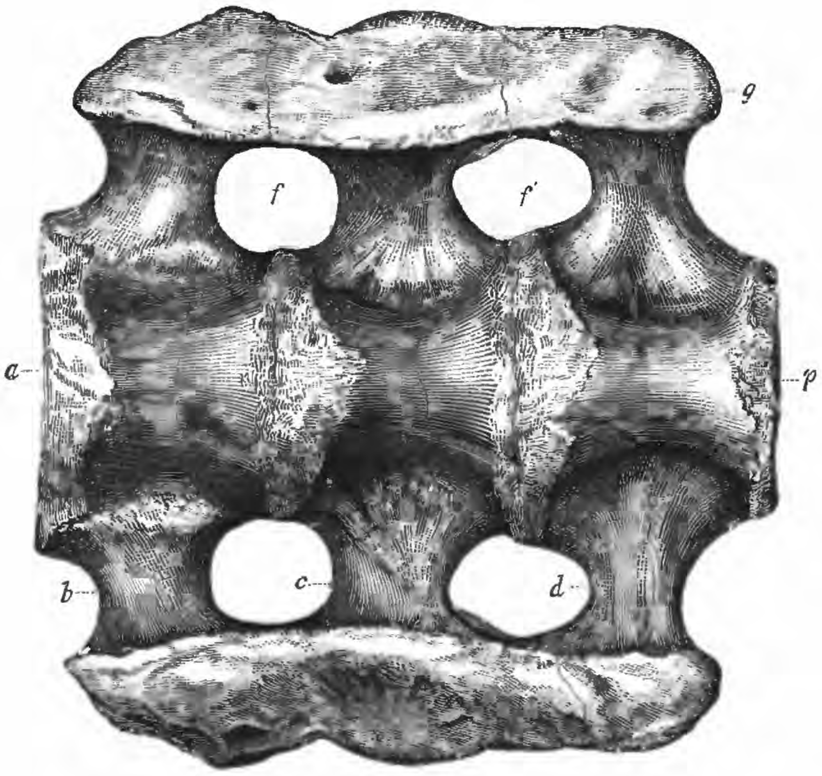

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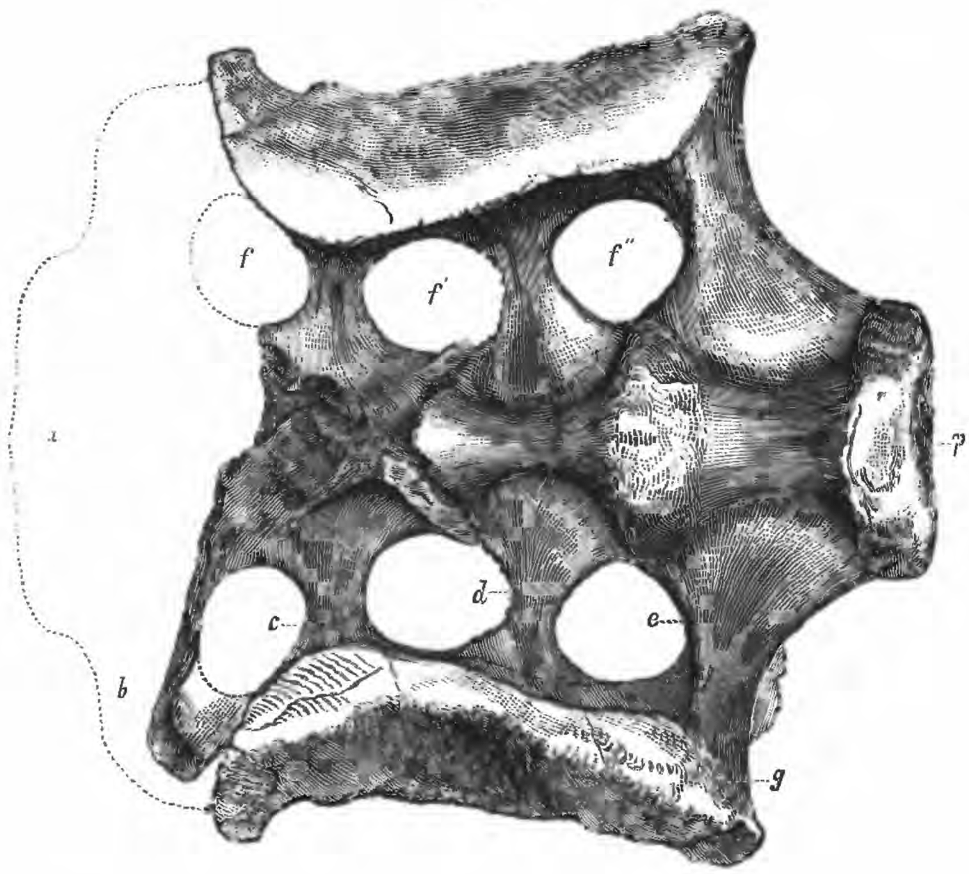

ATLANTOSAURUS AND APATOSAURUS.

Jurassic.

PLATE XVIII.

PLATE XVIII

JURASSIC DINOSAURS.—SAUROPODA.

ATLANTOSAURIDÆ.

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a, metapophysis; *b*, ball; *c*, cup, *d*, diapophysis, *f*, lateral foramen; *h*, hatchet bone; *n*, neural canal; *p*, parapophysis; *z*, anterior zygapophysis; *z'*, posterior zygapophysis.

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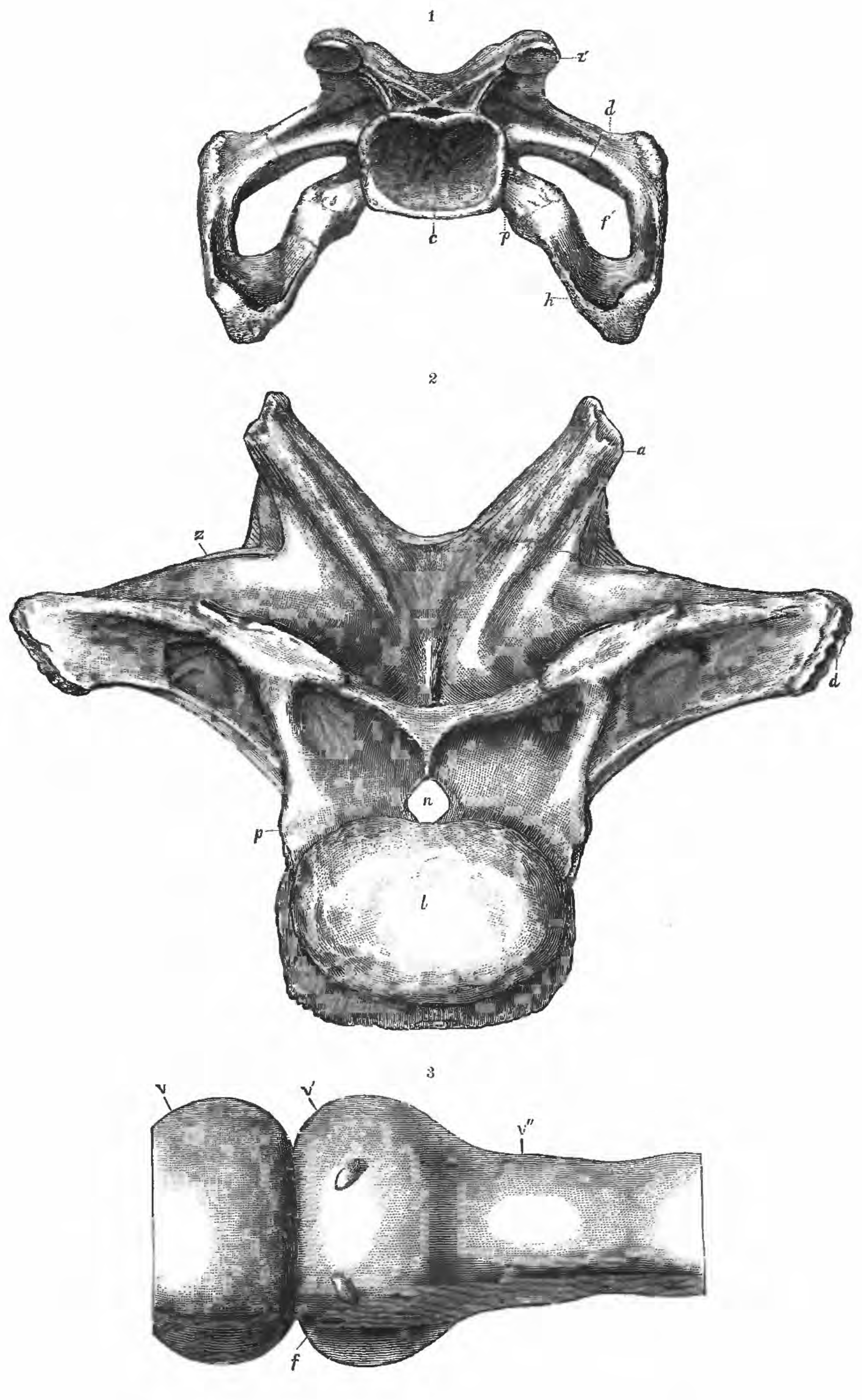
f, foramen; *v*, cast of cavity in first true sacral vertebra; *v'*, cast of cavity in second sacral vertebra; *v''*, cast of cavity in third vertebra.



APATOSAURUS.

Jurassic.

PLATE XIX.

PLATE XIX.

JURASSIC DINOSAURS.—SAUROPODA.

ATLANTOSAURIDÆ AND MOROSAURIDÆ

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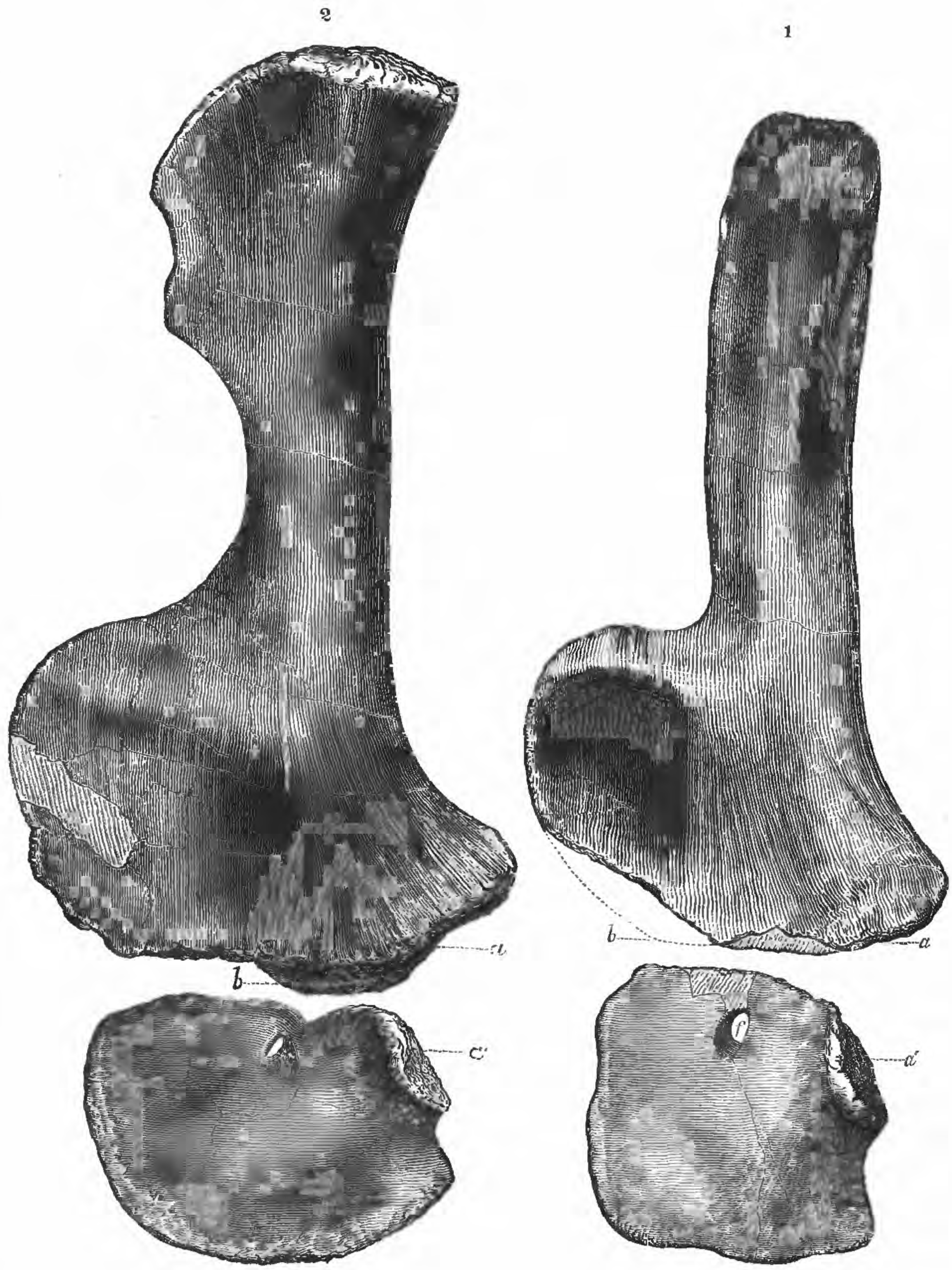

APATOSAURUS AND MOROSAURUS

Jurassic.

PLATE XX.

PLATE XX.

JURASSIC DINOSAURS.—SAUROPODA.

ATLANTOSAURIDÆ

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FIG. 1. Tooth of ***Brontosaurus excelsus*** Marsh; natural size 168
a, outer view; *b*, posterior view; *c*, inner view; *d*, front view

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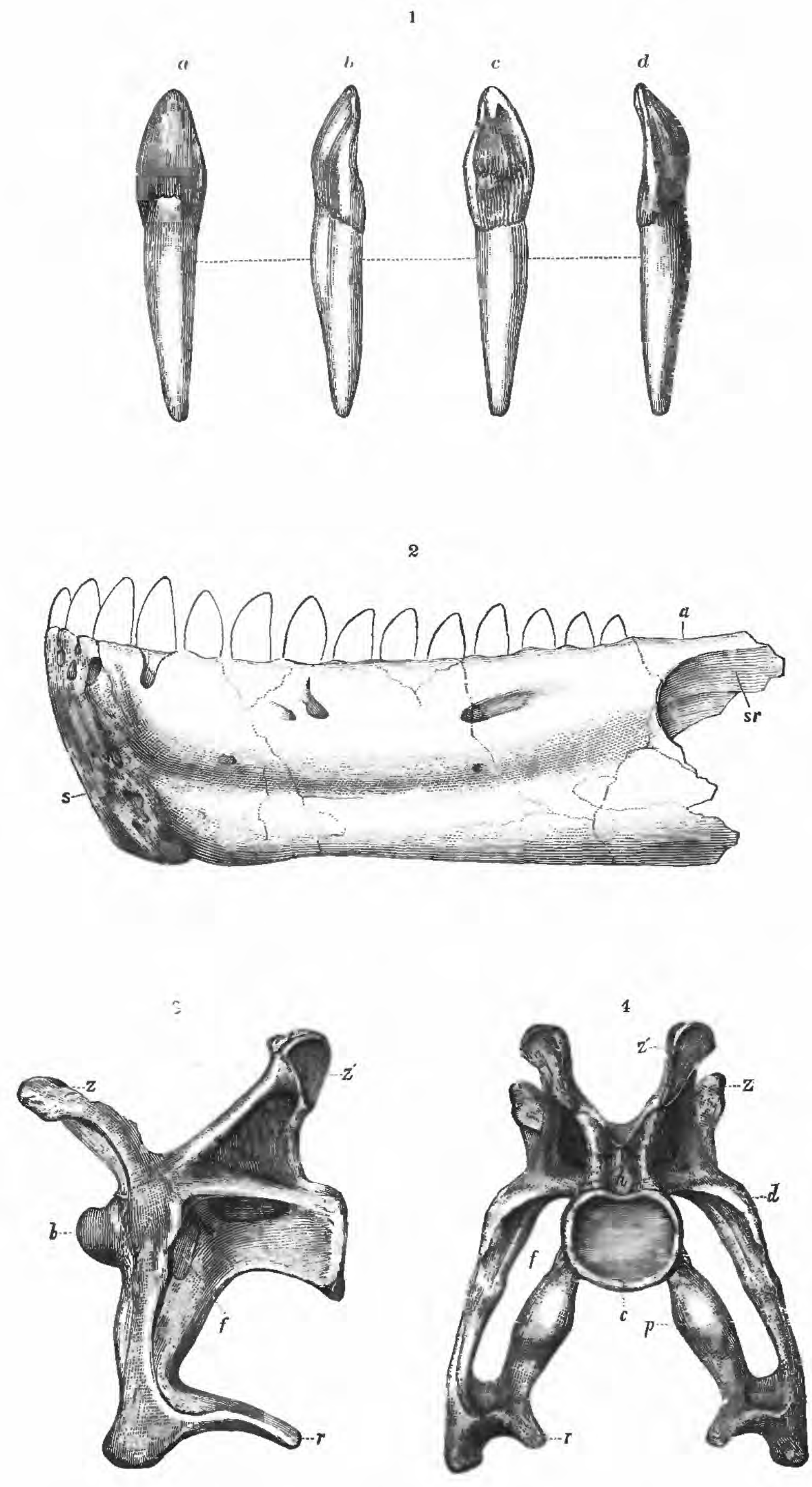

BRONTOSAURUS EXCELSUS Marsh.

Jurassic.

PLATE XXI.

PLATE XXI.

JURASSIC DINOSAURS.—SAUROPODA.

ATLANTOSAURIDÆ.

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All the figures are one-twelfth natural size.

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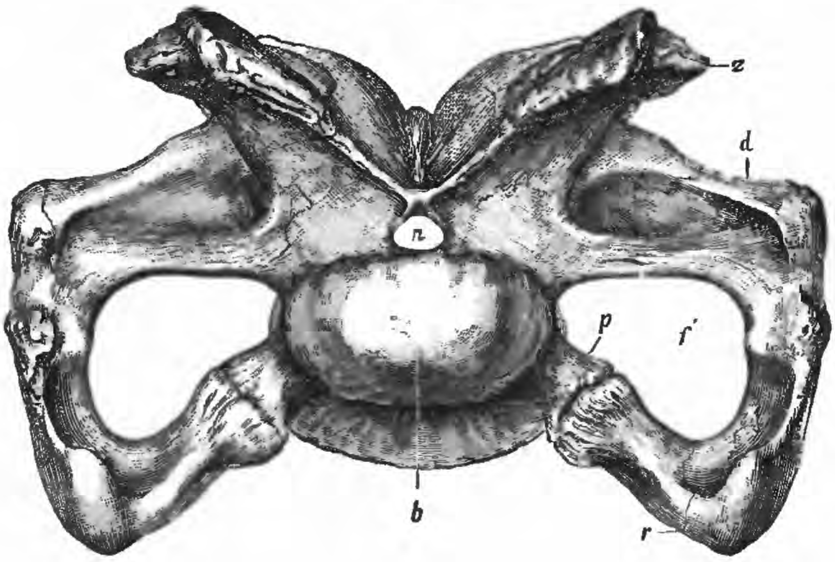

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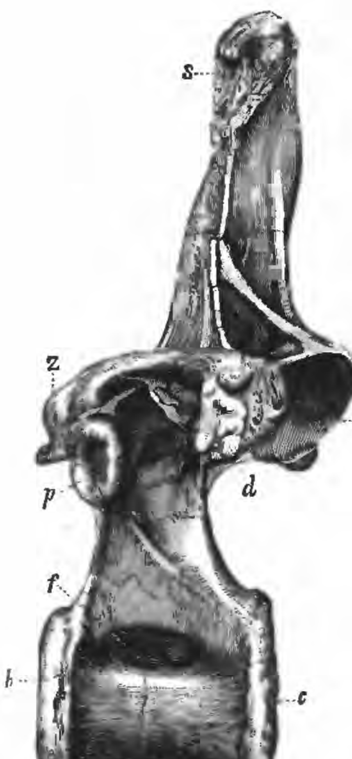

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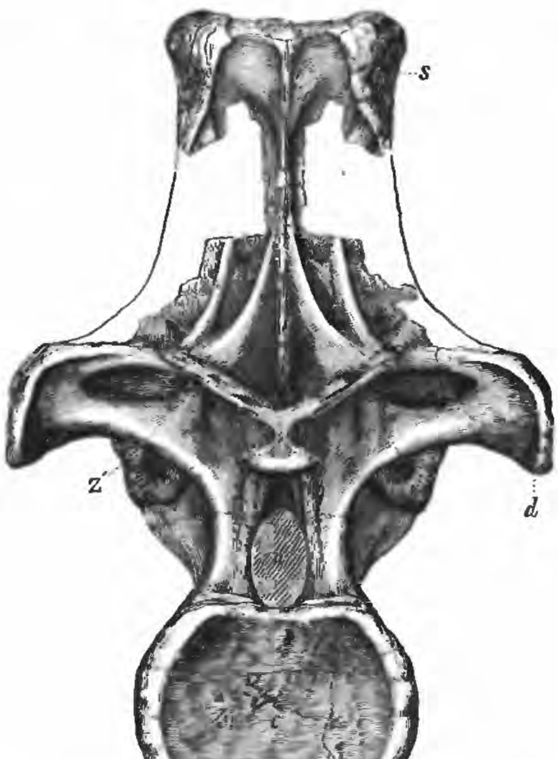

BRONTOSAURUS EXCELSUS.

Jurassic.

PLATE XXII.

PLATE XXII.

JURASSIC DINOSAURS.—SAUROPODA.

ATLANTOSAURIDÆ.

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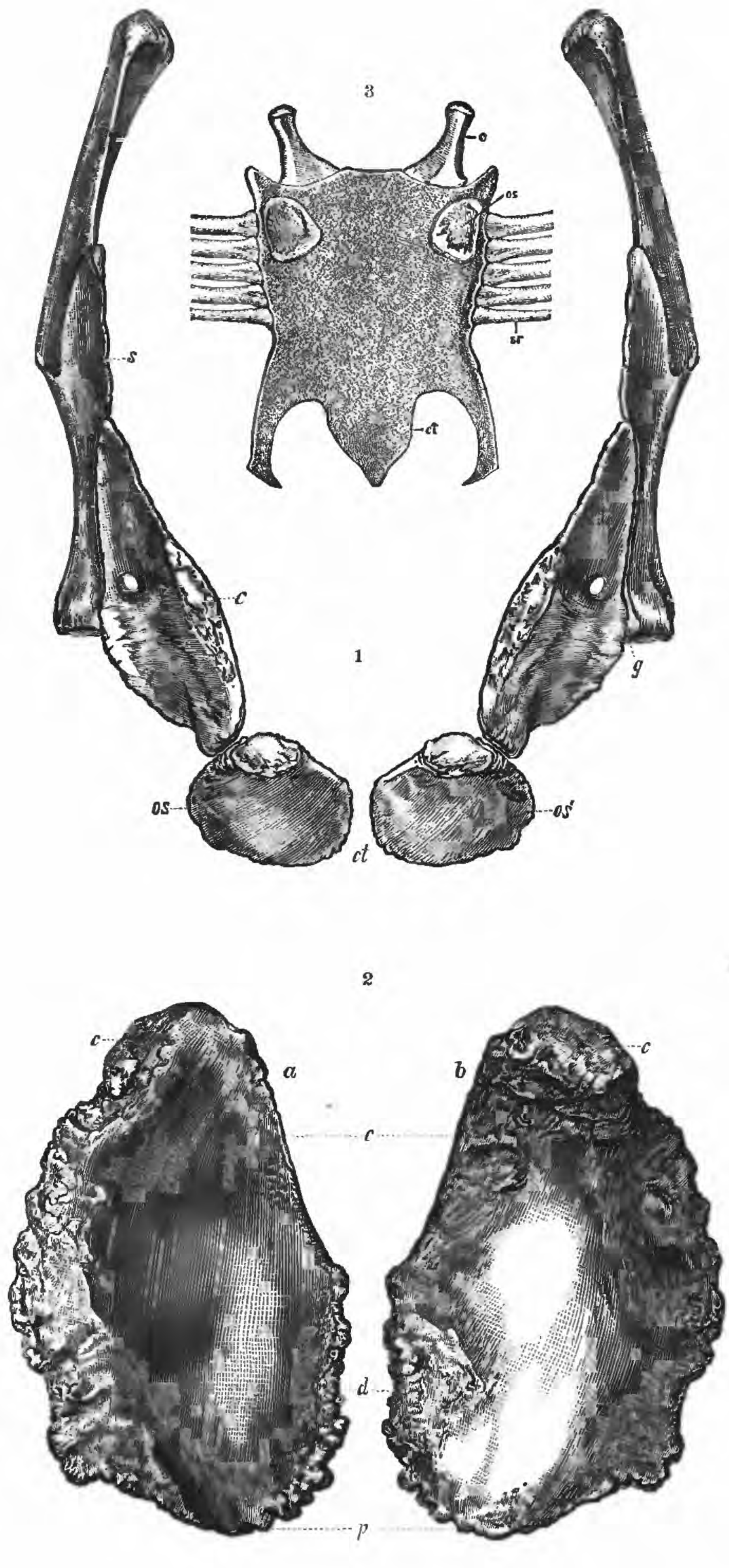
c, coracoid; *ct*, sternal cartilage; *os*, ossified sternal bone; *sr*, sternal rib.



STERNAL PLATES OF BRONTOSAURUS AND YOUNG STRUTHIO.

PLATE XXIII.

PLATE XXIII

JURASSIC DINOSAURS.—SAUROPODA.

ATLANTOSAURIDÆ

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c, cavity; *g*, face for union with ilium, *nc*, neural canal	

Both figures are one-tenth natural size

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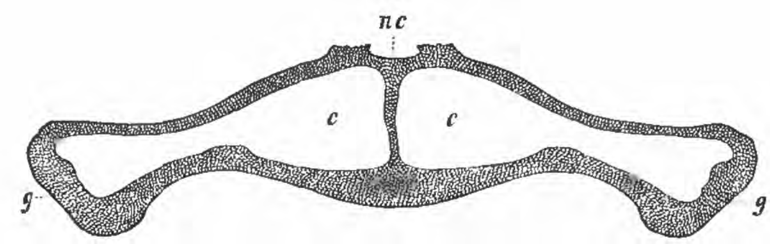

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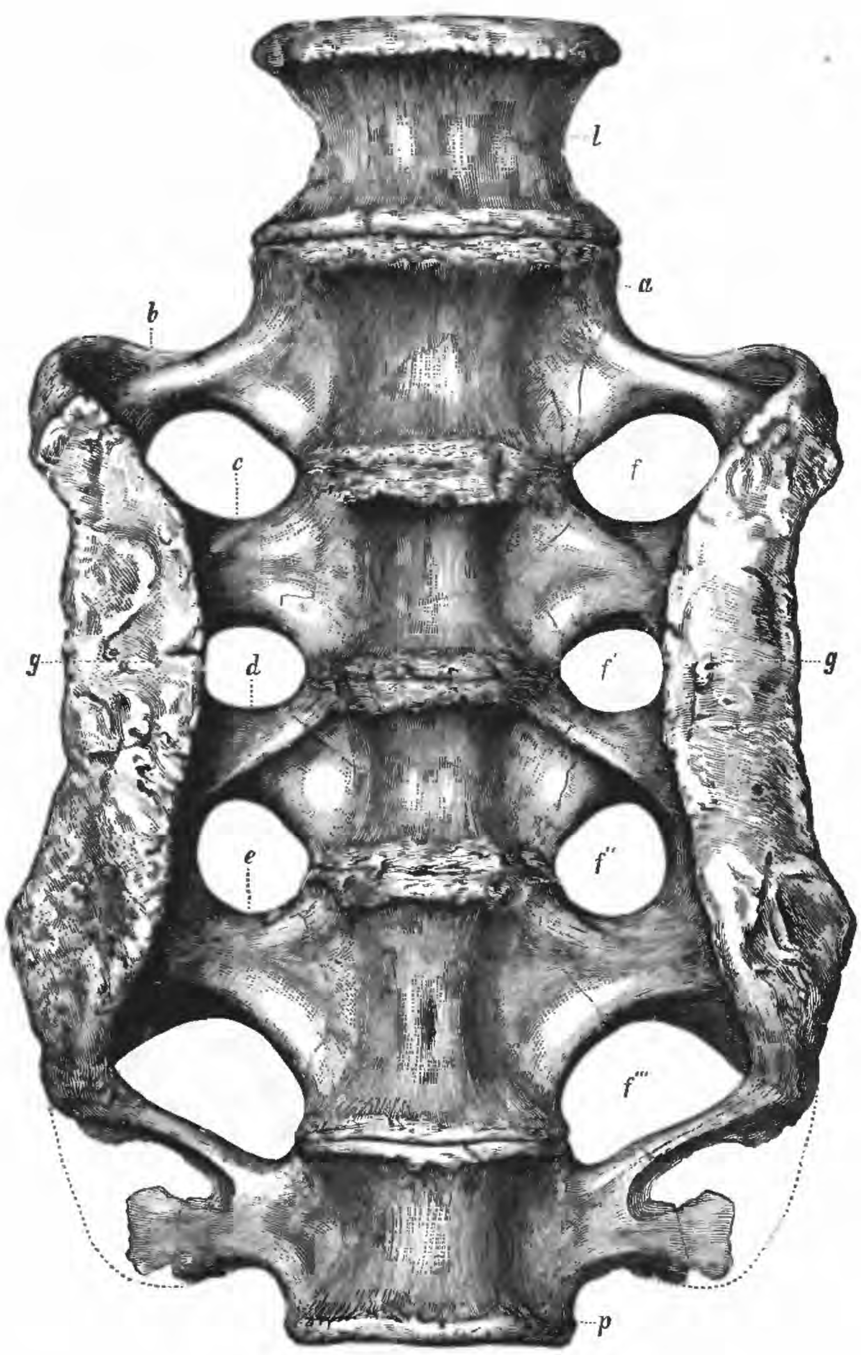


BRONTOSAURUS EXCELSUS.

Jurassic.

PLATE XXIV.

PLATE XXIV.

JURASSIC DINOSAURS.—SAUROPODA.

ATLANTOSAURIDÆ

Page.

FIG. 1. Ischia of *Brontosaurus excelsus* Marsh; seen from above; one-twelfth natural size 172

1*a*, distal ends.

a, acetabular surface; *e*, extremity; *il*, face for ilium; *pb*, face for pubis, *s*, symphysis.

FIG. 2. Fourth caudal vertebra of *Brontosaurus excelsus*, side view 171

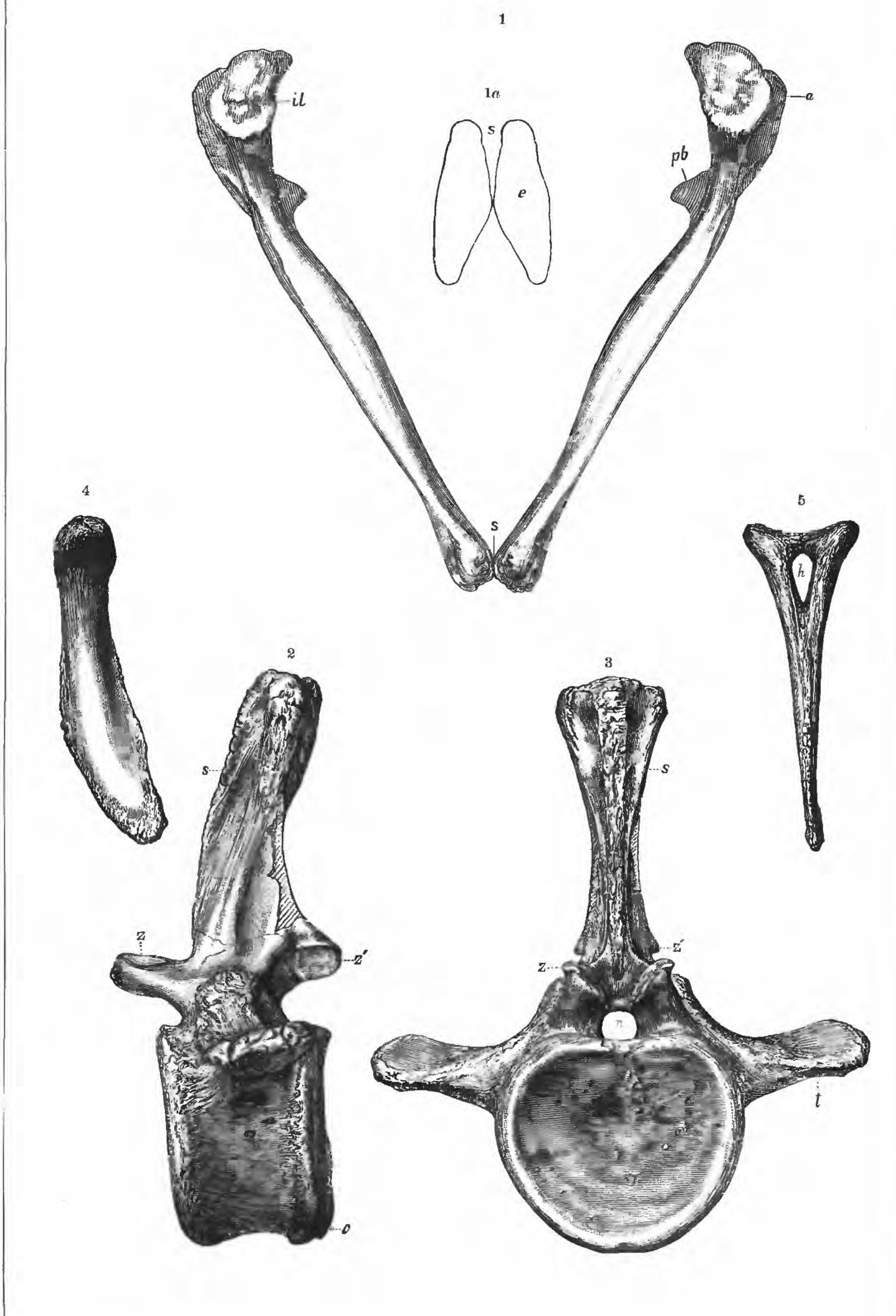
FIG. 3. The same vertebra; front view 171

FIG 4. Chevron of *Brontosaurus excelsus*, side view 172

FIG. 5 The same; front view 172

Last four figures are one-eighth natural size.

c, face for chevron; *h*, hæmal orifice, *n*, neural canal; *s*, neural spine, *t*, transverse process, *z*, anterior zygapophysis; *z'*, posterior zygapophysis.



BRONTOSAURUS EXCELSUS.

Jurassic.

PLATE XXV.

PLATE XXV

JURASSIC DINOSAURS.—SAUROPODA.

DIPLODOCIDÆ

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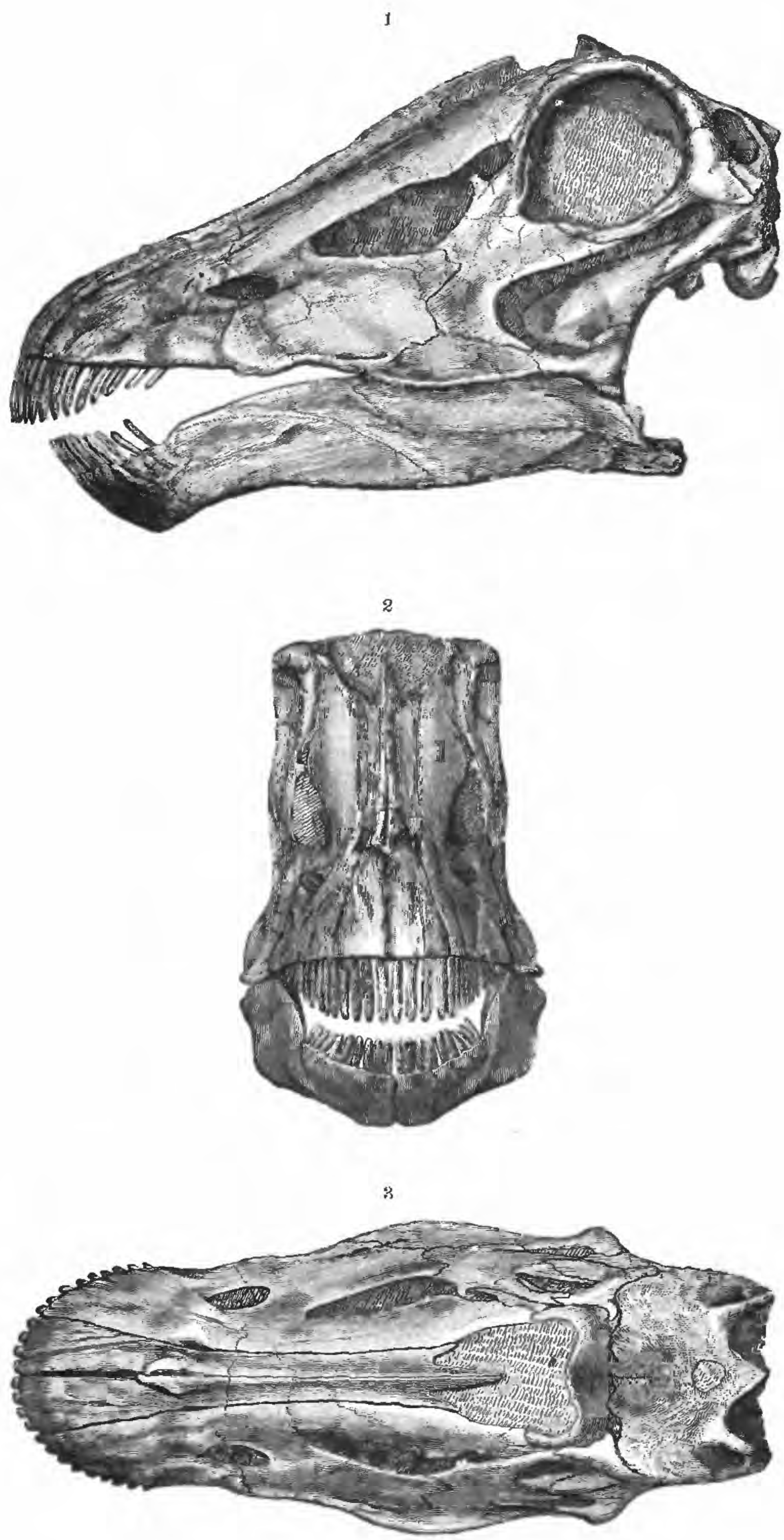
FIG 3	The same skull; top view	175

All the figures are one-sixth natural size.



DIPLODOCUS LONGUS Marsh.

Jurassic.

PLATE XXVI.

PLATE XXVI.

JURASSIC DINOSAURS.—SAUROPODA.

DIPLODOCIDÆ.

Page

FIG 1. Maxillary teeth of *Diplodocus longus* Marsh; side view; one-half natural size 179

FIG. 2. Section of maxillary bone of *Diplodocus longus*, showing functional tooth (fourth) in position and five successional teeth (2–6) in dental cavity, one-half natural size 179

a, outer wall; *b*, inner wall; *c*, cavity; *e*, enamel; *f*, foramen; *r*, root.

FIG 3 Cervical vertebra, with rib, of *Diplodocus longus;* side view; one-eighth natural size 180

a, metapophysis; *b*, ball; *c*, cup; *f*, foramen in centrum, *r*, rib; *z*, anterior zygapophysis; *z'*, posterior zygapophysis

FIG 4. Twelfth caudal vertebra of *Diplodocus longus*, side view; one-sixth natural size 180

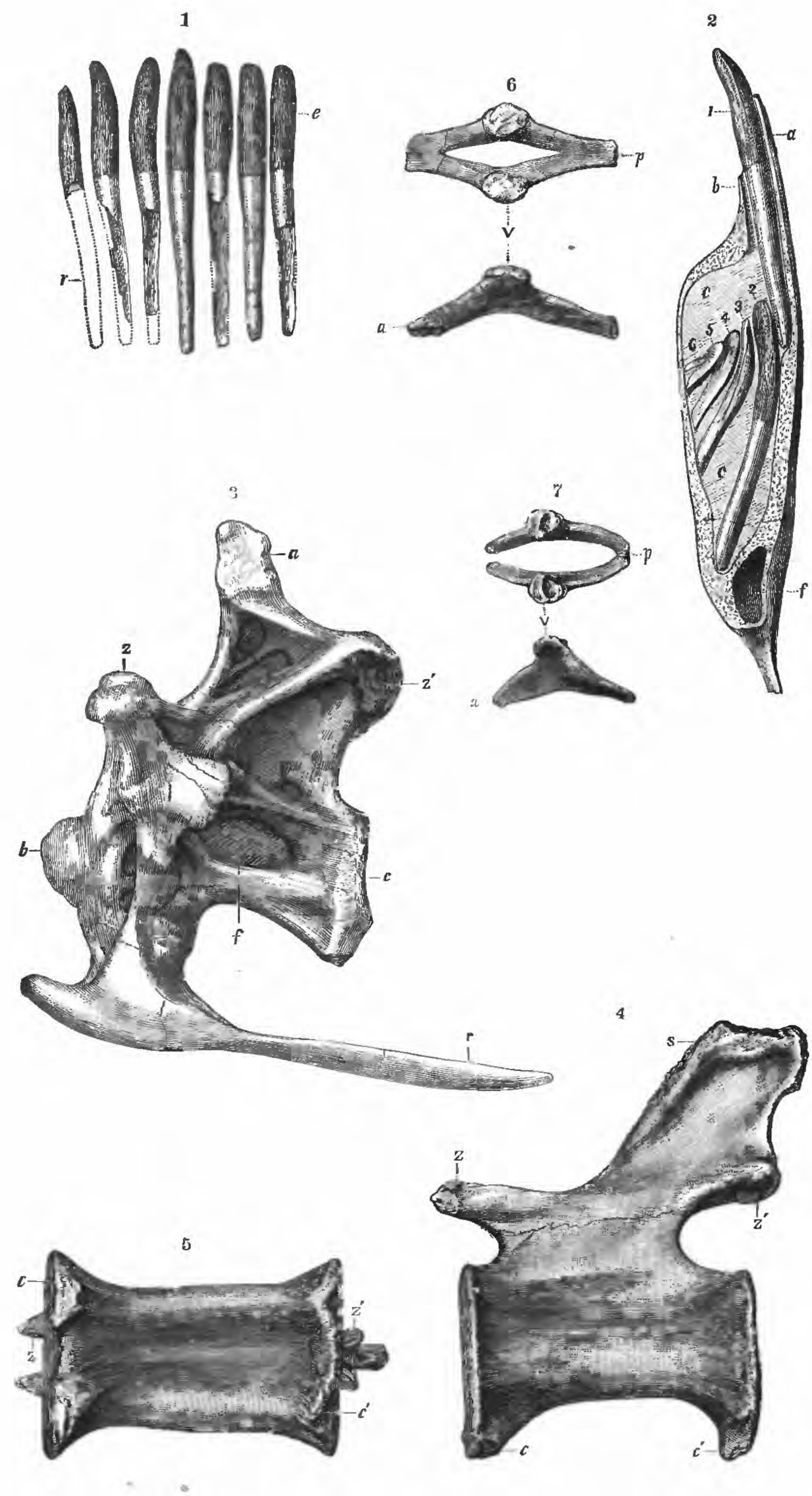
FIG. 5. The same vertebra, bottom view; one-sixth natural size 180

c, anterior face for chevron, *c'*, posterior face for chevron; *s*, neural spine; *z*, anterior zygapophysis, *z'*, posterior zygapophysis.

FIG. 6 Chevron found attached to tenth and eleventh vertebræ of *Diplodocus longus;* top and side views, one-tenth natural size 180

FIG 7. Chevron of another individual; top and side views; one-tenth natural size 180

a, anterior end; *p*, posterior end, *v*, faces for articulation with vertebræ.



DIPLODOCUS LONGUS.

Jurassic.

PLATE XXVII.

PLATE XXVII.

JURASSIC DINOSAURS.—SAUROPODA.

DIPLODOCIDÆ.

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FIG. 1. Atlas of *Diplodocus longus* Marsh; side view, one-half natural size.... 180

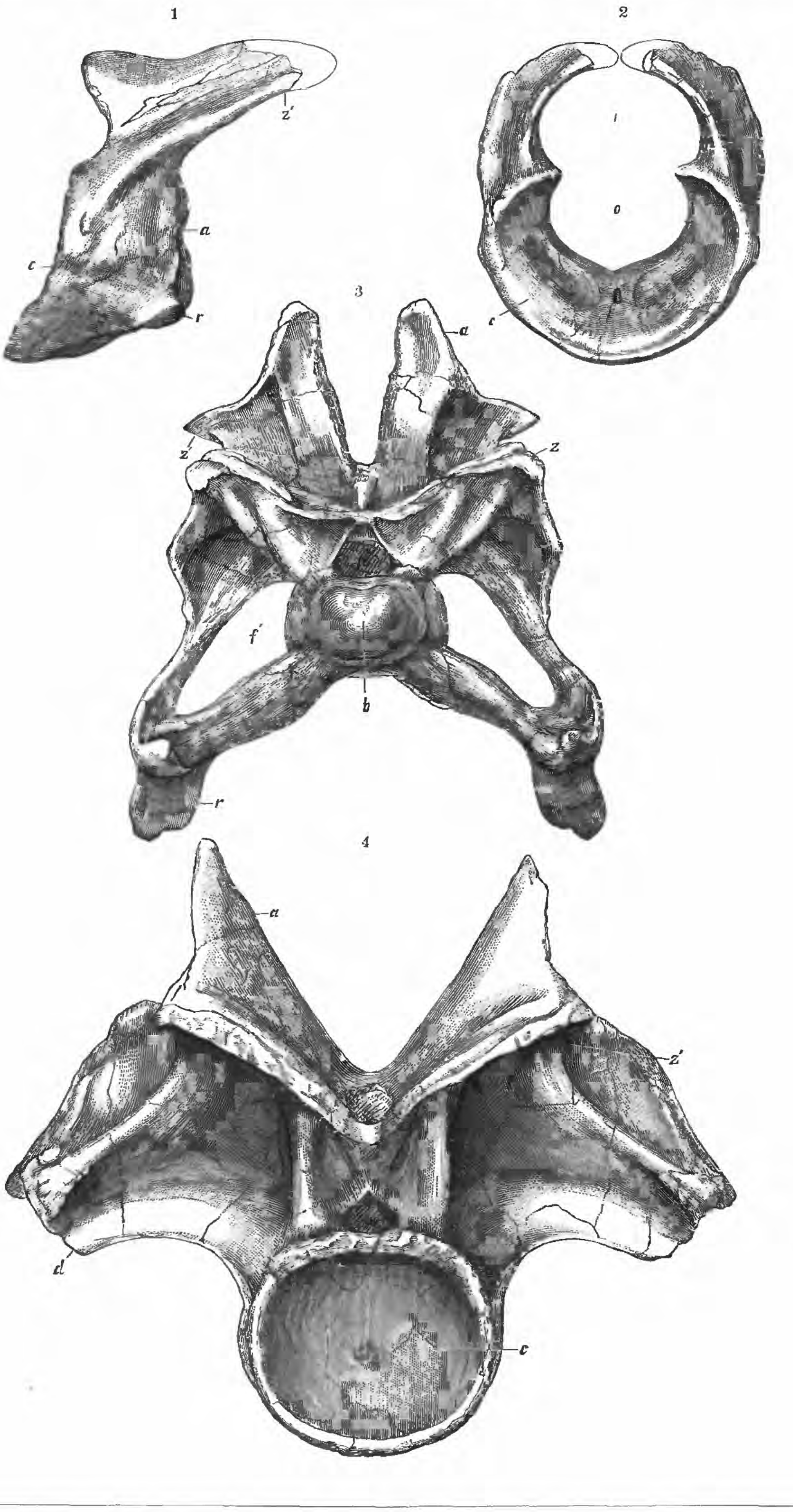
FIG. 2. The same; front view; one-half natural size........................ 180

a, articular face for axis; *c*, cup, *n*, neural canal, *o*, cavity for odontoid process of axis; *r*, face for rib, *z'*, posterior zygapophysis

FIG. 3. Cervical vertebra of *Diplodocus longus;* front view; one-eighth natural size.. 180

FIG. 4. Dorsal vertebra of *Diplodocus longus,* back view; one-eighth natural size.. 180

a, metapophysis; *b*, ball, *c*, cup; *d*, diapophysis; *f'*, lateral foramen, *n*, neural canal; *r*, rib; *z*, anterior zygapophysis; *z'*, posterior zygapophysis.



DIPLODOCUS LONGUS.

Jurassic.

PLATE XXVIII.

PLATE XXVIII.

JURASSIC DINOSAURS.—SAUROPODA.

DIPLODOCIDÆ

Page.

FIG. 1 Sacrum and ilium of *Diplodocus longus* Marsh, seen from below; one-tenth natural size.. 180

1*a*, transverse section through second vertebra, *c*, cavity

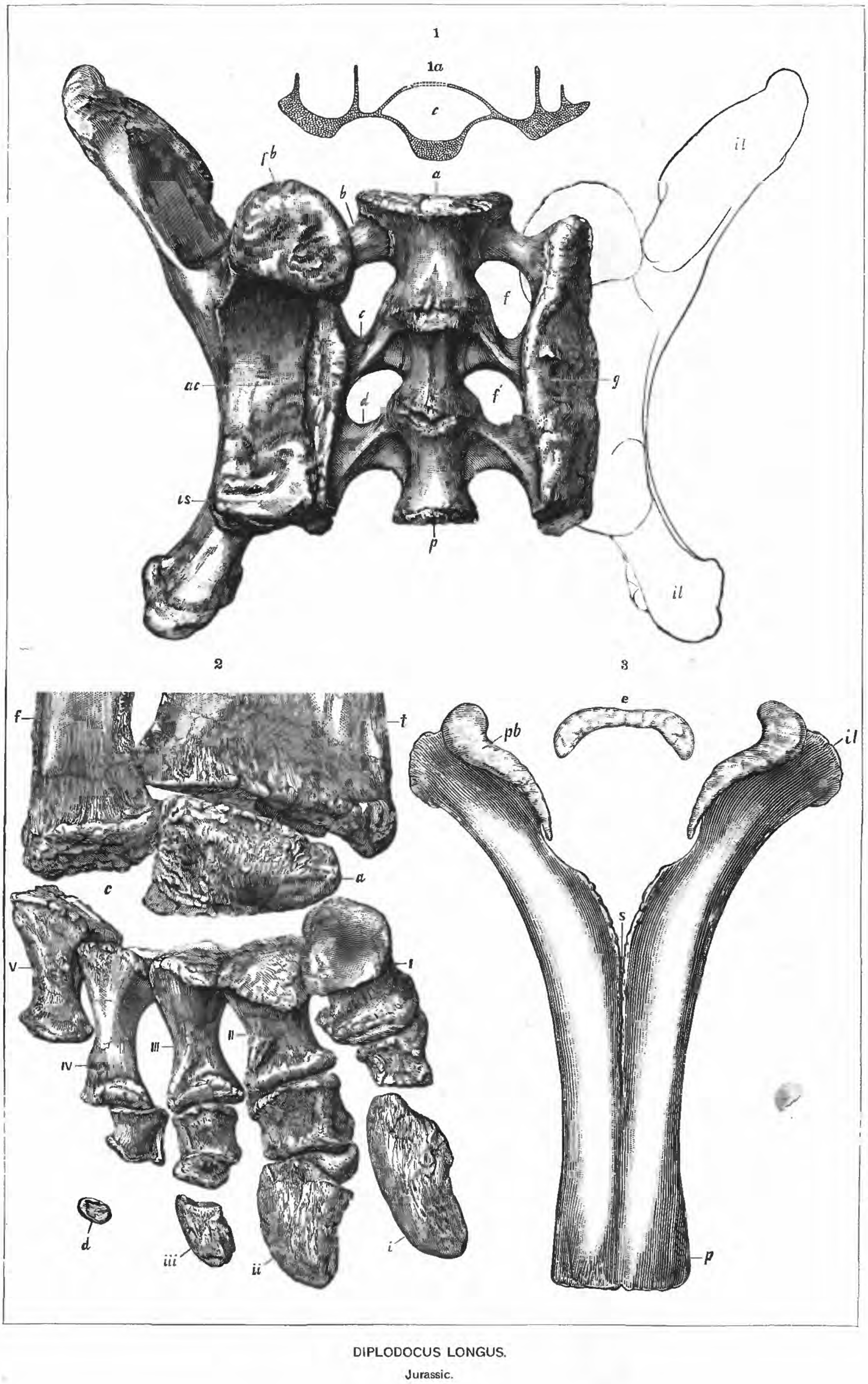
a, first sacral vertebra; *ac*, acetabular surface; *b*, transverse process of first vertebra, *c*, transverse process of second vertebra; *d*, transverse process of third vertebra; *f*, *f'*, foramina between sacral vertebræ; *g*, face for ilium, *il*, ilium; *is*, face for ischium, *p*, last sacral vertebra; *pb*, face for pubis

FIG. 2. Right foot of *Diplodocus longus*, front view; one-eighth natural size.. 180

a, astragalus; *c*, place for calcaneum; *d*, distal phalanx; *f*, fibula, *t*, tibia; *I–V*, metatarsals; *i–iii*, ungual phalanges

FIG 3. Ischia of *Diplodocus longus*; inferior view; one-eighth natural size.... 180

e, distal ends; *il*, face for ilium; *p*, distal extremity; *pb*, face for pubis; *s*, symphysis.



DIPLODOCUS LONGUS.

Jurassic.

PLATE XXIX.

PLATE XXIX

JURASSIC DINOSAURS.—SAUROPODA.

DIPLODOCIDÆ

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FIG. 1. Left metacarpals of *Diplodocus longus* Marsh, with first phalanx of first digit in position; front view 180

FIG. 2 Left metatarsals of *Morosaurus grandis* Marsh; front view............ 183

Both figures are one-fourth natural size.

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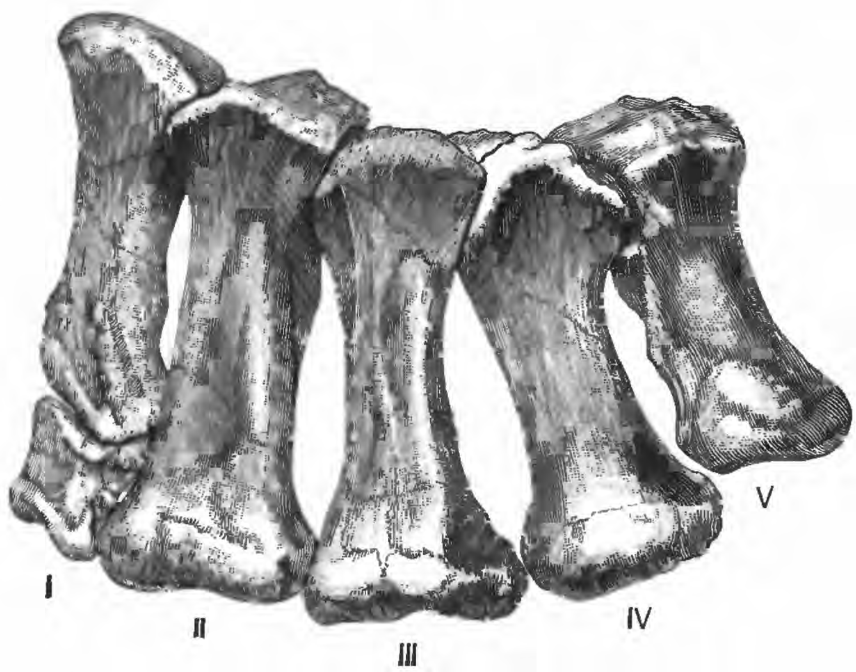

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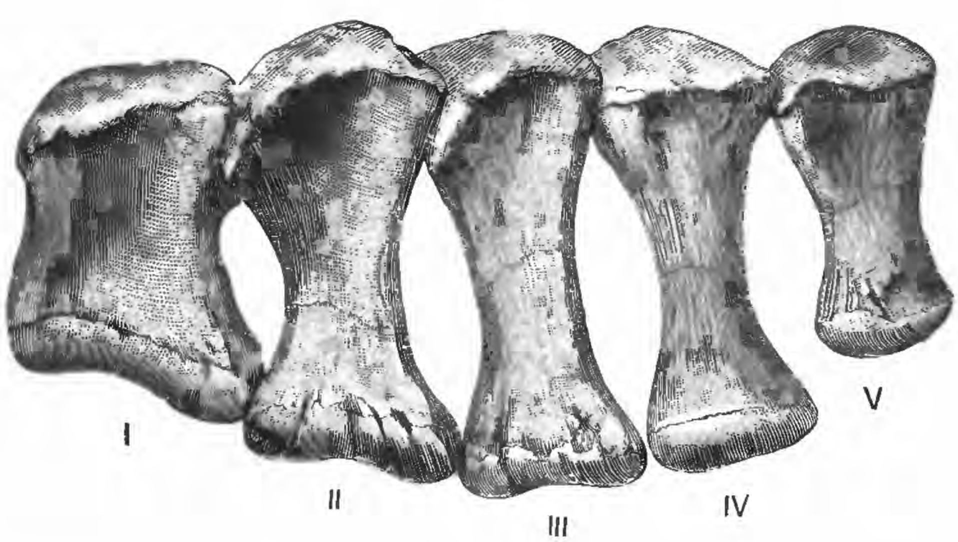

DIPLODOCUS AND MOROSAURUS.

Jurassic.

PLATE XXX.

PLATE XXX.

JURASSIC DINOSAURS.—SAUROPODA.

MOROSAURIDÆ.

Page

FIG. 1. Skull of *Morosaurus agilis* Marsh; posterior view, one-half natural size 181

a, postoccipital bone, *b*, lateral plate of atlas; *c*, odontoid process, or centrum, of same; *eo*, exoccipital, *i*, inferior portion of atlas; *n*, neural canal; *p*, parietal; *po*, postorbital; *s*, squamosal; *so*, supraoccipital.

FIG. 2 Portion of skull, with brain cast, of *Morosaurus grandis* Marsh; top view, one-fourth natural size 181

c, cerebral hemispheres; *cb*, cerebellum; *fp*, postfrontal; *fr*, frontal; *ol*, olfactory lobe; *on*, optic nerve; *op*, optic lobe; *p*, paroccipital process; *pr*, parietal; *q*, quadrate, *s*, squamosal.

FIG 3 Left dentary bone of *Morosaurus grandis*, outer view; one-third natural size .... - 181

a, edentulous margin; *s*, symphysis; *sr*, face for surangular.

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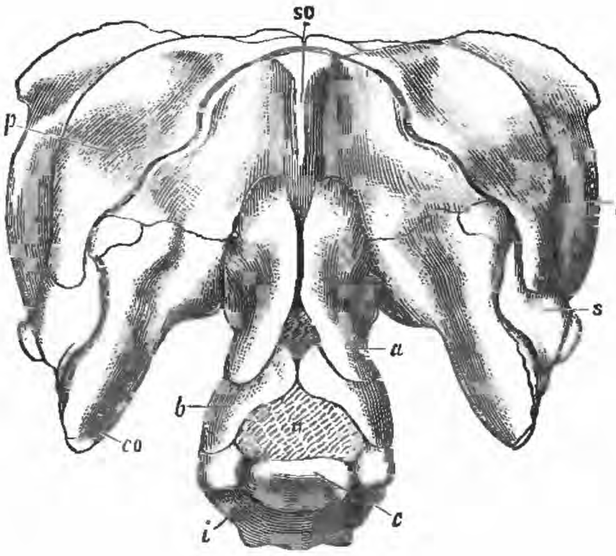

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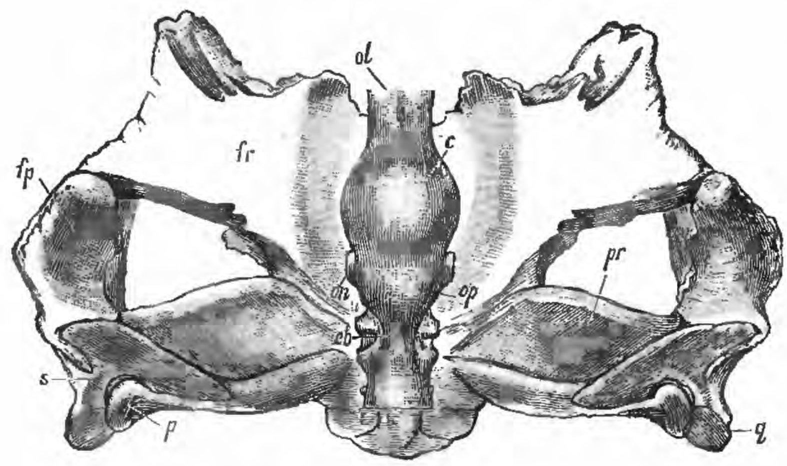

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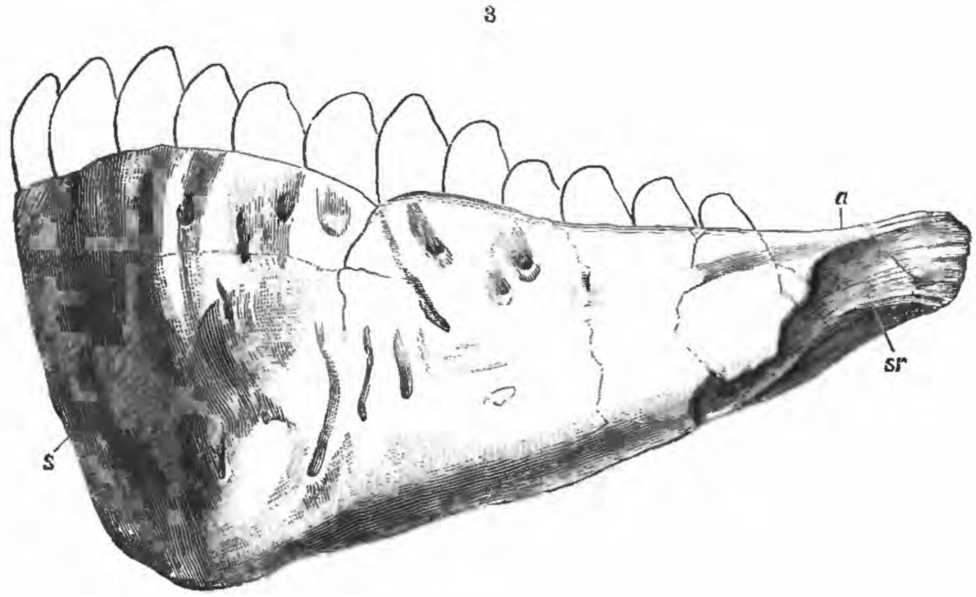

MOROSAURUS.

Jurassic.

PLATE XXXI.

PLATE XXXI

JURASSIC DINOSAURS—SAUROPODA.

MOROSAURIDÆ.

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FIG 4 The same, front view, one-eighth natural size *a*, odontoid process; *ax*, centrum of axis; *d*, diapophysis, *f*, foramen in centrum; *s*, neural spine, *z*, anterior zygapophysis	182
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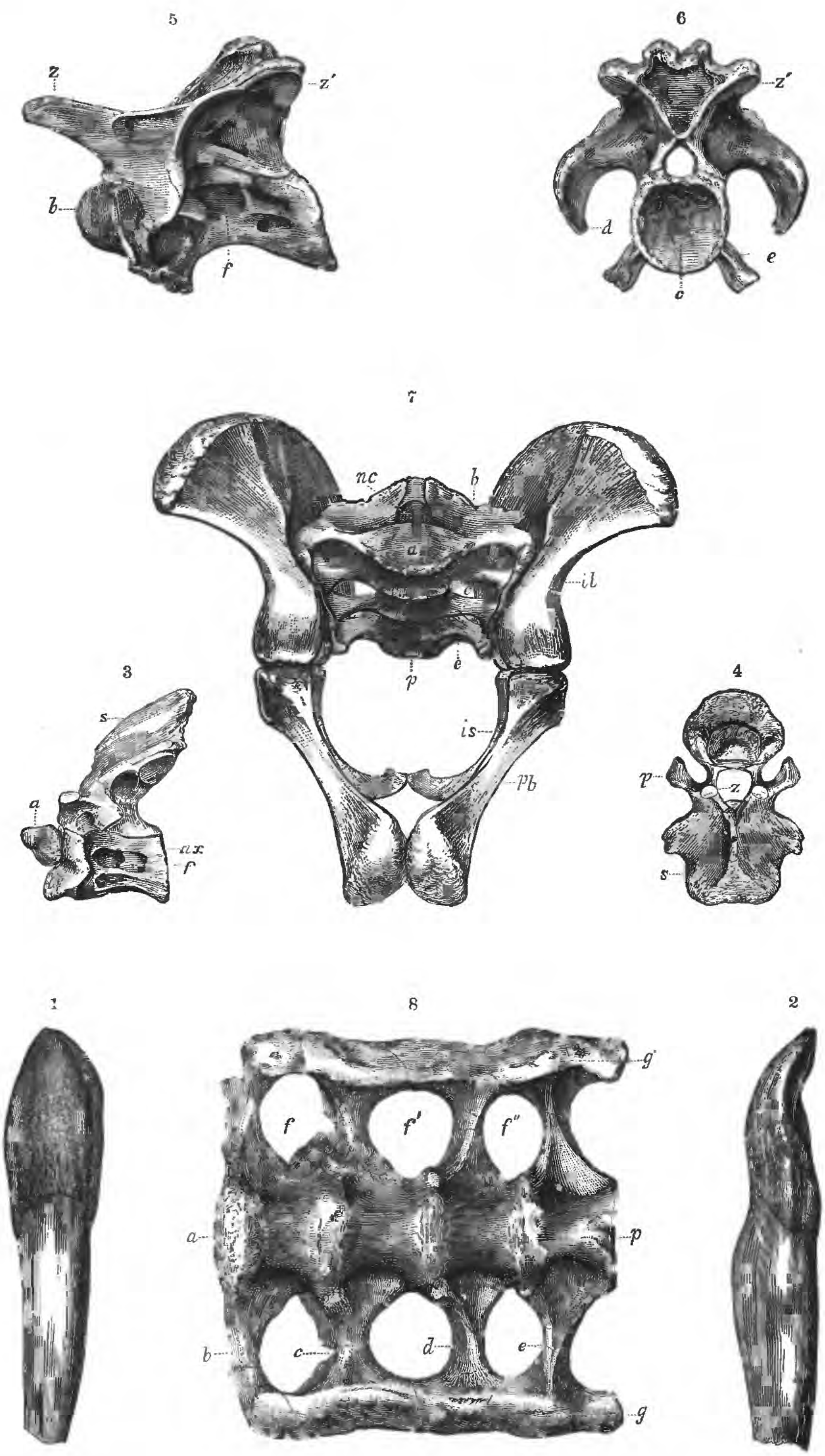

MOROSAURUS GRANDIS Marsh.

Jurassic.

PLATE XXXII.

PLATE XXXII

JURASSIC DINOSAURS.—SAUROPODA.

MOROSAURIDÆ.

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All three figures are one-fifth natural size	
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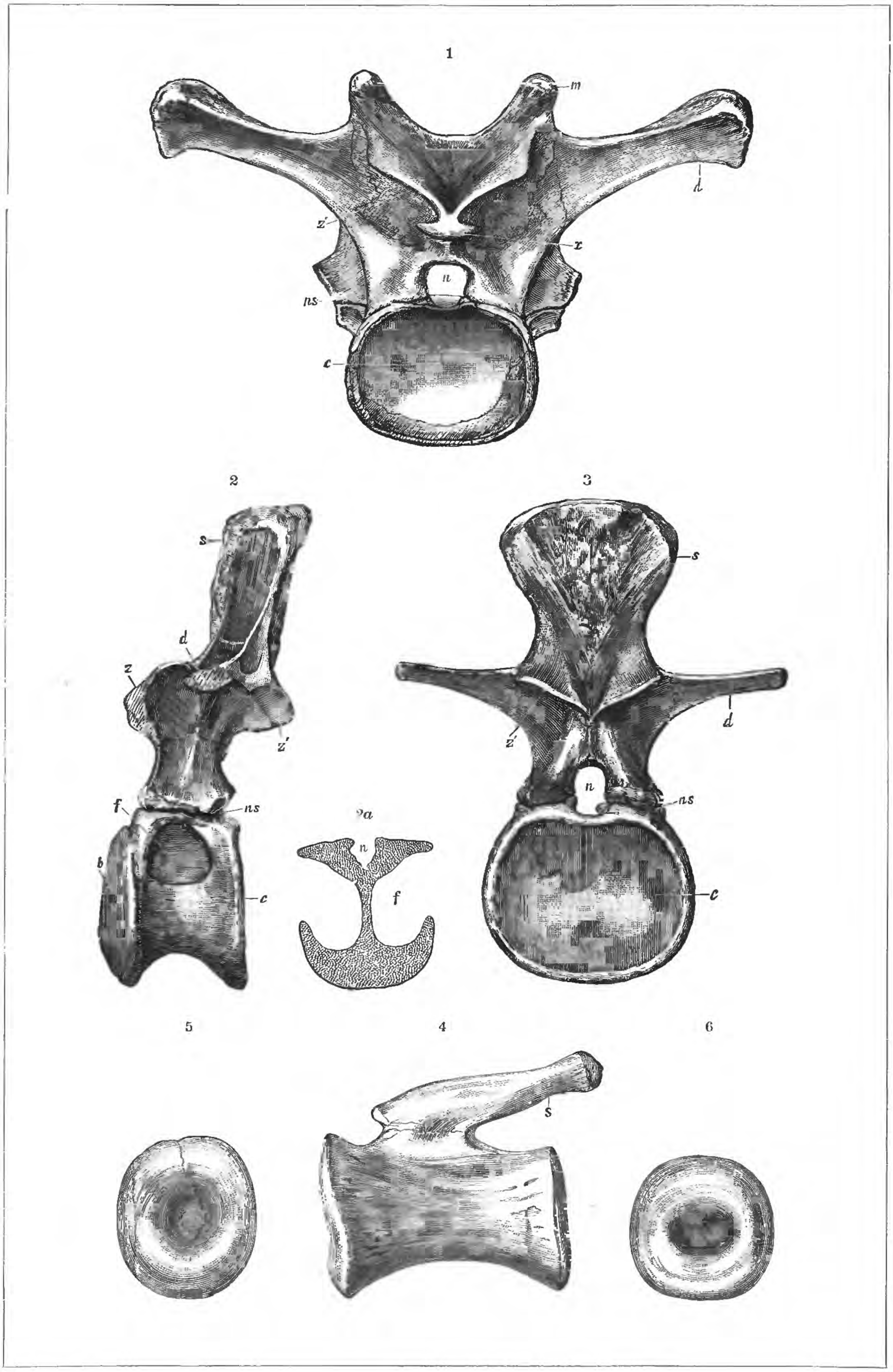
b, ball; *c*, cup, *d*, diapophysis; *f*, foramen in centrum; *m*, metapophysis, *n* neural canal, *ns*, neural suture; *s*, neural spine; *x*, hyposphene, *z*, anterior zygapophysis; *z'*, posterior zygapophysis.



MOROSAURUS.

Jurassic.

PLATE XXXIII.

PLATE XXXIII

JURASSIC DINOSAURS.—SAUROPODA.

MOROSAURIDÆ.

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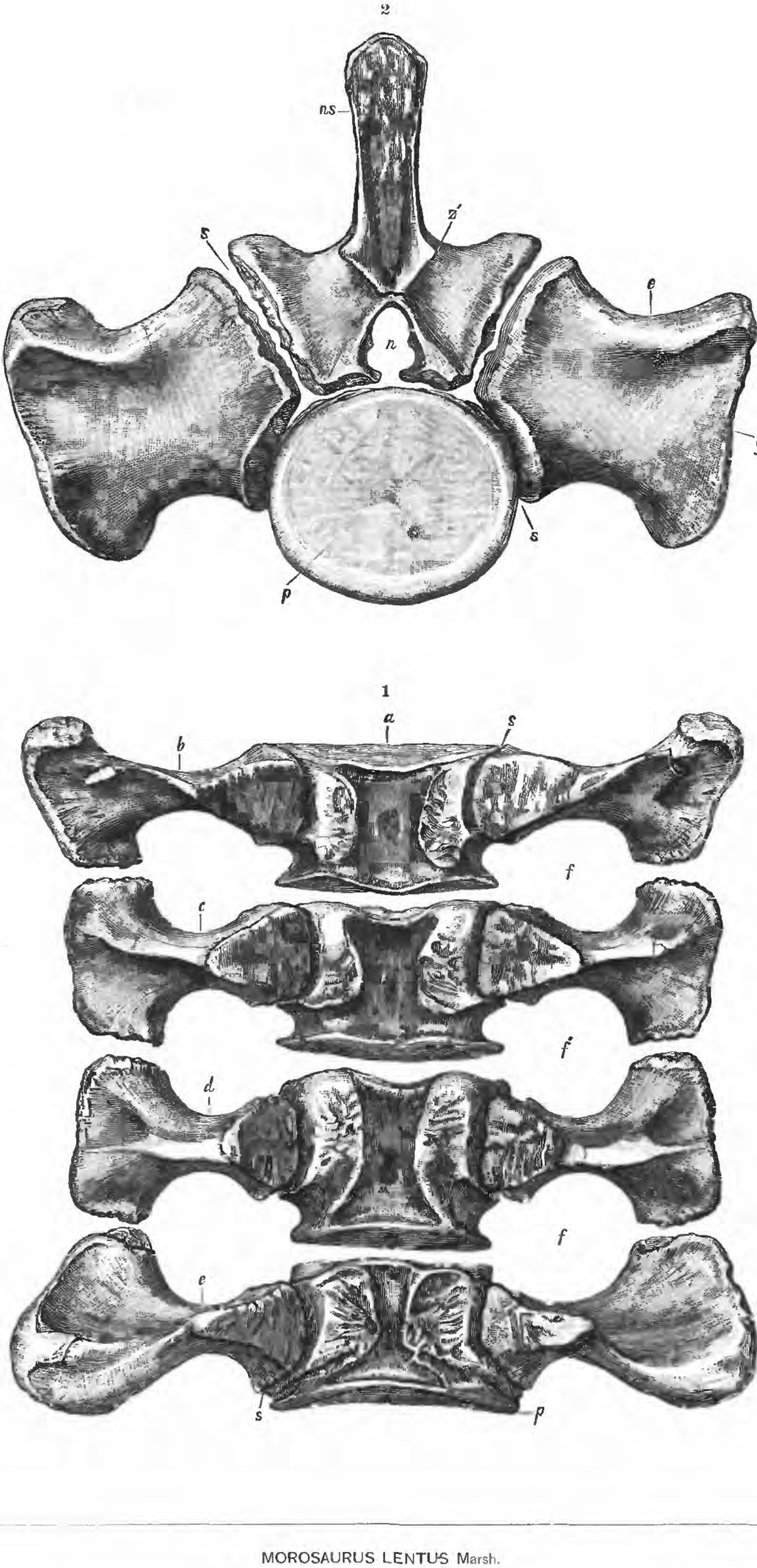
FIG. 1. Sacrum of *Morosaurus lentus* Marsh; seen from above. 183

FIG. 2. Last sacral vertebra of *Morosaurus lentus*, posterior view 182

a, anterior face of centrum of first sacral vertebra, *b*, transverse process of first vertebra, *c*, transverse process of second vertebra; *d*, transverse process of third vertebra; *e*, transverse process of last sacral vertebra; *f*, *f′*, *f″*, foramina between transverse processes of sacral vertebræ, *g*, surface for union with ilium; *n*, neural canal, *ns*, neural spine; *p*, posterior face of centrum of last sacral vertebra, *s*, suture, *z*, posterior zygapophysis

Both figures are one-fifth natural size



MOROSAURUS LENTUS Marsh.

Jurassic.

PLATE XXXIV.

PLATE XXXIV.

JURASSIC DINOSAURS.—SAUROPODA.

MOROSAURIDÆ.

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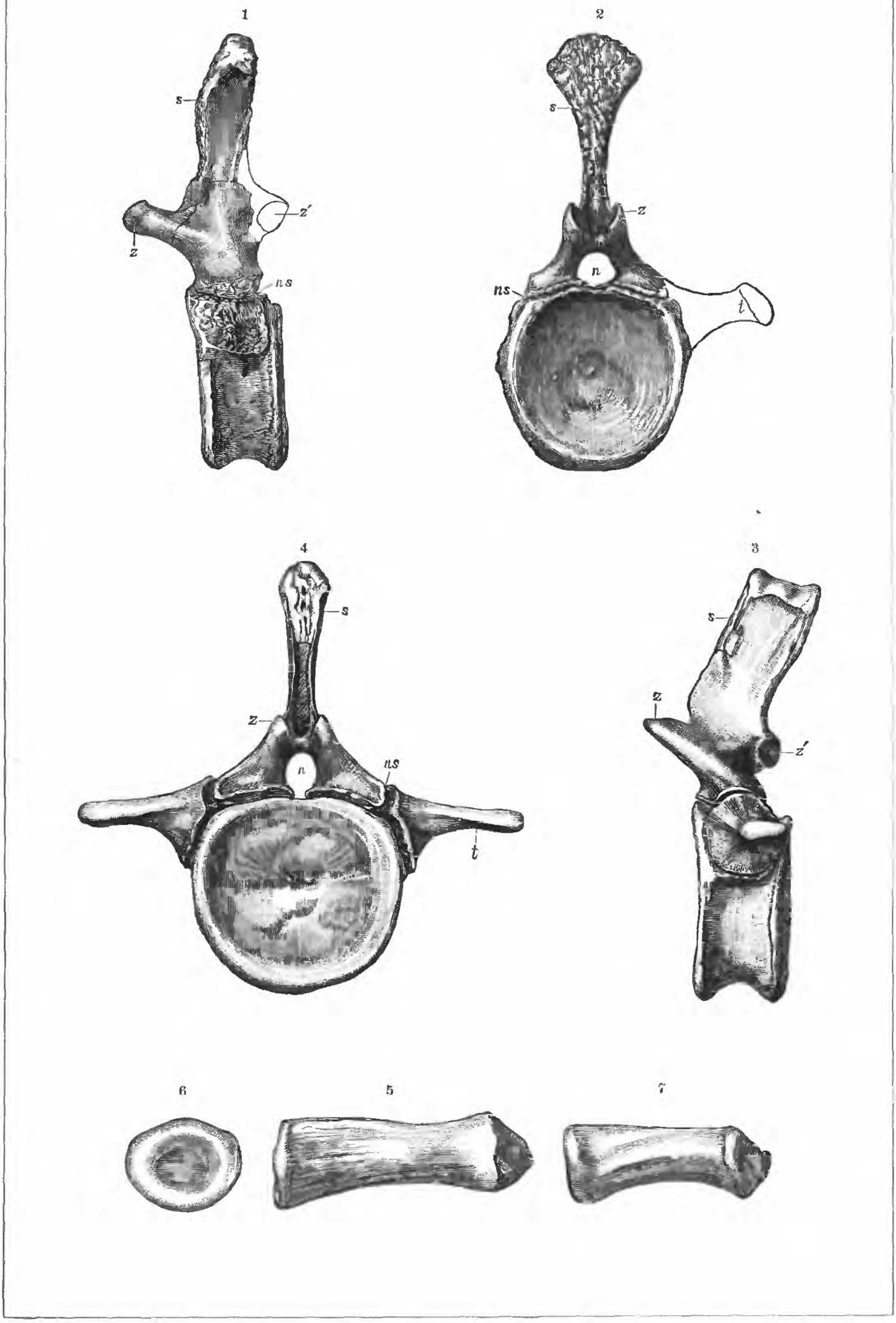
FIG. 7. More distal caudal of same animal; side view	182

Last three figures are natural size.

n, neural canal; *ns*, neural suture; *s*, neural spine; *t*, transverse process; *z*, anterior zygapophysis, *z'*, posterior zygapophysis.



MOROSAURUS.

Jurassic.

PLATE XXXV.

PLATE XXXV

JURASSIC DINOSAURS.—SAUROPODA.

MOROSAURIDÆ

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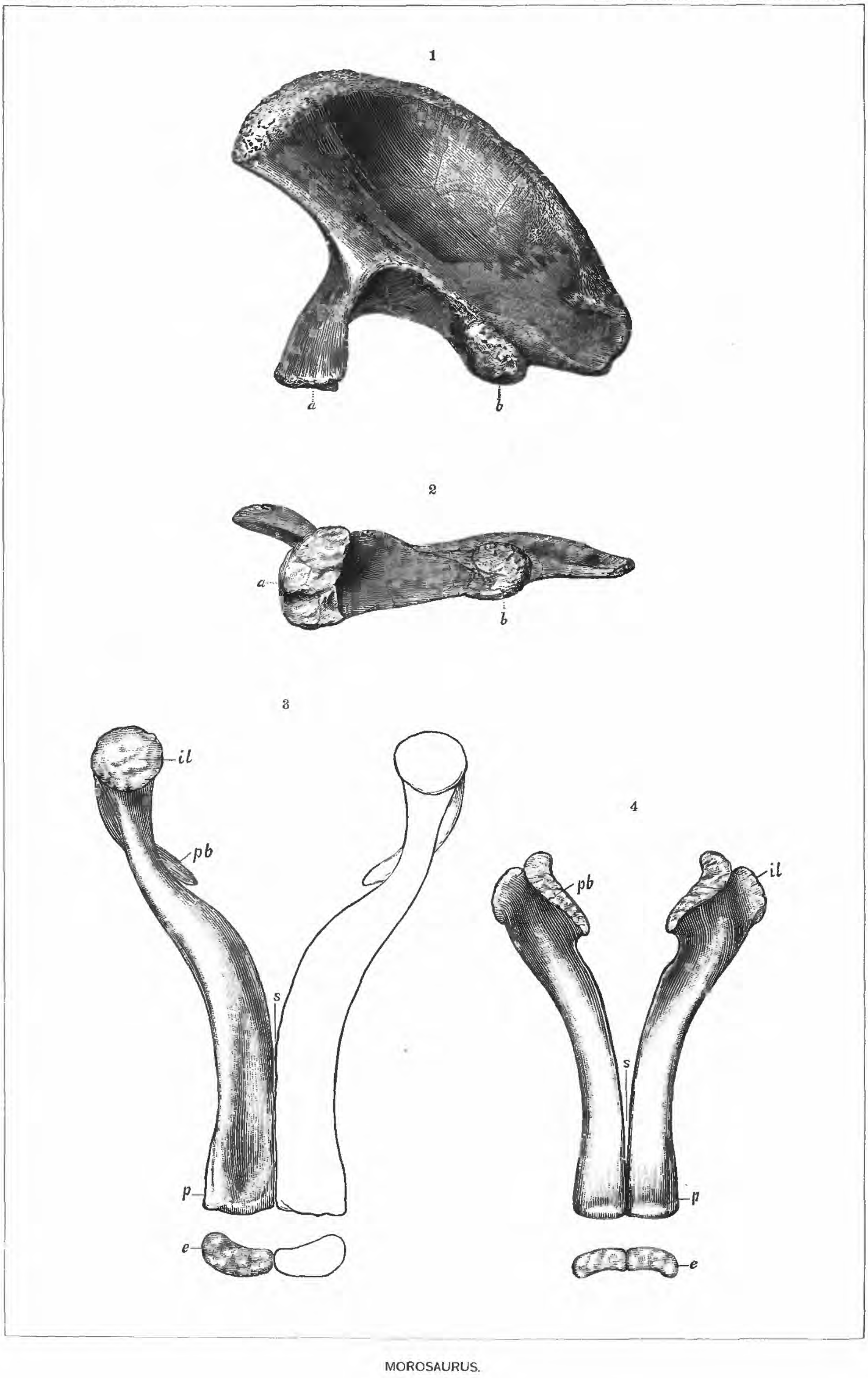
e, distal ends, *il*, face for ilium; *p*, posterior extremity, *pb*, face for pubis; *s*, symphysis	



MOROSAURUS.

Jurassic.

PLATE XXXVI.

PLATE XXXVI.

JURASSIC DINOSAURS.—SAUROPODA.

MOROSAURIDÆ AND ATLANTOSAURIDÆ.

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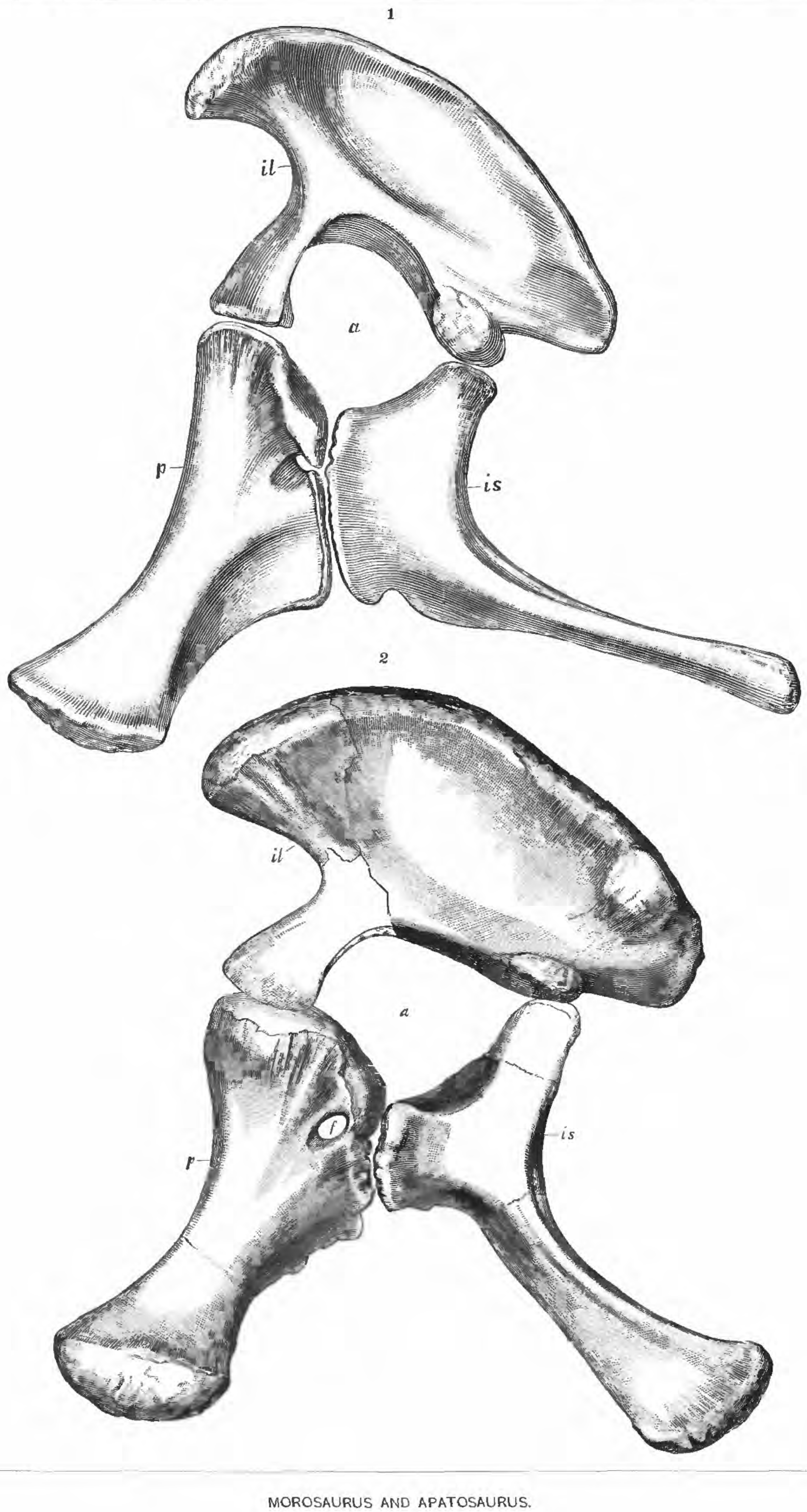
a, acetabulum; *f*, foramen in pubis; *il*, ilium; *is*, ischium; *p*, pubis.



MOROSAURUS AND APATOSAURUS.
Jurassic.

PLATE XXXVII.

PLATE XXXVII.

JURASSIC DINOSAURS.—SAUROPODA.

MOROSAURIDÆ.

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c, carpal bone, *I–V*, metacarpals

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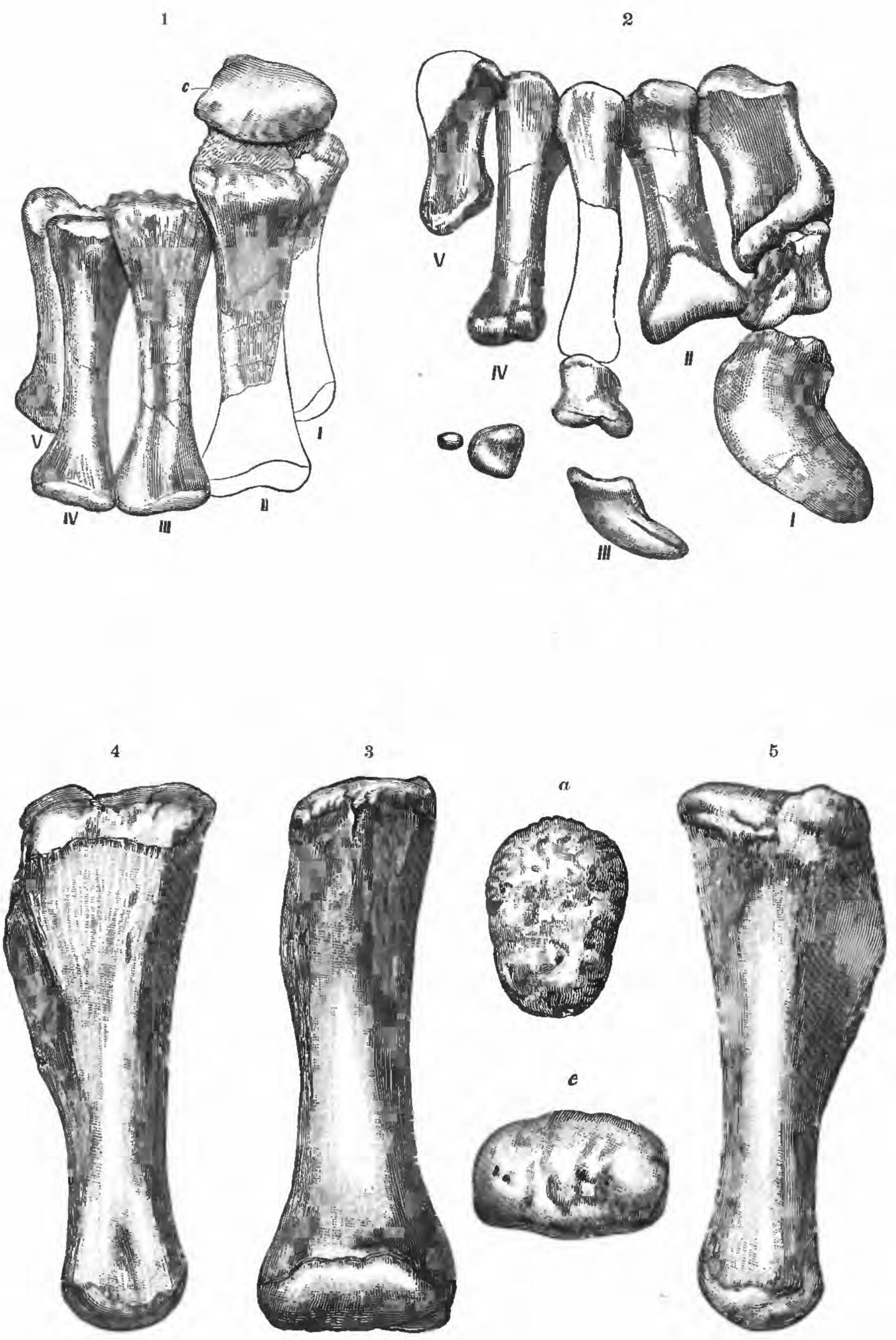
FIG 4 The same bone, inner view 182

a, proximal end, *e*, distal end

FIG 5 The same, outer view 182

Last three figures are one-half natural size



MOROSAURUS.

Jurassic.

PLATE XXXVIII.

PLATE XXXVIII.

JURASSIC DINOSAURS —SAUROPODA.

MOROSAURIDÆ

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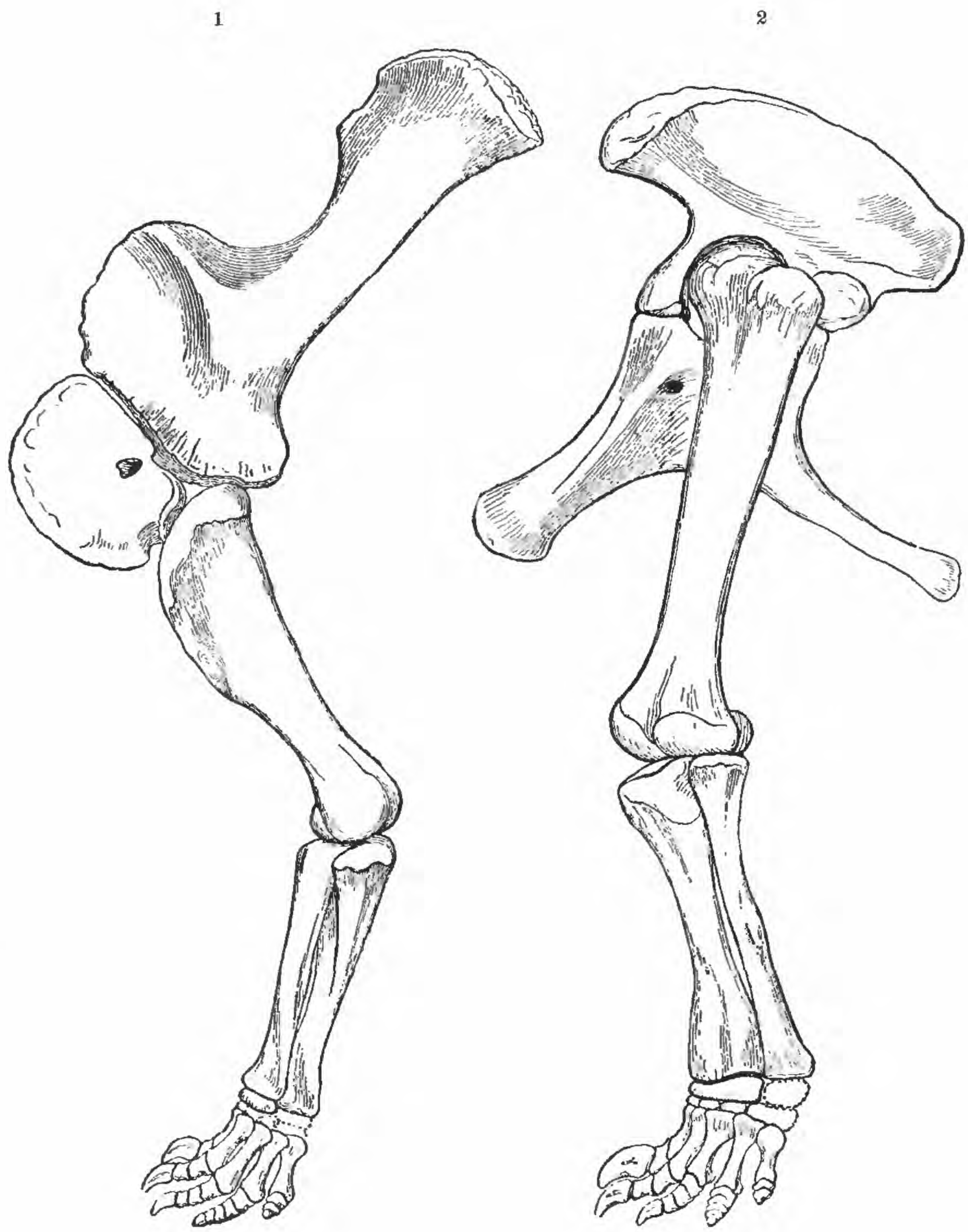
Both figures are one-twentieth natural size.



MOROSAURUS GRANDIS.
Jurassic.

PLATE XXXIX.

PLATE XXXIX.

JURASSIC DINOSAURS.—SAUROPODA.

ATLANTOSAURIDÆ, MOROSAURIDÆ, AND DIPLODOCIDÆ

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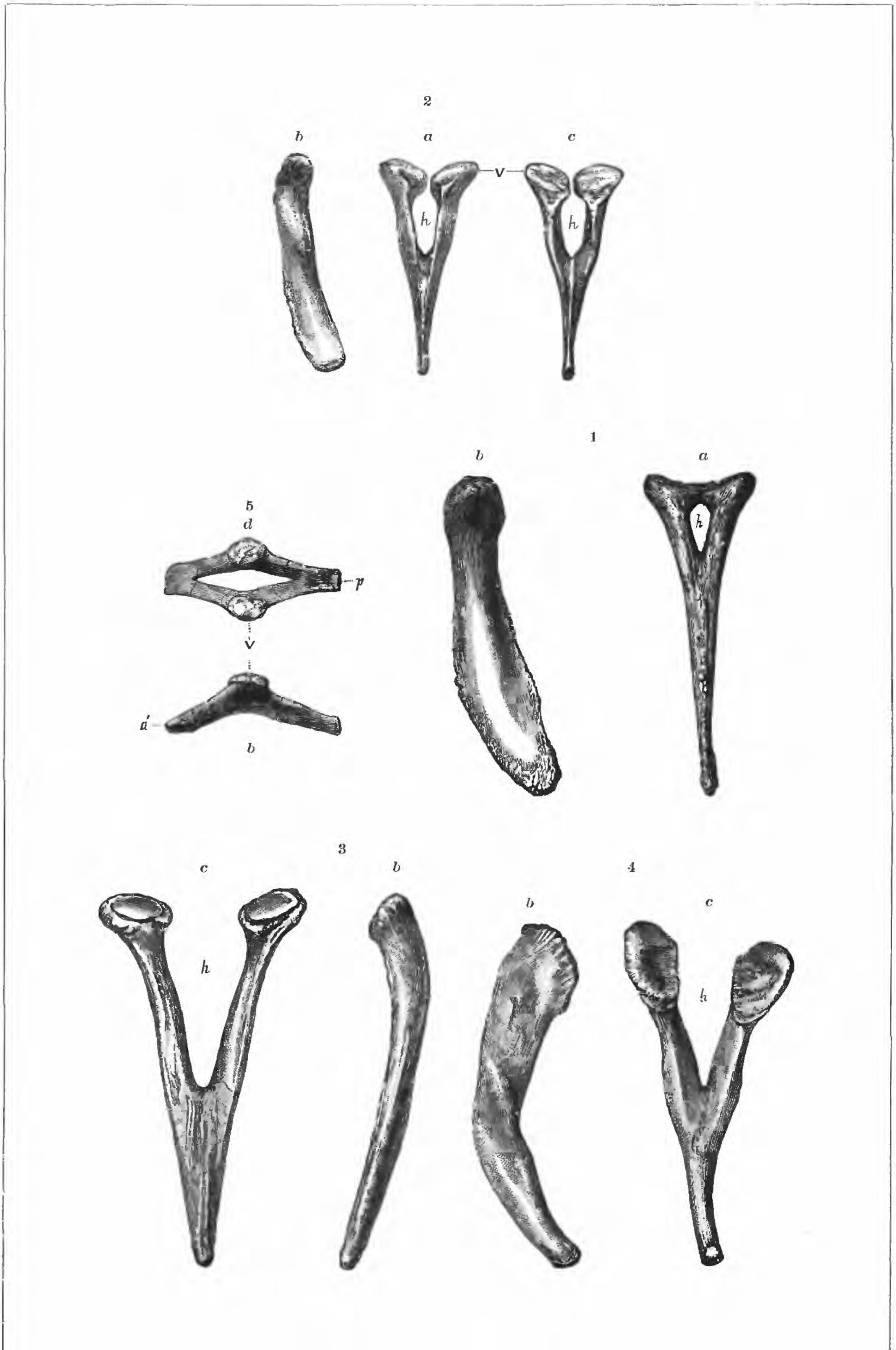
a, front view, *a'*, anterior end, *b*, side view, *c*, back view, *d*, top view; *h*, hæmal orifice; *p*, posterior end, *v*, face for vertebra.



BRONTOSAURUS, APATOSAURUS, MOROSAURUS, AND DIPLODOCUS.

Jurassic.

PLATE XL.

PLATE XL.

JURASSIC DINOSAURS.—SAUROPODA.

PLEUROCŒLIDÆ.

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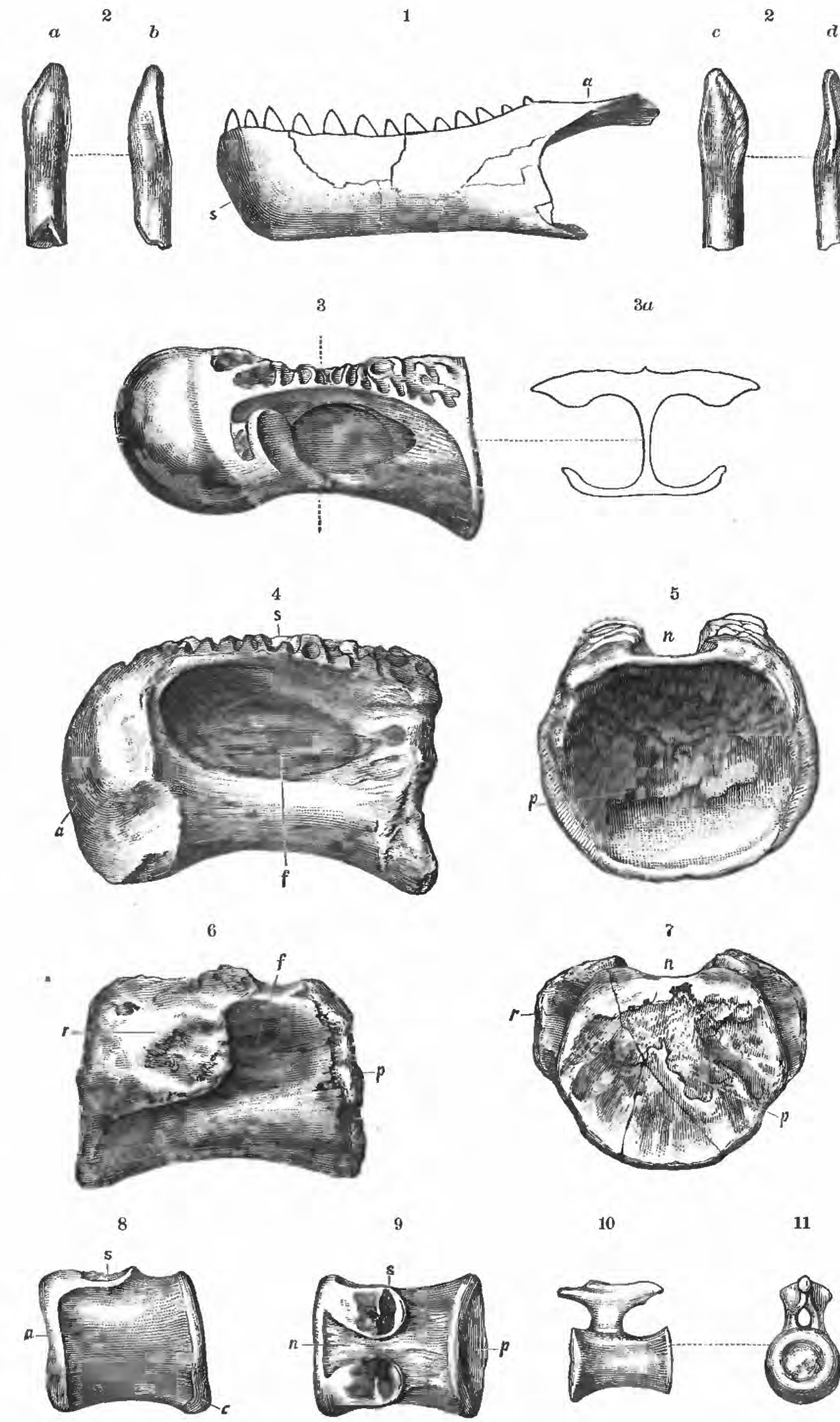
All the figures of vertebræ are one-half natural size

a, anterior end of centrum, *c*, face for chevron, *f*, foramen in centrum; *n*, neural canal, *p*, posterior end of centrum, *r*, face for rib, *s*, neural spine

Potomac formation, Maryland



PLEUROCŒLUS NANUS Marsh.

Jurassic.

PLATE XLI.

PLATE XLI.

JURASSIC DINOSAURS.—SAUROPODA.

PLEUROCŒLIDÆ

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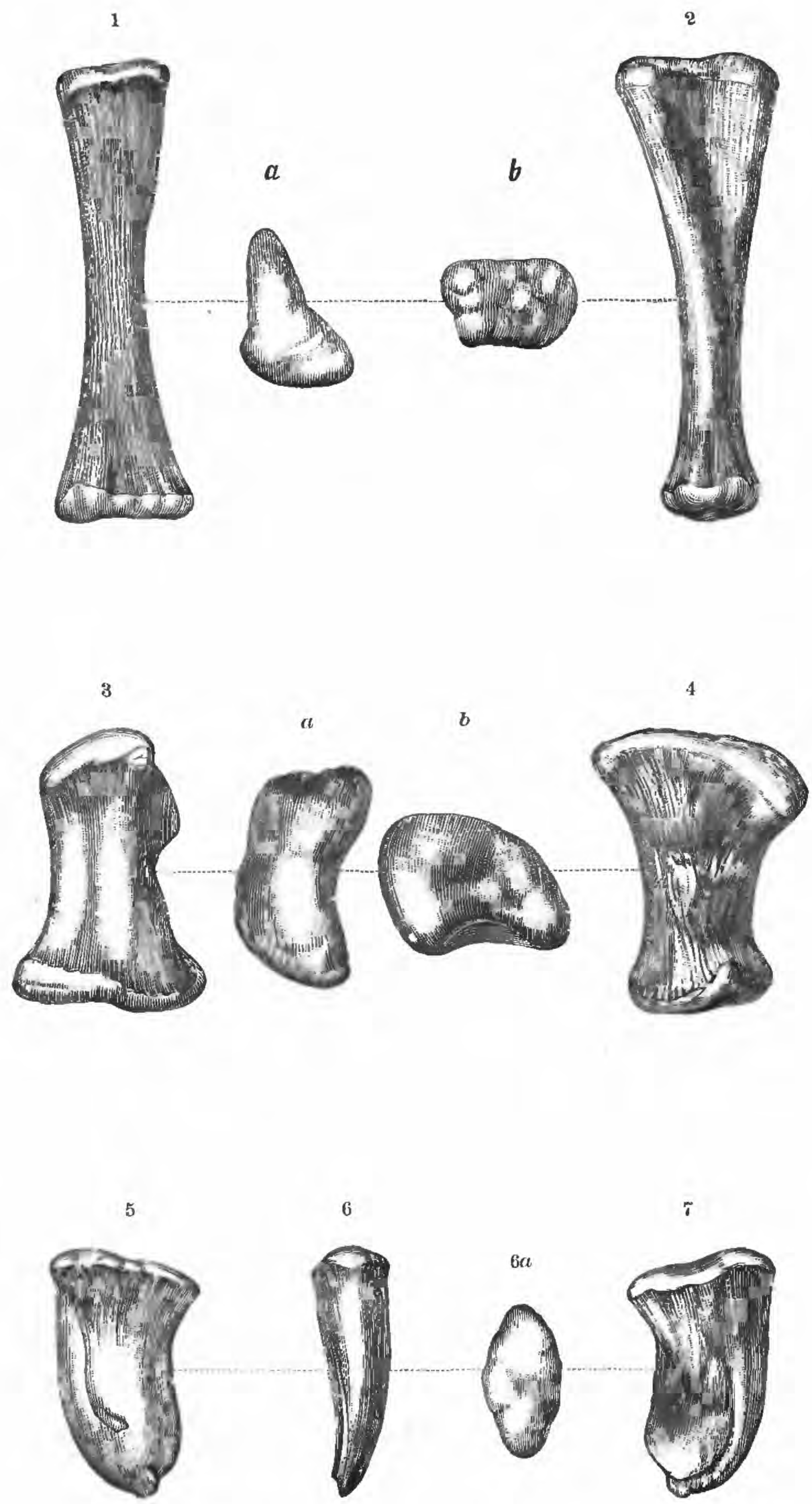
All the figures are one-half natural size

Potomac formation, Maryland



PLEUROCŒLUS NANUS.

Jurassic.

PLATE XLII.

PLATE XLII.

JURASSIC DINOSAURS.—SAUROPODA.

ATLANTOSAURIDÆ.

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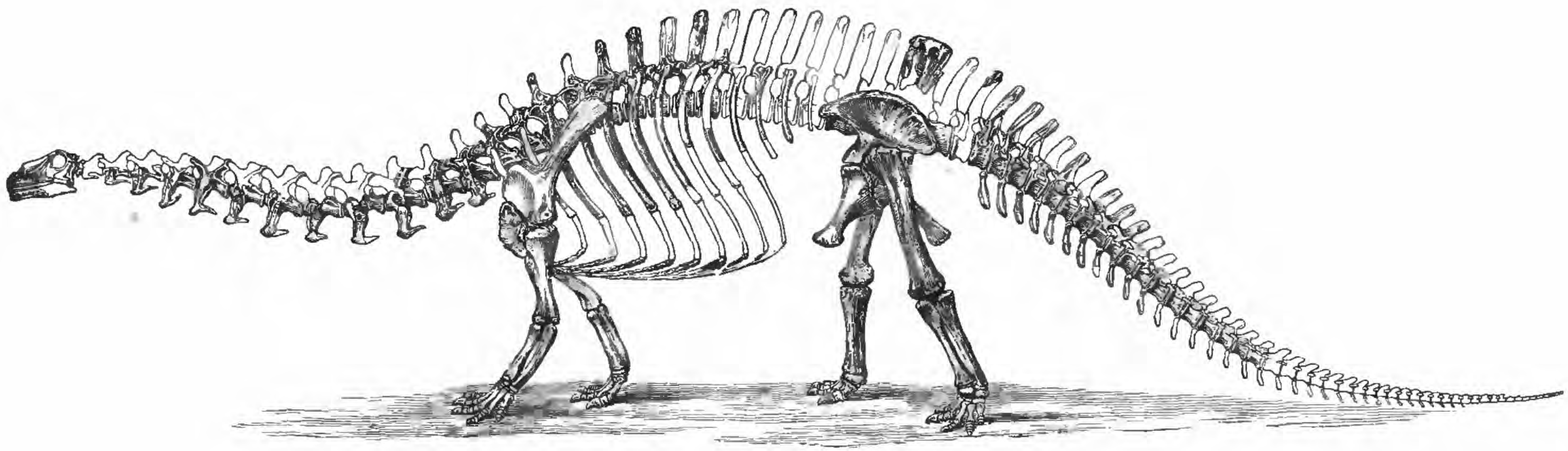
One-ninetieth natural size.
Jurassic, Wyoming.



RESTORATION OF BRONTOSAURUS EXCELSUS Marsh.

One-ninetieth natural size. Jurassic, Wyoming.

PLATE XLIII.

PLATE XLIII.

JURASSIC DINOSAURS.—PREDENTATA.

STEGOSAURIDÆ

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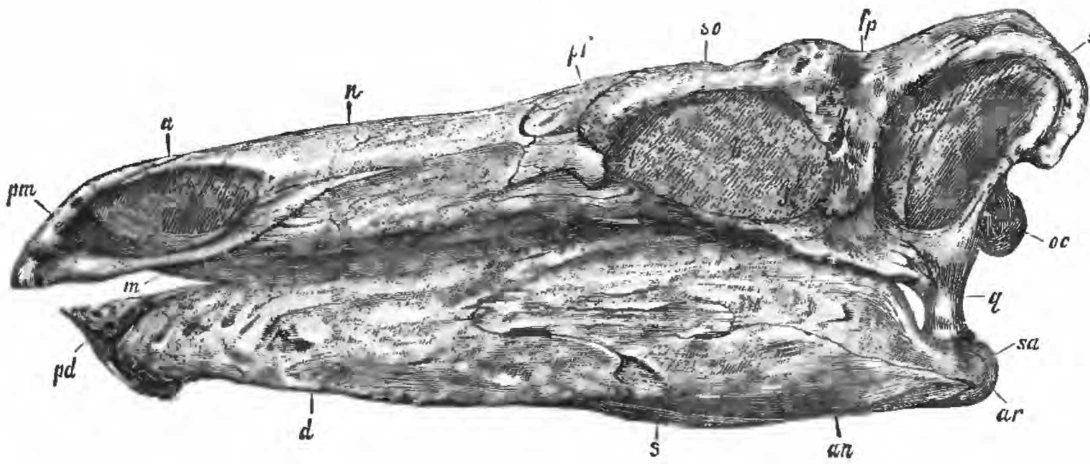
a, anterior nares, *an*, angular; *ar*, articular, *b*, orbit; *c*, lower temporal fossa; *d*, dentary, *e*, supratemporal fossa, *f*, frontal; *fp*, postfrontal, *j*, jugal; *l*, lachrymal; *m*, maxillary; *n*, nasal; *oc*, occipital condyle, *os*, supraoccipital, *p*, parietal, *pd*, predentary, *pf*, prefrontal, *pm*, premaxillary, *po*, postorbital; *q*, quadrate; *s*, splenial; *sa*, surangular; *so*, supraorbital; *sq*, squamosal.

All the figures are one-fourth natural size

1



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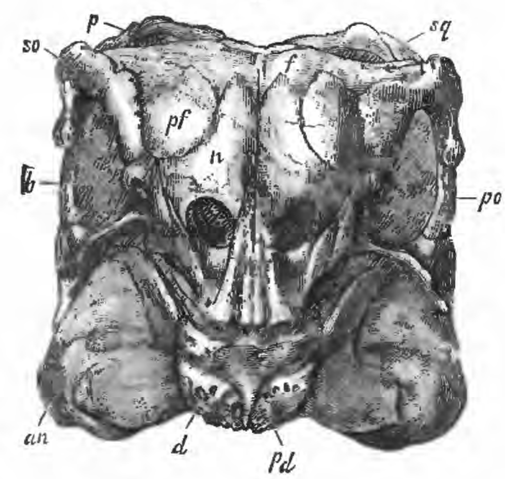

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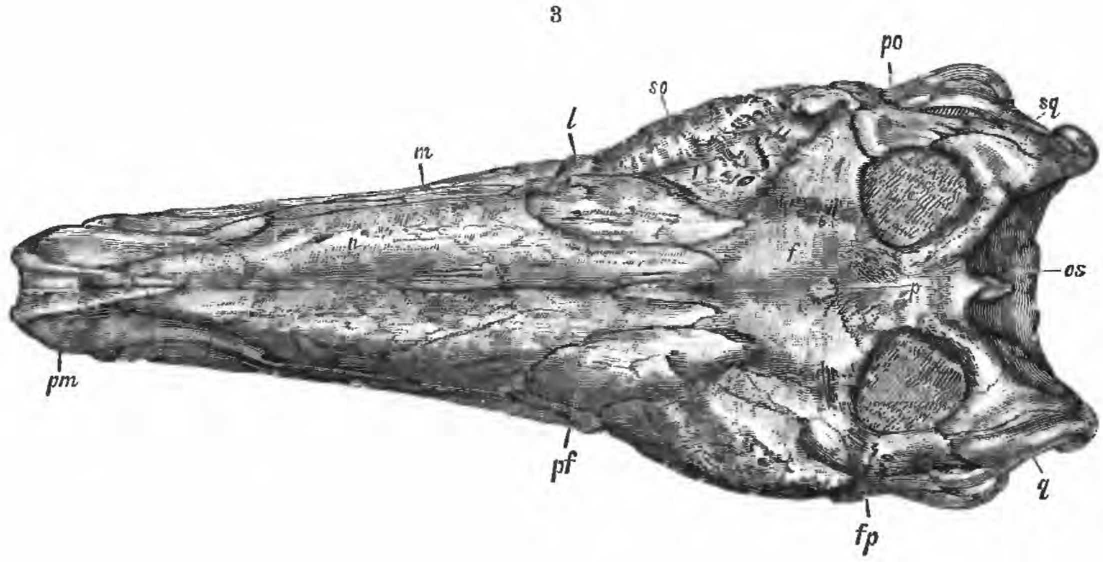

STEGOSAURUS STENOPS Marsh.

Jurassic.

PLATE XLIV.

PLATE XLIV

JURASSIC DINOSAURS.—PREDENTATA.

STEGOSAURIDÆ.

Page.

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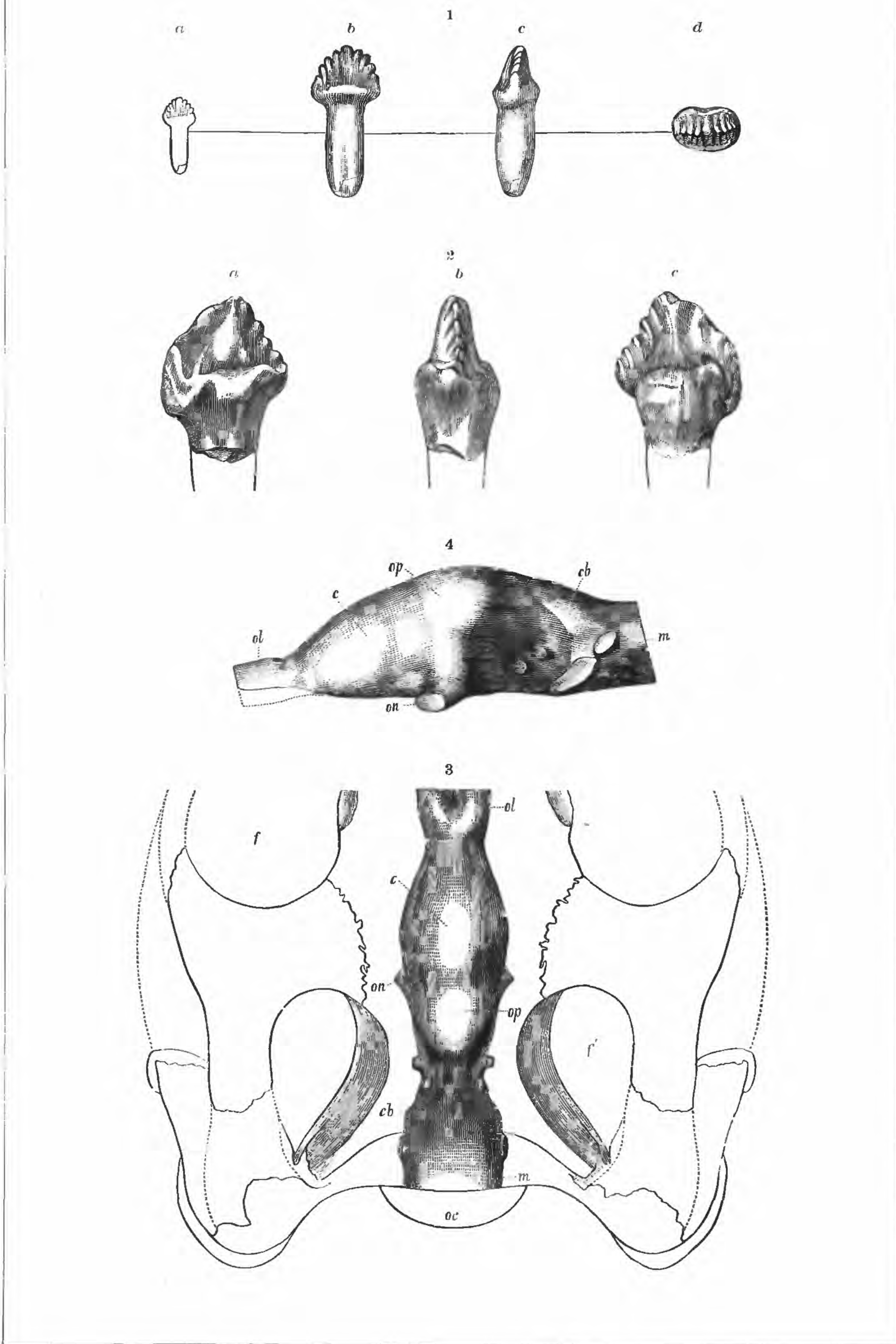
c, cerebral hemispheres; *cb*, cerebellum, *f*, orbital cavity; *f'*, temporal fossa, *m*, medulla, *oc*, occipital condyle, *ol*, olfactory lobes; *on*, optic nerve, *op*, optic lobes



STEGOSAURUS AND PRICONODON.

Jurassic.

PLATE XLV.

PLATE XLV.

JURASSIC DINOSAURS.—PREDENTATA.

STEGOSAURIDÆ.

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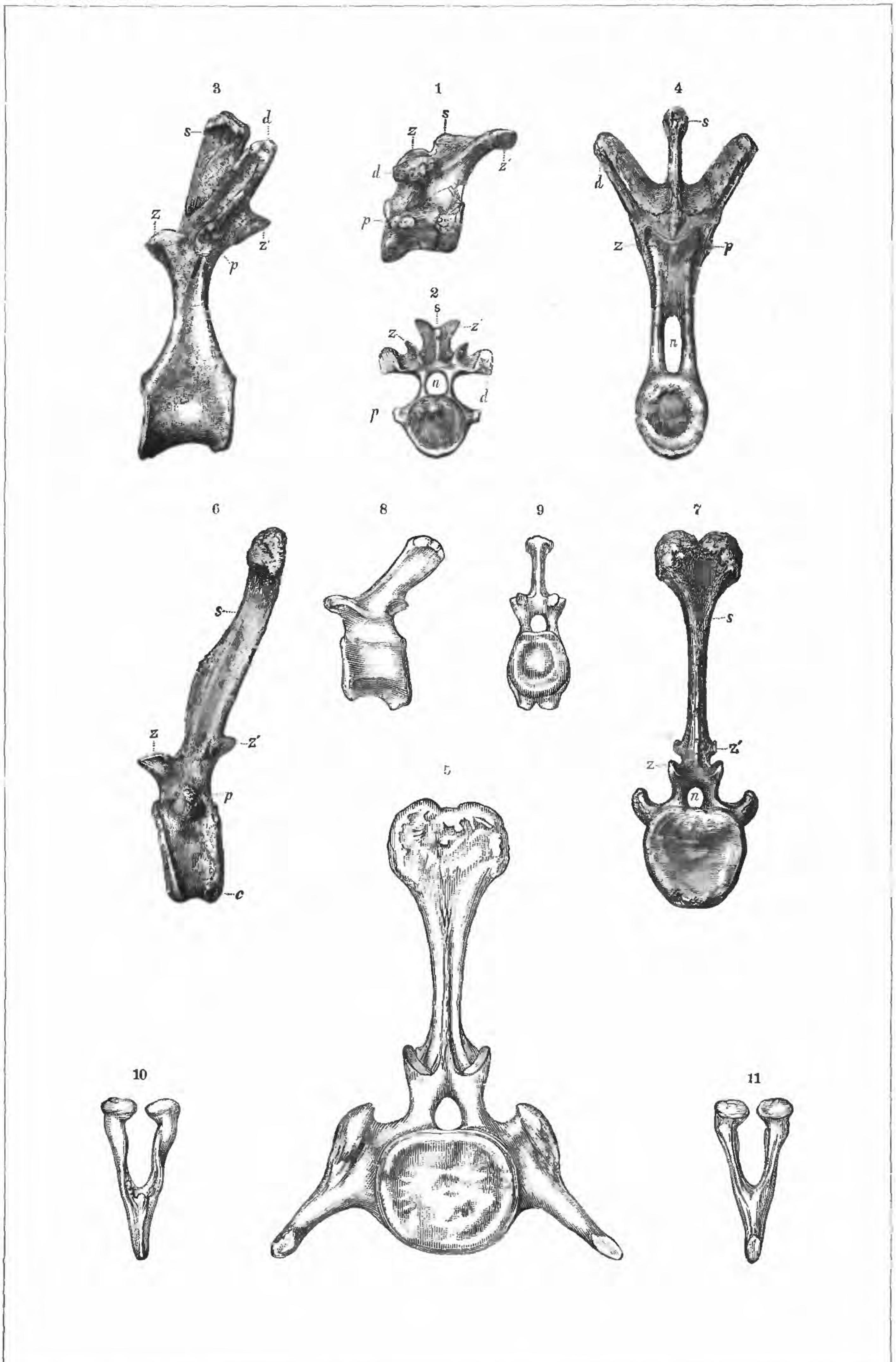
c, face for chevron, *d*, diapophysis; *n*, neural canal; *p*, parapophysis; *s*, neural spine, *z*, anterior zygapophysis, *z'*, posterior zygapophysis.

All the figures are one-eighth natural size.



STEGOSAURUS UNGULATUS Marsh.

Jurassic.

PLATE XLVI.

PLATE XLVI.

JURASSIC DINOSAURS.—PREDENTATA.

STEGOSAURIDÆ.

Page.

FIG. 1. Brain cast of *Stegosaurus ungulatus* Marsh; seen from above 190

c, cerebral hemispheres; *cb*, cerebellum; *m*, medulla; *ol*, olfactory lobes, *on*, optic nerve; *op*, optic lobes

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FIG. 3 The same cast, seen from above........ 190

a, anterior end, *f*, *f'*, *f''*, foramina between sacral vertebræ; *p*, exit of neural canal in last sacral vertebra

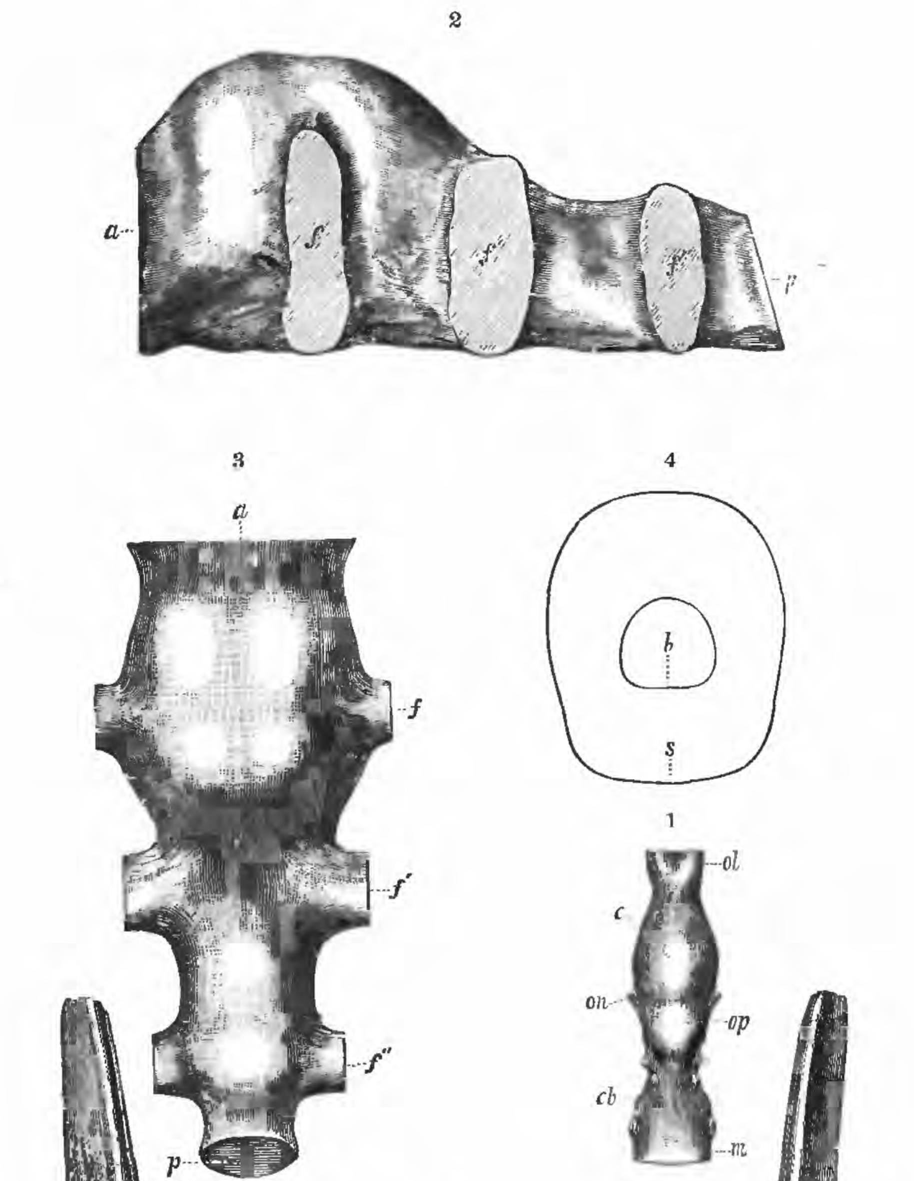
FIG. 4. Outlines representing transverse sections through same brain and sacral cavity................... 190

b, brain, *s*, sacral cavity.

All four figures are one-fourth natural size

FIG. 5 Sacrum and ilia of *Stegosaurus ungulatus*, seen from below, one-twelfth natural size... 190

a, first sacral vertebra; *ac*, acetabular surface, *b*, transverse process of first sacral vertebra; *e*, transverse process of last sacral vertebra; *il*, ilium; *l*, second lumbar vertebra from sacrum, *l'*, lumbar vertebra next to sacrum; *p*, last sacral vertebra



STEGOSAURUS UNGULATUS.

Jurassic.

PLATE XLVII.

PLATE XLVII.

JURASSIC DINOSAURS.—PREDENTATA.

STEGOSAURIDÆ

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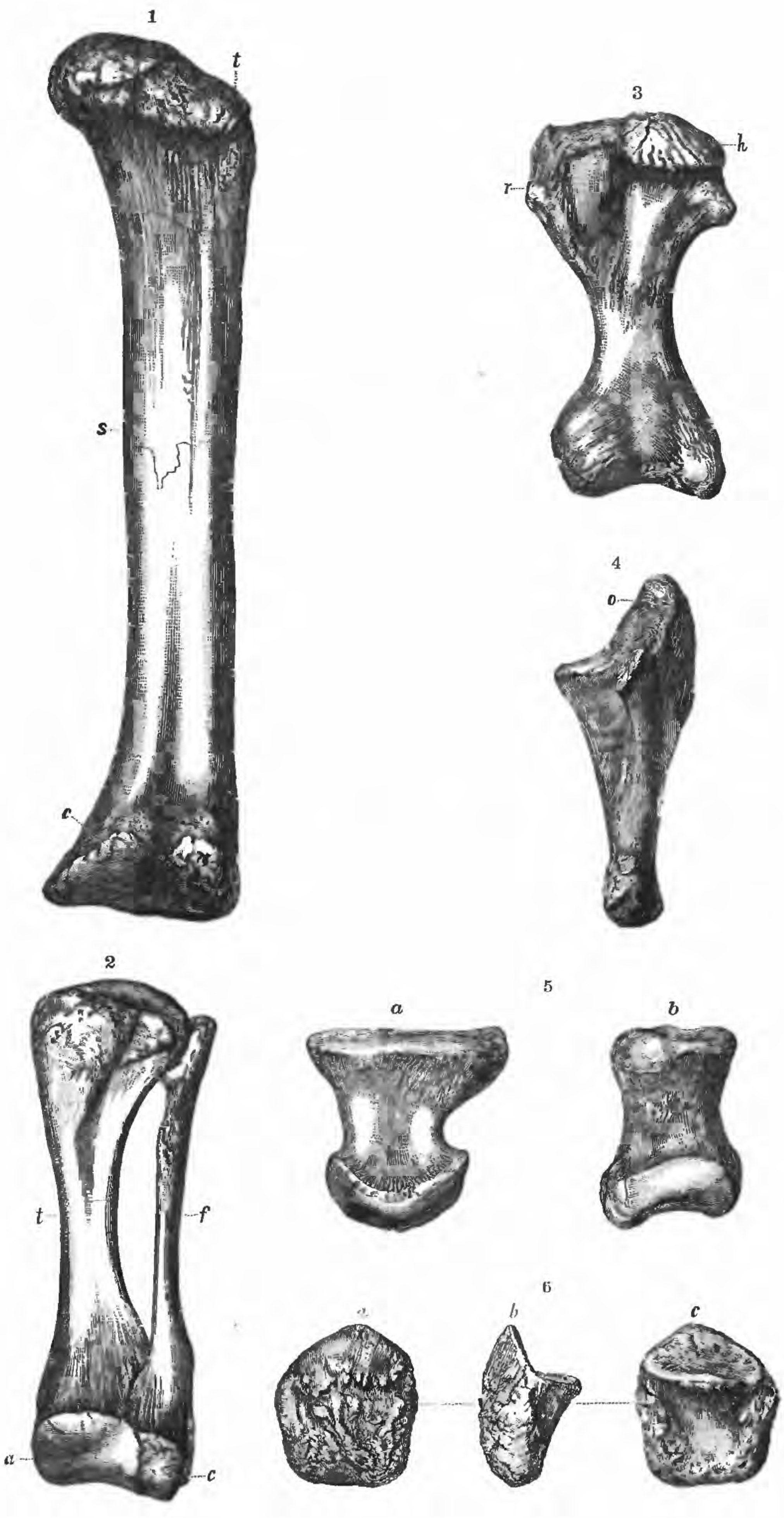

STEGOSAURUS UNGULATUS.

Jurassic.

PLATE XLVIII.

PLATE XLVIII.

JURASSIC DINOSAURS.—PREDENTATA.

STEGOSAURIDÆ

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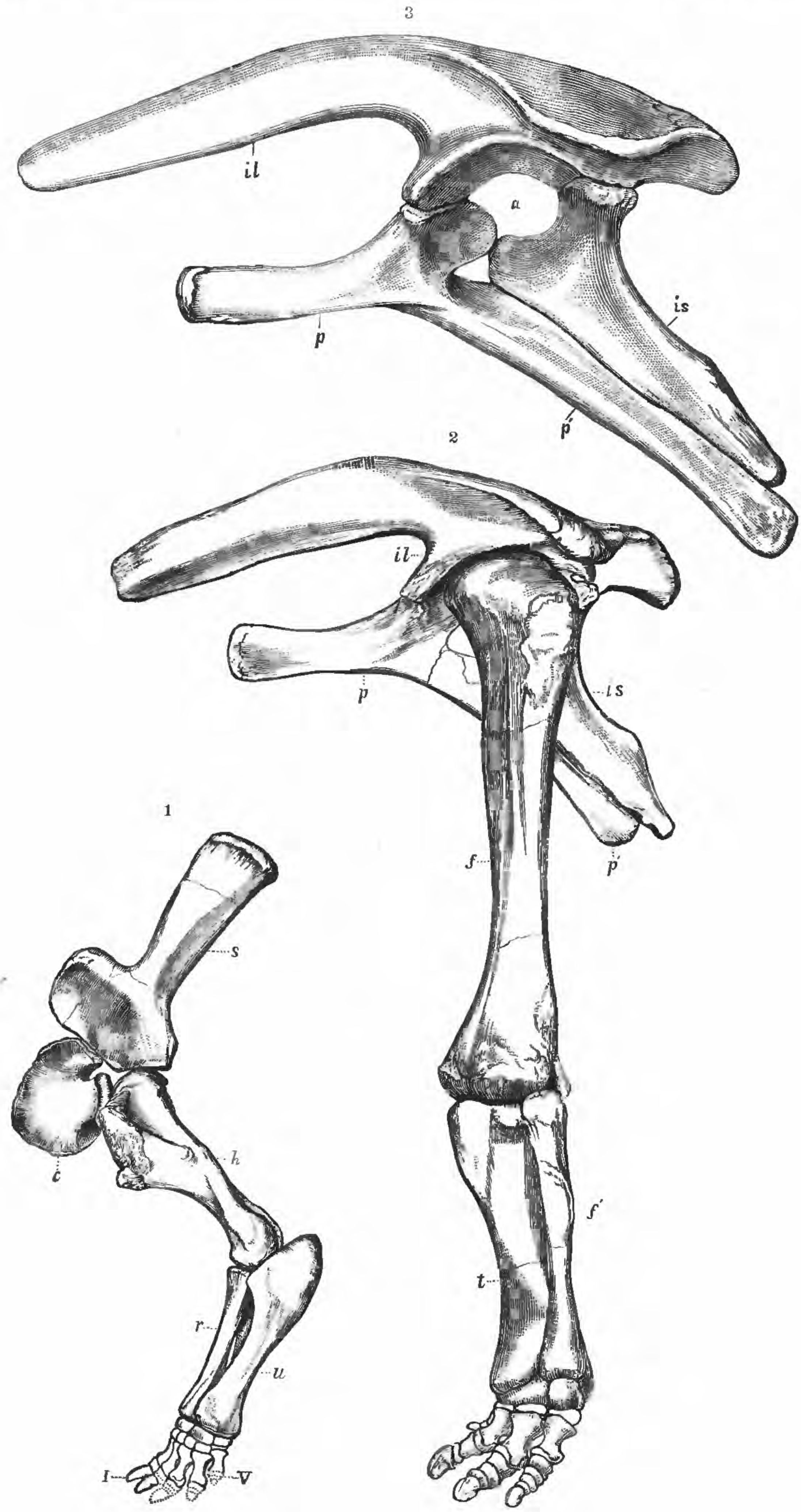
a, acetabulum; *c*, coracoid; *f*, femur; *f′*, fibula, *h*, humerus; *il*, ilium; *is*, ischium; *p*, pubis, *p′*, postpubis; *r*, radius, *s*, scapula, *t*, tibia; *u*, ulna: *I*, first digit; *V*, fifth digit.



STEGOSAURUS

Jurassic.

PLATE XLIX.

PLATE XLIX.

JURASSIC DINOSAURS.—PREDENTATA.

STEGOSAURIDÆ.

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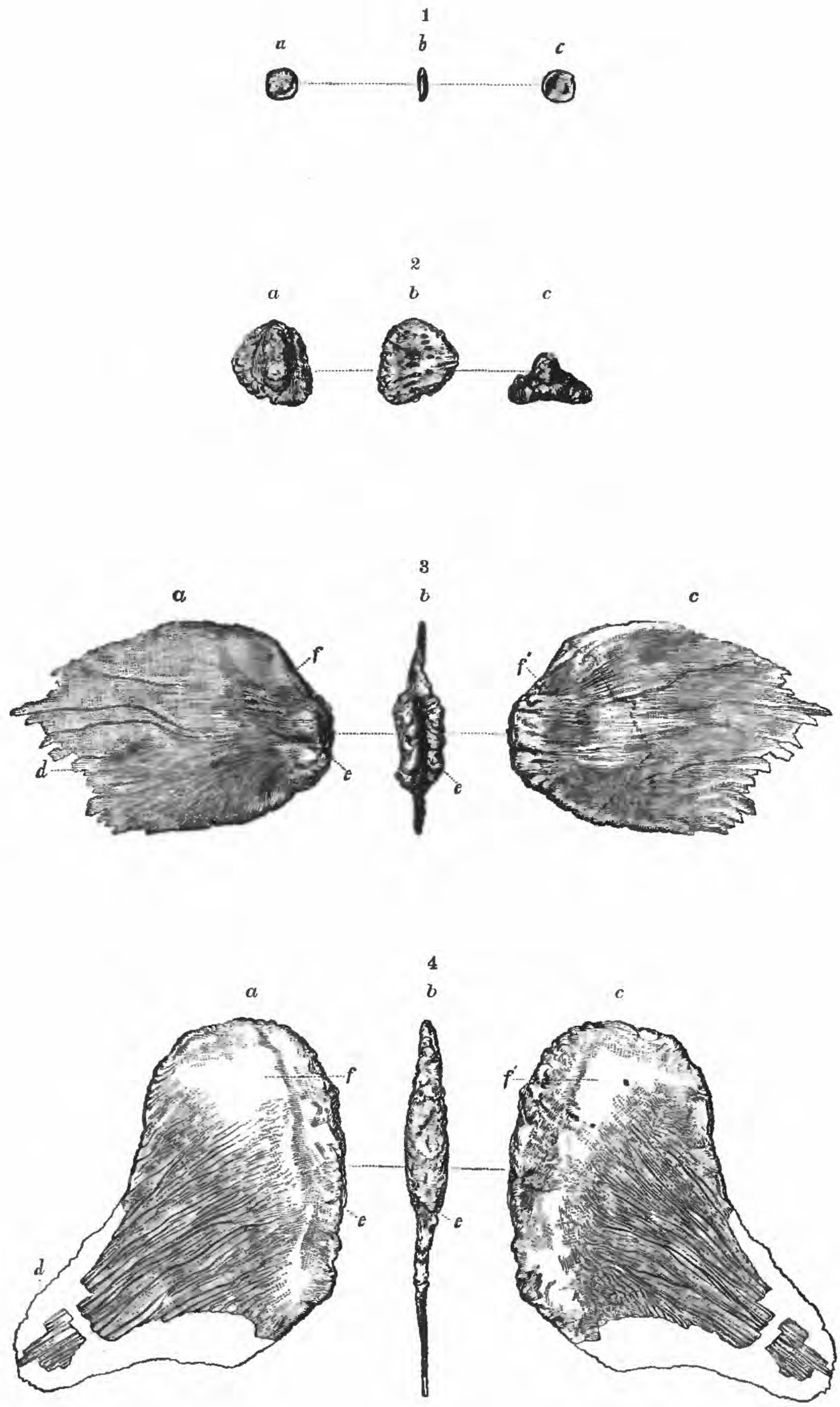
All the figures are one-twelfth natural size.



STEGOSAURUS UNGULATUS
Jurassic.

PLATE L.

PLATE L.

JURASSIC DINOSAURS.—PREDENTATA.

STEGOSAURIDÆ

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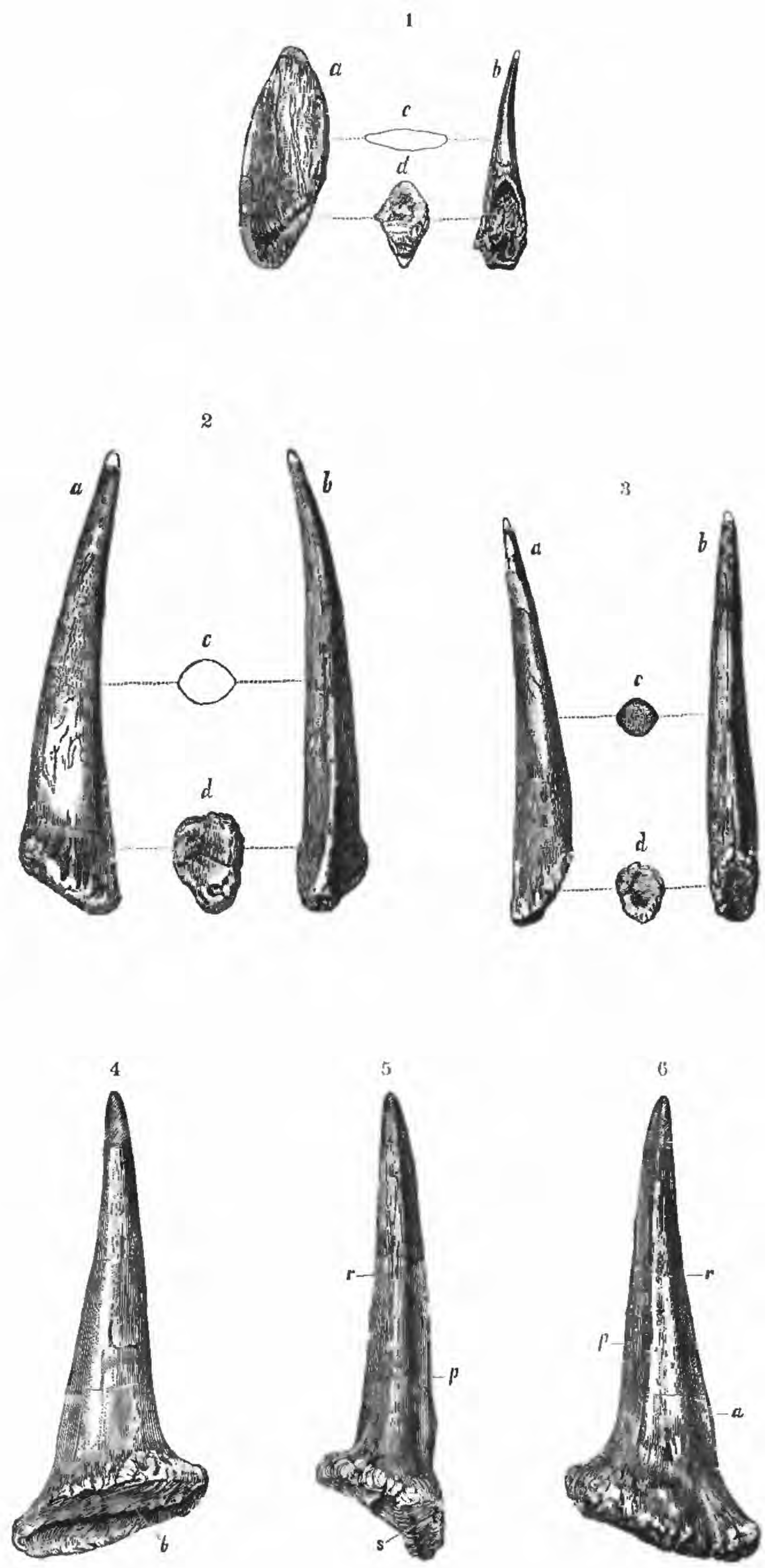
a, anterior, *b*, base; *p*, posterior, *r*, ridge; *s*, face for adjoining spine.	

All the figures are one-twelfth natural size.



STEGOSAURUS.

Jurassic.

PLATE LI.

PLATE LI.

JURASSIC DINOSAURS.—PREDENTATA.

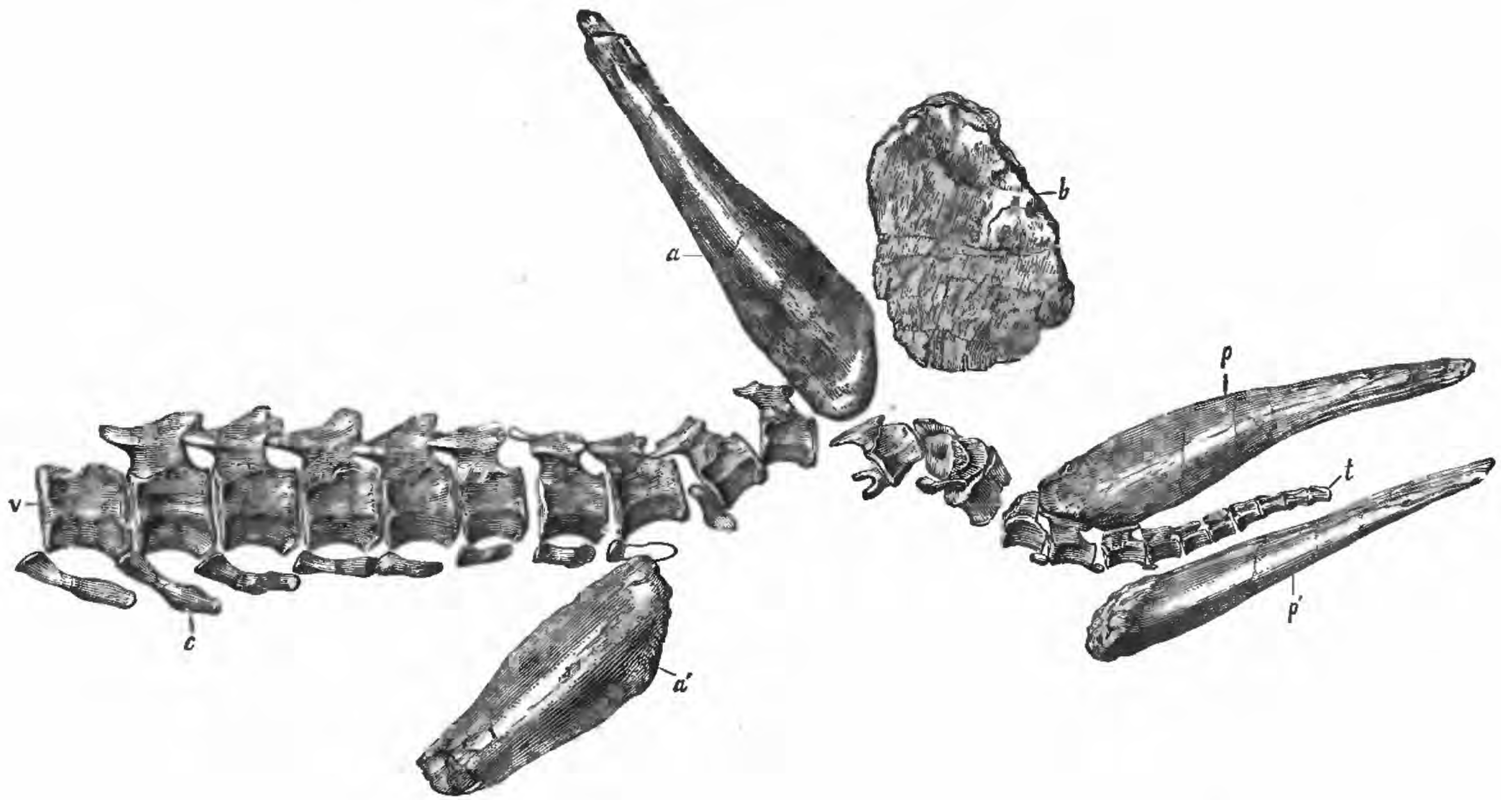
STEGOSAURIDÆ.

Page

Caudal vertebræ, spines, and plate of *Diracodon laticeps* Marsh, seen from the left; one-sixth natural size 193

a, right anterior spine; *a'*, left anterior spine; *b*, small caudal plate; *c*, chevron bone; *p*, right posterior spine; *p'*, left posterior spine; *t*, terminal vertebra; *v*, median caudal vertebra.

The bones represented are essentially in the position in which they were found.



DIRACODON LATICEPS Marsh.

Jurassic.

PLATE LII.

PLATE LII.

JURASSIC DINOSAURS.—PREDENTATA.

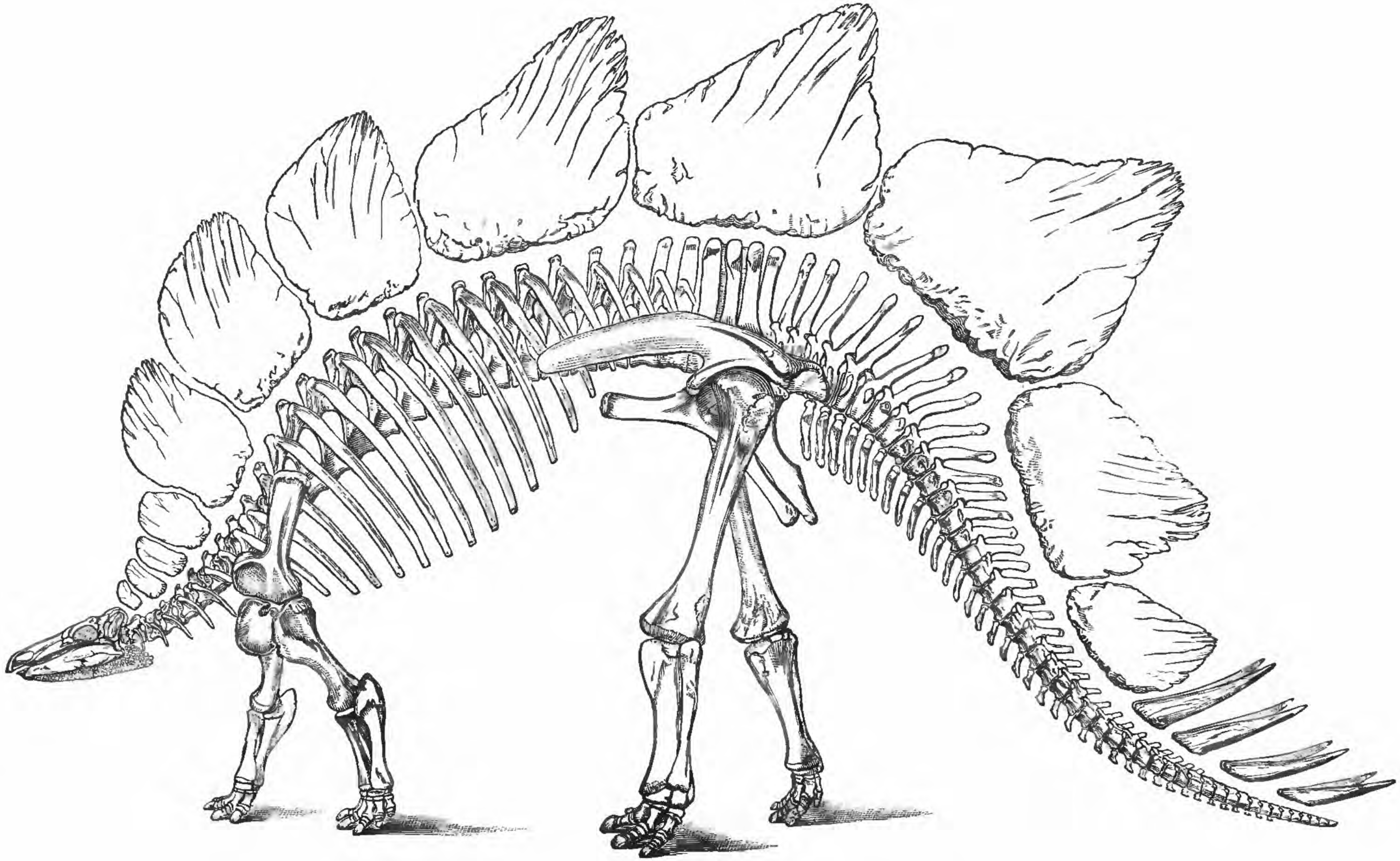
STEGOSAURIDÆ.

Page.

Restoration of *Stegosaurus ungulatus* Marsh 194

One-thirtieth natural size.

Jurassic, Wyoming.



RESTORATION OF STEGOSAURUS UNGULATUS Marsh.

One-thirtieth natural size. Jurassic, Wyoming.

PLATE LIII.

PLATE LIII.

JURASSIC DINOSAURS.—PREDENTATA.

CAMPTOSAURIDÆ.

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a, exterior narial opening; *an*, angular; *bo*, basioccipital; *d*, dentary, *f*, frontal; *fp*, postfrontal; *if*, infraorbital fossa; *j*, jugal; *l*, lachrymal; *m*, maxillary, *n*, nasal, *o*, orbit; *pd*, predentary; *pf*, prefrontal; *pm*, premaxillary, *q*, quadrate; *qj*, quadratojugal; *s*, squamosal; *sa*, surangular, *sf*, supratemporal fossa; *so*, supraorbital bone.	
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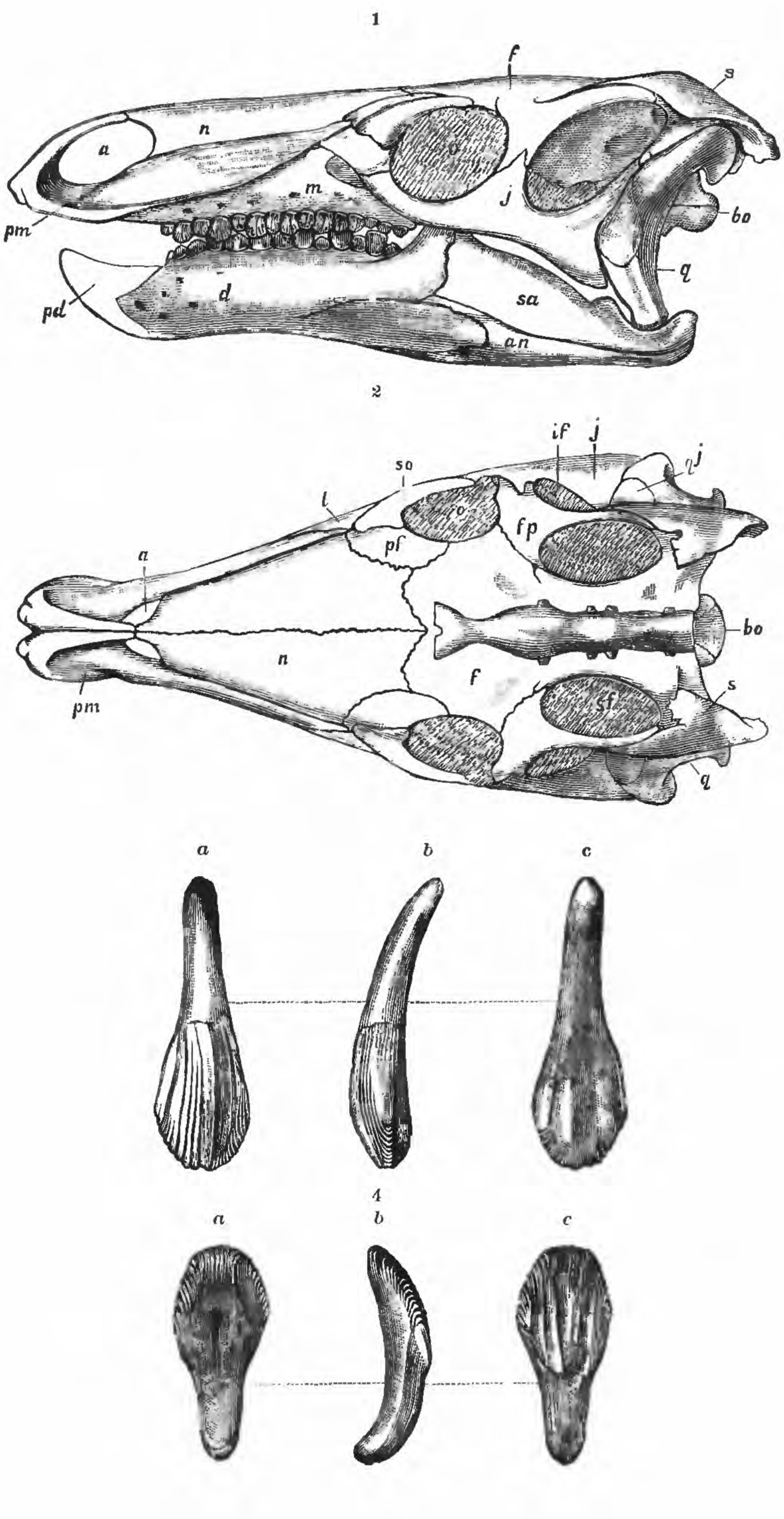


CAMPTOSAURUS MEDIUS Marsh.

Jurassic.

PLATE LIV.

PLATE LIV.

JURASSIC DINOSAURS.—PREDENTATA.

CAMPTOSAURIDÆ

Page

FIG 1. Left fore leg of *Camptosaurus dispar* Marsh, outer view; one-twelfth natural size 196

c, coracoid; *h*, humerus; *r*, radius; *s*, scapula; *u*, ulna, *I*, first digit, *V*, fifth digit

FIG. 2. Left hind leg of same species; outer view; one-twelfth natural size .. 199

a, astragalus; *c*, calcaneum, *f*, femur; *f'*, fibula; *il*, ilium; *is*, ischium; *p*, pubis; *p'*, postpubis; *t*, tibia, *I*, first digit; *IVmt*, fourth metatarsal.

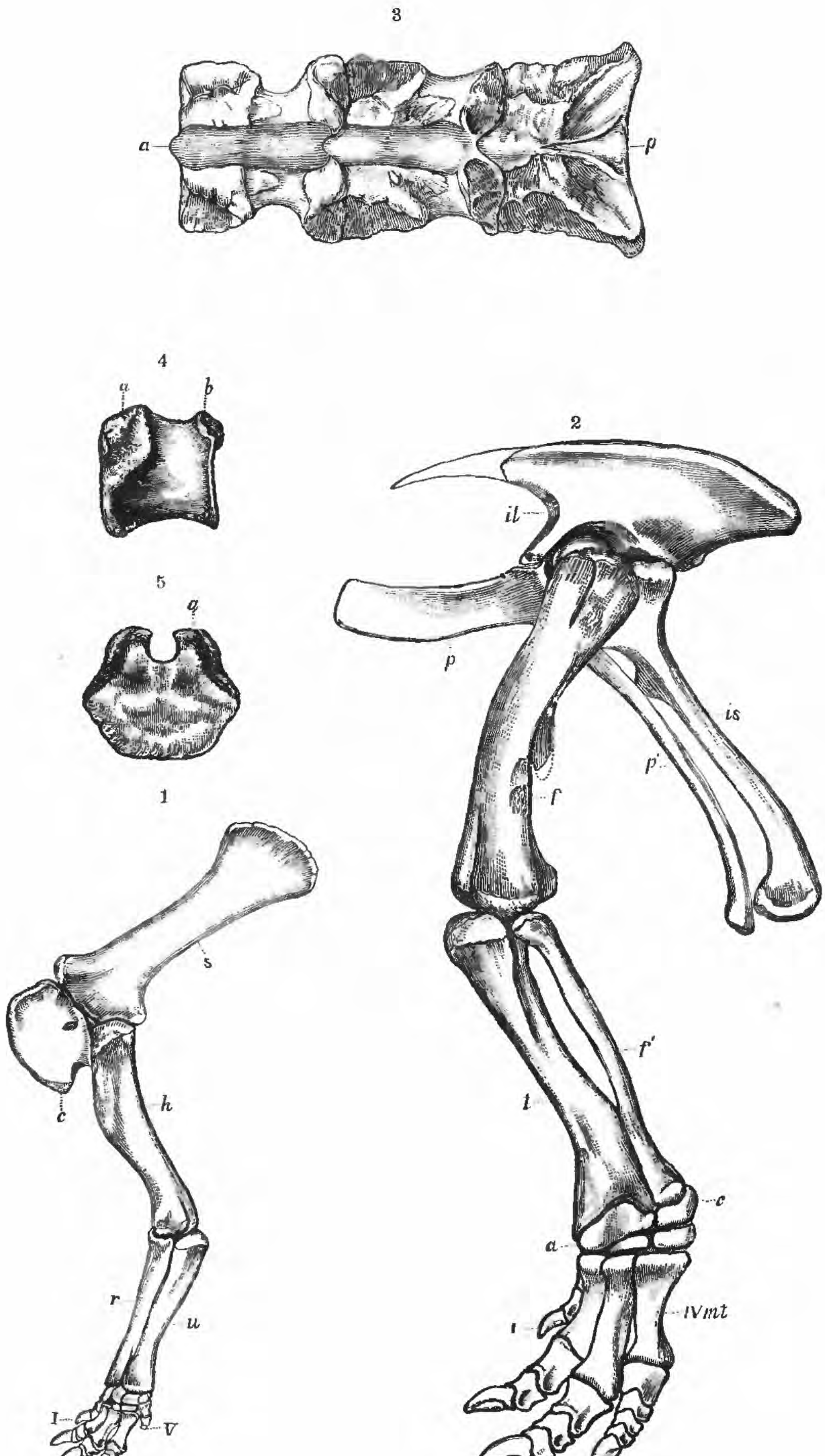
FIG. 3. Posterior sacral vertebræ of *Camptosaurus dispar*, showing peg-and notch articulation; top view; one-fourth natural size.................. 197

a, anterior end; *p*, posterior end.

FIG. 4 Sacral vertebra of same individual, seen from the left; one-sixth natural size... 197

FIG. 5 The same vertebra, front view; one-sixth natural size 197

a, anterior face for transverse process; *b*, posterior face.



CAMPTOSAURUS DISPAR Marsh.

Jurassic.

PLATE LV.

PLATE LV

JURASSIC DINOSAURS.—PREDENTATA.

CAMPTOSAURIDÆ AND LAOSAURIDÆ

Page

FIG. 1. Lower tooth of *Laosaurus consors* Marsh; natural size 199

a, outer view, *b*, posterior end view, *c*, inner view.

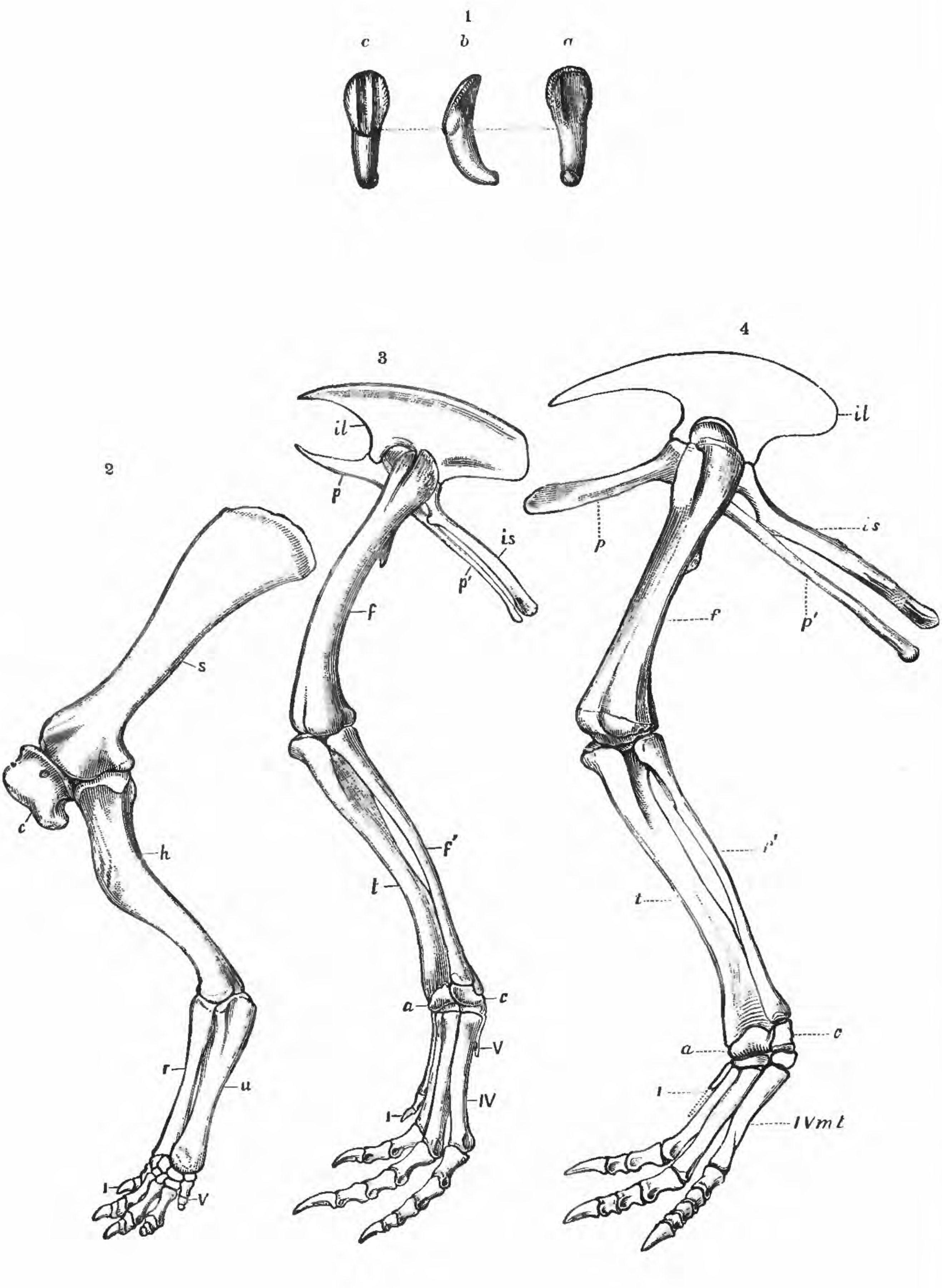
FIG. 2. Left fore leg of *Camptosaurus nanus* Marsh, outer view; one-fourth natural size 196

c, coracoid; *h*, humerus; *r*, radius, *s*, scapula, *u*, ulna, *I*, first digit, *V*, fifth digit

FIG. 3. Left hind leg of *Laosaurus consors;* outer view, one-sixth natural size. 199

FIG. 4. The same of *Dryosaurus altus* Marsh, outer view, one-eighth natural size 198

a, astragalus; *c*, calcaneum, *f*, femur, *f′*, fibula; *il*, ilium, *is*, ischium, *p*, pubis; *p′*, postpubis, *t*, tibia; *I*, first digit, *IV*, fourth digit, *IVmt*, fourth metatarsal; *V*, fifth metatarsal



CAMPTOSAURUS, DRYOSAURUS, AND LAOSAURUS.

Jurassic.

PLATE LVI.

PLATE LVI

JURASSIC DINOSAURS.—PREDENTATA.

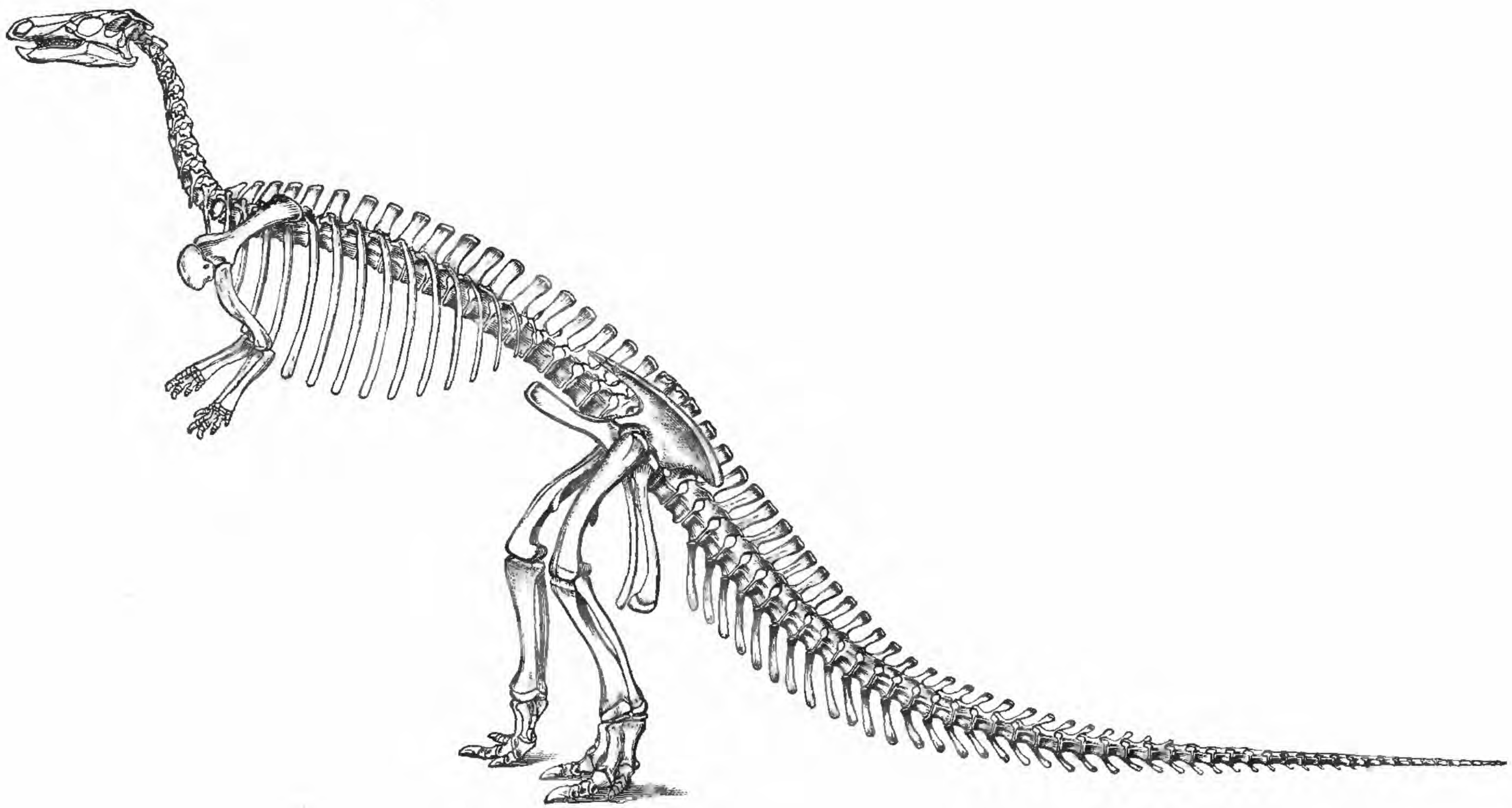
CAMPTOSAURIDÆ

Page.

Restoration of *Camptosaurus dispar* Marsh 197

One-thirtieth natural size.

Jurassic, Wyoming.



RESTORATION OF CAMPTOSAURUS DISPAR Marsh.

One-thirtieth natural size. Jurassic, Wyoming.

PLATE LVII.

PLATE LVII.

JURASSIC DINOSAURS.—PREDENTATA.

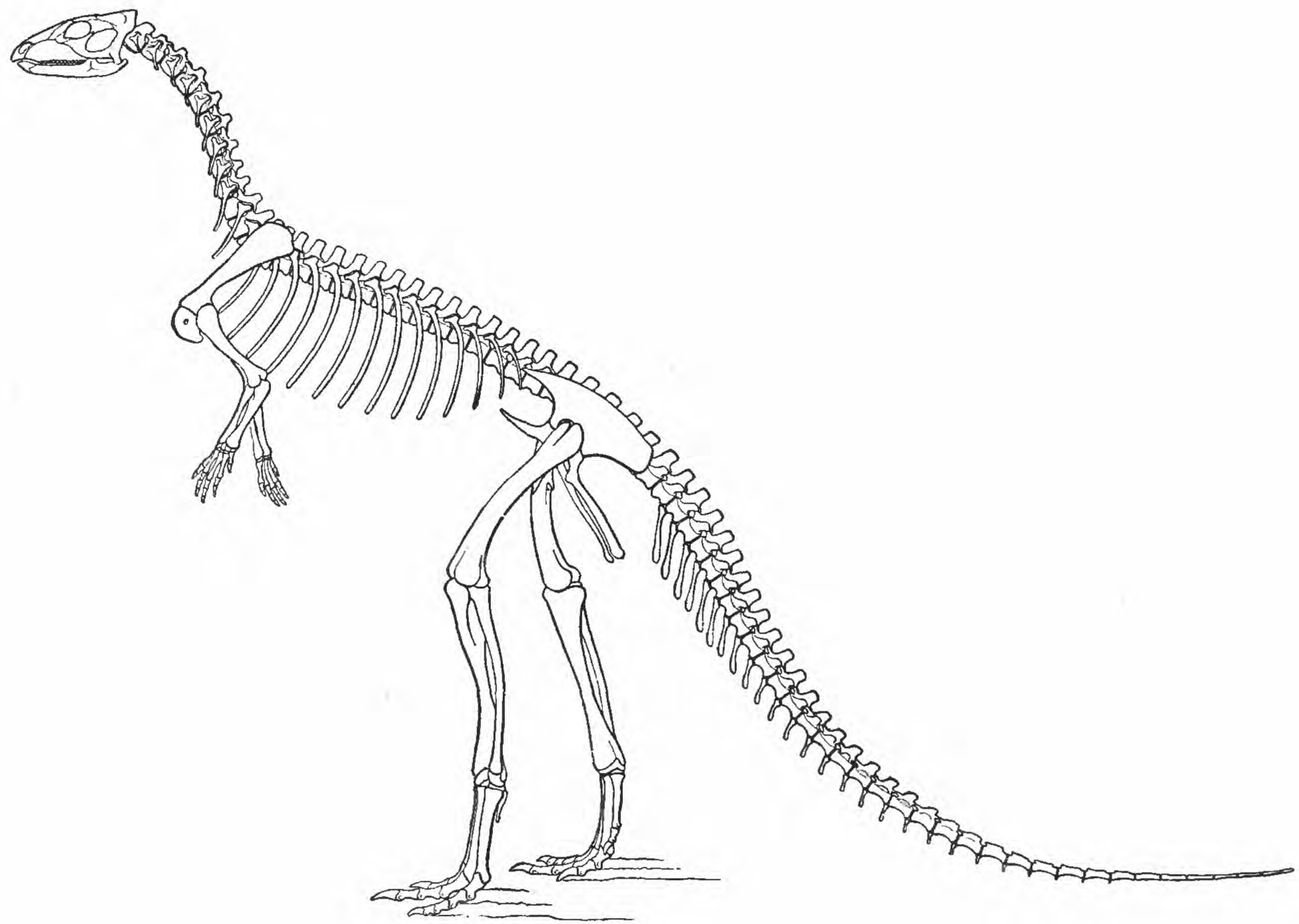
LAOSAURIDÆ

Page.

Restoration of *Laosaurus consors* Marsh 202

One-tenth natural size

Jurassic, Wyoming



RESTORATION OF LAOSAURUS CONSORS Marsh.

One-tenth natural size. Jurassic, Wyoming.

PLATE LVIII.

PLATE LVIII.

CRETACEOUS DINOSAURS.—THEROPODA.

ORNITHOMIMIDÆ.

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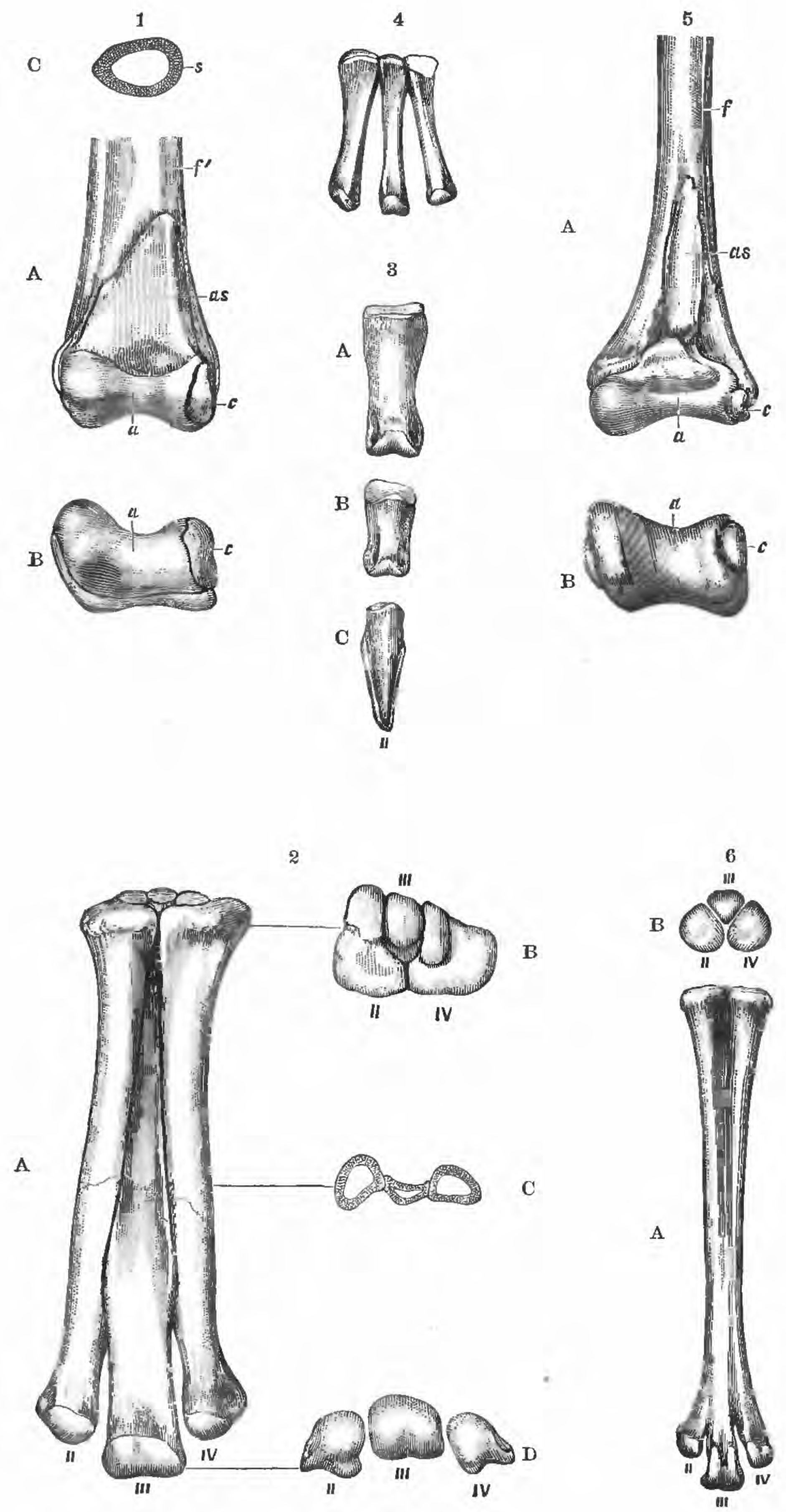
Last two figures are one-half natural size.

a, astragalus; *as*, ascending process of astragalus; *c*, calcaneum; *f*, fibula; *f′*, face for fibula; *II*, second metatarsal, *III*, third metatarsal; *IV*, fourth metatarsal



ORNITHOMIMUS VELOX Marsh.

Cretaceous.

PLATE LIX.

PLATE LIX.

CRETACEOUS DINOSAURS.—PREDENTATA.

CERATOPSIDÆ.

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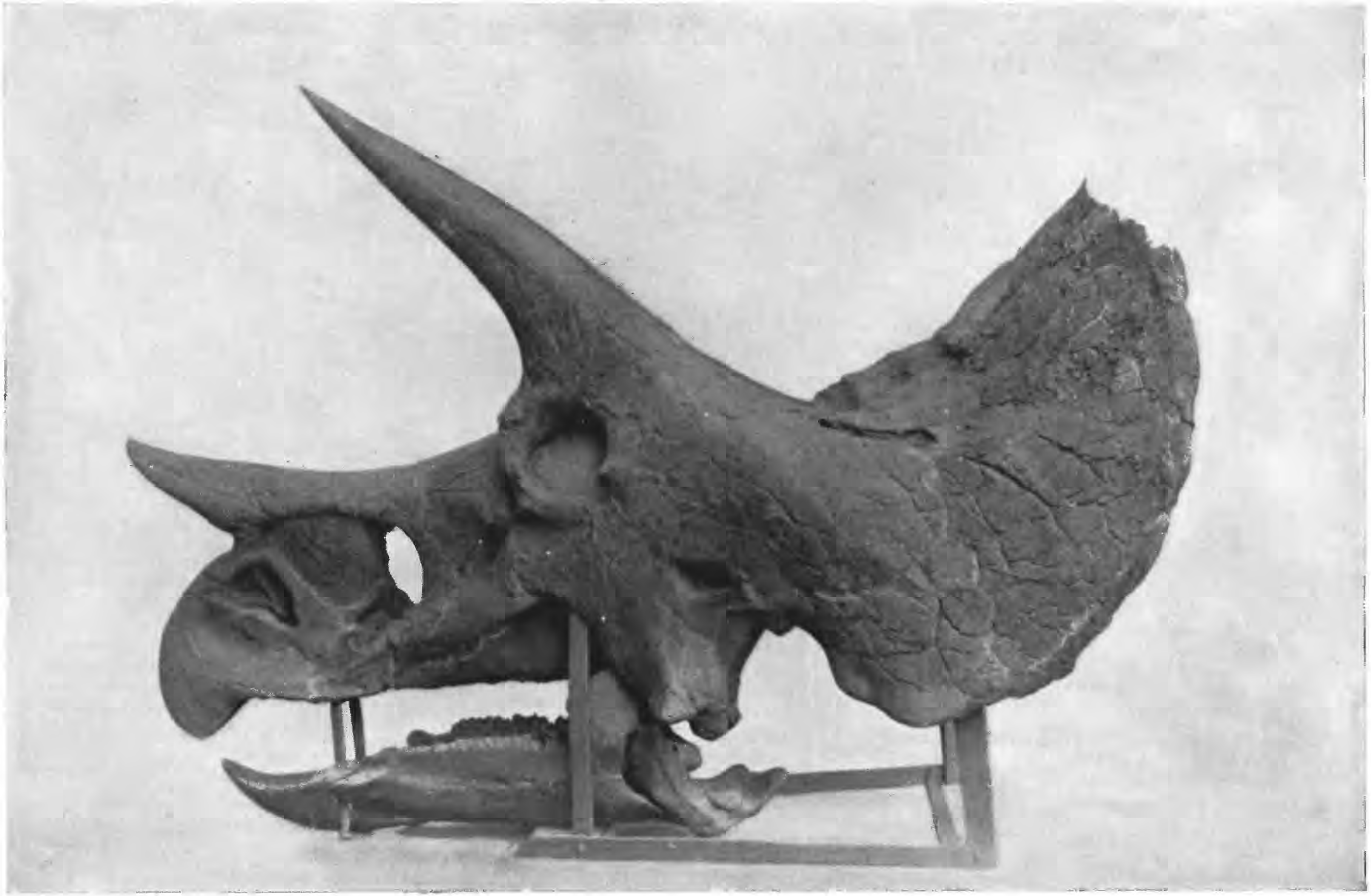
Skull and lower jaw of *Triceratops prorsus* Marsh, seen from the left side 208

One-ninth natural size

Cretaceous, Wyoming



TRICERATOPS PRORSUS Marsh.
Cretaceous.

PLATE LX.

PLATE LX.

CRETACEOUS DINOSAURS.—PREDENTATA.

CERATOPSIDÆ

Page.

FIG. 1. Skull of *Sterrholophus flabellatus* Marsh; seen from the left side........ 208
a, nasal opening; *b*, orbit; *c*, supratemporal fossa, *e*, epoccipital bone; *h*, horn core; *h'*, nasal horn core; *p*, predentary; *q*, quadrate, *r*, rostral bone.

FIG. 2. The same skull; seen from behind 208
d, dentary; *e*, epoccipital; *h*, horn core, *p*, parietal, *pd*, predentary; *q*, quadrate; *s*, squamosal

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c, supratemporal fossa; *d*, epijugal bone; *e*, epoccipital; *f*, frontal; *fp*, postfrontal; *h*, horn core, *h'*, nasal horn core; *j*, jugal; *m*, maxillary, *n*, nasal, *p*, parietal, *pf*, prefrontal, *pm*. premaxillary; *r*, rostral bone; *s*, squamosal; *x*, pineal foramen (?).

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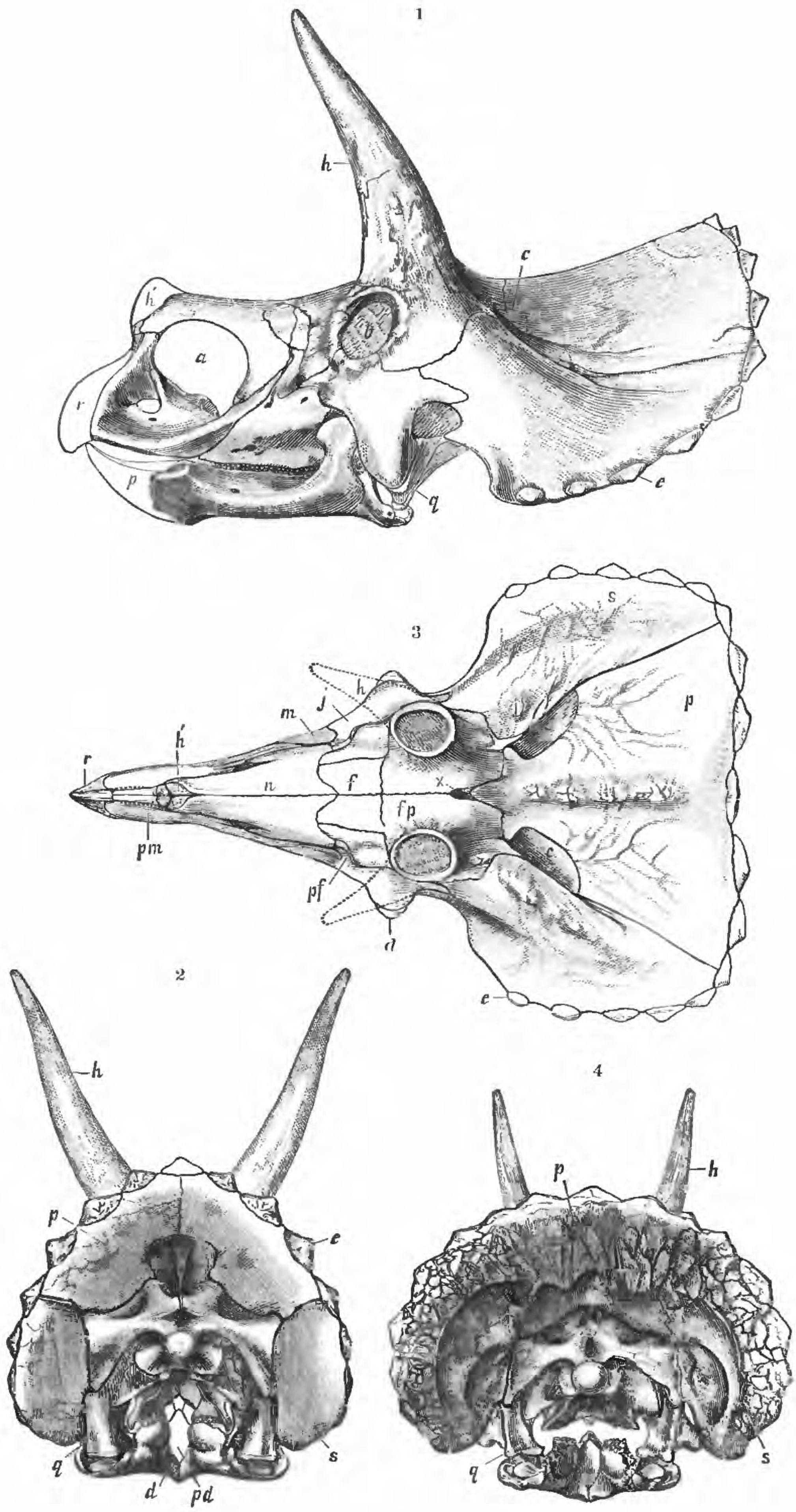
Letters as in fig. 2.

All the figures are one-twentieth natural size.



STERRHOLOPHUS AND TRICERATOPS.

Cretaceous.

PLATE LXI.

PLATE LXI.

CRETACEOUS DINOSAURS.—PREDENTATA.

CERATOPSIDÆ.

Page.

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FIG 2 Front view of same 209
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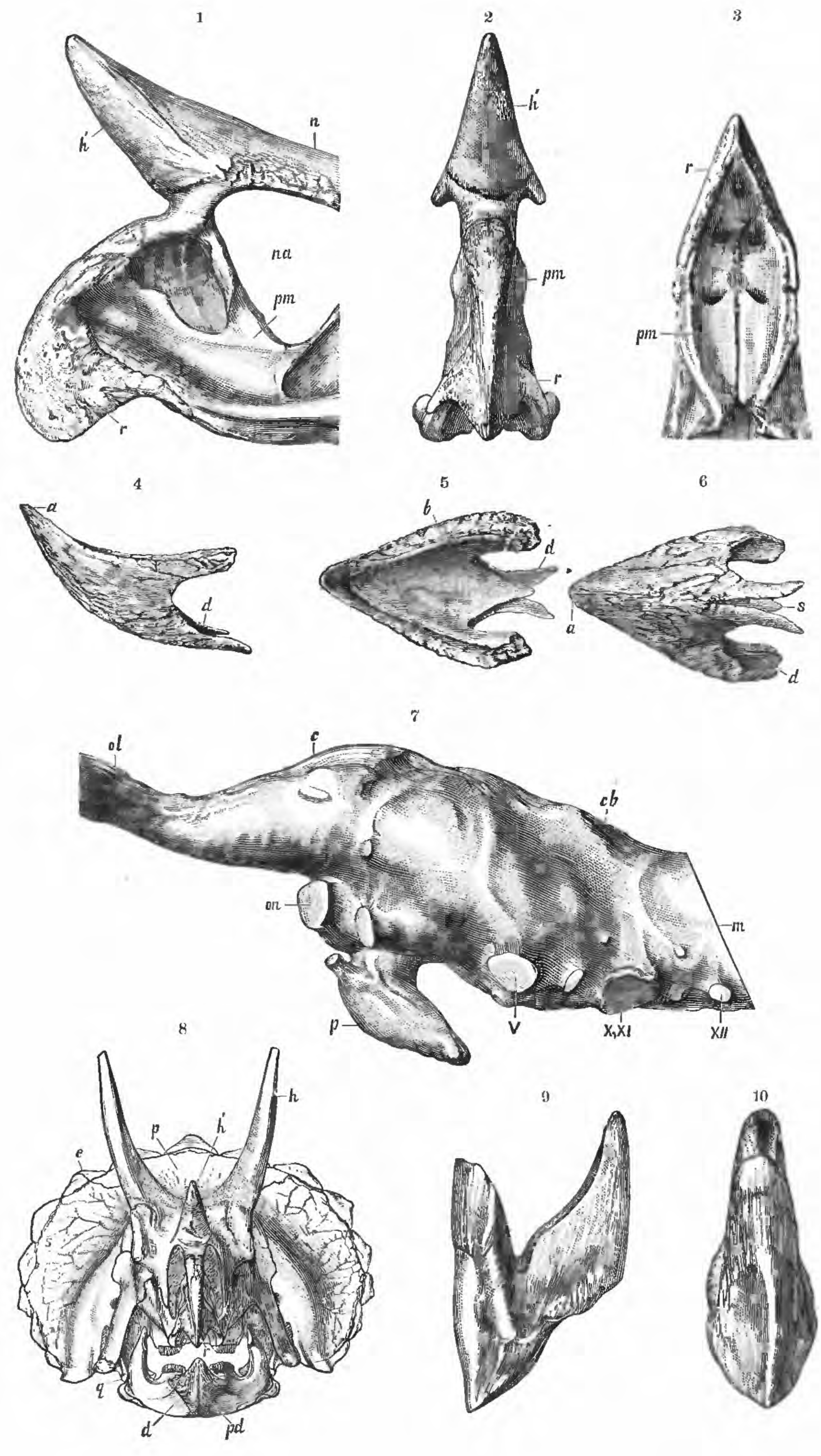

TRICERATOPS.

Cretaceous.

PLATE LXII.

PLATE LXII.

CRETACEOUS DINOSAURS.—PREDENTATA.

CERATOPSIDÆ.

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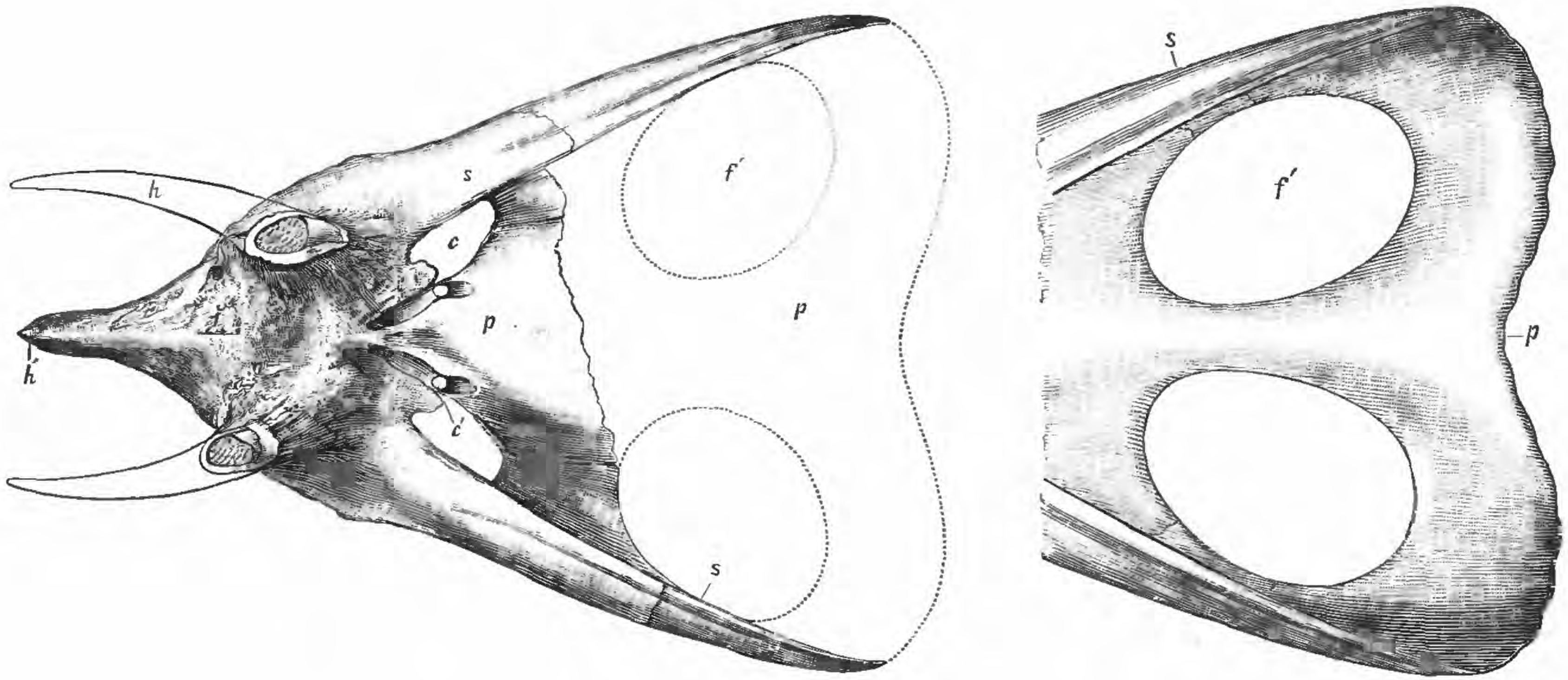
c, supratemporal fossa; *c'*, anterior temporal foramen; *f*, parietal fontanelle; *h*, horn core; *h'*, nasal horn core; *p*, parietal; *s*, squamosal.

Both figures are one-twentieth natural size.



TOROSAURUS.

Cretaceous.

PLATE LXIII.

PLATE LXIII.

CRETACEOUS DINOSAURS.—PREDENTATA.

CERATOPSIDÆ.

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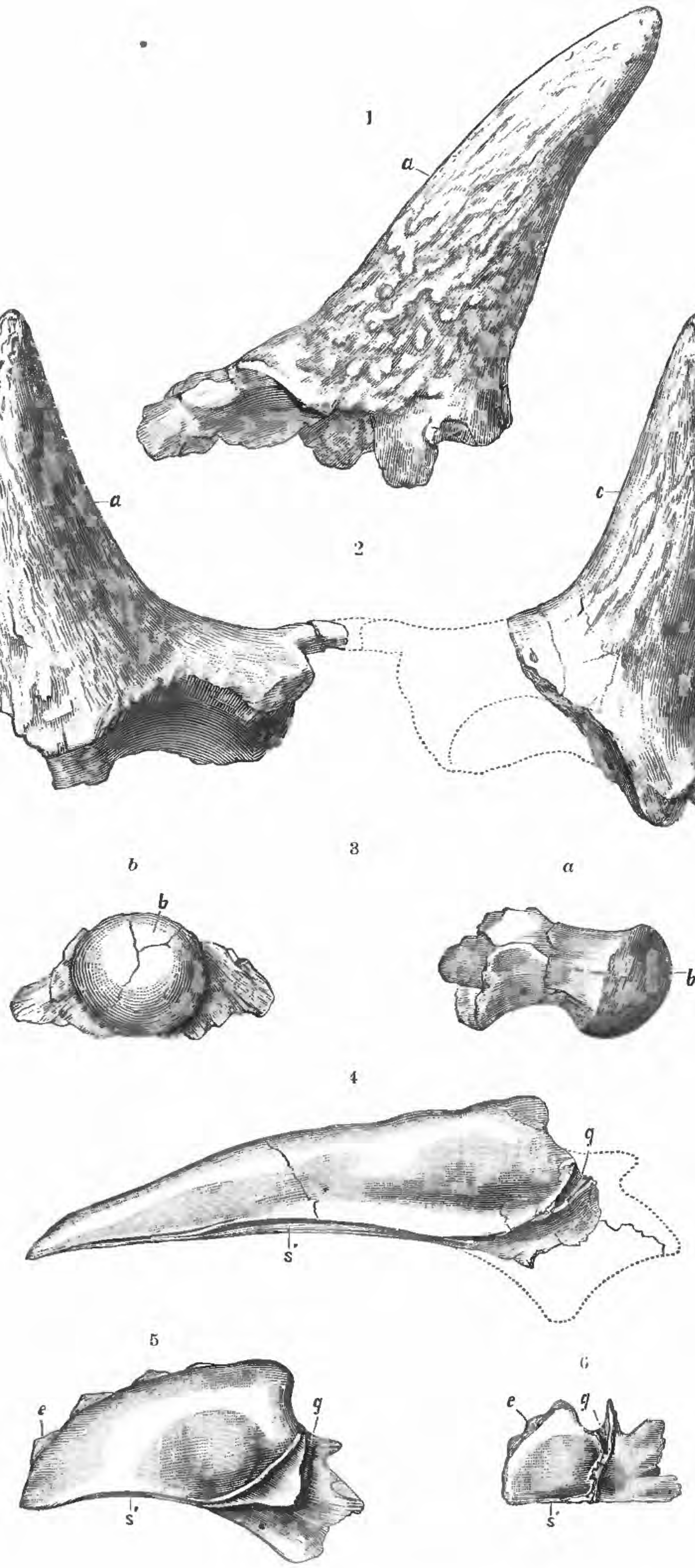
Last three figures are one-twentieth natural size	
e, epoccipital; *g*, groove for quadrate; *s'*, suture for parietal.	



CERATOPS, STERRHOLOPHUS, AND TOROSAURUS.

Cretaceous.

PLATE LXIV.

PLATE LXIV.

CRETACEOUS DINOSAURS.—PREDENTATA.

CERATOPSIDÆ.

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a, anterior face of atlas; *d*, diapophysis; *n*, neural canal; *p*, posterior face of fourth vertebra; *r*, rib; *s*, neural spine of axis; *s'*, neural spine of third vertebra; *s''*, neural spine of fourth vertebra; *z'*, posterior zygapophysis

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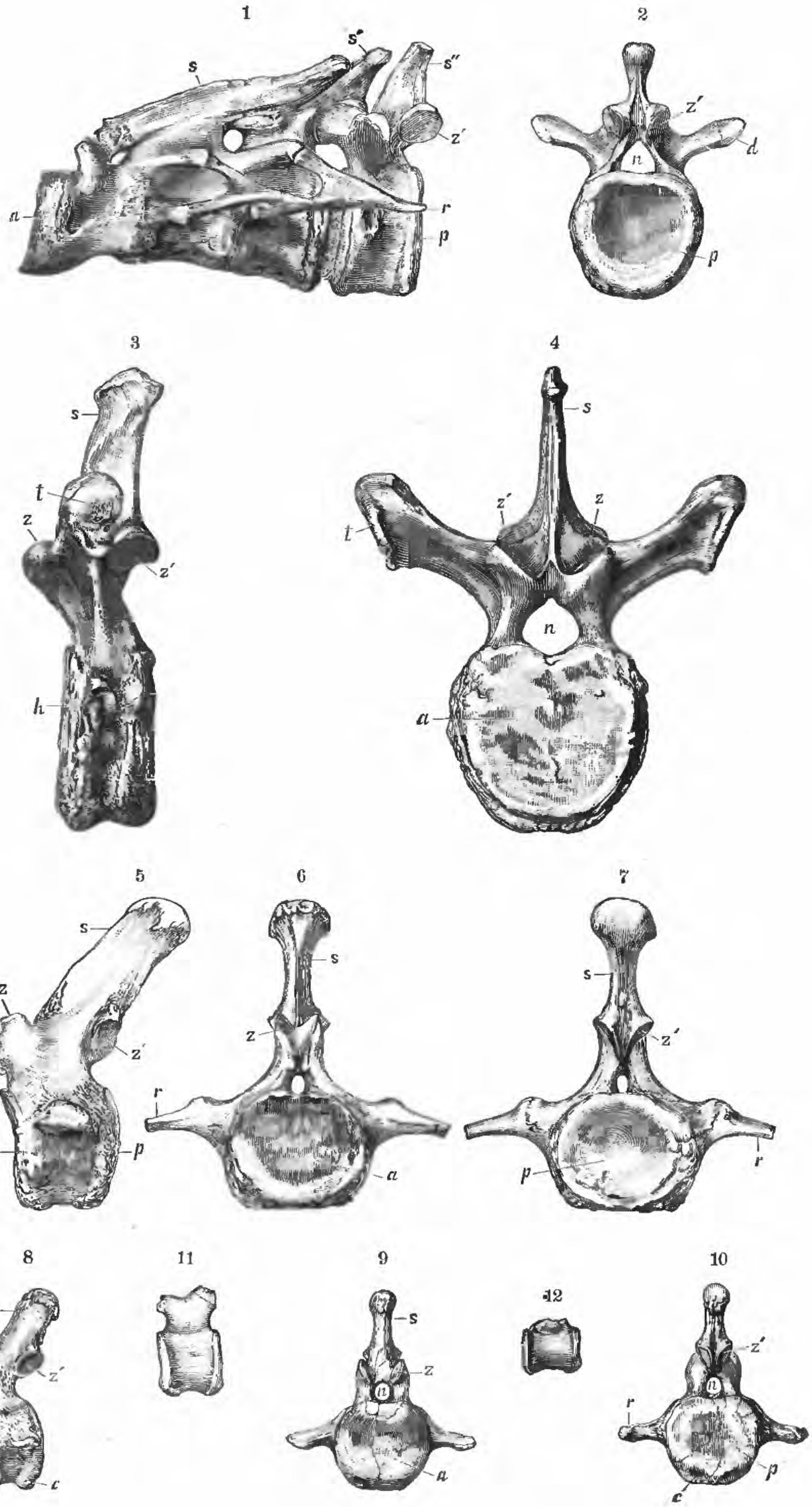
FIG. 12. More distal caudal of same species; side view	212

a, anterior face of centrum; *c*, face for chevron; *h*, facet for head of rib; *n*, neural canal; *p*, posterior face of centrum; *r*, rib; *s*, neural spine; *t*, facet for tubercle of rib; *z*, anterior zygapophysis; *z'*, posterior zygapophysis.

All the figures are one-eighth natural size



TRICERATOPS PRORSUS.

Cretaceous.

PLATE LXV.

PLATE LXV.

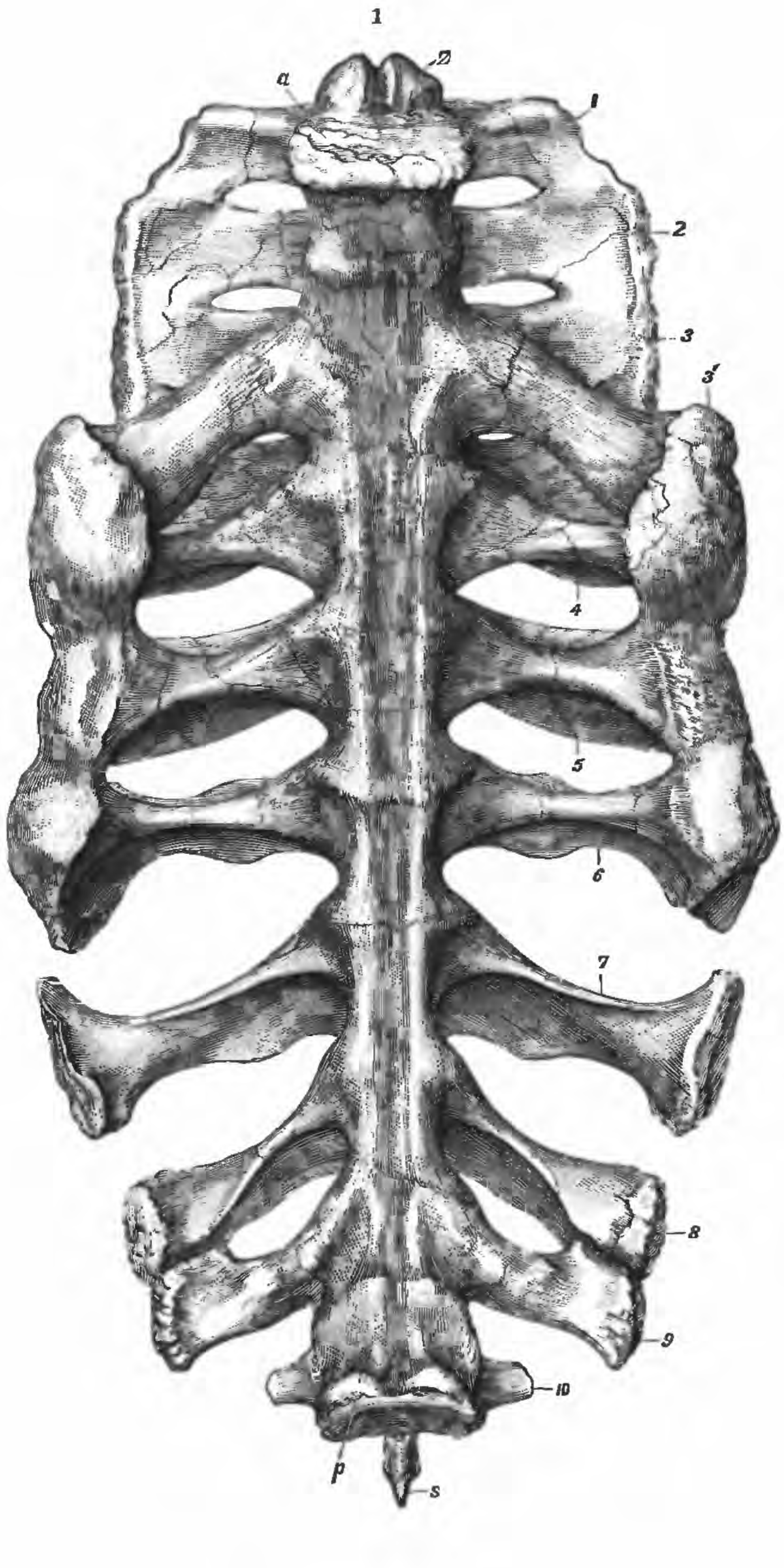
CRETACEOUS DINOSAURS.—PREDENTATA.

CERATOPSIDÆ.

Page

Sacrum of *Triceratops prorsus* Marsh, seen from below; one-eighth natural size. 212

a, anterior face of first sacral vertebra, *p*, posterior face of last sacral vertebra; *s*, neural spine of last vertebra; *z*, anterior zygapophysis of first vertebra, *1-10*, transverse processes, left side



TRICERATOPS PRORSUS.

Cretaceous.

PLATE LXVI.

PLATE LXVI.

CRETACEOUS DINOSAURS.—PREDENTATA.

CERATOPSIDÆ

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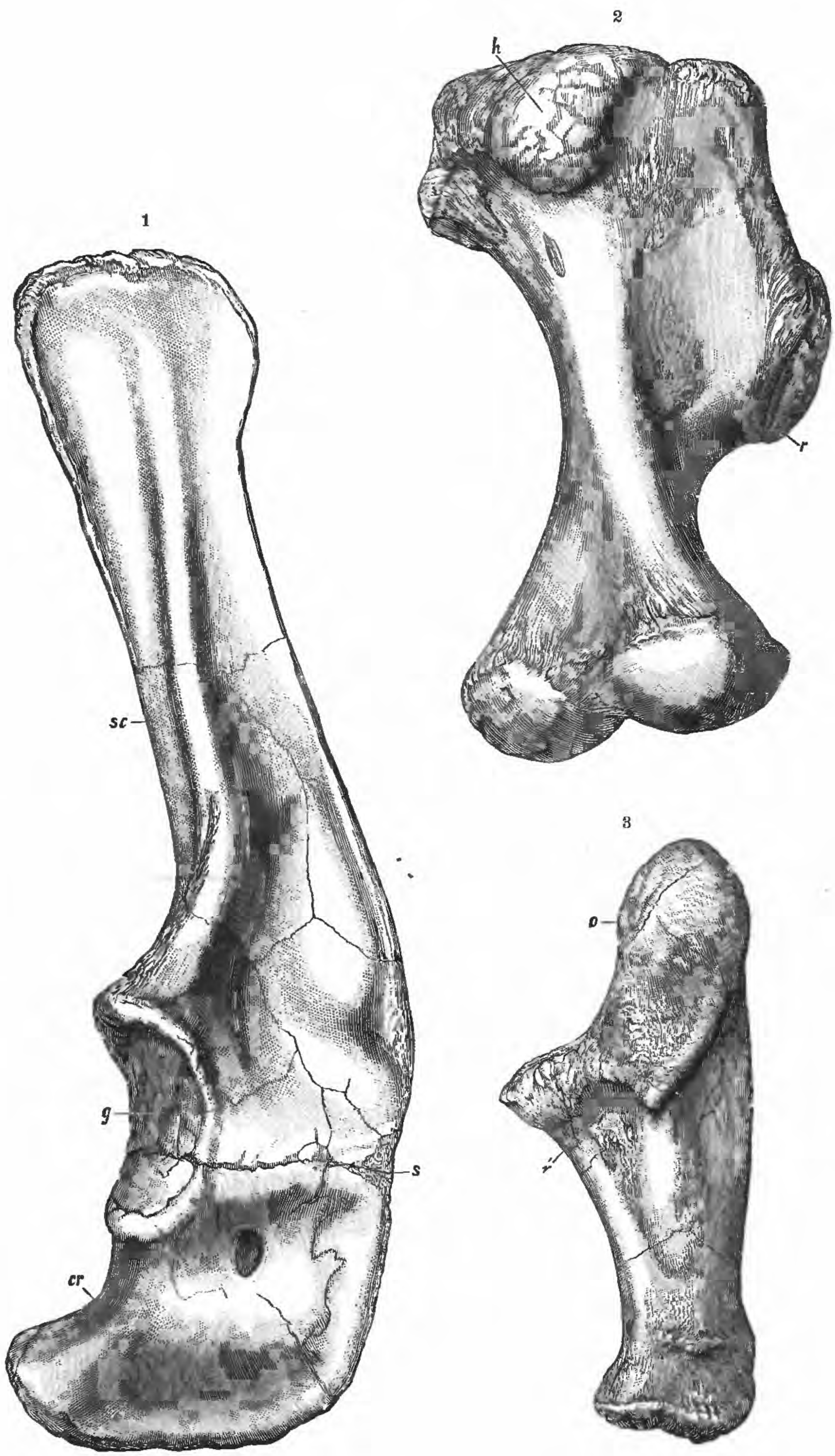
cr, coracoid, *g*, glenoid fossa, *h*, head; *o*, olecranon process; *r*, radial crest; *r′*, face for radius, *s*, suture, *sc*, scapula

All the figures are one-eighth natural size.



TRICERATOPS PRORSUS.

Cretaceous.

PLATE LXVII.

PLATE LXVII.

CRETACEOUS DINOSAURS.—PREDENTATA.

CERATOPSIDÆ

Page

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a, acetabulum; *il*, ilium, *is*, ischium, *p*, pubis.

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FIG. 3. The same pubis, showing postpubic process, inferior view.......... 213

FIG. 4. The same; outside view.......... 213

a, proximal end; *b*, face for ilium; *c*, postpubic process; *d*, distal end.

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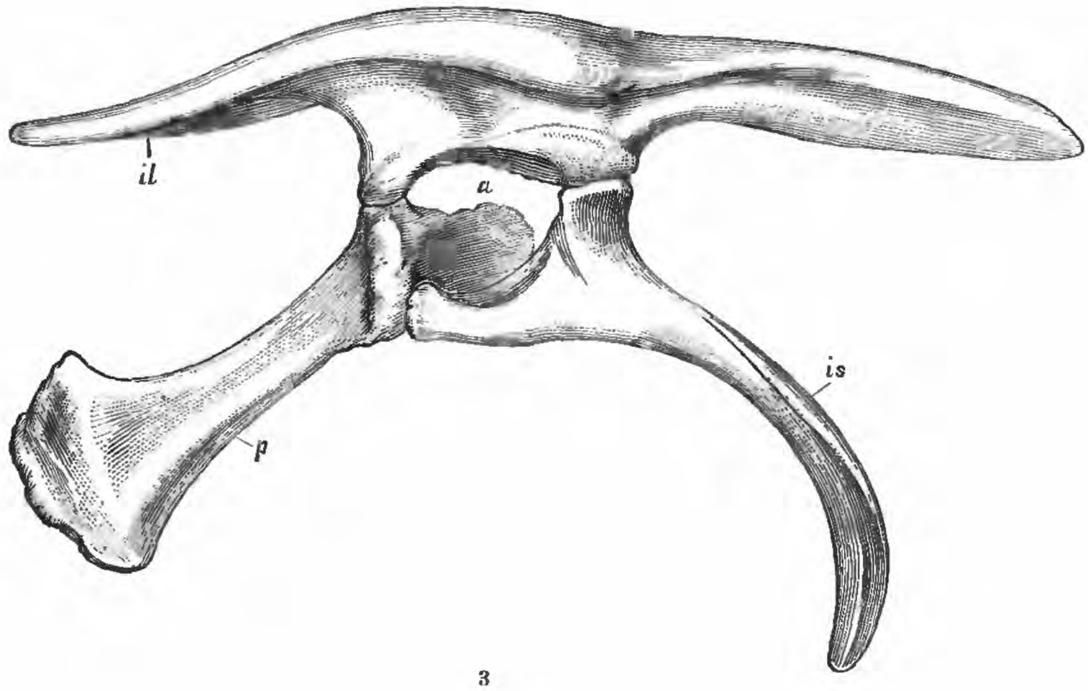

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4

STERRHOLOPHUS AND TRICERATOPS.

Cretaceous.

PLATE LXVIII.

PLATE LXVIII.

CRETACEOUS DINOSAURS.—PREDENTATA.

CERATOPSIDÆ.

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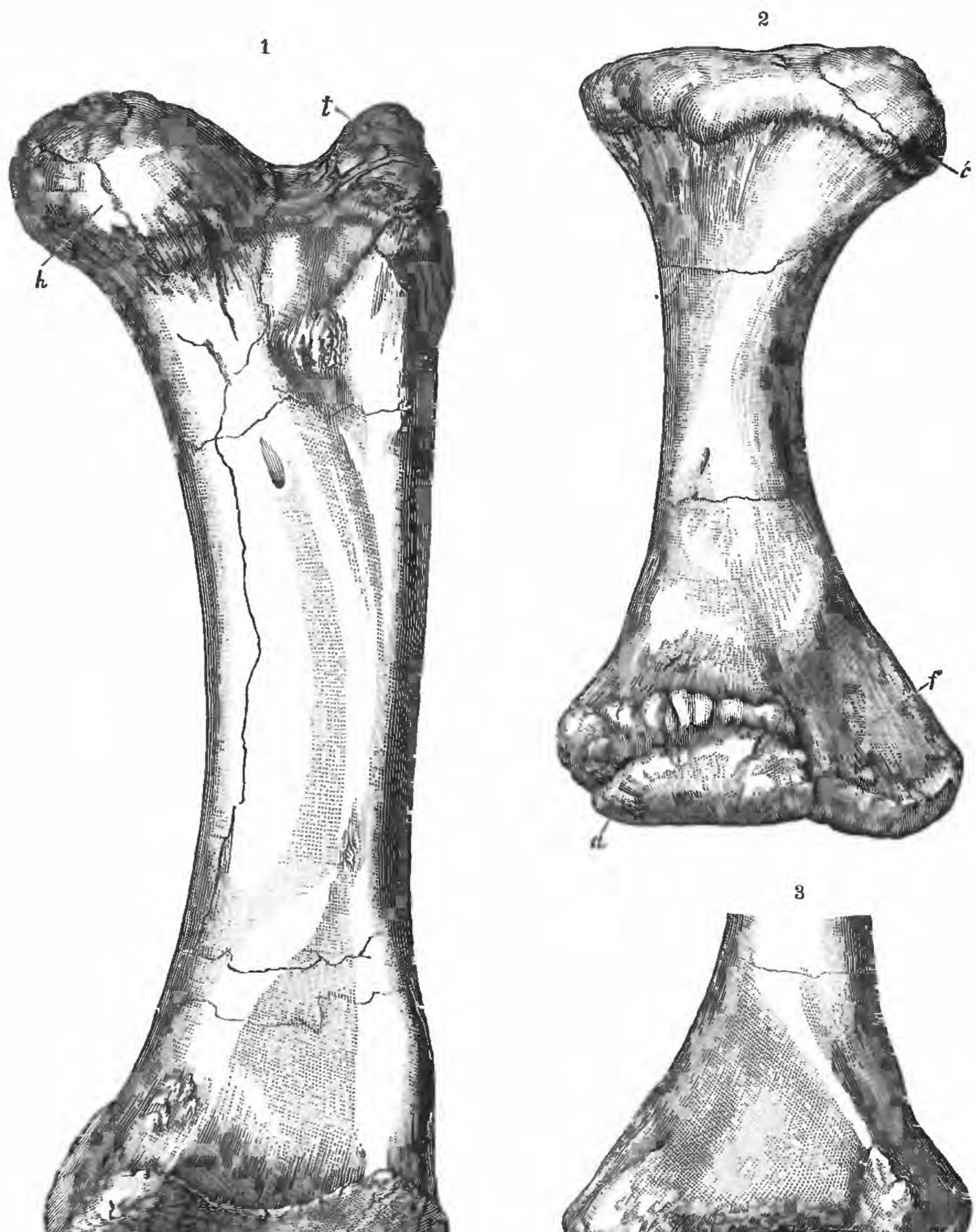
FIG 3	The same tibia; distal end; back view	214

a, astragalus; *c*, inner condyle; *c′*, cnemial crest; *f*, face for fibula; *h*, head; *t*, great trochanter.

All the figures are one-eighth natural size



TRICERATOPS PRORSUS.

Cretaceous.

PLATE LXIX.

PLATE LXIX

CRETACEOUS DINOSAURS.—PREDENTATA.

CERATOPSIDÆ

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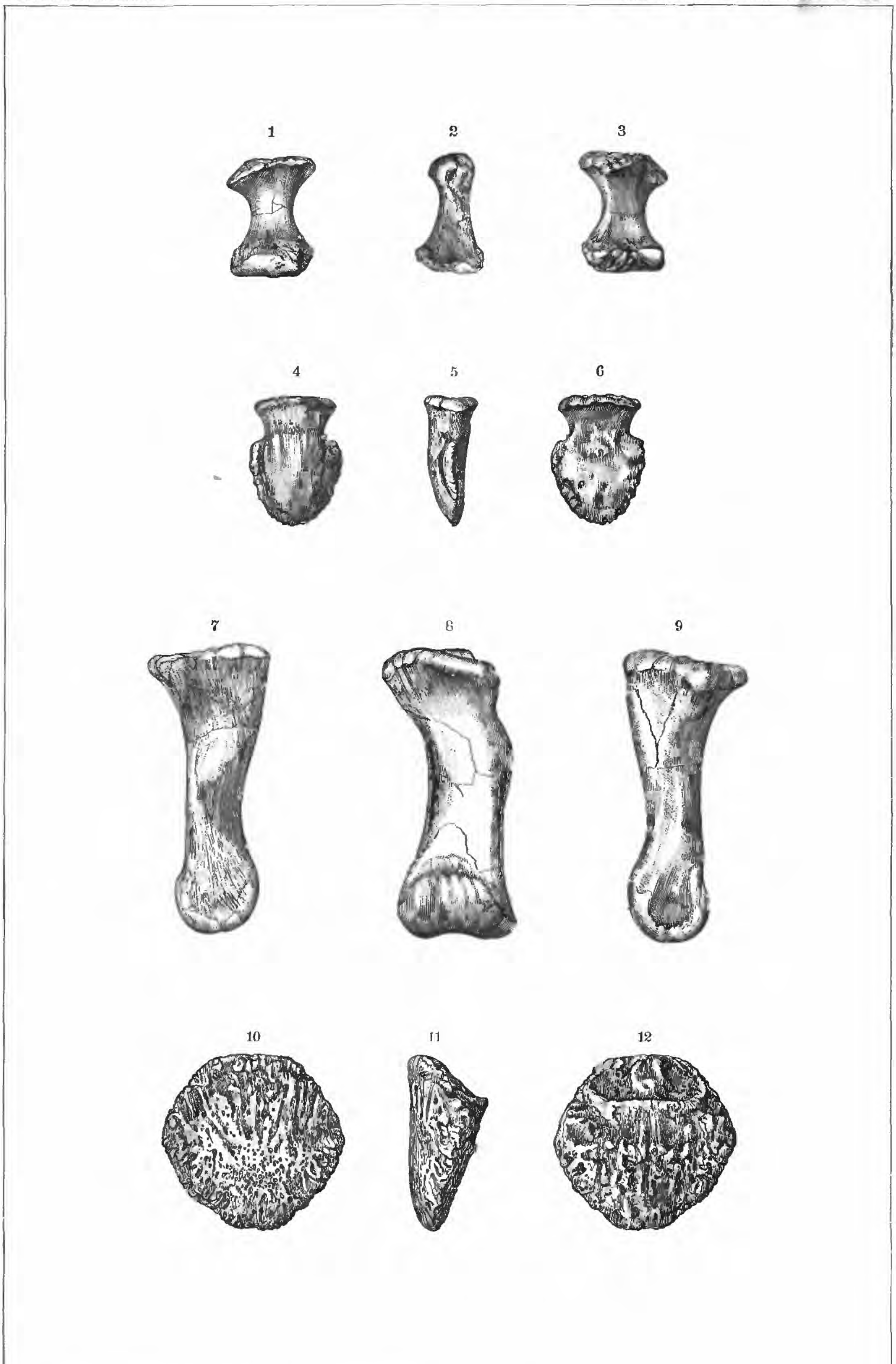

STERRHOLOPHUS AND TRICERATOPS.

Cretaceous.

PLATE LXX.

PLATE LXX.

CRETACEOUS DINOSAURS.—PREDENTATA.

CERATOPSIDÆ.

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	All the above figures are one-eighth natural size.	
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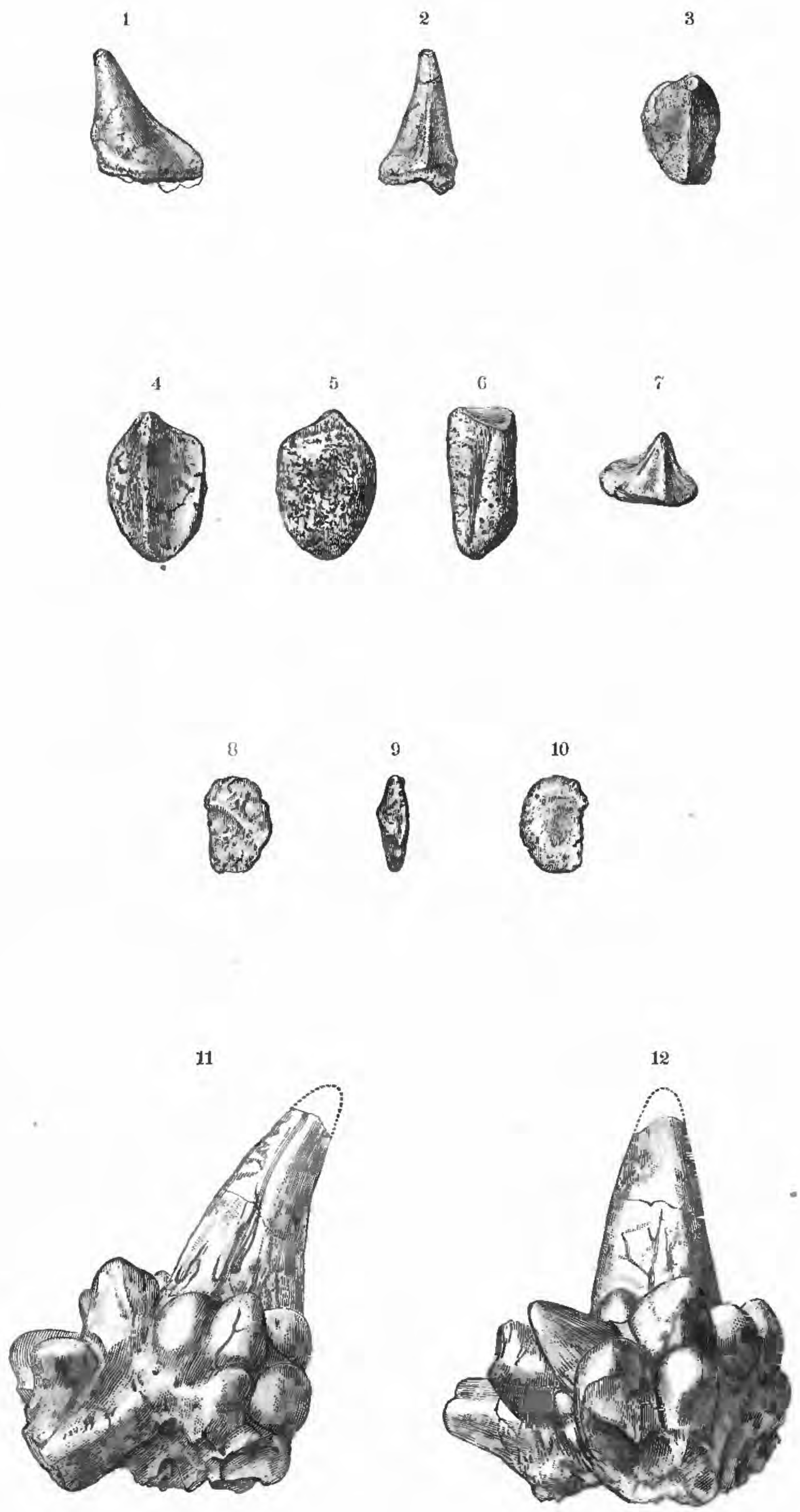


TRICERATOPS.

Cretaceous.

PLATE LXXI.

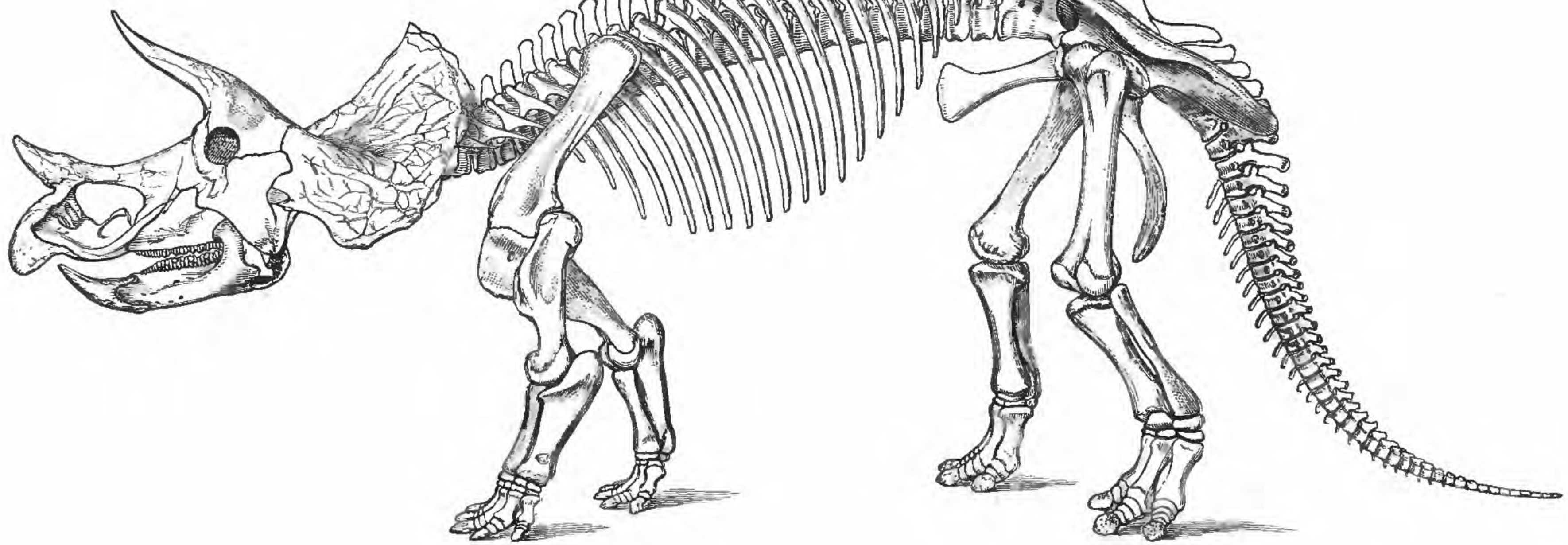
PLATE LXXI.

CRETACEOUS DINOSAURS.—PREDENTATA.

CERATOPSIDÆ.

Page

Restoration of *Triceratops prorsus* Marsh 218
One-fortieth natural size
Cretaceous, Wyoming



RESTORATION OF TRICERATOPS PRORSUS Marsh.

One-fortieth natural size. Cretaceous, Wyoming.

PLATE LXXII.

PLATE LXXII.

CRETACEOUS DINOSAURS.—PREDENTATA.

CLAOSAURIDÆ.

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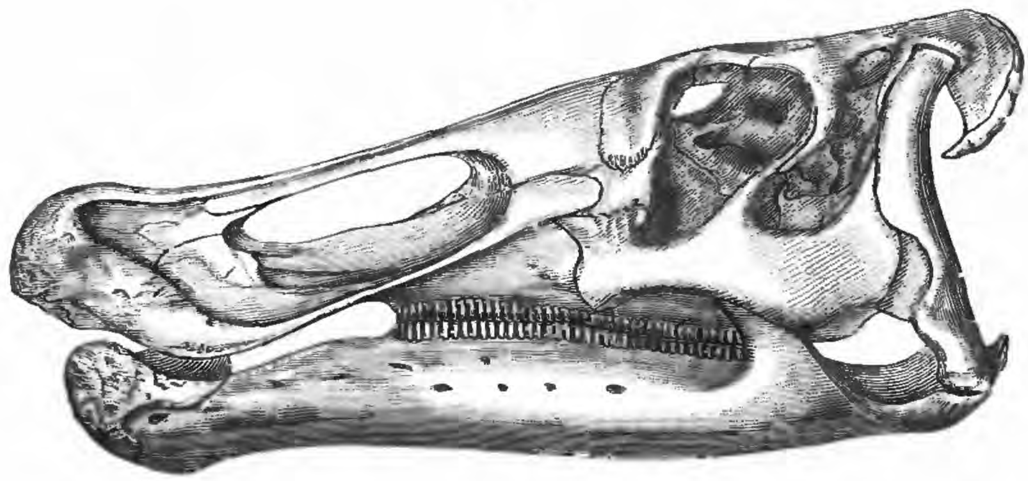
Fig. 3. The same skull, seen from above	220

All the figures are one-tenth natural size.

1



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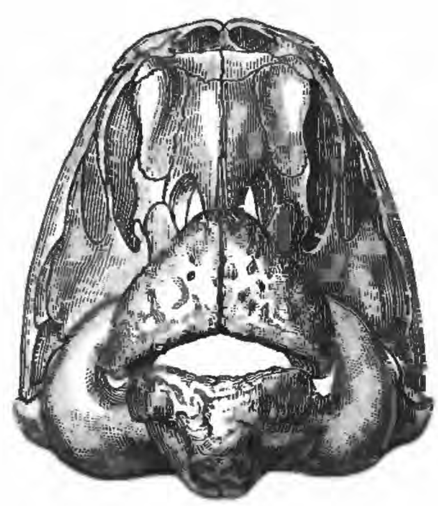

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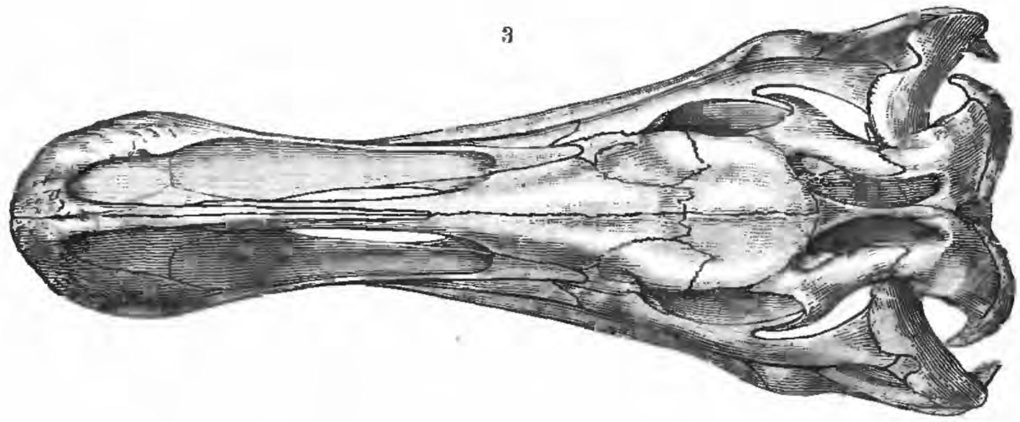

CLAOSAURUS ANNECTENS Marsh.

Cretaceous.

PLATE LXXIII.

PLATE LXXIII.

CRETACEOUS DINOSAURS.—PREDENTATA.

CLAOSAURIDÆ

	Page
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c, coracoid, *h*, humerus; *r*, radius; *s*, scapula; *u*, ulna; *I*, first digit, *IV*, fourth digit	
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a, astragalus; *c*, calcaneum; *f*, femur; *f'*, fibula; *il*, ilium; *is*, ischium, *p*, pubis, *p'*, postpubis; *t*, tibia, *II*, second digit; *IV*, fourth digit	
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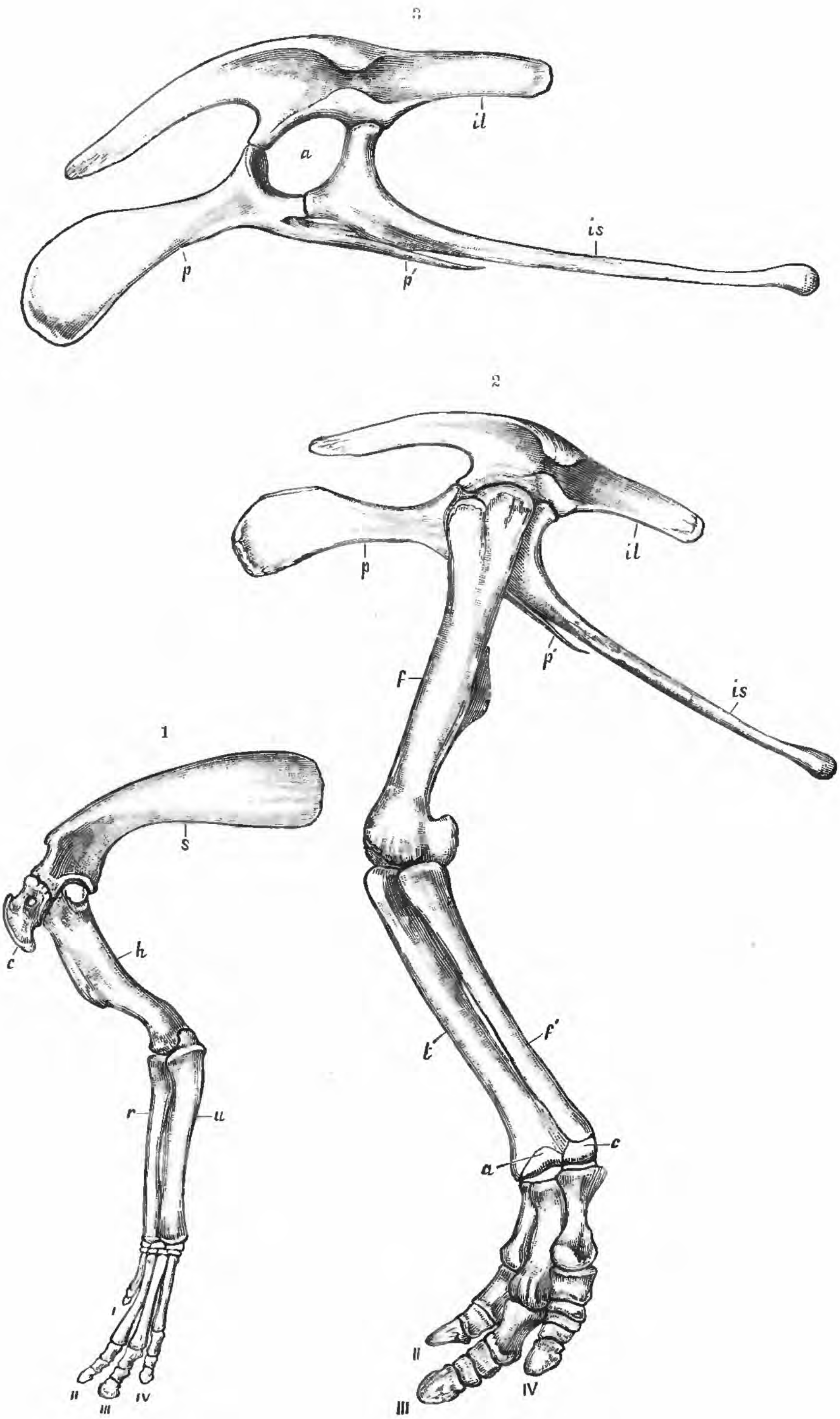
a, acetabulum; other letters as in fig. 2	



CLAOSAURUS ANNECTENS.

Cretaceous.

PLATE LXXIV.

PLATE LXXIV.

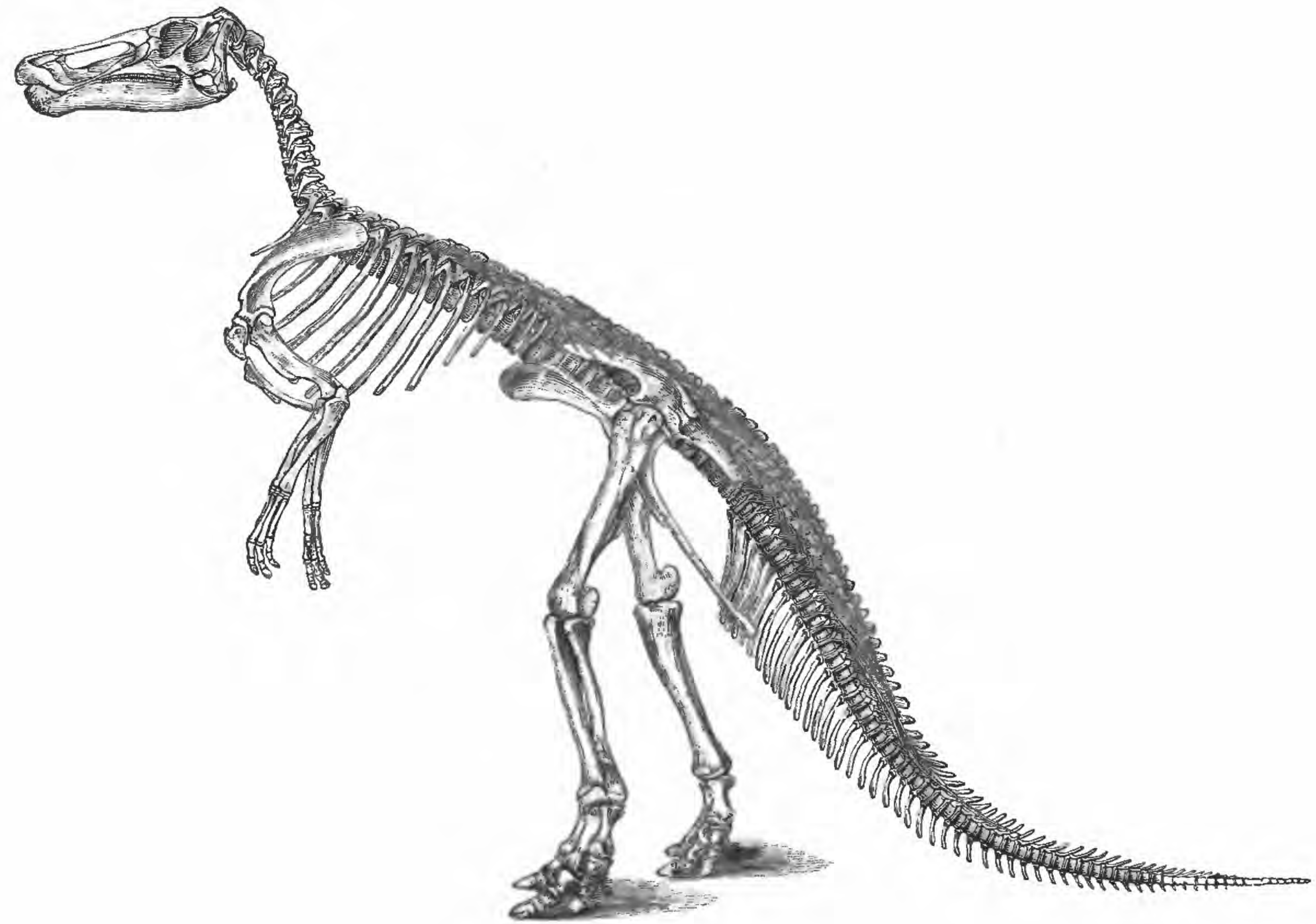
CRETACEOUS DINOSAURS.—PREDENTATA.

CLAOSAURIDÆ

	Page.
Restoration of *Claosaurus annectens* Marsh	224

One-fortieth natural size

Cretaceous, Wyoming.



RESTORATION OF CLAOSAURUS ANNECTENS Marsh.

One-fortieth natural size. Cretaceous, Wyoming.

PLATE LXXV.

PLATE LXXV.

CRETACEOUS DINOSAURS.—PREDENTATA.

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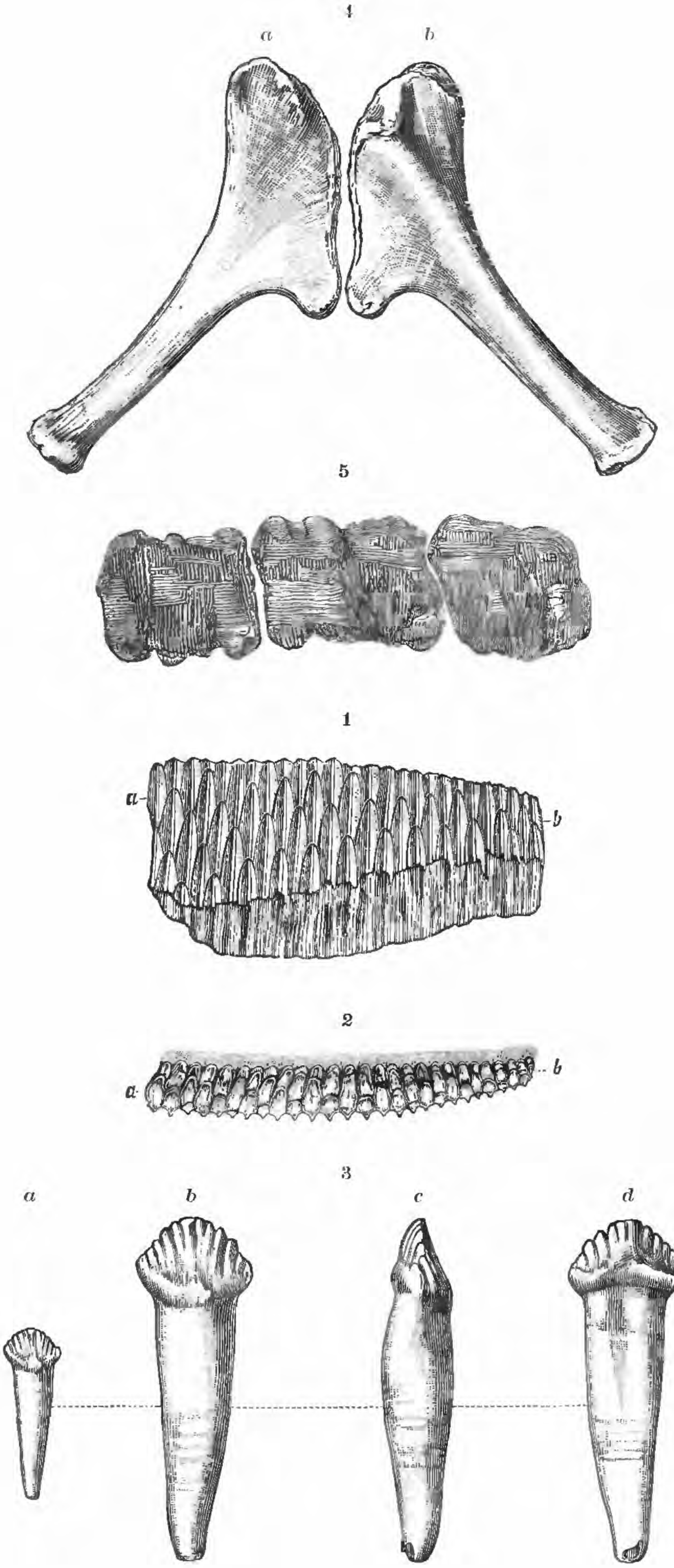
FIG. 5 Dermal ossicles of *Nodosaurus textilis* Marsh; natural size	225



CLAOSAURUS, TRACHODON, NODOSAURUS, AND PALÆOSCINCUS.

Cretaceous.

PLATE LXXVI.

PLATE LXXVI

DINOSAURIAN SKULLS; SHOWING SIZE OF BRAIN

Page.

FIG 1 Skull and brain cast of *Sterrholophus flabellatus* Marsh; seen from above; one-twentieth natural size........ 211

c, supratemporal fossa; *d*, epijugal bone, *e*, epoccipital bone, *f*, brain cast, *h*, horn core, *h′*, nasal horn core; *n*, nasal bone; *p*, parietal, *r*, rostral bone; *s*, squamosal

FIG 2. The same of *Claosaurus annectens* Marsh, one-tenth natural size 222

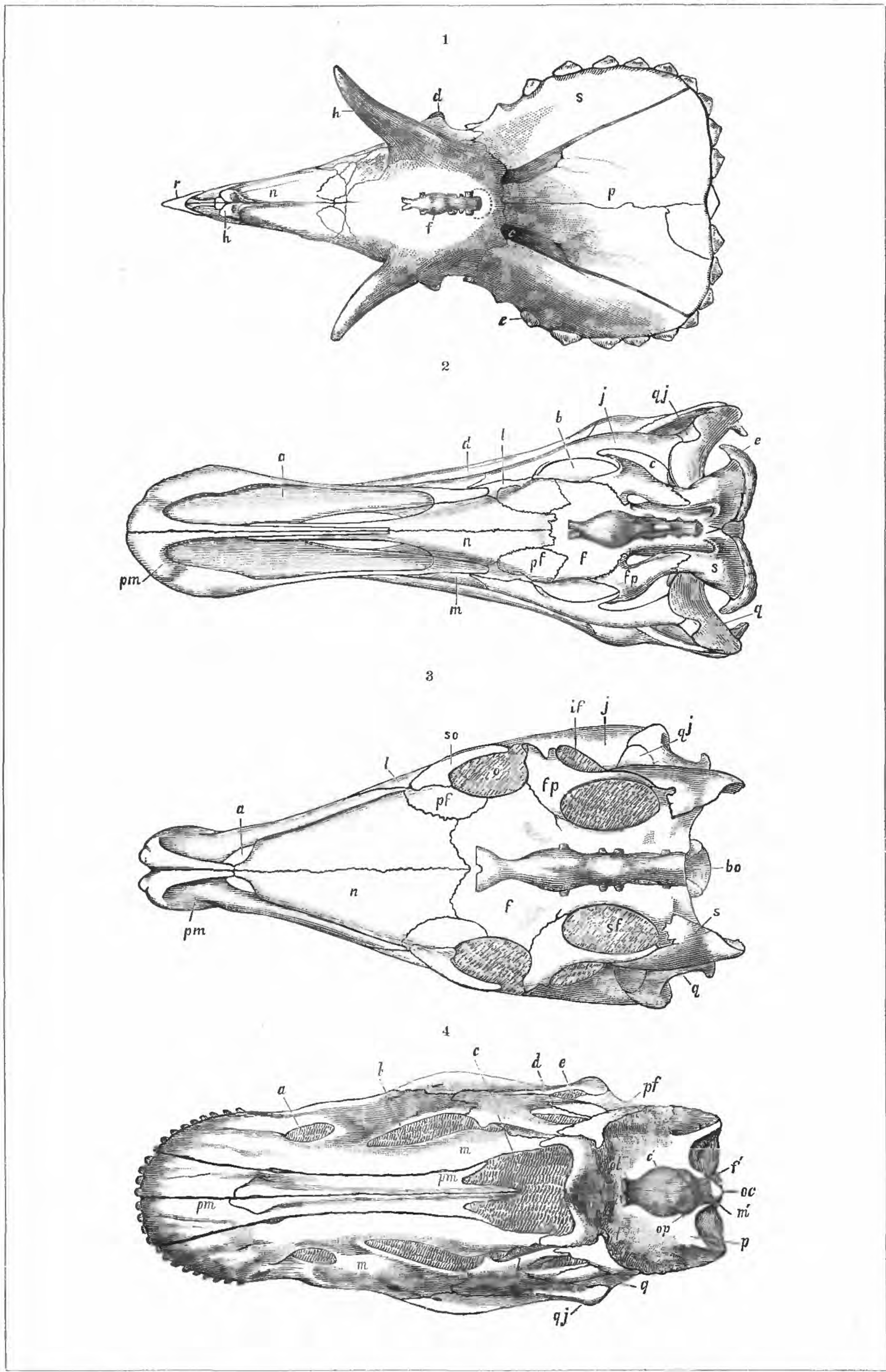
a, nasal opening, *b*, orbit, *c*, infratemporal fossa, *d*, dentary, *e*, exoccipital, *f*, frontal; *fp*, postfrontal; *j*, jugal, *l*, lachrymal; *m*, maxillary; *n*, nasal, *pf*, prefrontal; *pm*, premaxillary, *q*, quadrate; *qj*, quadratojugal; *s*, squamosal

FIG. 3 The same of *Camptosaurus medius* Marsh; one-fourth natural size 227

a, nasal opening, *bo*, basioccipital; *f*, frontal, *fp*, postfrontal; *if*, infratemporal fossa; *j*, jugal; *l*, lachrymal, *n*, nasal, *o*, orbit, *pf*, prefrontal; *pm*, premaxillary; *q*, quadrate, *qj*, quadratojugal; *s*, squamosal; *sf*, supratemporal fossa; *so*, supraorbital bone

FIG 4. The same of *Diplodocus longus* Marsh, one-sixth natural size.... 178

a, aperture in maxillary; *b*, antorbital opening; *c*, nasal opening; *c′*, cerebral hemispheres; *d*, orbit, *e*, lower temporal fossa, *f*, frontal bone, *f′*, fontanelle, *m*, maxillary bone; *m′*, medulla, *n*, nasal bone, *oc*, occipital condyle; *ol*, olfactory lobes, *op*, optic lobe; *p*, parietal bone; *pf*, prefrontal bone, *pm*, premaxillary bone, *q*, quadrate, *qj*, quadratojugal bone.



SKULLS OF DINOSAURS; SHOWING SIZE OF BRAIN. CAMPTOSAURUS, CLAOSAURUS, DIPLODOCUS, AND STERRHOLOPHUS.

PLATE LXXVII.

PLATE LXXVII.

BRAIN CASTS OF DINOSAURS

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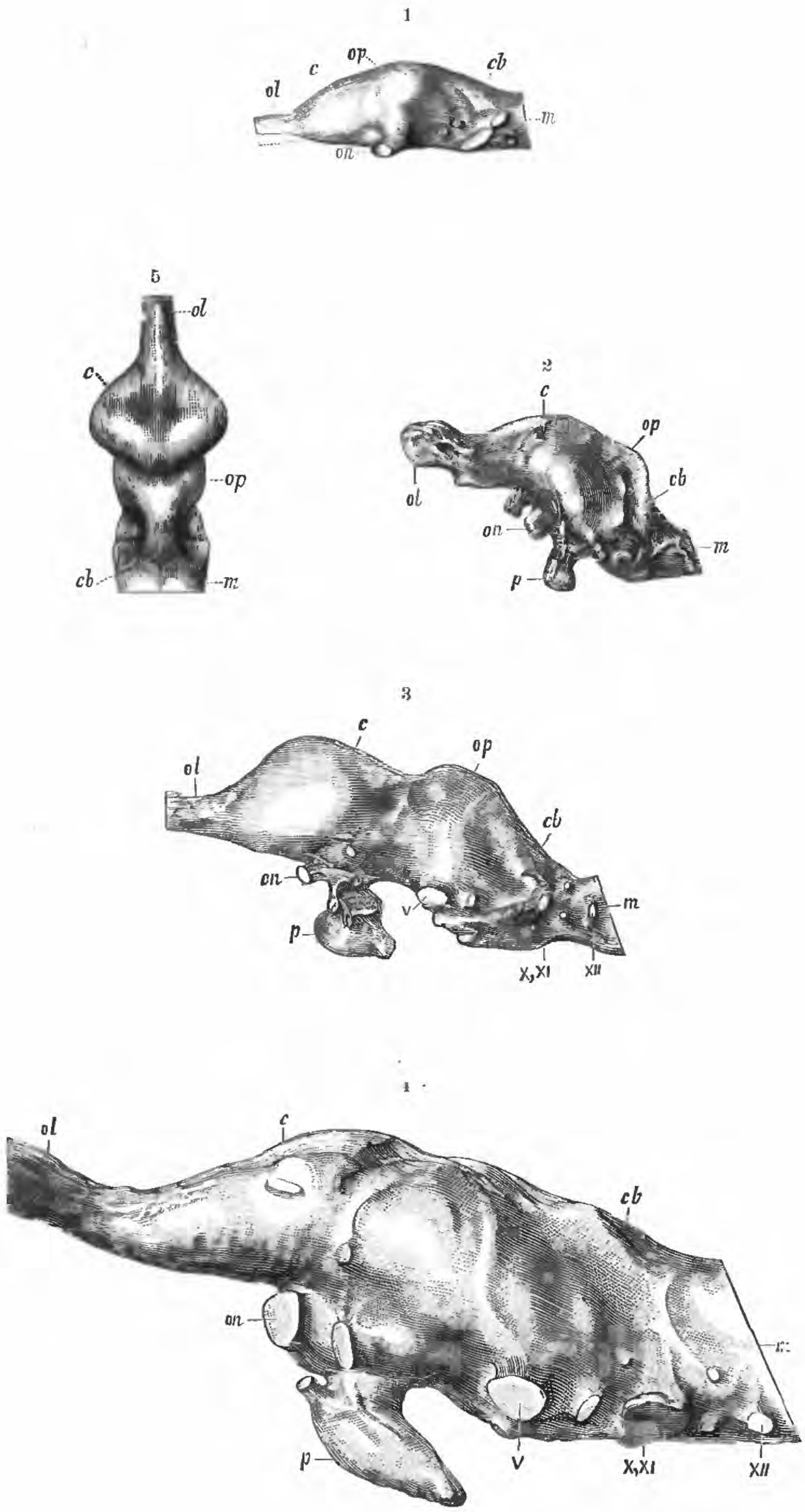

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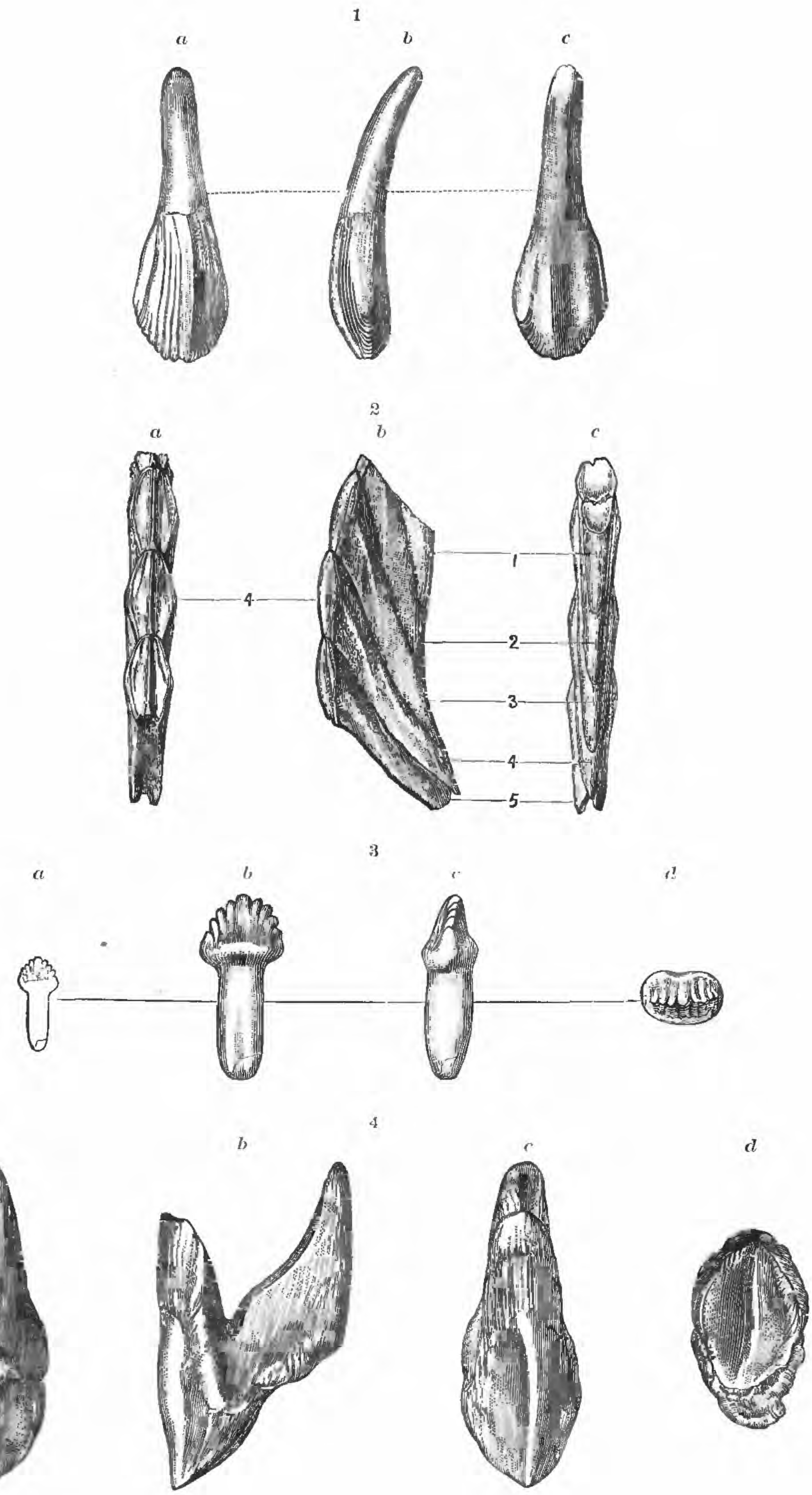

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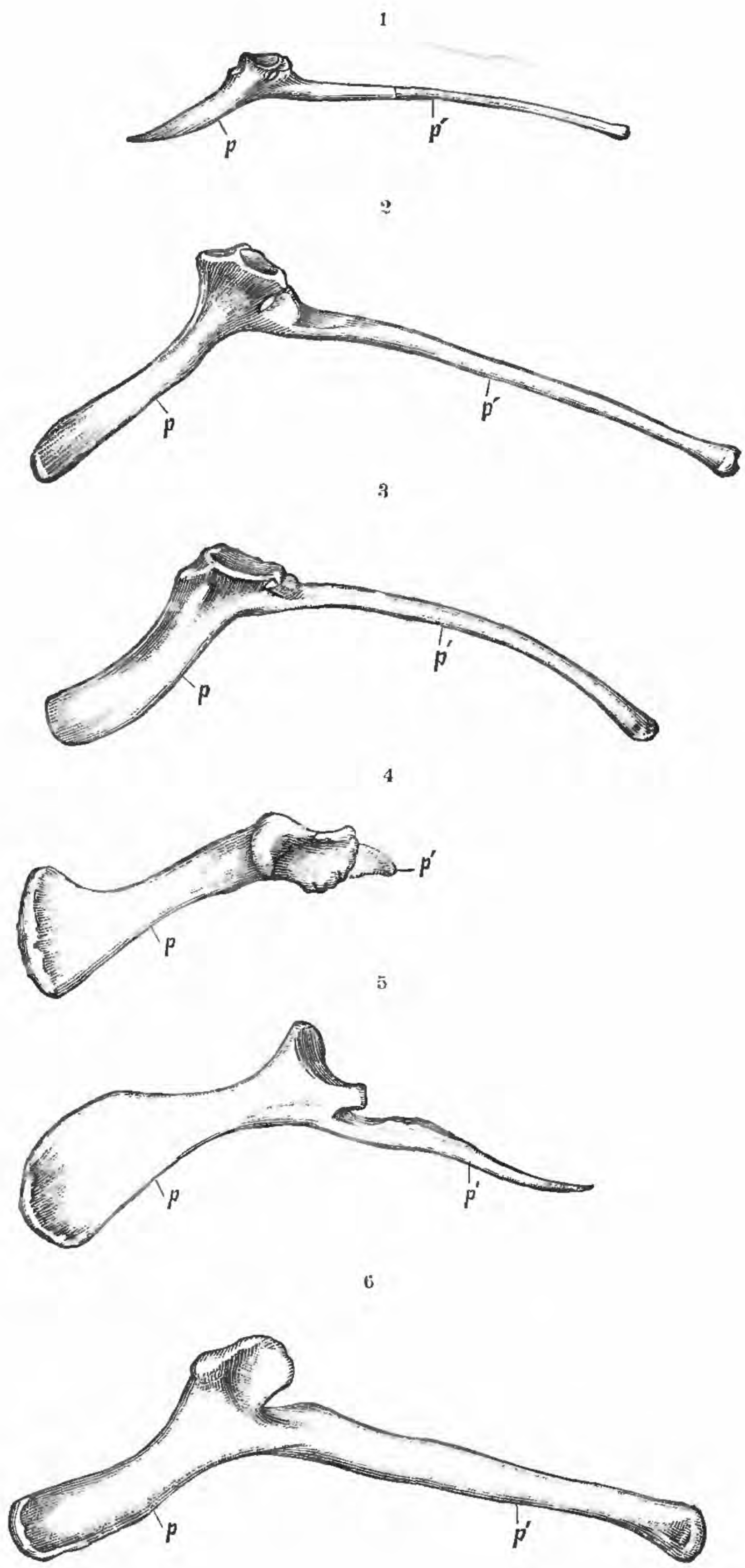
p, prepubis; *p′*, postpubis



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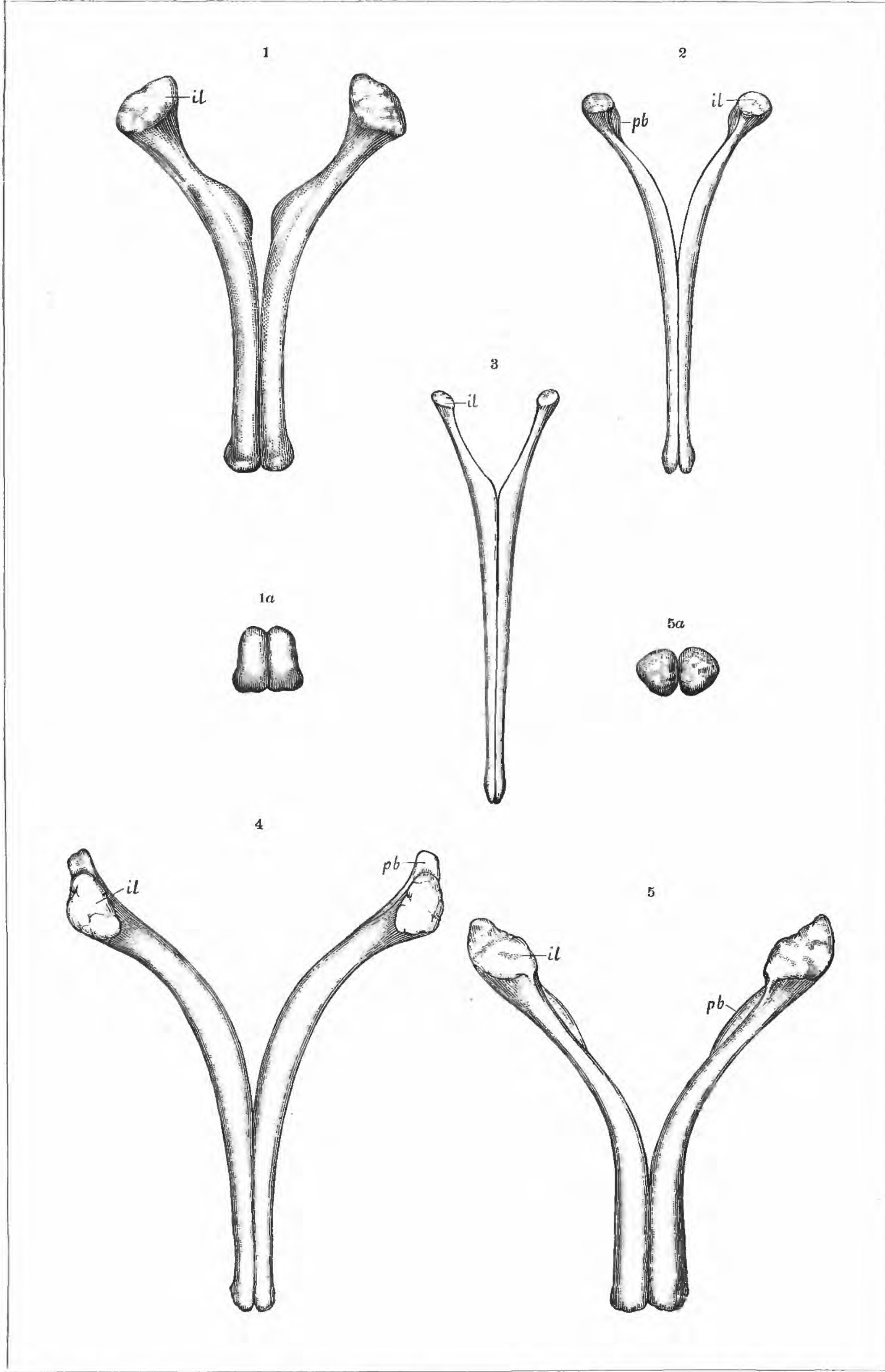

ISCHIA OF PREDENTATE DINOSAURS. CAMPTOSAURUS, CLAOSAURUS, DRYOSAURUS, STEGOSAURUS, AND TRICERATOPS.

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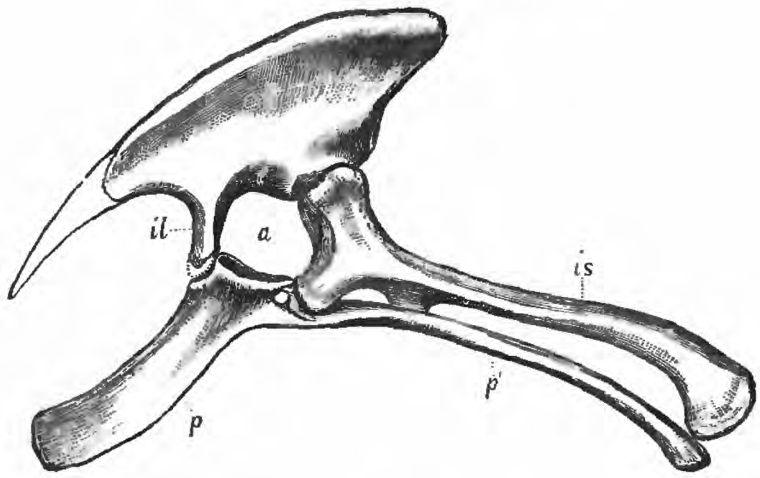

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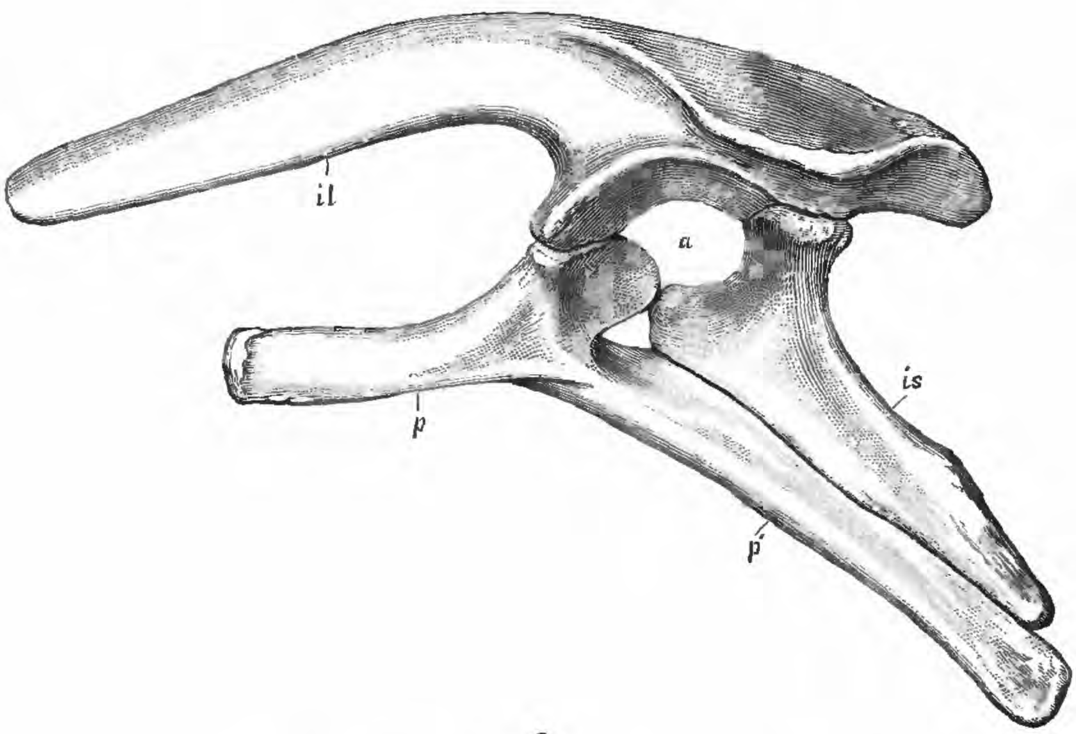

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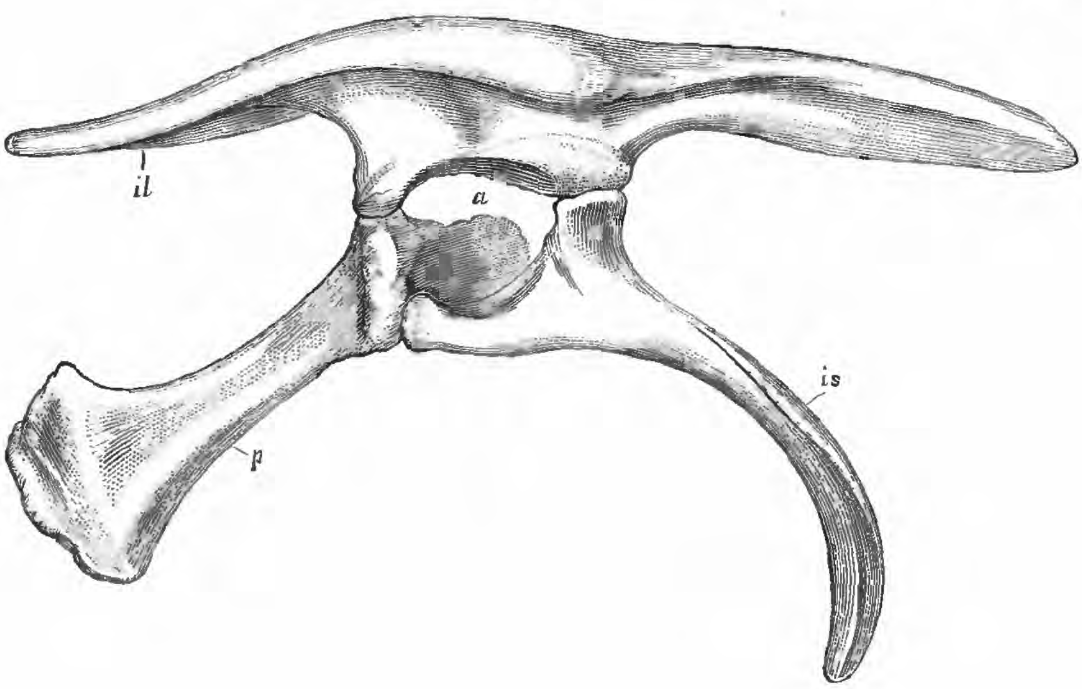

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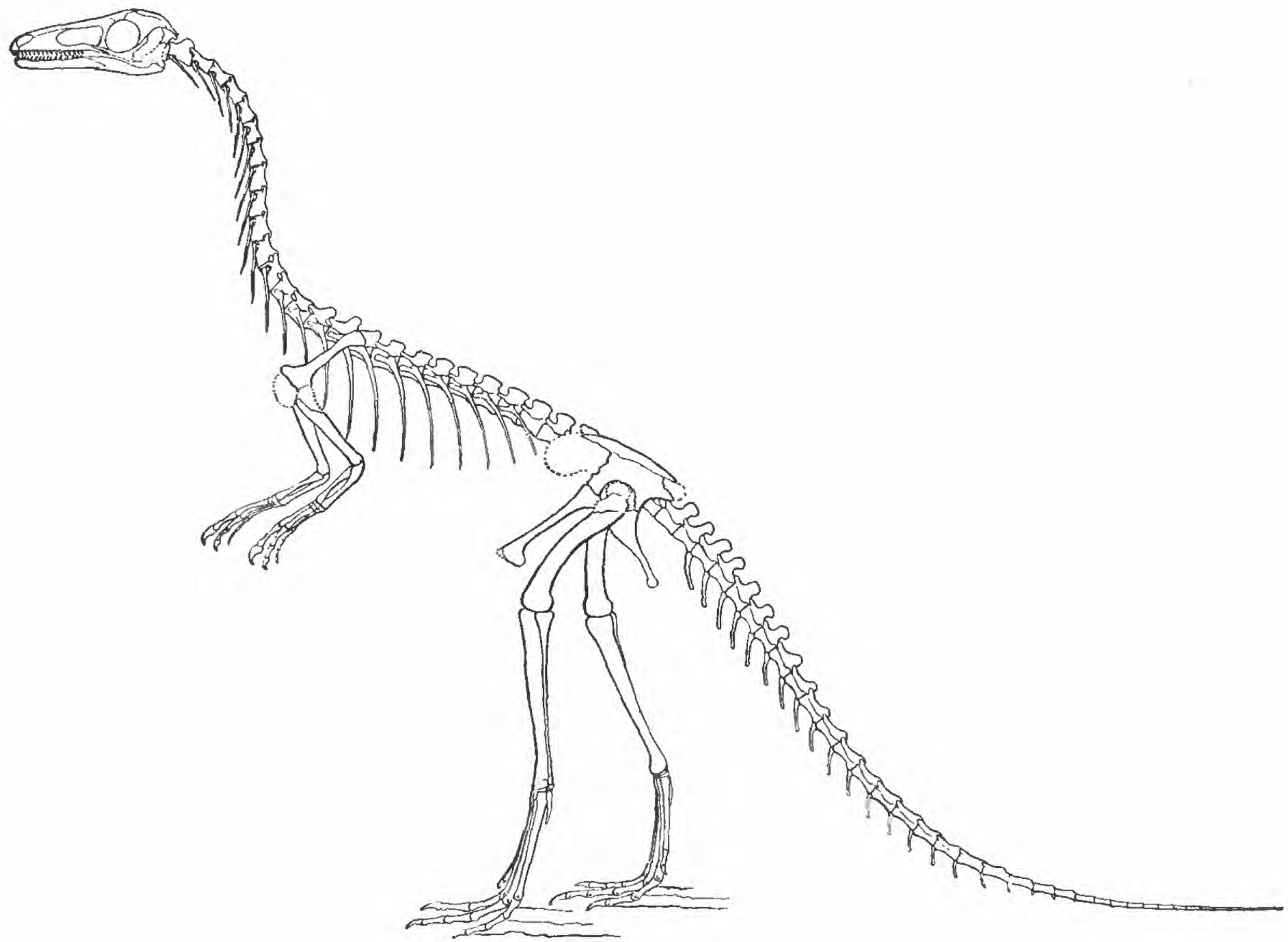

RESTORATION OF COMPSOGNATHUS LONGIPES Wagner.

One-fourth natural size. Jurassic, Bavaria.

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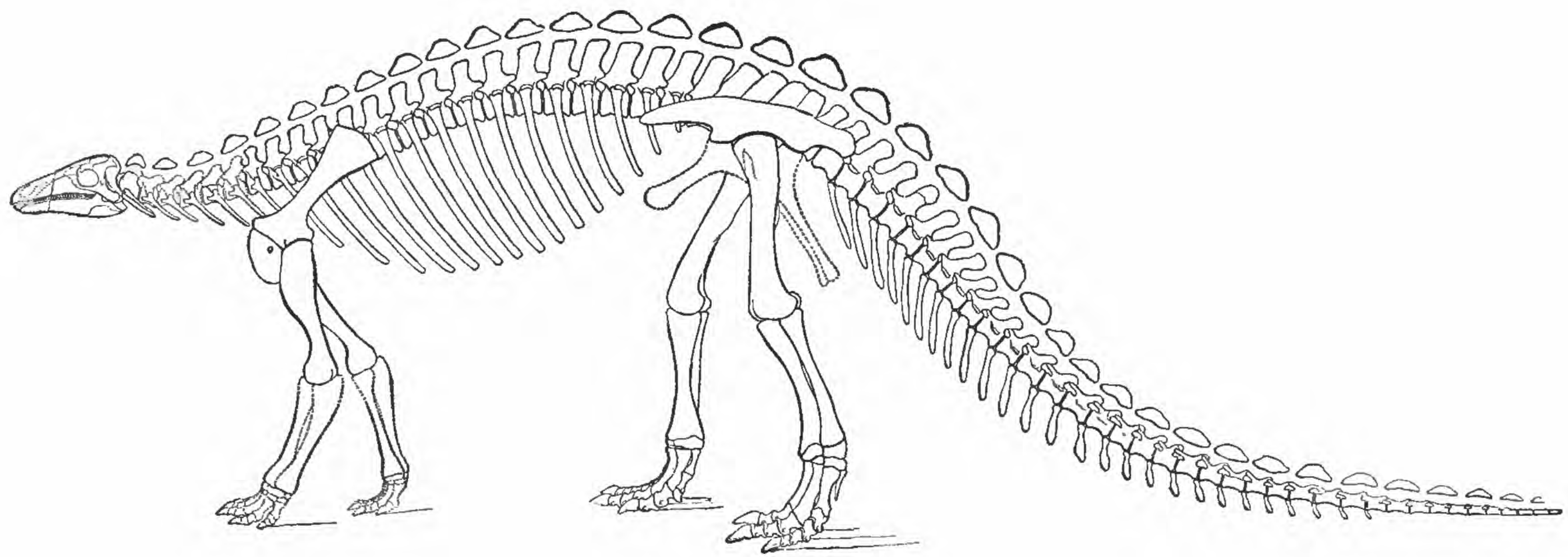

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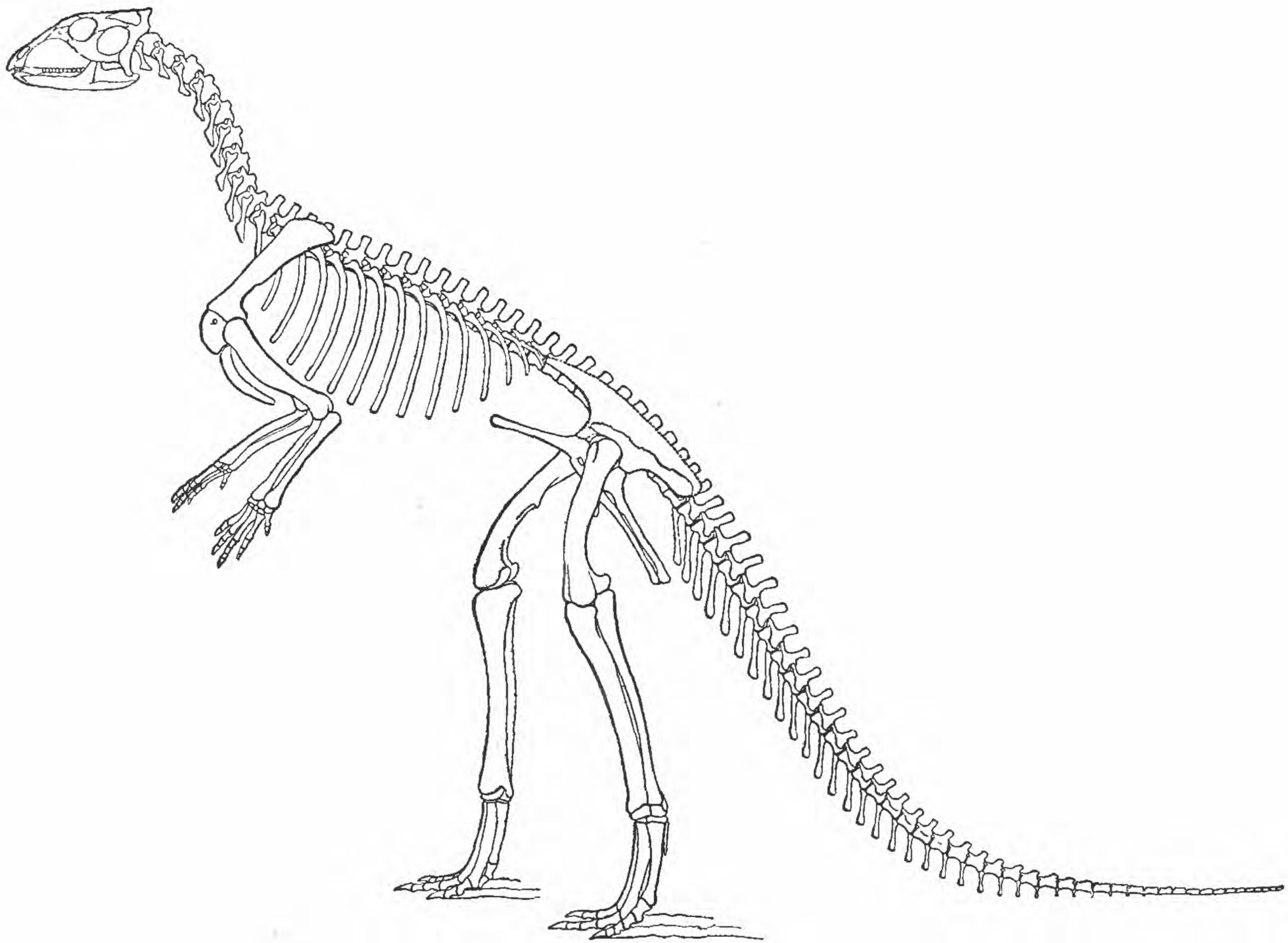

RESTORATION OF HYPSILOPHODON FOXII Huxley.

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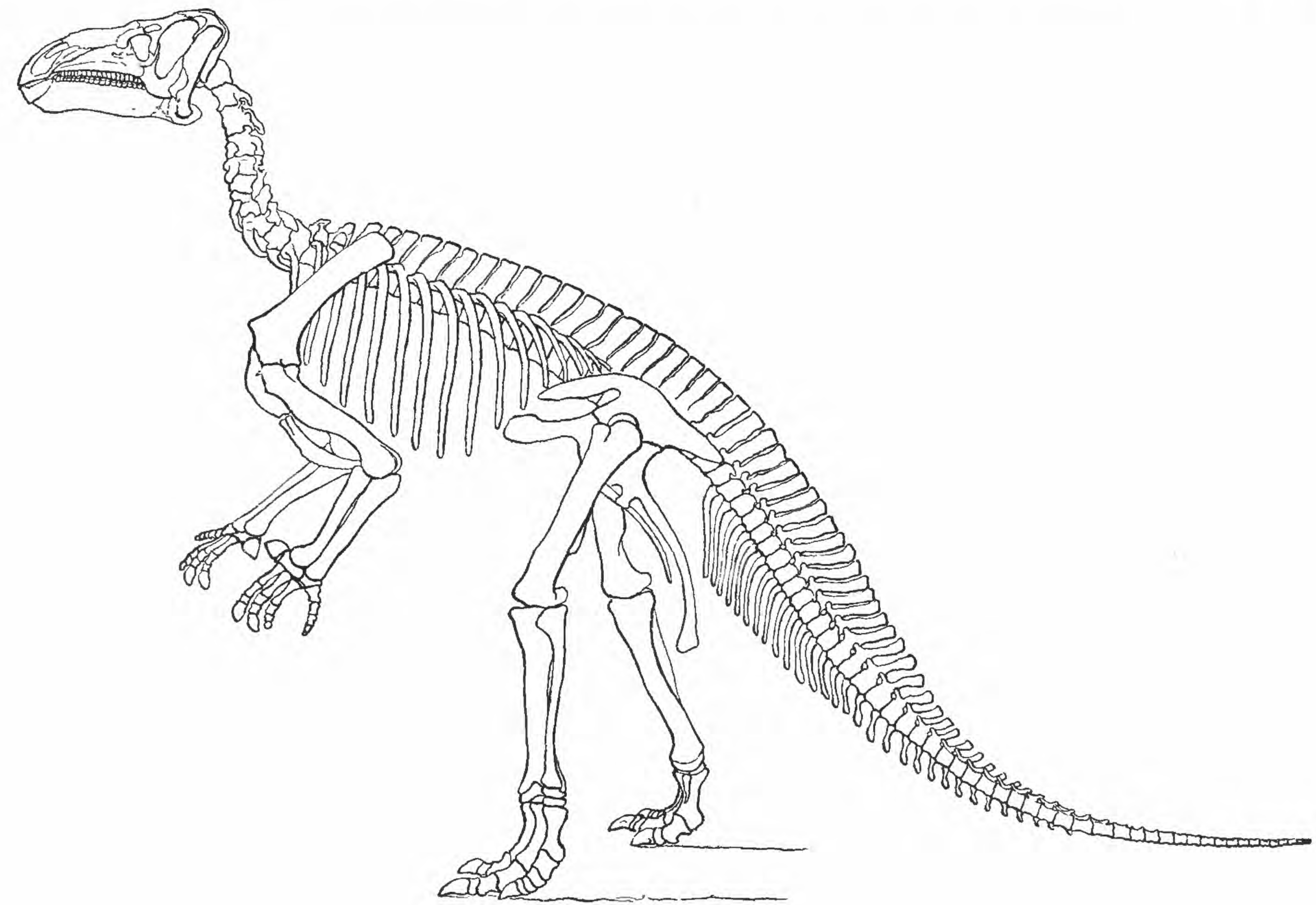

RESTORATION OF IGUANODON BERNISSARTENSIS Boulenger.

One-fortieth natural size. Wealden, Belgium.

GLACIER BAY AND ITS GLACIERS.

BY

HARRY FIELDING REID.

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A. Hoen & Co. Lith. Baltimore.

GLACIER BAY AND ITS GLACIERS.

BY HARRY FIELDING REID.

INTRODUCTION AND NARRATIVE.

My first visit to Muir Glacier, Alaska, in 1890,[1] excited in me so much interest in that region that I decided on a second expedition in 1892. Being unable to get together a party, as I had done in 1890, I engaged two men at Tacoma to do camp work and to help generally in the work of exploration. The hut built in 1890, near the end of the glacier ("Camp Muir"), was made a base camp, and we occupied it from July 7 to September 7, making excursions of six or eight days' duration to various parts of the surrounding region. In crossing the ice we drew our impedimenta on a sled, and we found that the labor of carrying these things to the smooth part of the glacier was materially lessened by the board walk which Captain Carroll, of the steamship *Queen*, had constructed across the moraine for the benefit of tourists. A small boat, 16 feet long, served us for our excursions by water. Our usual plan was to fill the boat with all the provisions it would hold after putting in the tent, blankets, and instruments, and we returned when provisions grew short or when rainy weather made my time more profitable in the hut. We had rather a wet season, about two days out of three being rainy. The small size of our boat was a decided advantage in a region where the tides are at times over 20 feet high, for whenever we landed the boat had to be carried, for safety, high up the beach. We learned to do this after it had floated off two or three times on the rising tide, necessitating a pretty cold bath to recover it.

We rowed over a large part of the bay, pushing our way through the ice and exploring the inlets. The ice did not usually fill the bay, but was massed by winds and currents on the side or in a broad streak in the center. Sometimes it was so thick that progress could be made only by pushing against the cakes; sometimes large tracts of water were clear. The occasional breaking and rolling of the large bergs made it imperative to keep away from those which appeared to

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[1] Studies of Muir Glacier, Nat Geog Mag, Vol IV, pp 19-84

have been for some time in the water. The strong winds blowing off the glaciers, especially in Muir Inlet, often made the rowing very laborious. Except during strong southerly gales, none of which occurred in the summer of 1892, or as a result of falling ice, there were no large waves; but those from the latter cause were remarkable. We once approached to within a quarter mile of the ice cliffs of Muir Glacier, which towered impressively above us. Suddenly a large berg broke off, followed immediately by a second, and then several arose from below. Great breakers, which must have been 30 feet high, rushed forward, but fortunately subsided into an even swell before reaching us. The fragments of ice spread out with great rapidity and in a few minutes quite surrounded our boat.

On the last trip of the *Queen* in 1892, Captain Carroll took her up the bay into Queen and Rendu inlets, and it was on this occasion that he made the soundings given in my map; the names "Queen Inlet" and "Carroll Glacier" commemorate the first trip of a ship to the upper part of Glacier Bay. Captain Carroll kindly took my party with him, leaving us in Rendu Inlet, and we spent three days in these waters, surveying and photographing. In places the ice was very thick, and once we narrowly escaped spending the night in our boat hemmed in by the floes. After we extricated ourselves we were lighted back to camp by a fine aurora, while phosphorescent sparks gleamed in the water at every stroke of the oars. We returned to Camp Muir early on the morning of September 2 to find a note saying that the *Topeka* had been there the previous day. This was the last steamer of the season to visit Muir Glacier. We had not expected her for two or three days, but the weather being fine the captain had pushed ahead in order that the tourists might enjoy a clear day at the glacier. During our absence some Siwashes had entered the hut and stolen our flour and some less important articles, but fortunately the mate of the *Queen* had given us a good supply of hard-tack, saying in answer to our protest, "You won't find a store around every corner in Alaska."

After waiting a few days to see if the *Topeka* would call for us after visiting Sitka, I decided to leave one man in charge of our baggage and instruments at the hut and with the other to work my way to Juneau, where I could find a tug and return to Camp Muir for the man who had remained there. I accordingly started on September 4, spent that night on one of the Beardslee Islands, the next on Pleasant Island, in Icy Strait, and was picked up the following day by the U. S. S. *Pinta*, commanded by Lieut. Commander Washburn Maynard. I then learned that our absence from Camp Muir had been reported to the governor at Sitka, and that he had sent the information to Captain Maynard, who immediately started in search of us. Captain Maynard treated us with the greatest kindness. He took the *Pinta* up to Muir Glacier, got my other man and our belongings, and carried us to Sitka to await the next steamer south.

GLACIER BAY: GENERAL FEATURES.

Glacier Bay empties into Icy Strait, which, in its turn, opens into the Pacific Ocean through Cross Sound, just south of the great Fairweather range of mountains. The higher summits of this range, La Perouse, Crillon, Lituya, and Fairweather, loom up grandly as one enters the bay, dwarfing into insignificance the mountains in front o them, which would otherwise attract marked attention; for, as will bef seen later, they supply nearly all the glaciers which enter the bay. The bay trends northwest and southeast, and is about 50 miles long from its head, at the ends of the Grand Pacific and Johns Hopkins glaciers, to its mouth, between Points Carolus and Gustavus.

The northwest-and-southeast line marks a most important direction in the growth of the western part of this continent. In the region we are especially considering, all the more important features are parallel with it, and the secondary features are at right angles to it. We find the coast-line, the Fairweather range, the valley of Brady Glacier, Glacier Bay, with the mountains on both sides of it, the main stream of Muir Glacier, *and* Endicott Valley, Icy Strait, and Lynn Canal, with its flanking ranges of mountains, all in this direction; whereas Cross Sound, Geikie and Queen inlets, the northern tributaries of Muir Glacier, Charpentier and Johns Hopkins glaciers, with the neighboring mountains, run at right angles to it. This direction is so general that we are forced to believe that the main features which it characterizes are due to the same general causes, and that their parallelism is not an accident of erosion.

The direction of the bay gives rise to some remarkable effects of light and shade. In the summer, when the sun sets in the northwest, I have seen the mountains black in the evening shadows, and the setting sun send a flood of light down the trough of the bay, making the islands glow as if they were on fire. As the sun slowly circled toward the north, here and there a peak would come out from the shadow of the distant mountains and look like a flame leaping to the sky.

The bay varies greatly in width. Reid Inlet,[1] which is really its upper end, has a breadth of some 2 miles; it unites with Rendu and Queen inlets to form a broader body of water, but contracts a short distance lower down, where a mass of hard limestone on the northeast and another of igneous rock on the southwest approach within 2 miles of each other. Formerly, when this part of the bay was filled with ice, these rock masses must have formed a gorge, partially damming back the ice, and being themselves subject to immense pressure and grinding from the icy torrent that poured between them. It must be remembered that a velocity of 20 or 30 feet a day is as great a torrent for ice as half as many miles an hour is for water; it can occur only with great

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[1] This name was given by the United States Board on Geographic Names

breadth and depth in the body of a glacier, or at the end of a tide-water glacier, and this latter presents many analogies to a waterfall.

The rock masses bear evidence of their experience in the smooth, flowing outline they here give to the bay, and in their steepness, at the water level they are very nearly vertical. Once when rowing along the northern shore I could place my hand against the limestone rock without leaning over the side of the boat. The rock was seen to be highly polished and covered with glacial scratches parallel with the trend of the bay.

Tidal and Hugh Miller inlets open opposite each other, and below them the bay suddenly more than doubles its breadth, having there a width of 5 miles, which it retains pretty uniformly as far as Muir and Geikie inlets, these being also nearly opposite each other. In this part the shores, though still precipitous, are not so steep as just above, for there is some talus at the foot of the mountains, and in most places a small boat could effect a landing.

Below Muir Inlet the northeastern shore recedes, broadening the bay to nearly 10 miles. At one time the bay actually retained this breadth to its mouth, but since then there have been great deposits of blue clay and gravels, which have formed the Beardslee Islands and the lowland to the southeast, and have so choked up the mouth of the bay as to leave a comparatively narrow opening, only 2½ miles wide, opposite Rush Point. This has evidently been kept open by the tides, which must flow rapidly enough to carry in or out of the bay every six hours a large quantity of water, enough, indeed, at spring tides, to change the level of the whole surface of the bay—an area of 330 square miles—18 or 20 feet. This amounts to about 1¼ cubic miles of water passing Rush Point four times a day.

Between Muir Inlet and the Beardslee Islands the precipitous mountains on the northeastern shore are broken by valleys in only two places. The larger of these, whose entrance is 9 or 10 miles below Muir Glacier, is formed by the union of several valleys. It seems well adapted by its contour to accumulate a glacier, but it is kept quite free of ice by its southern exposure and the warm and moist southwesterly winds which prevail here. It offers a strong contrast to the valleys of the Dirt and White glaciers, immediately to the north. It contains a large stream, which has brought down much detritus and formed a sand spit projecting nearly a mile into the bay. This sand spit and the two neighboring islands form a sheltered harbor, Sandy Cove, where undoubtedly good anchorage can be found. The stream, very curiously, no longer empties into the cove, but, flowing past its head, enters the bay between the precipitous sides of the mountain and a detached mass of rock.

Similar detached or nearly detached rock masses are a peculiar feature of Glacier Bay. They occur in many places. Three miles north of Sandy Cove the mountain looks as though a great semicircular canal had been gouged out, separating a mass of rock, 550 feet high and

3,000 feet long, from the rest of the mountain, of which it seems an integral part. At the entrance of Tidal, Hugh Miller, and Geikie inlets we again find good examples of rock masses practically isolated. This peculiar topography is a mark of long erosion, and is produced by valleys eating back from opposite sides of a ridge until they unite, making low divides, and leaving isolated rock masses. The Paleozoic age of the clastic rocks (see page 433) also indicates that they have been long exposed to erosion. Among mountains like the Alps, Sierra Nevadas, and the Fairweather Range, of late geologic age, the glaciers, in general, have their origin in great cirques with precipitous walls, at high altitudes; but in the region about Glacier Bay the walls of the cirques have been entirely eroded away, and glaciers on one side of a ridge are continuous, at low altitudes, with glaciers on the other side.

The mountains between Geikie Inlet and Point Carolus are precipitous, but are broken below the end of Drake Island by several valleys. A good deal of sand has been brought down by streams, so that the immediate shore is in many places low land.

THE ISLANDS.

These are of two kinds—sand islands and rock islands. Of the former, in addition to the Beardslee group, there are two east of the Marble Islands; one, Caroline Shoals, in Muir Inlet; one in the middle of Geikie Inlet; and three small ones in Hugh Miller Inlet. There are probably two or three along the shore behind Willoughby Island, but I was unable to examine this region properly. These islands are all in front of the valleys, whence they have derived the material of which they are made. They will be considered further in connection with the sand and gravel deposits of the bay.

The rock islands are of every size, from that of the mere dots at the end of Sebree Island to that of Willoughby, 3¼ miles long, and even the great limestone mass behind Drake Island is separated from the igneous rocks to the west by a valley, which almost divides it from the mainland. In their material they represent all the rocks that occur near the bay—limestone and slate, and both light and dark igneous rock. They occur sometimes singly, sometimes in groups, and are generally elongated, with their axes in the direction in which the ice formerly moved. They have been smoothed and scratched by the ice and worn into roches moutonnées, forms characteristic of glaciated knolls. They bear numerous erratics, some of which are so nicely balanced that they can be easily overturned and made to plunge into the water below. This is also true of the shores of the bay.

Willoughby and Drake islands are evidently closely connected with the similar rock of the neighboring mainland; so are the islands about Hugh Miller Inlet, and Sebree and Garforth islands, in Muir Inlet; but Marble, Composite, and Lone islands, standing, as each does, quite alone and as distant from one shore as from the other, offer but little information to enable us to explain their curious positions. Future soundings may throw some light on this question. Sturgess Island is probably the remains of a dike, for it is of igneous rock. Triangle Island, in Queen Inlet, is connected with the near shore by a ridge under water, discovered by Captain Carroll when he took the steamship *Queen* into this inlet August 29, 1892.

The mountains are almost bare of vegetation in the upper part of the bay. Here and there a patch of horsetails, willow herb, or dwarf willows, a few inches high, is noticed as a small spot of green when one is near by. Between Tidal and Muir inlets the mountains are quite green and supply food to mountain goats and ground hogs, and in places bushes of alder and cottonwood 10 to 15 feet high offer cover to the beautiful white and gray ptarmigan. On the opposite shore of the bay we found strawberries in August.

In the neighborhood of Sandy Cove coniferous trees (probably spruce) occur 1,500 or 2,000 feet above tide. This lower limit of the trees gets lower as we go southward, descending to tide level near the Beardslee Islands. The more northerly of these islands are entirely bare; the more southerly are thickly wooded with large trees. The corresponding part of the opposite shore is also wooded, and trees could be seen in the valley near the end of the arm stretching southward from the upper part of Geikie Inlet. The lower limit of the trees probably marks the upper limit of the ice when it last filled the bay, one hundred or two hundred years ago. The slope thus marked amounts to between 1° and 1.5°, which is a little less than that of the present surface of Muir Glacier.

THE INLETS AND GLACIERS.

Many inlets open into the bay and add much to its beauty; in fact, the principal interest of the region centers in these inlets and their tributary valleys. The first one we pass when sailing up the bay is Berg Inlet, which enters from the west some 2 miles southwest of the southern end of Willoughby Island. The entrance is divided by an island, which appears to be merely a sand bank. The inlet seems to extend 6 or 8 miles inland, but I did not have an opportunity of entering it; my estimate is based on the general appearance of the surrounding mountains. Icebergs float on its waters, and some become stranded near its entrance. I think they are brought in by the tide from Glacier Bay. Although this inlet must receive the drainage from glaciers near its head, I hardly think any glacier actually reaches its waters, for there is an entire absence of that barrenness so characteristic of the mountains surrounding the tide-water glaciers of the bay. Its shores are low for perhaps a mile from the water's edge and are covered with vegetation, probably alder and cottonwood. Captain Beardslee writes of this inlet: "Between the inlet and the bay there is a bar about 100 yards wide, on the shoalest part of which there are 3½ fathoms at high water, with deep water inside."[1]

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[1] U S Hydrographic Notice, No 97, 1880

RENDU GLACIER.

Muir Inlet attracts attention from the first by the way in which its shores open out, allowing its beautiful glacier to be seen from a long distance down the bay. This has already been described.[1] One is apt to be disappointed in Muir Glacier on first seeing it at a distance of 15 or 20 miles, for then its ice cliff, 200 feet high, looks scarcely more than a line along the water; and even when, as is usual, the ship comes to anchor at a distance of three-quarters of a mile, it is difficult to realize the great size of the ice front; but when the ship steams up to within 200 or 300 yards of the glacier, the ice cliffs seem to grow higher and higher, and one begins to realize how stupendous they are. Think of a distance of nearly 2 miles in some familiar locality, and imagine yourself walking that distance along the base of a vertical wall of ice as high as the higher church steeples, and you will gain a conception of the actual size of the end of Muir Glacier which can hardly be acquired in any other way.

The mountains on the west side of Muir Inlet are divided by a deep cut which runs east and west. The middle of this valley is occupied by the interesting Dying Glacier, which belongs to the past and is melting away. At each end of the glacier the valley has a nearly level floor of sand and gravel, extending on one side to Muir Inlet and on the other to Tidal Inlet, which fills the western end of the cut and opens into Glacier Bay some 10 miles northwest of Muir Inlet. Tidal Inlet is almost straight, 4½ miles long and less than half a mile wide. For the greater part of its length, especially on the north side, the mountains descend sheer into the water, offering no possibility of landing. The bare scars remain in several places from which hundreds of tons of rock have disappeared into the waters below. Here and there streams dash down the steep mountain sides, telling us of snow fields which the lower slopes of the mountains hide from view. Some of these streams have sunk into channels in the limestone and burst into sight through openings in the face of the cliff. The entrance to the inlet is protected by a remarkable natural breakwater. It was the view of this efficient protection in 1890 that decided me to make use of this inlet for tidal observations; hence its name. On the north side of the inlet, and near its mouth, opens the valley of the Twin Glaciers. These beautiful ice streams unite about 4 miles back from the water, their junction being marked by a very broad and dark medial moraine, the appearance of which from the inlet is quite striking. The end of the glacier, however, is hidden by a turn of the valley.

The views in this inlet are charming. The still water, with here and there an iceberg, brought in by the tide, forms the foreground; the steep mountains on either side frame the picture. If we look to the eastward, Mount Case and Mount Young rise up over the clean-cut saddle of Dying Glacier; if to the westward, snowy Fairweather and double-peaked Lituya challenge our admiration.

No soundings have been made in this inlet, but it gave me the impres-

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[1] Nat Geog Mag, Vol IV, p 25

sion of considerable depth. At the upper end, and also in front of the valley of the Twin Glaciers, it has doubtless been made much shallower by deposits of sand and gravel.

On the opposite side of the bay Geikie and Hugh Miller inlets are related very much as are Muir and Tidal inlets. The first named cuts through the mountains almost at right angles to the trend of the bay, and several valleys open into it from both sides. It is 1 to 1½ miles wide and 8½ miles long, though it is so much foreshortened when looking into it that it appears not more than half that length. The upper end is dominated by a group of peaks, of which the Black Thorn is the most prominent. The sides of the inlet are steep and are covered with glacial débris, seamed with gulleys, to a height in places of 1,100 feet. Much of this has of course been washed down and has made a narrow beach, so that one can land almost anywhere.

Three valleys open on each side of the inlet, and are so nearly opposite each other as to suggest that each pair is one valley cut in two by the inlet. They open respectively near the entrance, near the middle, and at the head of the inlet. The first one on the southeast separates the limestone from the igneous rock. This valley and the next one are continuous with others opening into Glacier Bay to the southeast, and are in part occupied by the waters of the inlet. The third valley, at the head of the inlet, is occupied by Wood Glacier,[1] which touches the water in one or two points. It does not end in a vertical face, but has a sloping end, like ordinary alpine glaciers; in fact, just as it would have if the inlet were entirely drained. This glacier apparently has an outlet to the southeast, draining into Berg Inlet. In places it is very much covered by débris.

The three valleys on the northwest side connect with Hugh Miller Inlet, and all contain glaciers. That in the first valley is not visible from this side; that in the third valley, the Geikie, is a tidewater glacier; it comes in from the northwest, ending a little behind the general shore-line, so that it can not be seen until one is quite near it. Its vertical end is 140 feet high and three-fourths of a mile broad, and it discharges bergs, which, however, are not large. Its ice is continuous on one side with that of Wood Glacier, and on the other rests on deposits of stratified sands, like the wings of Muir Glacier. Its valley connects with that of Charpentier Glacier. Near its mouth it receives as a tributary from the south a small glacier, which joins it after a steep fall of 1,500 feet with a slope of 17°.

Three miles from its mouth Geikie Glacier connects on the north with the Charpentier, and on the south with another glacier which apparently flows to the southwest, draining into Taylor Bay (Cross Sound), thus forming a pass, probably not exceeding 2,000 feet high, between

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[1] Named after Lieutenant Wood, who seems to have been the first white man to enter Glacier Bay. See "Among the Thlinkits in Alaska," Century Mag , July, 1882, p 323 Professor Muir was there in 1879, Lieutenant Wood in 1877 The latter evidently took great interest in the natives, and less in the physical geography of the region

the Glacier Bay and the Taylor Bay basins. The valley at the head of Taylor Bay contains the Brady Glacier, the extent of which is quite unknown. The Pacific Coast Pilot (p. 191, edition of 1891), issued by the United States Coast and Geodetic Survey, says that it is "supposed to originate near Mount Crillon." From what I could see on my first visit, in 1890, I concluded that this glacier must extend even to the flanks of Mount Fairweather. My present acquaintance with the region inclines me to believe that the Brady Glacier originates on the flanks of Mount Crillon, and that its basin is limited on the north by a spur running from this mountain to the northeast.

The middle valley on the northwest side of Geikie Inlet is marked by an immense deposit of sand and gravel which fills its eastern end. The glacier in it, the Favorite (named after the steamer *Favorite*, in which Captain Beardslee first entered Glacier Bay), ends 2 miles from the inlet. It is comparatively clean and is not loaded with lateral moraines. This is probably a mark of rapid diminution, the glacier melting down and depositing the material on the mountain side as fast as it falls on its surface. The end, also, is very sloping, which is a sign of rapid retreat. A little below the end of the glacier a tributary valley enters from the southwest, containing a remarkable isolated deposit of sand, which will be described further on (see p. 437). There is a dirty little glacier on the opposite side of the inlet, so covered with débris as to be hardly noticeable.

The low sand island about 2½ miles from the entrance of the inlet indicates small depth of water in its neighborhood, probably due to filling up by detritus brought from Favorite Valley. The other parts of the inlet seem to be quite deep.

Hugh Miller Inlet differs from all the others in having promontories and large islands which break it up and give it a very irregular form. It has not great extent, but is surrounded by ice- and snow-covered mountains, and receives two tide water glaciers, the Charpentier and the Hugh Miller, the ends of which make up an important part of its boundary. These glaciers occupy almost parallel valleys running nearly north, and present some singular resemblances to each other. Each extends far back into the mountains, receiving small tributaries from both sides, and connects by a low pass with the valley on the other side of the range. The end of each is divided by solid rock into two parts, one of which rises in a vertical cliff from the water, while the other has a sloping end almost reaching the water. Thus each presents the features of both a tide-water and an alpine glacier. The Hugh Miller Glacier discharges but little ice compared with the Muir, and the Charpentier still less. The opening of this inlet faces down the bay, and through it Hugh Miller Glacier is visible for a long distance. On entering the inlet, we see the alpine end of Charpentier Glacier on the left as a smooth and rather dirty ice slope ending on gravel a short distance from the shore. A mile back this ice suddenly changes its character, and becomes very white and much broken, a most puzzling condition until we recognize that it is here flowing past the still ice to the tide-water end of the glacier, hidden from our view by the promontory which projects so far into the inlet. Where the glacier now ends on the shore it once pushed out into the water, but as it became smaller practically all the ice followed the deeper channel leading to the present tide-water ending, so that the alpine end is probably almost stationary ice slowly melting away.

Hugh Miller Glacier spreads over a very large space north of the inlet, forming what might be considered a piedmont glacier, separated from the bay by a large mass of igneous rock, to the northwest of which it approaches, but does not reach, the water. From the general direction of its valley it is at this latter place that one would expect its principal ending, instead of by a lateral opening into Hugh Miller Inlet.

Queen, Rendu, and Reid inlets converge to a common point in the neighborhood of Composite Island. This island is made up of two kinds of igneous rock, one light and the other dark, and their line of junction is so well marked as to be easily visible 10 miles away in bright weather.

Queen Inlet, about 2 miles wide, stretches away to the north for 3 miles and then makes a sudden turn to the northeast, and 2 miles farther is blocked by the ice cliffs of Carroll Glacier. The mountains confining the waters of the inlet are steep, though the glaciers and streams have made extensive deposits at their base. The inlet narrows to 1 mile at its head, where it attains its greatest depth, 90 fathoms. Near the eastern shore, at the bend of the inlet, is a low, rocky island (quartz diorite), which I have called Triangle Island, from its shape.

Several unimportant valleys, containing small, dirty glaciers, drain into the inlet. In the largest of these, which enters from the northwest, the glacier is rather cleaner than in the others and attracts more attention than it deserves, for it is visible a long way down the bay and appears to be the most important glacier draining into the inlet, the Carroll being hidden by the mountains on the east; but when the latter, guarded by Sentinel Peak, bursts into sight all else is forgotten. Its ice extends from the steep mountain slopes on one side of the inlet to those on the other, and seems to struggle for a freer way through the narrow passage. In the summer of 1892 the eastern side of the ice front was straight, and the western side formed a segment of a circle with the concavity toward the inlet. Bergs of comparatively large size occasionally break off, though the supply of ice is not very great. Over the ice front we see a low spur of Gable Mountain, and, at a greater distance, the line of nunataks which separate Cushing Plateau and the main channel of Muir Glacier. The view is limited right and left by the nearer mountains. Carroll Glacier is fed by the snows of the mountains to the northwest, only some of which I am able to include in my map, and flows in a southeasterly direction to Queen Inlet, the

END OF CHARPENTIER GLACIER

distance from the end of its longest tributary to its mouth being between 15 and 20 miles. It lies at a much lower level than the Cushing Plateau, from which the ice pours over in a broken flood to join it. There are several large moraines on the Carroll Glacier, but they can not be well seen from Queen Inlet. From a summit just south of the Cushing Plateau I once saw them as sharply defined, black lines sweeping along in magnificent curves on the white ice, to which they offer such strong contrast. Near the end of the glacier they are mostly swallowed up in the crevasses, making dirty, vertical streaks in the ice front.

Rendu Inlet and Rendu Glacier occupy a long, narrow valley extending for many miles between parallel ridges. The upper part of the valley bends slightly toward the west, so that the origin of the glacier can not be seen from the inlet. The mountains on each side rise directly from the water, though enough talus and débris have collected to make landing easy for small boats. The desolate, barren mountain slopes are charged with deposits of sand and gravel, down which small streams have cut innumerable gullies. These deposits, which also exist on the sides of Queen Inlet, are stratified, laid down undoubtedly by running waters, and though the layers appear horizontal they probably have a slight slope toward the mouth of the valley. Notwithstanding its barrenness, this is one of the most picturesque parts of Glacier Bay. The ice cliffs of the glacier, about 140 feet high and two-thirds of a mile broad, extending completely across the valley, limit the extent of the inlet. The mountains rise on each side, peak after peak, bearing on their shoulders small glaciers and dazzling snow fields. The jagged crest of Mount Abdallah is sharply outlined against the sky, and looks very dark in contrast with the beautiful snow-couloirs which streak its cliffs. Its appearance and its position in the very axis of the bay make it a very conspicuous mountain. The marked differences between Rendu and Queen inlets come from the fact that the former is parallel with the mountain ridges and the latter cuts across them. The direction of Rendu Glacier is continuous with that of the inlet, and we can see its course for a long distance, whereas Carroll Glacier is at right angles to Queen Inlet, from which we see only its breadth. On the eastern side of Rendu Inlet, near its upper end, is a knoll of white marble, which stands out prominently and is an excellent point to which to refer the position of the glacier. My plane-table station, *a*, was on the northern end of its summit. In 1892 the glacier's end against the eastern shore of the inlet was about 1,680 meters (1,850 yards) from this point. This glacier does not discharge much ice, and we therefore infer that its velocity is not very great. It receives two steep tributaries from the west, not far from its mouth; but none of the glaciers on its eastern side, within 6 or 7 miles of its end, are large enough to descend to the level of the Rendu. That it receives many tributaries is shown by the numerous lines of moraine—some strong, some faint—which mark its surface.

On the western side of Rendu Inlet, about 2½ miles from its mouth, prospectors have opened a mine from which they have obtained some silver ore, but its inaccessibility makes its future very unpromising.

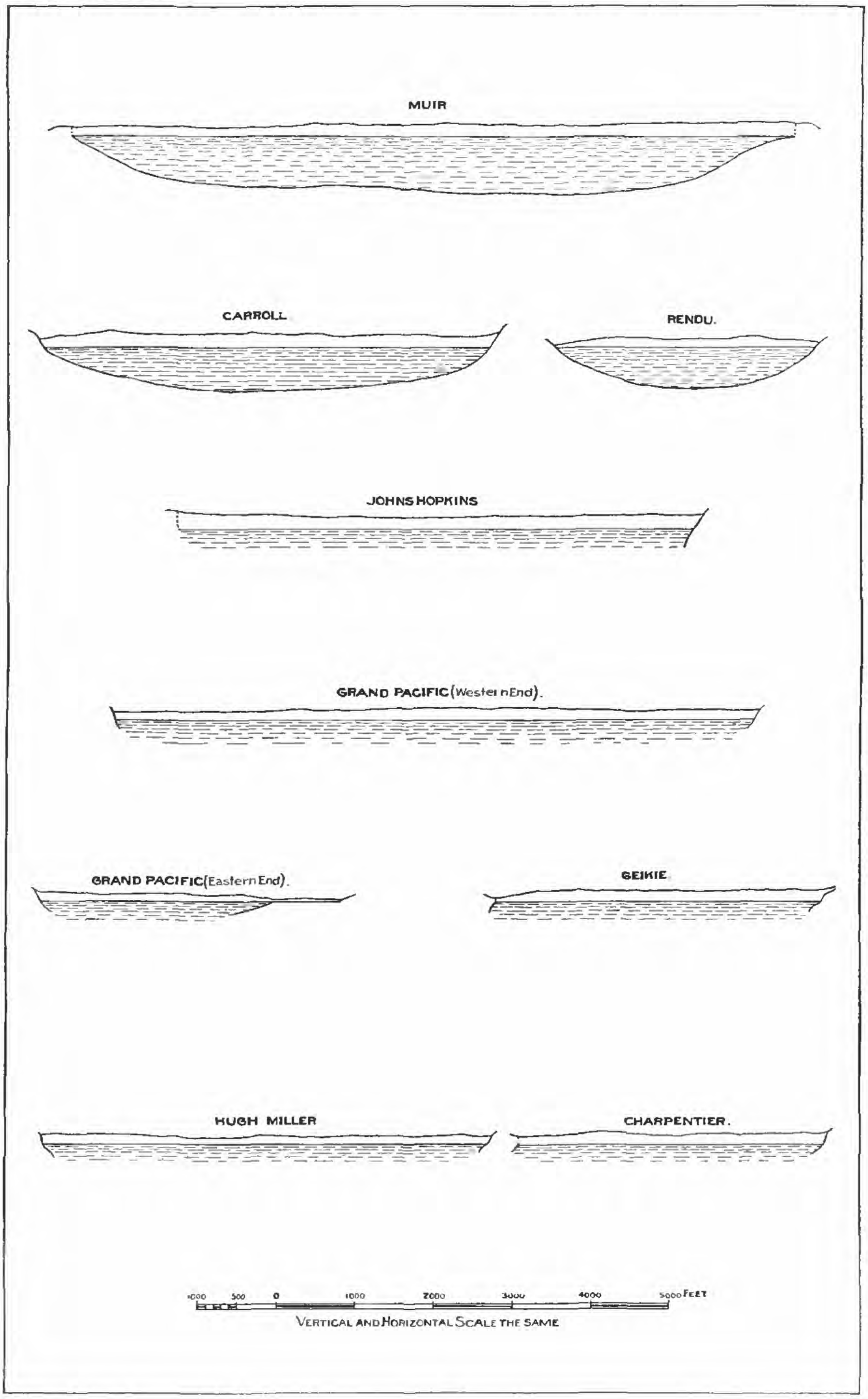
Reid Inlet is about 9 miles long, and enters the bay from the northwest. At its mouth it is 2 miles wide, but near its head it nearly doubles this breadth. Its northeastern shore is unbroken by a valley, being formed by the ridge which separates it from Rendu Inlet. The southern shore is much broken up by ridges and valleys running almost at right angles to the inlet. From the more westerly of these valleys glaciers stream out and unite before breaking off into the water.

The head of the inlet receives two large glaciers, the Johns Hopkins and the Grand Pacific, which enter from the southwest and northwest, respectively. Their ends are separated from each other by a mountain mass some 5,000 feet high, whose topography I was unable to work out. A rocky knoll, half island, half nunatak, divides the end of the last-mentioned glacier into two parts, from both of which ice breaks off; but the western end is by far the more important. The calving of the bergs from this and from the Johns Hopkins Glacier opposite is continuous, keeping the inlet well covered with floating ice and the air pulsating with the thunder of the falls. The very large quantity of ice continually being thrown off suggests a considerable thickness and a rapid motion for these glaciers. The Johns Hopkins seems to gather its ice in an immense amphitheater surrounded by Mounts Fairweather, Lituya, and Crillon, and having an area of perhaps 200 square miles. It must be a region of magnificent mountain scenery, but it is very difficult of access.

The Grand Pacific Glacier lies in the continuation of the trough of Glacier Bay. The most distant point of it visible to me was about 10 miles from its mouth, and was about 2,000 feet high. This point lay on the sky line, and no mountains could be seen beyond, though there must be large névé fields to supply the ice for so large a glacier.

I have collected in the following table such data as we have for the various tidewater glaciers of Glacier Bay. Pl. LXXXIX will show at a glance the relative breadths and heights, and also in three cases depths, of these glaciers. The soundings giving these depths were made by Captain Carroll. There is considerable difference between the breadths of the glaciers, but those whose thicknesses are known show but small differences in this dimension. Muir Glacier is two and a half times as broad as Rendu, but only one-sixth thicker.

Another interesting point is the relation between the breadth and depth. Muir Glacier is ten times and the Rendu five times as broad as it is deep. Rivers are generally much broader than this in comparison to their depth.



PROFILES OF THE ENDS OF THE GLACIERS.

Table showing dimensions of glaciers at Glacier Bay, Alaska.

Glacier.	Breadth.	Depth of water.	Height of ice front.	Thickness of ice at end.	Average slope of surface.
	Feet.	*Feet.*	*Feet.*	*Feet.*	°
Muir	[a] 9,200	720	130–210	900	[c] 1.8 [d] 1.6 [e] 1.5
Carroll	5,500	540	100–200	700	1.9
Rendu	3,300	600	60–150	700	3.5
Grand Pacific (western end)	8,200	....	[b] 135–190	....	2.4
Grand Pacific (eastern end)	3,900	....	[b] 0–110	....	....
Johns Hopkins	6,600	....	[b] 145–260	....	....
Hugh Miller	5,600	....	85–140	....	3.0
Charpentier	3,900	....	120–155	....	3.4
Geikie	[a] 4,200	....	30–150	....	4.2

[a] This does not include the wings.

[b] These heights are less reliable than the others; they were measured at a distance of several miles over water covered with floating ice. Refraction may have made the measurements greater than they should be.

[c] Within 5 miles of the end.

[d] Within 10 miles of the end.

[e] Within 25 miles of the end.

HARD GEOLOGY.[1]

The rocks about Glacier Bay are both igneous and sedimentary. Of the former, diorites, quartz-diorites, and diabases are the principal; the latter are argillites and limestones. Their approximate distribution can be seen by a glance at the accompanying map, Pl. XC.

The coarse-grained diorites and quartz-diorites occur in large intrusive masses. Microscopic examination shows that they have been subjected to considerable dynamic action since their solidification. Professor Williams considered them very old. They are intersected, as are also the sedimentary rocks, by numerous dikes, which run in all directions and have all breadths from 20 feet or more down to a fraction of an inch. The latter are fine grained, and do not show evidence of much dynamic action. They often look like dark ribbons on the light quartz-diorite.

The sedimentary rocks are much folded, so that it is impossible to form an estimate of their thickness, which, however, must be several thousand feet. They have been so much metamorphosed as largely to obliterate their planes of stratification. In places, such as the Marble Islands and on the shores of Rendu Inlet, the limestone, in general a bluish-gray dolomite, has been changed into white marble. The argillites are dark, almost black, slate. No fossils were found in them, but in the limestone Professor Cushing found Leperditia, and a specimen of Lons-

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[1] For a detailed description of the rocks of this region see papers by Prof. H. P. Cushing and Prof. G. H. Williams in the Nat. Geog. Mag., Vol. IV, pp. 56–74, and Professor Cushing's paper in the Trans. New York Acad. of Sciences, Vol. XV, 1895, pp. 24–34. A large part of the geologic map of this region is due to Professor Cushing.

daleia (identified by Prof. H. S. Williams) was picked up by a tourist in the summer of 1892 on the moraine at the end of Dirt Glacier and given by him to Prof. J. J. Stevenson, who was his fellow traveler.[1] This determines the limestone as Carboniferous. The argillites must be older, for they underlie the limestones, but no clew was found to their age. The quartz-diorites are probably younger than the argillites, for Professor Cushing describes a contact between them showing stringers of the former penetrating the latter. The argillites and the limestones a hundred miles farther east on the Taku River, described by Dr. C. W. Hayes,[2] seem to belong to the same horizon as the Glacier Bay series, as do also those described by Dr. G. M. Dawson[3] as occurring in the interior region east and northeast of the Coast Ranges, 250 to 350 miles northeast of Glacier Bay. Carboniferous fossils were found in these limestones and Cambro-Silurian graptolites in the underlying argillites, suggesting that the similar rocks of Glacier Bay may be of the same age. Farther south, in Vancouver Island, Dr. Dawson[4] describes argillites and Carboniferous limestones occurring interbedded with volcanic rocks, above which are Mesozoic sedimentary rocks of the same kind. The argillites near Juneau and on the eastern shore of Lynn Canal are, on account of their proximity to those of Glacier Bay, more likely contemporary with the latter than, as Dr. Dawson suggests, with the later argillites of Vancouver Island. This group of rocks, therefore, seems to be widely distributed toward the south, east, and northeast. In the northwest, however, the rocks of the St. Elias range are totally different; they have been found by Prof. I. C. Russell[5] to be late Tertiary or early Pleistocene. Topographic differences suggest that there is a great fault in the valley of Brady Glacier, between Glacier Bay and the Fairweather Mountains (the southern part of the St. Elias range), bringing the early and later rocks into contact.[6]

At the northern entrance of Hugh Miller Inlet erratics of actinolite-schists and garnetiferous mica-schists are numerous. The rocks were not found in place and were probably brought here from farther west.

Pieces of garnetiferous mica schist were also found on the eastern side of the entrance to Geikie Inlet. They appeared to have fallen from a dike which exists here. I did not examine the place very carefully, as I was not aware at the time that the occurrence of these rocks in dikes is extremely rare.

THE GRAVELS.

The sand and gravel deposits of Glacier Bay may be divided into two classes, the low-level and the high-level deposits. We shall see later that these two series were probably laid down at different times.

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[1] Scot Geog Mag, Feb, 1893, p 5

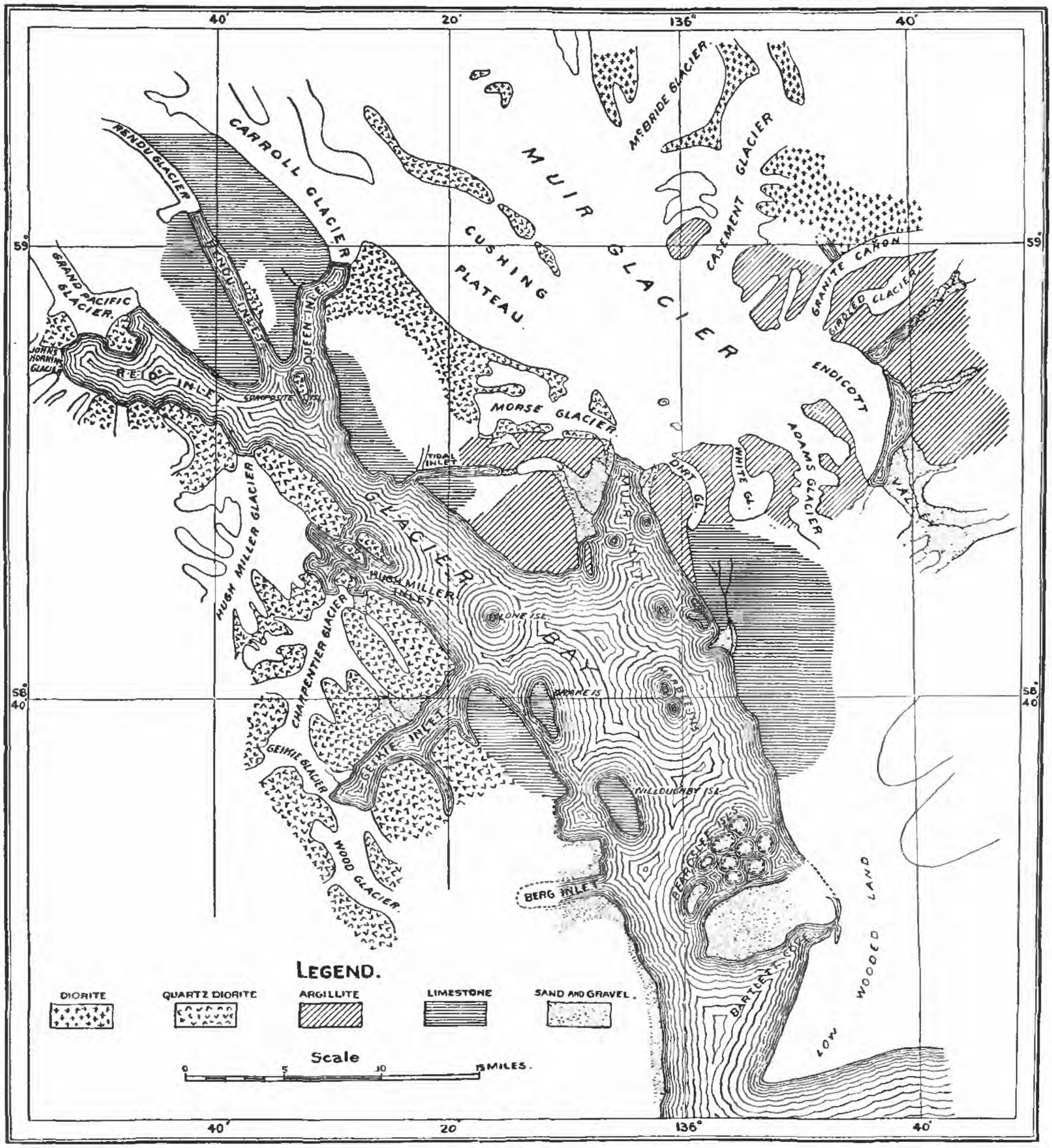
[2] Nat Geog Mag, Vol IV, p 138

[3] Ann Rept Geol Surv Canada, 1887-88, Pt I, p 32B

[4] Ibid, 1886, p 9B

[5] Nat Geog Mag, Vol III, p 172

[6] Ibid, Vol IV, p 24



GEOLOGIC MAP OF THE GLACIER BAY REGION.

The most marked examples of the low-level deposits are the Beardslee Islands. Large deposits also occur on both shores of Muir Inlet, on the northwestern shore of Geikie Inlet, and in Endicott Valley, and smaller ones at Sandy Cove and higher up the bay. They also seem to occur about Berg Inlet. These deposits are composed of sands and small gravels, the latter being subangular or rounded. They are a mixture of various kinds of rocks and are roughly stratified, showing that they were laid down by running water. The present thickness of these gravels is about 200 feet on some of the Beardslee Islands. In Muir Inlet their greatest thickness is about 50 feet less. Their under surface is nowhere more than a few feet above high tide. The low land southeast of the Beardslee Islands is covered by a forest of considerable age and is undoubtedly much older than the low-level gravels of the bay. The latter, with the exception of the Beardslee Islands, occur so directly in front of the valleys from which they have derived their material that there is no doubt as to its source.

The deposits in Muir Inlet have been described and discussed by Professor Wright,[1] Professor Cushing,[2] and Professor Russell.[3] Professor Russell, Professor Wright, and I concurred in the opinion that the valley occupied by Muir Glacier and Inlet was at one time completely filled by the gravels of a large alluvial cone, having its origin at the end of the glacier, then higher up the valley. The source of this stream was probably not stationary, but shifted from side to side as its channel became blocked up by its own deposits. Later the glacier advanced, cutting away the central part of the deposit on account of the more rapid movement in the middle, but only slightly cutting down the sides. Professor Cushing, looking for a cause which would not require so much erosion by the glacier, suggested, provisionally, that the deposits might have been laid down on a slowly subsiding floor, which was afterwards elevated to its present level. But as these deposits are rather coarse, and were laid down by swiftly running streams, the accumulation must have been rapid, and it would have required an unusually rapid subsidence to keep the surface near tide level.

This difficulty, however, may be avoided. The changes that took place in the glacier between 1890 and 1892 (see p. 440) called my attention to the fact that the central and lateral parts of the glacier are largely independent of each other, both as to the quantity of their ice supply and their rates of motion, and consequently as to their extent. The gravels accumulated in large quantities higher up the valley during the long period when the glaciers of this region were smaller than at present. When Muir Glacier began to advance, its center must have pressed out beyond the sides, and it may thus have caused the drainage streams on each side to flow between it and the mountains and deposit their material along the sides of the valley only, where

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[1] The Ice Age in North America, 1889, p. 57.
[2] Am. Geol., Vol. VIII, 1891, p. 219.
[3] Ibid., Vol. IX, 1892, p. 190.

the floor was about at the level of the present surface of the inlet. As this projecting tongue became thicker and thicker it would gradually spread over the gravels deposited on its sides, forcing the streams closer to the mountains, near which the deposits would thus reach a higher level. The sides of the glacier would also advance, stopping deposition under themselves, but allowing the accumulations to increase in front. This would continue until the spreading of the projecting center and the advancing sides covered the deposits. The drainage stream would then either be held up in a narrow channel between the ice and the mountain side or its points of emergence from the ice would, in a very short time, be moved to a considerable distance down the valley, where the water is too deep for its deposits to be seen now. The gravels in the valley of Dying Glacier were probably derived from that of Muir Glacier, for this valley is so small and its glaciers are so insignificant that it is hardly likely that the material could have originated there.

Geologists who credit glaciers with but slight erosive powers will probably prefer the above explanation to that offered by Professor Russell; but, independently of one's opinion in this matter, I do not think there are any observations which decide definitely in favor of either explanation; for, although I feel certain that Muir Glacier would advance in the way just described, it may be that the gravels were deposited when the end of the glacier was still some distance higher up the valley. Some gravels, however, occur in places which seem to favor the idea that they were deposited while the glaciers were in general advancing. (The existence of the buried forests precludes the idea that the glaciers had retreated from this ground shortly before the gravels were deposited there; but the glaciers, though in a general state of advance, may have made several oscillations, alternately covering and leaving bare the gravels as they were being deposited.) Thus, at the southern end of Sebree Island and also of Sturgess Island, 2 or 3 miles farther down the bay, there are stratified gravels. It is hardly possible that these were deposited when the gravels of the inlet were laid down, i. e., when Muir Glacier was smaller than it is at present, but more likely that a stream from the ice deposited them when the glacier's end was near by.

Gravels occur on the sides of Nunatak G and of Tree Mountain, and just south of Girdled Glacier the ice still partially covers them.

The deposit on the northwestern shore of Geikie Inlet merits special notice. It is almost opposite the middle of the inlet, and has evidently derived its material from Favorite Valley. It is composed of small, subangular fragments, roughly stratified; its surface is undulating, is scattered over with angular rocks, and is cut through by many ravines. In fact, it is exactly like the deposits in Muir Inlet. On its eastern side it rises gradually from the water up to a height of about 400 feet, but falls steeply on the western side in a series of terraces to the val-

STRATIFIED GRAVELS, EASTERN SIDE OF MUIR INLET.

ley bed below. Into this valley there opens from the southwest a small tributary valley, which contains a most remarkable deposit of sand and gravel, 200 feet thick (Pl. XCII). This deposit formerly filled the valley, but streams have cut down its sides, thus completely separating it from the mountain slopes. It is roughly stratified, and coarser grained below than above. Its surface is rather smooth, with a few large rocks scattered over it. Its upper end is continuous with the floor of the valley, which rises rapidly, and its lower end forms a part of the southwestern wall of Favorite Valley, and shows the stream terraces belonging to the latter's system.

There are, as for the Muir Inlet gravels, two ways of explaining this curious arrangement: (1) We may assume that Favorite Valley and its tributary were formerly filled with the stratified gravels, and that when the glacier advanced it carried away the gravels in its direct course, at the same time blocking up the tributary valley, which must also have contained a small glacier. On the retreat of the ice the streams formed the terraces; later small streams cut away the sides of the sand deposit in the tributary valley. (2) Or we may assume that when the deposits, which still remain high above the present valley floor, were laid down, the valley itself was protected by being occupied by the glacier, larger then than at present. A lake several hundred feet in diameter, with its surface proper below high tide, occurs in these gravels. It looks like a kettle-hole left by the melting of a mass of detached ice. If this is its origin, then the glacier must have retreated from this point shortly before the gravels were deposited, or have been oscillating back and forth over it. When, later, the great advance came, the ice must have sunk into this hole and thus have prevented it from being filled up with débris.

We can not assign these gravels to a period since the last great advance, and suppose this lake was made lately, for the scattered moraines over their surface show that the ice has overridden them, and their close resemblance in every way to those of Muir Inlet requires us to assign to both the same cause and approximately the same age. In fact, all the low level gravels were probably deposited about the same time, just before or during the last great advance of the ice, for we find the glaciers in all the inlets overriding them, and they themselves cover old forests in many places.

The high level deposits occur in greatest development in Geikie and the three upper inlets of the bay. I did not see any indication of them in or south of Muir Inlet. They form a more or less thick lining, resting against the mountain slopes at all altitudes up to 1,000 or 1,500 feet. Their rough stratification appears horizontal, but probably slopes with the valley in which they occur. They are not perfectly continuous. They seem to have been deposited by streams flowing along the sides of the glaciers when the latter were much thicker than at present. Since the glaciers have become smaller, streams formed by rain and melting snow have cut numerous gullies in these deposits, causing a vertical, streaky appearance.

The difference between the low-level and the high-level deposits is not merely one of position; they have been formed under different circumstances. The former were laid down either when the glaciers were small and stationary or when they were advancing, probably with many oscillations; the latter when the glaciers were large, and probably when they were diminishing, though it is possible that they were laid down during the advance and have been overridden by the ice. This matter is still obscure. I measured the height of these gravels at the upper end of Geikie Inlet and found it to be 1,100 feet. This does not, however, necessarily mark the greatest height which the ice reached.

RECENT GEOLOGIC HISTORY OF GLACIER BAY.

In several places beneath the low-level gravels—at the southern end of Sebree Island, in the Beardslee Islands, at the buried forest on the western side of Muir Inlet, and among the stumps exposed at very low tide on the eastern side of the inlet—there is a smooth, stiff blue-gray clay. At the buried forest it must be 50 to 75 feet above tide, and Professor Wright[1] says it is in some places 20 feet thick. What I saw of it in the Beardslee Islands was only a little above high tide. This clay and the deposits forming the lowland to the southeast of Glacier Bay are the earliest of the recent formations. I could not examine the latter, but it seemed to consist of morainal material, indicating a very early invasion of the ice.

The blue clay resembles that which lies under Lake Erie and the deposit now being laid down at the bottom of Glacier Bay. Its material must have been derived from glacial streams, and its freedom from sand shows that the glaciers could not have been near by; so we infer that the glaciers were comparatively small. The fine texture of the clay makes it evident that it was laid down in still water; it therefore marks a period when the land was at least 75 feet lower than it is now, and perhaps more. After this came an elevation, and forests sprang up on the clay. They occupied most of the shores of Glacier Bay and extended some distance from the water, their remains having been found in place on both sides of Muir Inlet, on Sebree Island, on the western shore of the bay between Geikie and Hugh Miller inlets, and near Girdled Glacier. Stumps occur in place on the southern slope of the spur which bounds Girdled Glacier on the south. I did not notice them in July, but three weeks later they could not have been overlooked. I think they were exposed by a landslide of the gravels, which here are full of water and very loose. Pieces of wood were found on the northern side of this glacier, and detached logs have been found on the moraines coming from Adams and Casement glaciers, now regions of ice and snow; also on Nunatak G, on Sturgess and

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[1] The Ice Age in North America, 1889, p 59

SAND DEPOSIT NEAR GEIKIE INLET

Drake islands, in Geikie and Hugh Miller inlets, near Tidal Inlet, and in the upper part of the bay. This shows a very small extension of the glaciers and a milder climate than at present. Large trees are now found standing with their roots clasping old decayed logs, showing that these conditions must have lasted for several hundred years. I have already given my reasons for believing that this was only a few hundred years ago [1] This forest landscape was destined to be destroyed. Floods brought down sand and gravel and covered up the trees, killing them, and leaving a desolate region. They were probably caused by increased precipitation, which at the same time made the glaciers creep out of their mountain fastnesses and fill the valleys. Gradually they grew, rode over the gravels, and united with others, until the whole region about Glacier Bay was one vast, gently-sloping field of ice, reaching to and covering the Beardslee Islands. In the region of Muir Inlet the ice was about 3,000 feet thick, and at the upper end of the bay probably 1,000 feet thicker. Its appearance must have been very much like that of the upper part of Muir Glacier at present, only it was larger.[2] It was apparently about in this condition when Vancouver's officers saw it 100 years ago, though the exact extent of the ice at that time can not be made out from their descriptions. It seems certain that the ice at its maximum did not extend to Bartlett Cove, for there the land is covered with a forest of great age, and that it did override the Beardslee Islands, for they bear only a few small trees of recent growth, and are sprinkled over with angular blocks brought there by the glacier. The high sand bluffs and the steep ravines with sharply cut edges show that these islands have not been long exposed to atmospheric denudation. It is probable that they were deposited by streams from the ice, perhaps during a short stationary period, and that the glacier then rode over them, but soon retreated, leaving the scattered moraine which we find on their surface. A large stream from the melting ice seems to have cut the channel which enters the head of Bartlett Cove. A slight subsidence may have deepened the channels between the islands (see p. 440).

The retreat of the glaciers must have begun 100 or 150 years ago. As the ice melted back on the islands it deposited a little morainal material, and its streams cut ravines. After getting free of the islands the glacier had a magnificent front, 6 or 8 miles across, though its height was probably not much over 300 feet.[3] Large bergs must have broken off in great numbers and made Cross Sound difficult to navigate, which accords with Vancouver's report. In places, notably in Geikie, Rendu, and Queen inlets, streams held up by the ice against the mountain sides continued to deposit the high-level gravels there as the ice subsided,

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[1] Nat Geog Mag , Vol, IV, pp 38, 39

[2] See a picture of the main ice stream of Muir Glacier in Nat Geog Mag , Vol IV, p 53

[3] The highest ice cliff measured in Greenland is that of the Upernivik Glacier—349 feet This remarkable glacier was found to move at the rate of 99 feet a day in summer time See Petermann's Mitteil , Vol XXXIV, 1888, p 68

and thus coated large surfaces on the mountain slopes. Slowly the end of the glacier went back, leaving independent glaciers in the tributary valleys. In this way Muir and Geikie glaciers became independent and gradually retreated up their valleys, repeating the history of the great trunk glacier, depositing a thin coating of morainal material on the gravels,[1] and allowing their drainage streams to cut numerous channels in them as they became exposed. It was in this way that the terraces in the valley of Dying Glacier, near Camp Muir, and in Favorite Valley were formed, and that the curious sand deposit near the latter valley was isolated from the neighboring mountains, and that the many buried forests were exposed. We are still in this period of retreat; the glaciers are getting smaller and the inlets larger, and unless some change in the present climatic conditions occurs the length of the glaciers and of the inlets will have greatly changed 50 years from now.

Since the time when the forests grew in Muir Inlet there has been a subsidence of the land of at least 20 feet, for trees in place on the eastern shore of the inlet, which must have grown above high tide, are now exposed only when the tide is very low.

CHANGES IN MUIR GLACIER BETWEEN 1890 AND 1892.

The positions of the end of Muir Glacier in 1880, 1886, and 1890 show an apparently continuous recession at the rate of about 250 yards a year (see map, Pl. XCV *a*). Therefore, on my return to Glacier Bay in 1892 I expected to find the glacier's end still higher up the valley, and was much surprised that the ice front had advanced on an average 300 yards. Starting from the same point on the eastern shore which it reached in 1890, the line of the end ran forward into a sharp point similar to that seen by Professor Wright in 1886, then curved in again, and finally reached the western shore about 300 yards in advance of its former position.[2] The height of the ice cliffs had not changed.[3] The two wings, however, had melted back more than 100 yards. This very marked difference in the behavior of the middle and sides of the glacier drew my attention to the fact that they are really independent of each other—are, indeed, almost distinct glaciers. The water front derives its supply, as shown by the moraines, from the main ice stream of Muir Glacier and from its two northern tributaries, and these regions are still active accumulators of snow. The eastern wing receives scarcely any supply at all, for Dirt, White, and Adams glaciers end against the ice of the eastern part of Muir, but have not enough supply to carry their ice to the terminus near the inlet. The western wing was supplied by Morse Glacier, but is now receiving no ice. The movement of these wings is insignificant; their ends are not in a condition of equilibrium, receiving by flow as much ice as they lose by melting, but are nearly

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[1] This superficial moraine is very clearly shown at the northern end of Hugh Miller Inlet. Its reddish color makes it easy, even at a distance, to distinguish it from the gray gravels underneath.

[2] This form did not continue during the summer, on August 2 there was a tremendous breaking away of ice, especially from the point, obliterating this feature completely.

[3] Photographs have reached me which show that the end of Muir Glacier had retreated in 1894 to its position in 1890.

inert masses of ice steadily melting away. This is shown, not merely by the melting back of the ends, but also by the lowering of the surface. The portion of the glacier facing the water is in quite a different condition, for here the supply of ice is approximately equal to the loss by melting and breakage; and anything that alters, even in a slight degree, either of the factors, alters appreciably in a short time the position of the end. Suppose, for instance, some cause should double everywhere the velocity of motion of the ice, and that the rate of loss by breakage and melting should remain unaltered; the center of the glacier would advance about 7 feet a day, whereas the sides, which move only a fraction of an inch in a day,[1] would have their rate of retreat, about 5 inches a day, but slightly diminished. On the other hand, if anything should reduce the movement all over the glacier, the center would retreat much more rapidly than the sides. Mr. Prentiss Baldwin has mentioned this difference between the center and sides of Muir Glacier.[2] But, as I have already said, the great difference in the conditions of the regions from which the center and sides receive their supply of ice makes their variations in velocity also largely independent of each other.

It is reported that during the winters of 1891–92 and 1892–93 there was an unusually large snowfall in Alaska. This would result in a small general increase in the thickness of the ice. For the region above the snow line this is evident; and below, the ice would be protected from melting later into the summer than usual. We should expect from this a slight increase in velocity, causing an advance in the ice front and a smaller rate of melting back of the ice wings.

Can this explain the advance? Do glaciers respond so quickly to meteorological variations? We can not answer these questions at present. Data are now being collected all over the world with the object of discovering the relation between variations of glaciers and of climate. (See p. 444).

Other changes which occurred between my two visits to Muir Glacier are the following: The stream which issued from the eastern end of the ice front[3] has divided into two branches; one enters the inlet below the water a hundred yards or so from the shore with such force that it rises 8 or 10 feet above the general level of the water; the second branch comes in as an ordinary stream at the corner of the inlet, its channel for a short distance from the glacier's end being marked by a great depression of the ice. The inlet is growing wider by the cutting back of the gravel cliffs on both shores. Besides the general sinking of the two sides of the glacier 30 or 40 feet below the general level of the center, the crevasses on the eastern side approach nearer to the border of the ice than formerly. At the present time Morse Glacier scarcely

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[1] Nat Geog. Mag, Vol IV, p 45, where, however, a typographical error makes the movement 2 inches instead of $\frac{1}{2}$ inch

[2] Am Geol, Vol XI, 1893, p 374.

[3] Nat Geog Mag., Vol IV, pp. 32, 42.

connects on the western side with the Muir, and the depression between the two is occupied by a stream and quite a quantity of gravel deposits.

From the moraine which surrounds the end of Dirt Glacier there projects a long ridge of stratified sands and gravels—an esker, evidently deposited by a stream in a channel through the ice. It is about 100 yards long, has a somewhat winding course, and rises 20 to 30 feet above the present level of the ice. This does not give its whole thickness, for it extends to an unknown distance below the surface. This ridge did not appear at all in 1890, and either did not then exist or, what is more probable, was under the ice. It marks, therefore, a melting of not less than 30 feet from the surface of the ice in two years. (See Pl. XCIII.)

In 1890 we camped for two or three nights on the northeastern side of Tree Mountain on a spur which projected into the glacier. On returning in 1892 to this camp I found the ice, by aneroid, 40 feet lower than in 1890. This agrees fairly well with the estimate which I made, viz, a melting away of the surface of 15 feet a year and some additional sinking due to flow.[1] I was obliged to depend on my memory for the height of the ice in 1890, but as the marks of our former camp fire still remained, which was not then more than 15 feet above the ice, I do not think a material error has been made.

CHANGES TO BE EXPECTED.

There are many parts of the Glacier Bay glaciers where the supply of ice is markedly not equal to the waste, and where, therefore, rapid shrinkage is taking place. Some of these places are: the two small valleys east of Snow Dome, Granite Canyon and Endicott Valley, the 40 square miles of Cushing Plateau, the Dying Glacier, the alpine end of the Charpentier Glacier, the piedmont portion of the Hugh Miller Glacier, and many small glaciers of less importance. The present state of the region as recorded in my map will enable us to follow these changes in the future.

The Hugh Miller piedmont glacier is probably melting away at the rate of 15 feet a year. Its upper surface is 950 feet above tide. Let us by a guess put its thickness at 700 feet and suppose that the supply of ice equals the quantity lost by flow. In 50 years it will have entirely melted away and the Hugh Miller Glacier will follow the course of what is now probably a deep channel leading to its tide-water ending, or it will end as an alpine glacier.

The Dying Glacier is probably less than 450 feet thick in the thickest part. If its protected position allows a loss by melting and flow of only 15 feet per year its valley will be free of ice in 30 years.[2] The alpine end of Charpentier Glacier has a slope at its end of about 15

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[1] Nat Geog Mag, Vol IV, p 38

[2] My former estimate was probably too small Nat Geog Mag, Vol IV, p 42

AN ESKER NEAR THE END OF MUIR GLACIER.

degrees. If it is melting at the rate of 10 feet a year and is receiving little or no ice from behind, which seems probable, it is receding at the rate of nearly 40 feet per year. Its greatest thickness, at its line of junction with the swiftly flowing part of the glacier, can not be more than 300 feet, so that it will have entirely melted away in 30 years.

Great changes may be expected in Endicott Valley. The observation at the side of Tree Mountain makes the rate at which the surface is lowering 20 feet a year. Between Tree Mountain and Girdled Glacier the upper surface of the glacier is about 1,400 feet above tide. If its bed slopes from Endicott Lake uniformly to Muir Inlet, its greatest thickness would be something like 1,000 feet; it can hardly be greater than this. At its present rate of sinking the ice will have disappeared from this valley in 50 years.

Marked changes may be expected in that portion of Muir Glacier to the east of a line drawn from Snow Dome to the eastern side of Muir Inlet. None of the tributary glaciers supply much ice to it, and by the time Endicott Valley is free of ice this region will probably also be uncovered and the glaciers now pouring into it, the Dirt, White, Adams, and Girdled, will be ordinary alpine glaciers.

The Cushing Plateau is receiving but little ice in comparison to the huge surface it exposes to melting, though its elevation, 2,000 feet, reduces the melting to perhaps 10 feet a year. The ice is also flowing off in both directions, so that 15 feet a year seems a reasonable rate to assume for the lowering of its surface. It probably derived its ice from the northwest, when the nunataks which bound it on that side were entirely covered, and not from the small glaciers entering it from the south. The rather steep slope at its western end renders it improbable, I think, that its thickness exceeds 1,000 feet; so that apparently only 70 years will elapse before the disappearance of the ice from this region.

These very great alterations can, I think, be predicted with some confidence, for we have been dealing with regions which owe their ice to some source which no longer supplies it, and it is therefore steadily melting and flowing away. The question is not like that of the recession of an ordinary alpine glacier, the position of whose ends depends on the difference between the rate of melting and that of supply. Here the supply is practically cut off and we have merely to do with the waste, of which we can form a reasonably good estimate. Glaciers are apparently subject to periodic variations of many different periods. The changes which I have described (pp. 438-440), if they are periodic, recur only after many hundreds of years. Upon these are superposed, probably, a variation of 35 to 50 years, and, certainly, annual and daily variations, though the last are too small to be observed. It is hardly likely that the smaller variations which will recur during the next hundred years will materially affect the above estimates of retreat

The rate of recession of the ice fronts is a much more difficult question, for although we may feel satisfied that the generally rapid recession which has prevailed for the last hundred years will continue for some time into the future, there will certainly occur temporary variations in the rate, and even short advances, such as was shown lately by Muir Glacier.

The study of the glaciers of the Alps has revealed a periodicity in their size; they increase, reach a maximum, decrease, reach a minimum, and begin again to increase, two or three times in a century. As different glaciers begin their advance at quite different times, it is difficult to find the relation between their variations and meteorological changes. The general interest in this subject resulted in the appointment by the International Congress of Geologists at Zurich, in 1894, of a committee to collect information regarding the changes of glaciers in the various regions where they occur.[1] In America, in addition to the great shrinkage since the Ice Age, we find evidences of a decrease in the size of glaciers in the last 100 or 200 years, such as have been described by Professor Russell,[2] by me in this paper, and by others; but we have not yet recognized a variation of comparatively short period, like that found in the Alps. It is probable, however, that more frequent observations will show the existence of such a variation.

There are two glaciers in North America which are so frequently visited that we should be able to keep a pretty complete record of their changes. These are the Illecellewaet, in British Columbia, and the Muir. The map, Pl. XCV*a*, shows the position of the end of the latter at four periods, and the stations *L* and *M*, from which I surveyed the ice front. *M* is on the projecting bluff about 300 yards north of Camp Muir. *L* is exactly opposite on the other side of the inlet, just north of the large gully 300 yards north of the end of the bluff, by which it can be easily reached. These stations are 2,670 yards apart, and are excellently situated for determining the position of the ice front. Two photographs from each of these points would be necessary to show the whole of the ice front and the lateral wings, and would be sufficient to make a map of the end of the glacier. A single photograph from either point showing the opposite corner of the inlet would give definite, though much less, information. In taking the photograph the camera should be as level as possible (the swing-back should not be used), and the two pictures from the same station should be taken without changing the focus. Any such photographs sent me will be carefully kept and will serve as data for recording the changes in

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[1] See Forel's reports in the Jahrbuch des Schweizer Alpen Club from 1881 to the present, and Richter's articles in Zeitschr des deutsch u Ost Alpen Vereins, 1883 and 1891, also Journal of Geology, Vol III, pp. 278–288, where I have made a short résumé of the results so far obtained and given methods of observation I shall be glad to send instructions to persons having the opportunity and the willingness to record the extent of any American glacier Address me at the Johns Hopkins University, Baltimore, Md

[2] Climatic changes indicated by the glaciers of North America, Am Geol , Vol IX, 1892, p 322

the extent of Muir Glacier. On the photograph should be marked the station at which it was taken, the date, and whether or not a rectilinear lens was used. The longer the focal length of the lens the better, and negatives or positives on glass give more accurate results than prints. Photographs from stations *E* or *V* would also be useful

VELOCITY OF MUIR GLACIER.

The very different rates obtained by Professor Wright in 1886 and by me in 1890 for the velocity of flow of Muir Glacier have been discussed by Professor Wright,[1] Professor Cushing,[2] and Mr. Baldwin.[3] The two latter, one of whom was with me and the other with Professor Wright, have both concluded that the observations are irreconcilable, and either that one set was in error or that there was a remarkable change in the motion of the glacier between our visits. If such a change had taken place the quantity of ice breaking off from the glacier in 1886 and 1890, respectively, must have been quite different. Allowing for a large temporary retreat of the glacier's end during the summer of 1890,[4] I find that the amount of ice breaking off would correspond to a maximum velocity of about 27 feet a day if the position of the ice front had remained unchanged. Professor Wright tells us that this was the case during his visit. According to his measurements, therefore, there must have been more than twice as much ice discharged in 1886 as in 1890. This could not have escaped the notice of officers commanding the steamers which enter Glacier Bay. I wrote to Captain Carroll of the steamship *Queen*, who makes several visits annually to this region, and questioned him on this point. He answered: "For the years 1890, 1891, and 1892 there was more ice coming from Muir Glacier than there was in any of the seven years previous to 1890. I never saw so much ice coming from the glacier, before or since, as there was in that year [1890]." His letter was dated May, 1893.

Again, if an increase of 1,000 yards in length corresponds to a tenfold increase in velocity, it is evident—though the problem can not be solved as a simple proportion—that when the glacier was several miles longer than at present its velocity must have been far greater than we can possibly admit.

These considerations, I think, make it probable that some undiscovered source of error has crept into Professor Wright's observations.

The substantial correctness of my own measurements has not been questioned, and I therefore thought it inadvisable in 1892 to take the time from other observations to repeat them; but I should like to correct a misunderstanding on the part of Mr. Baldwin. He says:[5] "Professor Reid made only two observations on his most rapidly moving flags, on

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[1] Am Geol, Vol X, p 397

[2] Ibid, Vol XI, p 276

[3] Ibid, Vol XI p 366

[4] Indicated on the map, Pl XCVa

[5] Am Geol, Vol XI, p 370

July 21 and four days later." I made two independent determinations of the motions of the flags from July 21–24, and another from August 4–8, making three independent sets of determinations of the movement of the ice near the center of the glacier; and these sets accord well with one another.[1]

GIRDLED GLACIER.

This glacier presents some peculiarities which merit a careful examination. It flows down a somewhat narrow valley with a surface slope of about 6°, spreading out at its mouth, where it abuts against the ice of Muir Glacier. (See maps, Pls. LXXXVI, XCIV.) The end is encircled by two moraines. The inner one is very thin and is made up of small pieces of the slate of the neighboring mountains. The outer one is of gray quartz-diorite, which material occurs about Granite Canyon. It is composed of large blocks, and, unlike the inner moraine, rises some 20 feet above the ice outside of it, but only 5 feet above that inside; it is fringed by many fine examples of glacier tables. The breadth of each of these moraines and of the interval between them is about 400 feet. Outside of these is a third moraine, also of quartz-diorite, which comes out of Granite Canyon, passes almost half way around Girdled Glacier, and then suddenly changes its course and passes on to Muir Inlet.[2]

The inner limit of the inner moraine marks the junction of Girdled and Muir glaciers. The ice of the former, clean and white, with many air bubbles, is in strong contrast with that of the latter, which is free of air, and therefore looks much darker. The contrast is also increased by the moraine which here covers Muir Glacier. (See Pl. XCV.) This contrast is not confined to the surface, for the difference in the two kinds of ice is apparent in the crevasses, which intersect them both, as far down as one can see. The junction dips at an angle of about 60° toward Girdled Glacier, and the well-marked ribboned structure runs parallel with it. Clearly the ice of Muir Glacier is much older and has had more time to free itself of air and become compact.

To determine the movement of the ice, six flags were set out on July 30. One (No. 6) was on the Granite Canyon moraine, at the point where it changes its direction; a second (No. 5) was in the main stream of Girdled Glacier; and the other four were some 200 feet inside of the inner moraine. Knowing that the melting of the ice would soon cause the flags to fall, three small plates of sheet iron were placed about each one, for as these absorb the sun's heat well the ice melts more rapidly under than around them, and they sink in and are not blown away by the wind or displaced by slipping. This proved a satisfactory method of marking points in the ice.

Observations were made on the flags from the points *N* and *S*.

The flags were again set up, and observed on August 23, after an interval of 24 days, their proper positions being recovered by means of

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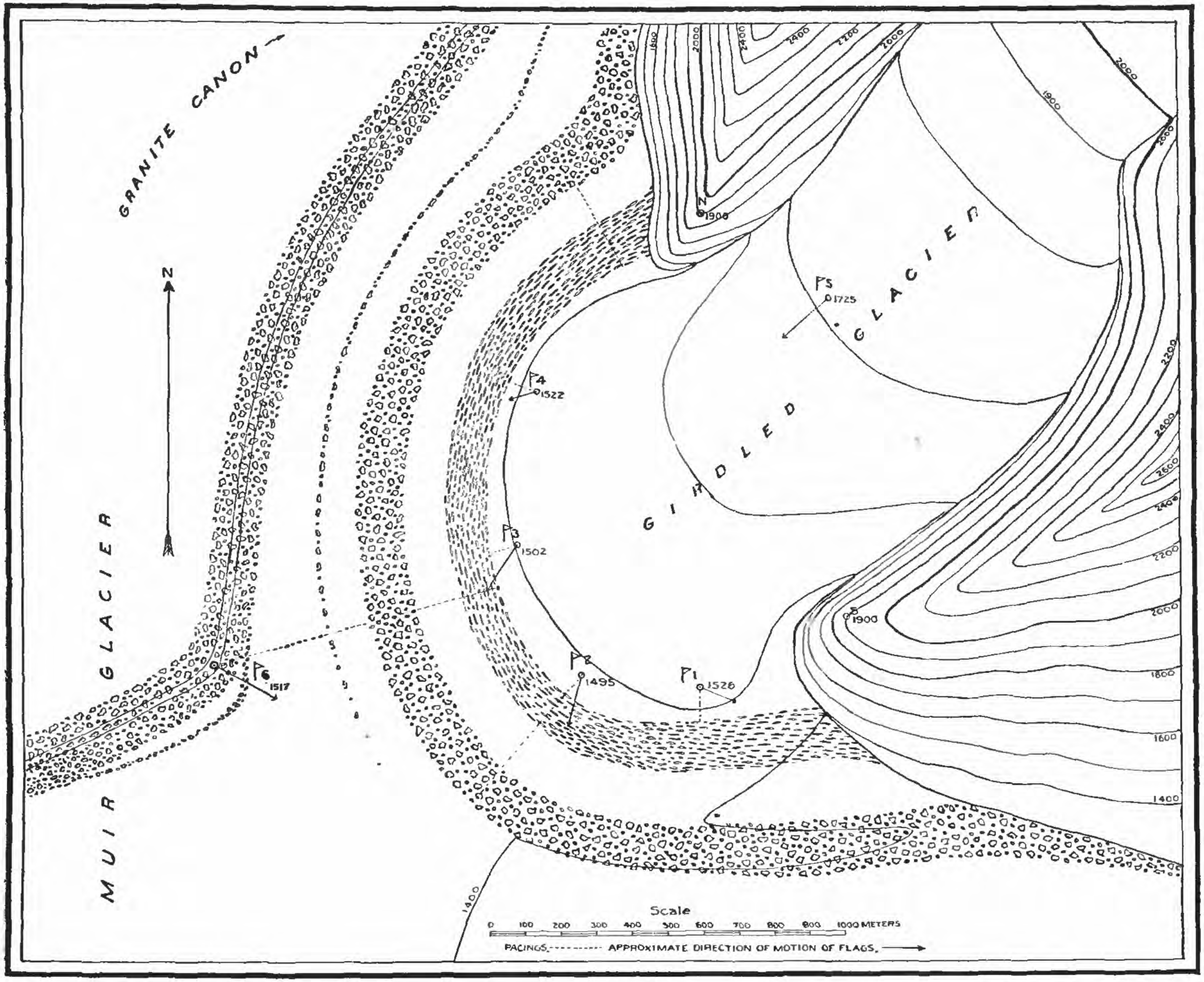
[1] Nat Geog Mag, Vol IV, pp 43, 44

[2] See ibid, Vol IV, Pls VI, XI



MAP OF THE MORAINES OF GIRDLED GLACIER.

the iron plates. The amount of the movement is given in the following table, the approximate directions being shown by the arrows on the map:

Table showing motion of the flags in the ice of Girdled Glacier.

Flag	In 24 days	Per day
	Feet	*Inches.*
1.....	3.6	1.8
2.....	4.9	2.5
3.....	5.2	2.6
4.....	2.6	1.3
5.....	5.6	2.8
6.....	6.6	3.3

The greatest angular change found was 6.5 minutes, and as the instrument read only to minutes the results can not be considered very accurate; but they show, first, that the motion is very slow; second, that we can look upon it as due to the natural spreading of the end of Girdled Glacier, superimposed on a general movement of all the ice toward Endicott Valley. Flag 6, of course, shows only the second of these movements, and flag 5 only the general flow of Girdled Glacier The direction of this latter flow was assumed.

In my former paper I gave reasons for believing that Endicott Valley formerly contained a glacier tributary to the Muir, and that, "the supply of snow having diminished in this region more rapidly than in the northwest, this tributary has diminished much more rapidly than the main glacier, until now the flow is actually reversed."[1]

At the time of the greatest thickness of the ice Muir Glacier must have been a thousand feet higher than at present in this region, receiving considerable supplies from Endicott Valley and Granite Canyon. The encircling moraines probably found their way to Glacier Bay.

Very soon after the snowfall diminished, Girdled Glacier, having but small reservoirs in which to accumulate its supplies, brought down only a very little ice; its motion became almost as slow as it is now, and its pressure against the ice in front had but little effect, because the mass of that ice was so great. The most important change that occurred during the shrinking of the ice was the reversal of flow in Endicott Valley, which, on account of its large size, modified profoundly the direction of motion over the eastern part of Muir Glacier. When this occurred the ice, carrying with it the moraines coming from Granite Canyon, swept around the end of Girdled Glacier into Endicott Valley at right angles to its former direction of motion. A great loop was thus formed in the moraines, one branch of which was deposited on the mountain side as the ice melted, the other being now represented by the moraines stretching from Berg Lake to Muir Inlet. The present Granite Canyon moraine has started on the same course, but

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[1] Nat Geog. Mag., Vol IV, p 36.

the exhaustion of the stores of ice in that canyon has so diminished the rate of flow that it has not progressed as far as the others. The smaller moraines to the east of it are in a more advanced, and those to the west in a less advanced, stage of plication. Although this explanation may be inaccurate in some details, I believe that it is essentially correct. There is one objection to it. We should expect the southern Berg Lake moraine to be composed of slate and the northern one of diorite, but we find just the reverse in the portion of the moraines south of Girdled Glacier. However, a few miles to the westward, where the moraines are much disturbed and interrupted, the northern one changes in composition from slate to diorite. Though improbable, it is not impossible, that this one may be the continuation of both the encircling moraines.

This is a very interesting example of several changes in a glacier due to a single change in climatic conditions. When the extent of the ice was at its height, Girdled Glacier was contributing its ice and moraines to the general system; when the precipitation diminished, it shrunk up and was entirely hemmed in by the ice from Granite Canyon, at a much higher level than at present. As this ice melted, the effective pressure of Girdled Glacier against it increased, until now it is slowly pushing the ice before it, for the crevasses which radiate from the end of the glacier seem to indicate a yielding of the ice, just as the radial crevasses at the end of the Rhone Glacier result from the spreading out of the ice under pressure from behind. When in the course of 50 or 100 years (see p. 443) the ice in front of Girdled Glacier shall have entirely melted away, there will still remain an alpine glacier in its valley.

HOLES IN THE ICE OF GLACIERS.

At the time of my first visit to Muir Glacier I was very much puzzled by a series of holes in the surface of the ice, which I could not explain. They were seen principally on the sides of the glacier not far from the end, in ice too disintegrated to hold water. The holes were from a few inches to 6 or 8 feet deep, and from 6 to 18 inches in diameter, and dipped up the glacier at a steep angle. They had smooth sides and rounded bottoms. Many lay on lines of old fissures that had closed up, and many seemed connected in some way with the ribboned structure, the bands of which sometimes divided and lined the hole. They were quite clean inside, containing neither stones nor dirt, and could not have been due to absorption of heat by such objects. I could find no satisfactory explanation of their origin.

Similar holes on the Mer de Glace, in Switzerland, attracted the attention of Count Rumford as early as 1804. His description of one applies well to those I saw on Muir Glacier. He describes it as "a pit perfectly cylindrical, about 7 inches in diameter and more than 4 feet deep, quite full of water. On examining it on the inside with a pole, I found that its

JUNCTION OF THE ICE OF GIRDLED AND MUIR GLACIERS.

sides were polished and that its bottom was hemispherical and well defined. This pit was not quite perpendicular to the plane of the horizon, but inclined a little toward the south as it descended;[1] and in consequence of this inclination its mouth, or opening at the surface, was not circular, but elliptical." He then gives the statement of the guides that the holes are numerous and melt down from the surface in the summer, freezing solid in the winter. He mentions no stones or mud in them, and thinks they are due to the deepening of some depressions in the ice by the sinking of the surface water, made denser by being slightly warmed by the air, and the consequent melting of the bottom of the hole.[2]

I think it was Tyndall who objected to this explanation, on the ground that as the same amount of heat falls on an equal area of the surrounding ice as on the water in the hole, the surface of the ice should be melted down as rapidly as the bottom of the hole, and no deepening should occur. Count Rumford's explanation, however, is unnecessary.

One day in 1892, as I was crossing Muir Inlet, I saw floating near my route a fine large iceberg of a glorious blue color, which had evidently not been afloat more than a day or two and which resembled the bergs broken from the glacier below the water. Attracted by its beautiful color, I landed on it to examine it more carefully, and was much astonished to see that the ice was not solid, but contained numerous long holes, ranging from a few inches to 8 or 10 feet in length, with a diameter from a tenth to a fifth as much. Some of these holes opened on the surface and were in every respect similar to those found on the surface of Muir Glacier described above. Others were completely inclosed in the ice and filled with water, as I found by cutting through to one of them. This class of holes must therefore no longer be looked upon as a surface phenomenon.

Mr. John Muir has suggested to me that they were formed by the closing of crevasses containing water, and this seems to be the true explanation, for the closing up of the intertwining crevasses of an icefall would undoubtedly leave cavities containing water, and the differential motion of the ice would draw them out into an oblong shape, with the upper part, where the motion is more rapid, carried slightly farther downstream than the lower part; and this is just the position the holes have on the surface of the glacier. Their appearance at the surface is, of course, due to the melting away of the ice above them. If they reach the surface where the ice is compact, small streams are pretty sure to carry some little mud into them. I think observers have thus been misled into classing them with holes sunk into the surface by the absorption of heat by this mud. The existence of cavities of one kind or another below the surface of the ice has long been known. Agassiz's borer once, when at a depth of 30 meters, suddenly dropped

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[1] That is, it dipped upstream. H. F. R.

[2] Philos. Trans. Roy. Soc., Vol. XCIV, 1804, p. 23, or Comp. Works, Boston, 1873, Vol. II, p. 251.

60 centimeters, and air bubbles issued from the hole.[1] He says also that baignoirs in which there is no débris are probably due to the closing up of crevasses, but he seems to refer to holes of very oblong sections left at the surface when the lower part of the crevasse is closed, and not to holes formed below the surface and afterward exposed.[2]

The existence of cavities containing water in the body of the glacier is a further confirmation, if any is needed, of the fact that the winter cold does not penetrate very far below the surface of the ice.

MELTING OF THE SURFACE OF MUIR GLACIER.

In 1890 an estimate of the rate of melting was obtained from the apparent rise of stakes planted in the ice. The objection to this method is that the bottom of the hole may melt, allowing the stake to sink, and thus give too small a melting rate. The ice where these measures were made was very porous, and the water could not collect in the holes, which diminishes the force of the objection. A better method suggested itself and was tried successfully in 1892. Two holes about three fourths of an inch in diameter were bored into the ice, starting an inch or so apart near the surface and diverging at an angle of about 60°. Rods were placed in the holes, and where they crossed each other, a little above the ice, they were notched and firmly bound together with wire, which kept the angle between them constant. The ends of the wire were twisted together and served as an index, their height above the ice being measured from time to time. If the bottoms of the holes melt, each stick prevents the other from sinking. If the holes melt on the sides and get larger in diameter, we get an upper and a lower limit for the melting by raising and lowering the sticks as far as the holes permit.

Two pairs of such sticks near the end of the glacier showed each a melting rate of 1.6 inch per day between July 15 and 20; a single pair showed 2.5 inches from July 14 to 15. During all this time the weather was cloudy and rainy. The observations of 1890, extending over 7 days, give about the same average, viz., 2 inches a day.[3]

A pair of sticks planted in the end of Girdled Glacier showed a melting of from 2 to $2\frac{3}{4}$ inches in one very bright day. The ice here is white with air bubbles and is almost impervious to water. The melting increased the diameter of the holes containing the sticks and filled them with water, giving the limiting values of the melting mentioned. Where the ice is porous this method offers no advantages over that of a single vertical stake, but where the ice is pretty compact and all holes contain water it is much better.

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[1] Syst Glac , 1847, pp 349, 350 See also Dollfus-Ausset, Mat pour l'Étude des Glaciers, Vol V, 1864, passim

[2] Syst Glac , 1847, p 100

[3] Nat Geog Mag , Vol IV, p 31

MISCELLANEOUS NOTES.

I once found the stones in a small pool near the entrance of Tidal Inlet to be of a brilliant vermilion color above the water, which was clear; they looked as if they had been painted. It occurred to me that this color might be of the same nature as red snow, patches of which I had seen on Morse Glacier; so I asked Dr. F. H. Herrick to examine it microscopically, and he found it to be a pure culture of *Protococcus nivalis.*

I revisited the buried forest and secured a number of specimens of the wood and bark, which, with some specimens found on the eastern side of the inlet, Dr. Frank H. Knowlton, of the United States National Museum, has been good enough to examine.[1] He identifies most of them as the spruce (*Picea Sitchensis* Carr.) or hemlock (*Tsuga Mertensiana* Carr.) now growing in Alaska. One specimen he considers uncertain, though he thinks it may possibly be a cypress. A branch found by Miss E. R. Scidmore in the gravels on the eastern side of Muir Inlet he identifies as the common alder (*Alnus rubra*, Bong.), which has again become plentiful in the neighborhood since the retreat of the ice. Most of these specimens are remarkably fresh; one of them, Dr. Knowlton says, is indistinguishable from recent wood.

Animal life is abundant about Glacier Bay; ravens, gulls, ducks, and ptarmigan were frequently seen, and one humming bird shot past us near the Girdled Glacier. Ground-hogs often startled us with their loud whistle, and traces of mountain goats and wolves were found, but the animals themselves were not seen by my party. Some native hunters seemed to know exactly the size of the flocks on certain mountains. Fish seem to be entirely absent from the upper part of Glacier Bay, but the hair seal is hunted here by the natives. The most interesting animal we saw was a large so-called blackfish, an animal related to the whales.[2] We were on the mountain side near the entrance of Geikie Inlet, about 100 feet above the water, when our attention was attracted by a hissing noise, and looking down we saw a large fish, which we estimated by comparison with our boat to be about 30 feet long, gliding rapidly through the water with no apparent effort. Two or three times it rose to the surface, spouted, and sank again, finally disappearing under the floating ice. It was like looking into a huge aquarium.

The almost continual cold wind from the glacier kept mosquitoes away from Camp Muir, but in some places they were very troublesome. One day on the shore of Geikie Inlet I could not keep still long enough to take a compass bearing without having half a dozen of them alight on my face.

In my former paper I stated that no crevasses were seen in the ice front to extend as low down as the water of the inlet, and that no bergs gave evidence of having come from the bottom of the glacier. In 1892,

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[1] Journ of Geol, Vol III, 1895, pp 527-532

[2] Probably *Globiocephalus scammonii* Cope Dall, Alaska and its Resources, p 578.

however, I did see one or two crevasses which reached the water line, and which must have been, therefore, about 175 feet deep.

The alpine end of the Charpentier Glacier rests on gravels. In the hundred feet or more between the glacier and Hugh Miller Inlet the gravels are streaked with uniform, straight, parallel grooves, a foot or two apart, which looked as if they had been plowed out, and in which flowed the water from the melting ice. I saw a berg in Muir Inlet which, though perfectly clean, had a furrowed surface corresponding exactly to the grooved gravels. This might have been due to unequal melting in the air or water, but the correspondence was so exact that it is highly probable that the berg came from the bottom at a point where the glacier rested on gravels. This is the only indication I have seen that ice ever breaks off from the bottom of Muir Glacier.

Berg Lake, formed by the damming of a side valley by the Endicott Valley ice, had been somewhat drained when I saw it at the end of July, 1892. Stranded bergs showed that the water was not less than 30 feet below its former level, and that this draining was recent was shown by the fact that the bergs had not melted away. The partial discharge of the lake is probably not of infrequent occurrence. The glacier faces the lake in a cliff 50 feet or more high, having a semicircular outline. Behind, the ice is greatly crevassed in concentric lines, and this, with the slope of the surface, shows that the ice is moving toward the lake.

The determination of the horizontal intensity of magnetic force made at Camp Muir in 1890 gave a value of 0.150 c–g–s units. The instrument which was then used was adapted only to determining the period of oscillation, and did not admit of observation of deflections. This was done some time later after my return. In 1892 I took with me the Case School magnetometer (see p. 459), and made a complete determination of this quantity at Camp Muir on August 28. I then obtained a value of 0.147 c–g–s units.

SOUNDINGS, TEMPERATURES, AND ANALYSES OF WATERS, MUIR INLET.

So far as I know, observations on the distribution of temperature and the composition of the water close in front of a tide-water glacier have not been made.[1] My own facilities were so poor that I did not accomplish very much; still, some interesting results were obtained. My apparatus was as follows: Around a wheel 6 feet in circumference was wound the steel sounding wire, about .03 inch in diameter, kept in place by a sheet-iron flange on each side. The axle turned in cast-iron bearings mounted on a simple wooden frame which was fastened to the bottom of our small open boat. At one end of the axle was a crank and handle; at the other was fastened an ordinary speed counter to count the turns of the wheel. On one side the felloes

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[1] Perhaps the Danes have made such observations (See p 457)

extended outside the flange, and in this extension was cut a groove, in which a cord was wound with the two ends fastened to the bottom of the boat; the pressure of the foot against this cord regulated its friction against the wheel, thus controlling the latter's speed. The sounding wire passed from the wheel over a pulley supported by a wooden strip at the stern of the boat, and then into the water. About 15 pounds of iron weights were used as a sinker. With this arrangement a sounding could be very easily made. The wire was allowed to run out about 2 fathoms a second, and was wound in again half as fast.

For temperatures, Negretti and Zambra deep-sea thermometers were used. Three of these instruments were lent me by the United States Commissioner of Fish and Fisheries. The frames with the arrangement for reversing I had made specially. They were of the usual form.

The bottles for collecting specimens below the surface had the form of those described by Lieut. Commander Z. L. Tanner,[1] slightly simplified; they were brass tubes about 10 inches long and 2 inches in diameter. Two light circular discs, with leather washers, connected by a rod, served as valves to close the ends of the tube. When the bottle was descending the valves would open; when at rest they would close by their own weight. A light framework fastened to the top of the bottle carried a screw with vanes so bent that when the bottle began to ascend through the water the screw would be forced down against the valves and hold them tightly closed. The screws of the water bottles and thermometers had ratchets which prevented their turning in the wrong direction; and therefore the reversal of the thermometers would not be delayed, nor the water bottles reopened, if there was an interruption in the steady winding in of the wire.

The method of procedure was as follows: One of the men held the oars and kept the boat as nearly as possible from shifting; the second man managed the sounding wheel; I sat in the stern and attended to the instruments. The thermometer was fastened to the wire by a string covered with rosin, 1 fathom above the sinker, and the water bottle was attached just above this. The position of the boat was determined by compass bearings, and then the wire was allowed to run out. The friction brake acted well; the wheel did not make more than a half revolution after the sinker reached the bottom. The speed counter then gave the depth, which was recorded. Five minutes were allowed for the thermometer to take the temperature of the surrounding water, and the wire was then wound in. The valves of the bottle were lifted and the specimen allowed to flow through a funnel into a numbered glass bottle. The thermometer was read and readjusted, and all was ready for a second determination. The apparatus was compact and worked excellently, the only difficulty being the unsteadiness of the boat, which required us to make our movements with great care.

Twenty-three specimens in all were taken, at five different stations;

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[1] Report of United States Commissioner of Fish and Fisheries, 1883, pp 66–68

these stations are marked in the map, Pl. XCV*a*, by the small letters *b*, *c*, *d*, *e*, *f*, with the corresponding depths in fathoms. On returning home I determined the specific gravities of the clear liquid at the temperature at which it was collected, referred to water at 39° F. (4° C.), by the method of Ditmar.[a] Dr. A. W. Smith, of the Case School of Applied Science, Cleveland, Ohio, then kindly determined the amount of sediment and the amounts of chlorine and of sulphuric anhydride, and the total quantity of solids remaining after evaporation, per hundred grams of the clear liquid. Dr. Smith writes as follows: "The sediment was dried at 100° C. and weighed on a tarred filter. Chlorine was obtained by titrating 10 grams with standard silver nitrate solution, using K_2CrO_4 as indicator. Sulphuric anhydride was obtained by the usual precipitation method, and weighing as barium sulphate; 50 grams of water were taken for this. For solids at a red heat, 10 grams were evaporated in a platinum dish on the steam bath, then carefully heated to a dull red."

The observations and determinations are collected in the table; the numbers of the specimens show the order in which they were collected. The third column gives the depth in fathoms at which the specimen was obtained; the numbers marked with an asterisk (*) are 1 fathom less than the depth of the water at their respective stations.

Table giving analyses of Muir Inlet waters.

Number of specimen	Station	Depth in fathoms	Sediment, grams per liter	Temp., deg F	Sp gr	Cl, grams per kilo	SO_3, grams per kilo	Total solids at red heat, per kilo	Approximate distance from glacier	
									Kilometers	Miles
8	*b*	Surf	.09	37.8	1.0150	10.41	1.074	18.28	5	3
7	*b*	5	6.32	37.7	1.0189	13.10	1.410	22.24		
6	*b*	15	7.28	37.7	1.0186	12.92	1.490	22.86		
5[1]	*b*	30	7.38	37.5	1.0184	12.89	1.468	22.60		
4	*b*	50	7.93	38.3	1.0187	13.03	1.522	22.90		
3	*b*	70	10.88	38.3	1.0185	12.89	1.528	22.76		
2	*b*	98*	7.61	35.7	1.0188	13.06	1.566	22.13		
8′[2]	*b*	93*	..	37.5	..	..	..	.		
13	*c*	Surf	.05	38.4	1.0174	12.11	1.574	20.66	5	3
12	*c*	10	5.28	37.9	1.0193	13.59	1.464	24.46		
11	*c*	30	9.13	37.5	1.0183	12.57	1.522	22.04		
10	*c*	60	12.98	37	1.0163	11.29	1.050	19.51		
9[3]	*c*	102*	12.77	34.5	1.0171	11.61	1.388	19.94		
18[4]	*d*	Surf	.07	36	1.0064	4.39	.522	7.65	1.3	8
17	*d*	10	4.56	38.5	1.0194	13.59	1.618	24.18		
16	*d*	30	6.16	37.5	1.0186	12.99	1.538	22.81		
15	*d*	50	6.41	38.9	1.0193	13.42	1.596	24.20		
14[5]	*d*	84*	7.21	38.5	1.0187	13.03	1.458	22.89		
20[6]	*e*	Surf	.53	36.5	1.0098	6.83	.746	11.90	1.8	1.1
19	*e*	64*		38.5	.	.	..	.		
1[7]	*g*	84*	6.57	39	1.0194	13.49	1.662	23.63	1.8	1.1
22[8]	*f*	Surf	.23	37.4	1.0100	7.08	.800	11.81	2.4	1.5
23	*f*	20	2.94	39.3	1.0208	14.51	1.592	25.11		
21	*f*	55*	4.23	38.9	1.0206	14.37	1.646	24.88		

[1] Collected about one hour before high tide
[2] Collected about one hour after specimen 2, boat must have drifted somewhat
[3] Collected at high tide
[4] Surrounded by ice, strong surface current to westward
[5] Collected two hours before high tide
[6] Collected one hour before high tide, strong surface current to southwestward
[7] Collected at about low tide
[8] Collected a little before high tide

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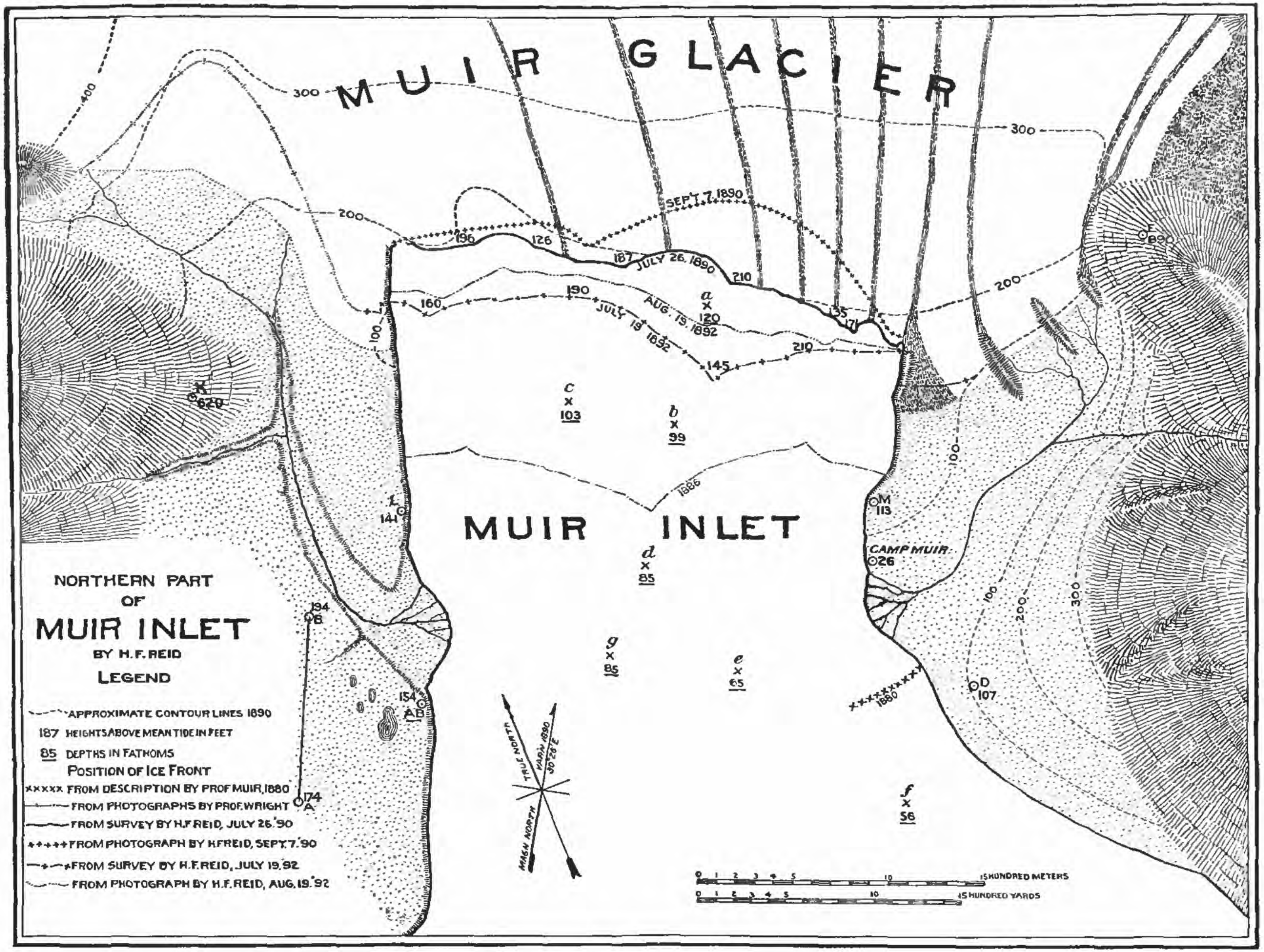
[a] Challenger Reports, Vol. I, p 55



MAP OF MUIR INLET.

Results.—An examination of the table shows:

1. There is on the surface a thin layer of water marked by low specific gravity and salinity. This layer was observed generally to have a strong current out of the inlet. It is thin, for no trace of it is found at a depth of 5 fathoms at *b*, or of 10 fathoms at *c* and *d*. This is evidently the water from the streams and melted ice somewhat mixed with the salt water of the bay.

2. The low temperature, specific gravity, and salinity of the two lowest specimens of station *c*, and the large amount of sediment they contain, show (since these conditions do not hold at *b*) that a subglacial stream empties in this neighborhood.

3. Excepting the waters considered in the last two paragraphs, there is a slight increase in temperature, specific gravity, and salinity as we go farther from the glacier. This simply shows a progressive mingling of the glacier water with the water of the bay. The difference in these quantities between the stations *f*, at a distance of 1½ miles from the glacier, and *b* and *c*, at a distance of one-fourth of a mile, is so small that we are justified in inferring that the water is quite saline and relatively warm in the immediate neighborhood of the ice, and that the melting thus produced is the principal or whole cause of waste near the bottom of the glacier. The rate of waste and the rate of flow determine the distance the ice extends.[1]

4. Except at station *b* the water does not seem to be well mingled, but exists in layers of slightly greater or less salinity. This is well marked at *d*, where the variations in temperature, salinity, and specific gravity seem to show that the incoming tide is thrusting forward a number of tongues as it advances. The differences in specific gravities are not sufficient to produce distinct currents. In calculating the pressures which tend to produce currents we must use the specific gravity of the water with the sediment in suspension. The specific gravities thus determined showed a great uniformity, varying between 1.0222 and 1.0230 in all my specimens except those collected at the surface, which were lighter.

5. The average temperature is about 38°. The lower surface temperatures at *d*, *e*, and *f* are due to streams or melting ice. A temperature of 33.5° was found near Caroline Shoals, in the midst of much floating ice. When the tide is out the ice front shows a recession between tide limits, due to melting under water. The increase in temperature and salinity below the surface makes it evident that this melting is not confined to the limits between which alone it can be seen. The low surface temperatures are not characteristic of the bay generally. At the head of Tidal Inlet I found a temperature of 48°, although the stream from Dying Glacier emptied near by. Bergs in the bay showed the effect of the higher surface temperature there by strongly marked melting just below the water line.[2] (See Pl. XCVI.)

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[1] Nat Geog Mag, Vol IV, p 47

[2] The cause of the low temperature of specimen 2 is not apparent, 8', taken an hour later at nearly the same place, marks 2° higher

6. The amount of sediment increases from the surface downward, and decreases as we go farther from the streams supplying it, as the natural results of settling. Specimen 3 is an exception; there are reasons for questioning the accuracy of this determination, but the matter is not of sufficient importance to state them.

7. The soundings show a considerable depth. The sounding of 120 fathoms at *a* was made by Captain Carroll in 1890, when the ice did not extend as far as in 1892. The other soundings in the inlet were made by me in the latter year. Stations *b* and *c*, about one-fourth of a mile from the ice front, were as near the glacier as I thought it safe to venture. What most strikes us is that the water is deeper near the glacier than farther off. The station marked *g* is the fifth of a series taken from Camp Muir outward, which showed depths of 43, 66, 73, 76, and 85 fathoms, respectively. I have not marked the others on the map, as their positions were too roughly determined. The position of the western subglacial stream makes it probable that a great depth does not occur between *g* and the western shore of the inlet. We have seen that the amount of sediment in the water diminishes as we go farther from the glacier, which means, of course, that it is deposited. We are thus led to infer that the inlet opposite Camp Muir has been filled up to the extent of 15 fathoms or more since the ice retreated from it about 10 years ago. This seems a very rapid rate, but is not without precedent. Professor Brewer[1] states that the depth of a hole in the channel of the Mississippi River near its mouth had been reduced 40 feet by sediment in less than a year, though how much less he does not say. This rapid deposition is due to the presence of salt water, which causes flocculation and rapid settling of the fine sediment. My former estimate was that the streams from Muir Glacier carried into the inlet an amount of fine matter equivalent to the annual abrasion of three-fourths of an inch over the whole bed of the glacier, 350 square miles.[2] If we suppose all of this to be deposited over the 4 square miles of the inlet within 3 miles of the end of the glacier (and this does not seem improbable in view of the small quantity found at *f*, which is 1½ miles from the ice, and which on account of its position just below the eastern subglacial stream is better supplied than the rest of the inlet at the same distance), we should find an annual filling up of 10 feet, assuming that equal parts of the volume of the mud are occupied by water and by the solid particles. This is about the proportion of the volume occupied by the particles in clays.[3] In ten years, therefore, we should have a deposit 100 feet thick. This estimate accounts satisfactorily for the difference in depth observed. It is possible, however, that it is too large (see p. 458). It will be a matter of some interest to see whether this rate of deposit is kept up during the next ten years.

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[1] Subsidence of particles in liquids, Mem Nat Acad Sci, Vol II, 1883, p 170

[2] Nat Geog Mag, Vol IV, p 51

[3] Soil Investigations, by Prof Milton Whitney, Fourth Ann Rept Maryland Agric Exper Station, p. 260

STRANDED ICEBERGS NEAR TIDAL INLET.

Indications of the rapidity of deposition were seen on the beach near Camp Muir. If while the tide was flowing out the water remained undisturbed for an hour or so, the beach was left with a covering of fine mud; but if winds or the calving of bergs produced waves, this mud was carried away and the beach left sandy. Alternations of quiet and disturbance sometimes left bands of alternate mud and sand.

The surface of the north Pacific Ocean opposite our station has a temperature in August of almost 50° F. and a specific gravity of 1.0250.[1] The specific gravities of the denser of my waters when reduced to the same temperature is about 1.0165 (specimen 5).

It will be found by comparison that my waters contain in solution a little more than half as much salts as the waters collected by the *Challenger* in various parts of the ocean,[2] and that the proportion of Cl and SO_3 to the total salts in solution is about the same in my waters and in those of the *Challenger*.

I have, unfortunately, not had access to the original reports of the Danish explorations in Greenland; but Dr. Rink gives a résumé of their work.[3] In the neighborhood of latitude 65° they found in the fiords a temperature ranging from 40° F. to 45° F. at the surface, and 29° to 32° at the bottom. The water was fresher at the surface than at the bottom. The amount of total salts in solution varied from 26.8 grams to 33.5 grams per kilogram, which is somewhat greater than in my specimens. The amount of sediment found in Sondre Stromfiord was only 0.77 grams per liter, about one-tenth of that in Muir Inlet. It is probable that a much smaller amount of water is discharged from the Greenland ice into the fiord named than is discharged into Muir Inlet, resulting in much greater dilution of the sediment. The amount of sediment in a stream flowing into the Isortok Fiord from the inland ice was only 0.44 grams per liter, whereas Professor Wright's examination of the water from a stream flowing from Muir Glacier[4] shows, when reduced to the same units, 12.12 grams per liter. My specimens 9 and 10 contain still more. Does this mean that the rock under the ice in Greenland has been thoroughly cleaned off by the long occupation by the ice and that only a small amount of abrasion is going on there, whereas the short time Muir Glacier has covered its bed has not sufficed to allow it to clear away all the débris, which it is still grinding up and discharging in its streams? This is a question which we can not answer; nor is the information that Dr. Rink gives sufficiently detailed to allow us to draw any very reliable conclusions from the above comparisons. The differences, however, are sufficiently marked to be mentioned. Helland[5] has given the quantity of sediment in the waters from a number of glaciers. In the outlet of the Alangordleck Glacier, in Green-

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[1] Berghaus's Physikal Atlas

[2] Challenger Reports, Vol I, pp 25, 41, and 43

[3] Petermann's Mitteil, 1888, Vol XXXIV, p 69

[4] Ice Age in North America, p 64

[5] Heim's Gletscherkunde, p 363

land, there are 2.37 grams of sediment per liter. In the stream from the Langedal Glacier, in Norway, there is only 0.513 gram per liter. These are the two in Helland's list which, in their respective countries, have the greatest amount of sediment. Both of these determinations were made in July. The stream from the Unteraar Glacier carries 0.142 gram per liter.[1] It appears, therefore, that Muir Inlet and the stream from Muir Glacier are far more loaded with sediment than any other glacial waters so far examined.

Another comparison is interesting. The total amount of sediment annually carried out from the Unteraar Glacier, in Switzerland, equals 6,000 cubic meters (7,850 cubic yards); from the Justedalsbraen, in Norway, 69,000 cubic meters (90,200 cubic yards);[2] and from the Muir Glacier 15,600,000 cubic meters (20,400,000 cubic yards). This estimate for Muir Glacier is based only on summer observations of the amount of sediment in the water, and is somewhat too large; nevertheless, it is strikingly greater than that for the other glaciers mentioned.

TIDAL OBSERVATIONS.

The oscillations of the land in Alaska have not been sufficiently observed to give us any definite information as to what is now taking place. The submerged stumps in Muir Inlet indicate that this region has sunk in comparatively recent time, whereas the raised beaches reported by Mr. Russell in Yakutat Bay mark a recent elevation there.[3] The topographical unity of the St. Elias and Fairweather ranges makes it probable that the latter also is still being or has lately been raised.

In order to aid in the solution of this problem, I decided to make observations which would give the present height above mean tide of a fixed mark in Glacier Bay. I selected a point at the entrance of Tidal Inlet which was well adapted to the purpose. A limestone knoll rising abruptly from the water offered a good surface for the bench mark. A small, steep beach enabled the tide poles to be set up not very far apart, and the natural breakwater around the entrance to the inlet kept the water very smooth, except on one occasion, when waves 3 or 4 inches high interfered with the accuracy of the observations.

The method employed is that given in Sir Wyville Thomson's Voyage of the Challenger, Vol. I, p. 86, which consists of nine observations of the height of the tide, so distributed as to annul the daily solar and lunar inequalities. They are all made in 32 hours and 32 minutes, and their average gives a very fair value for the height of mean tide.

The range of the tide amounted to about 23 feet. We could not take with us a pole of that length, and therefore took two, each 14 feet long. They were placed at different distances from the shore, so that the height of the water could always be seen against one of them. Some-

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[1] Heim's Gletscherkunde, p 363

[2] Ibid pp 363, 364

[3] Nat Geog Mag, Vol III, p 82

times the outer one was completely submerged, sometimes the inner one was high and dry. They were painted white and marked by black lines 2 cm. apart. Three guy-ropes fastened to heavy stones held each pole in place. The observations, which consisted merely in reading the height of the water on the pole, and later determining the vertical height of the bench mark on the rock above this reading, were commenced at 7.45 a. m. on July 9, 1892, and finished the next afternoon. The bench mark is a black cross, each arm 2½ inches long, surrounded by a black circle touching the ends of the arms. A second black circle 26 inches in diameter surrounds the first, the space between the two being painted red. This mark can be easily found; it is on the eastern side of the gray limestone knoll which lies at the southern side of the entrance to Tidal Inlet. Just how long this mark will remain it is hard to say, but the center of the circles can be found even after much of the paint has worn off. It would be well if a future traveler would make a second mark some years hence and determine its height relatively to mine.

The results of my observations show that the center of the cross was 3.668 meters, or 12 feet 5 inches, above mean tide. The observations were made during spring tides; the barometric pressure varied between 30.35 and 30.45 inches. A complete set of these observations has been sent to the United States Coast and Geodetic Survey.

THE SURVEY.

During the summer of 1892 the United States Coast and Geodetic Survey stationed observers at Tacoma, Sitka, and Port Mulgrave to determine the latitude and longitude of the two last-named places and of Mount St. Elias Chronometers were carried by the steamship *Queen* between Tacoma and Sitka. I took advantage of this to compare my chronometer with those on the *Queen* when she was in Glacier Bay on July 28 and August 10. Local time was determined with a 3½-inch Casella transit by altitudes of the sun. The mean of these comparisons gives me for the longitude of Camp Muir 136° 4.1′ W. The latitude, as determined in 1890, is 58° 49.7′ N.

The topographical survey was made with the plane-table, supplemented by transit, prismatic compass, and photographs. It is by means of the latter that I have been able to draw the 500-foot contour lines on the land and the 250-foot contours on the ice. I took these photographs with an ordinary camera, without expecting to measure them; therefore they do not give as accurate results as they would if an especially prepared camera had been used.

The plane table rested on a light aluminum mounting, which screwed on to the tripod of the transit. The latter, made by Casella for the Case School of Applied Science, with 3½-inch horizontal and vertical circles, had the telescope mounted on a brass plate fastened to the divided circle by three screws, so that it could be easily taken off and fastened to the ruler of the plane-table. A second plate, bearing a magnetometer box and telescope, could be mounted on the transit circle. (See p. 452.) This interchange of parts diminished both the cost and the weight of the instruments.

The chief difficulty in the survey arose from our very slow means of travel; this made it impossible in general to place signals at stations before occupying them. It was thus necessary to sight on some prominent object, such as a large rock, which was often difficult to identify on approaching it. Peaks offered the best means of locating a station by Bessel's three point method or by the aid of a bearing which had already been taken. The frequent occurrence of cloudy weather interfered very much with the work.

The line from *E* to *D*, which was determined in 1890, was taken as a base. By triangulation from this the line *C*–*X*[1] was found to be 5,964 meters (6,522 yards); this was the base for the plane-table work. The map was made on a scale of 1.100000 and is reproduced on a small scale as Pl. LXXXVI. It is to be engraved on a scale of 1:250000, and will then become a sheet of the Geologic Atlas of the United States. The region surveyed in 1890 is included in this map. Muir Glacier and the middle part of the bay are more accurately portrayed than the three upper inlets and the region near the bay's mouth.

The Granite Canyon and Endicott Valley moraines, the approximate positions of which were shown in my former map, are now fairly accurately drawn. Three stations were determined on the first of these by the three-point method, and corresponding points on the others were fixed by pacing. The eastern end of Nunatak *I*, where they are all united, was already accurately fixed.

The altitude of Muir Glacier at the divide near Tree Mountain was determined by aneroid barometer. In 1890 we found 1,240 feet for this height; in 1892, 1,400 feet. I have adopted the latter, though it may well be 100 or 200 feet in error. The altitudes of Snow Dome and Tree Mountain have been corrected from my photographs.

The regions in the southeastern and northwestern parts of the map delineated in black are drawn from charts of the United States Coast and Geodetic Survey and from information given in the Pacific Coast Pilot, edition of 1891.

Where possible the names of islands in Glacier Bay were taken from British Admiralty chart "From Port Simpson to Cross Sound." Reid Inlet was named by the United States Board on Geographic Names. Mr. Muir gave many names in this region, and I have retained them all except Main Valley, which I have changed to Endicott Valley, as the stream in it is evidently the source of the Endicott River, emptying into Lynn Canal. I have named the tributaries of Muir Glacier after my companions of 1890.

The soundings in the bay were made by Captain Carroll. They are

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[1] There are two knolls near the southern end of Sebree Island higher than any other part of the island, my station X was on the northern one C is the highest point of Garforth Island

placed only approximately on the map. The numbers indicate the depth in fathoms.

The map of Girdled Glacier (Pl. XCIV) was drawn on a scale of 1:10000 and reproduced on a scale one-half as large. The point on the moraine marked "flag 6" was determined by the three-point method (using peaks c_2, c_5, b_4, and b_7); and bearings were taken on stations *N* and *S*. The station *S* was then completely fixed by the angle measured between flag 6 and peak c_5. This distance from flag 6 to c_5 was taken graphically from my general map. The distances flag 6 to *S* and *S* to *N* were calculated through the proper triangles; the latter (1,228 meters) may be looked upon as the base-line for the survey of the Girdled Glacier moraines. The scale is probably a few per cent wrong. The positions of the flags were found by the transit, and the borders of the moraines in their neighborhood by pacing. The level of the ice just outside the encircling moraines was taken at 1,400 feet. The height of the other points above this were determined by aneroid. The contour lines are only approximate, but can not be far wrong.

SOME ANLOGIES IN THE LOWER CRETACEOUS OF EUROPE AND AMERICA.

BY

LESTER F. WARD.

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ILLUSTRATIONS.

SOME ANALOGIES IN THE LOWER CRETACEOUS OF EUROPE AND AMERICA.

BY LESTER F. WARD.

INTRODUCTION.

The subdivision of the Cretaceous by the English and Continental geologists differs in the one particular, that while the former make the Upper Cretaceous begin with the Gault the latter make it begin with the Cenomanian. The Lower Cretaceous consists in England of the Wealden beds resting upon the Purbeck, and the Neocomian proper corresponding in the main to the Lower Greensand. The Continental geologists usually divide it primarily into the Neocomian and Urgonian, but M. Lapparent subdivides the Neocomian into the Valanginian and the Hauterivian and reduces the Urgonian to the equivalent of the Atherfield and Punfield beds of England, giving the remainder to the Aptian. His Albian corresponds to the Folkestone beds and the Gault.

The object of this paper is to inquire whether the Lower Cretaceous beds of America present any analogies to those of Europe as thus defined. The best known of these are the Potomac formation of the eastern United States and the Comanche of Texas and adjoining States. Even these have been recognized only a short time, and it was formerly supposed that there was nothing in America corresponding to the lower members of the Cretaceous, the Dakota group being placed at the base of our Cretaceous and the Amboy Clays made equivalent to it, both of which were regarded as equivalent to the Cenomanian. Almost simultaneously with the proof of Lower Cretaceous strata in Virginia and Texas came similar proof of their existence in Alberta and on the Queen Charlotte Islands. The former of these districts is that in which the now somewhat well-known Kootanie beds were discovered. More recently the Kootanie formation has been recognized in the United States, viz, on the upper Missouri River in the vicinity of Great Falls, Mont. It is also probable that the lower portion of the Cretaceous of the Black Hills which has yielded gigantic cycadean trunks, much silicified wood, and a large number of fossil plants of Lower Cretaceous types, belongs to the Kootanie formation.[1] Lower Cretaceous strata are also now known to occur on the Pacific Coast, the Shasta formation belonging to that horizon. The Tuscaloosa formation of Alabama and Mississippi was long supposed to lie very low in the Cretaceous, and was definitely correlated by Dr. C. A White[2] with the Potomac formation in Virginia. But large collections of fossil plants from the Tuscaloosa beds prove that they can not be much lower than the Amboy Clays or Raritan formation of New Jersey.

With the exception of the Comanche series and the Pacific Coast deposits above referred to, the paleontological evidence of the age of all these beds is almost exclusively that of their plant remains, and the few shells that occur in them indicate either a fresh-water or brackish-water condition and seem to prove that they are for the most part estuarine or delta deposits. The case is somewhat the same in Europe, the entire Wealden and much of the Neocomian proper being of fresh-water origin, or at least having been deposited in somewhat shallow water. The American beds, except in Texas, consist chiefly of sands and clays, often hardening into sandstones and clay-shales, and are devoid, for the most part, of calcareous matter. In Europe, on the contrary, nearly all the deposits are partially calcareous and there are some true limestones.

Having devoted four years to a somewhat careful study of the Lower Cretaceous of America, and especially of the Potomac formation, but including field studies in the Tuscaloosa formation of Alabama, in the Comanche series of Texas and Arkansas, and in the Kootanie of Montana and the Black Hills, and being somewhat familiar with the rich fossil flora of this general horizon as developed in America, chiefly by Professor Fontaine, Dr. J. S. Newberry, Dr. Arthur Hollick, and Sir William Dawson, I felt more and more strongly the importance of comparing the conditions prevailing in this country with those of England and the Continent. This feeling, taken in connection with the practical necessity of seeing the collections from this horizon in the several museums of Europe, determined me to spend a portion of the past season there in the investigation of this question. What I accomplished was of course very slight, as I was only absent from this country two months, fully half of which was spent in transit and in attending scientific meetings. In fact, the only field work undertaken consisted of three excursions to critical localities, the first to the Isle of Portland, the second to the Isle of Wight, and the third to an important locality near Bologna, in Italy, in the valley of the Reno, where the "Scaly Clays" (*argille scagliose*) are best exposed. In the limited time at my disposal I decided, I think rightly, that the careful examination of a few such classical localities, the most typical of the entire Lower Cretaceous period, would be more profitable than a rapid survey of a much wider

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[1] See Science, New Series, Vol I, New York, February 1, 1895, pp 137-138

[2] Bull. U S Geol Surv No 82 Correlation Papers—Cretaceous, p 217

field without opportunity of closely examining any part of it. The remainder of the time at my disposal was spent in the museums of Europe in an inspection of the important types of fossil plants from this general horizon, especially in the careful study of the cycadean trunks in the British Museum, the Paris Museum, and at the University of Bologna, together with the microscopic preparations that have been made of this class of material. To this I may add here the bare mention of a visit to the south of France to inspect the Lower Cretaceous material lately collected in Portugal and then in the hands of the late Marquis Saporta, of which more will be said later. I shall confine myself chiefly to the three countries mentioned, viz, England, Italy, and Portugal, and speak of them in that order.

COMPARISON OF THE POTOMAC FORMATION OF AMERICA WITH THE WEALDEN OF ENGLAND.

In the last annual report of the United States Geological Survey, pp. 307-341, I have set forth somewhat in detail the stratigraphical relations of the Potomac formation. These need not be repeated here at length, and I shall confine myself to those more general considerations which furnish points of comparison between America and Europe. It is not, of course, to be expected that in countries so remote from each other the more detailed conditions will possess sufficient similarity to admit of comparison, and all that can be claimed, and that which properly constitutes the thesis of this paper, is that there do exist certain very general resemblances between the Lower Cretaceous strata of America and those of Europe. In one sense it is, of course, true that all sedimentary deposits the world over and throughout all geologic time have certain broad characters in common; but it is not with these that I propose to deal, but with characters which, though general in one sense, may be looked upon as specific in another; characters not common to all sedimentation; characters scarcely recognizable in Paleozoic deposits, and also differing widely from what we find in the Tertiary or Pleistocene age, and therefore to some extent confined to the Mesozoic—confined even to the Cretaceous, and in a great degree to the Lower Cretaceous. For example, it would seem that, at the beginning of the period at which the Cretaceous system is by common consent fixed, conditions existed on both sides of the Atlantic favorable to the production of large estuaries or lakes, in which were deposited heavy beds of sands and clays differing radically from anything which had preceded them, as well as from what followed them. In most cases the lower portions of these estuarine, fluviatile, or lacustrine deposits consist mainly of sands, while the upper portion consists mainly of clays; but throughout the sands there occur interstratified seams of clay, and throughout the clays layers of sand, while in general all sands are somewhat argillaceous and all clays somewhat arenaceous. This, as I have shown, is certainly the case in the Potomac formation of the Atlantic border; it is also true of that extension of the Potomac known as the Tuscaloosa formation of the Gulf border. The trans-Mississippi extension of the same system known as the Comanche series differs in the important particular of having heavy beds of limestone; but so far as I am aware the Kootanie formation is nowhere a marine deposit.

We will consider first the Potomac formation and examine a few of the descriptions which have been made of its characteristic materials by those who are most competent to speak in this connection. Prof. W. B. Rogers, when State geologist of Virginia, thus described the sand and sandstones in the vicinity of Fredericksburg:

> In composition they are merely a mixture of quartz and feldspar, in rather loose cohesion—the feldspar often decaying rapidly on exposure. In some varieties, the rounded pebbles are not larger than birdshot; in others, they attain a diameter of many inches. In certain localities, the sandstone has a fine, close texture, suiting it for various useful purposes, and is employed to a considerable extent in building. The quarries in the neighborhood of Fredericksburg and Aquia Creek present beds of great thickness of a homogeneous rock of this description, of which extensive use has been made in some of the public edifices in Washington, Richmond, and elsewhere. In the superior portion of these beds, lignites, silicified wood, and vegetable impressions are, freqnently to be seen.[1]

Prof. William M. Fontaine, describing the coarse sandstones of the James River system, says:

> The greater portion and the finer matter of the beds is a sort of incoherent grit, composed of grains of quartz, particles of feldspar in all stages of decomposition, and scales of mica, all mingled together without sorting and devoid of lamination, forming a mass without bedding, but penetrated by numerous and intricate false-bedding planes.[2]

Mr. W J McGee, in the original paper in which he named the Potomac formation, thus described its general characteristics:

> It is made up of fine, homogeneous, plastic clay, sand of various degrees of fineness, gravel, sometimes coarse and again fine, and occasional bowlder beds, which materials are sometimes indiscriminately intermingled, but generally occur as distinct strata or beds somewhat irregular in altitude, but exhibiting a general inclination of a few degrees to the eastward.[3]

In a notice of the above-quoted work, about the same date, Mr. McGee thus somewhat slightly expands his description of the Potomac formation:

> In structure and composition it is bipartite, the upper portion consisting of highly colored banded and mottled clays, with intercalations of sand and quartzose gravel, and the lower of sand and gravel with intercalations of clay. In both divisions stratification is inconstant and often absent, and the materials are sometimes indiscriminately intermingled. The formation is practically destitute of fossils in the District [of Columbia], but yields abundant plant remains in Maryland and Virginia. It appears to consist of inosculating deltas of the Potomac and other Atlantic

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[1] Geology of the Virginias, p. 70.

[2] Amer. Journ. Sci., 3d ser., Vol. XVII, 1879, p. 230.

[3] Report of the Health Officer of the District of Columbia for the year ending June 30, 1885, Washington, 1886, p. 20.

Coast rivers and the littoral deposits into which they merge, laid down along a bay-indented coast upon a highly inclined and irregular sea-bottom produced by combined depression and seaward tilting of a deeply corroded land surface in late Jurassic or early Cretaceous time.[1]

Describing the Fredericksburg sand in a later paper Mr. McGee says:

> It consists predominantly of locally lithified arkose with abundant pebbles either irregularly disseminated or arranged in bands and beds, and numerous bowlders of gneiss and vein-quartz (quartzite being altogether absent) up to two feet or more in diameter, together with heterogeneous sand containing a considerable element of finely divided diffused clay; while lenticular beds of clay are frequently intercalated in both arkose and sand, and in some exposures constitute the major part of the mass [2]

His latest utterance on this subject, so far as I am aware, is as follows:

> The basal formation of the coastal plain series (the Potomac) outcrops along the fall line from the Delaware to the James as a heterogeneous mass of sand, clay, arkose, and quartzitic or quartzic gravel. The arkose unquestionably represents the neighboring Piedmont crystallines; the quartzite is evidently derived from the extensive Paleozoic beds forming the Blue Ridge; the quartz represents the veins by which the Piedmont crystallines are frequently intersected.[3]

I have myself shown[4] that the Potomac formation consists in its most general aspects, and considered from base to summit throughout its entire extent, of the following subdivisions, which, though not always present at all points, occur in the order named and possess substantially the characteristics assigned to them:

I. *The James River series.*—Beds of dark, sometimes greenish, clay, weathering red or purple. When dark and carbonaceous, usually plant-bearing, often appearing as lenses in heavy beds of coarse sand.

II. *The Rappahannock series.*—Coarse feldspathic sand and sandstone, usually separated by thin layers of more or less argillaceous shale, often plant-bearing.

III. *The Mount Vernon series.*—A local bed of chocolate-colored clay, superposed upon the last-named member, yielding a peculiar flora.

IV. *The Aquia Creek series.*—Alternating sands and clays, the latter laminated and usually plant-bearing, the former much finer and softer than the feldspathic sand of No. II, but consisting largely of that member redeposited.

V. *The Iron Ore series.*—Highly colored, mostly red, purple, or mottled plastic clay, usually massive and nonfossiliferous.

VI. *The Albirupean series.*—Alternating sands and clays, more or less regularly interstratified, the sands much finer than in any of the lower members, the clays often carbonaceous and plant-bearing, sometimes of a light-drab color. At the top of the Albirupean series occurs what I call the Island series, confined to Staten Island, Long Island, Marthas

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[1] Amer Journ Sci, 3d ser, Vol XXXI, June, 1886, p 474

[2] Amer. Journ Sci, 3d ser, Vol XXXV, February, 1888, p 128

[3] Geology of Washington and Vicinity, by W J McGee, etc, Compte rendu du Congrès Géologique International à Washington en 1891, p 237

[4] The Potomac Formation, Fifteenth Annual Report, U S Geol Surv, 1893–94, Washington, 1895, pp 307–397

Vineyard, etc., consisting of reddish clays, in which ferruginous nodules occur holding plant remains. These clays sometimes take the form of red ferruginous shales, usually micaceous, scattered slabs of which found on the beaches of Long Island and Staten Island have yielded fossil plants.

In making the proposed comparisons between the Lower Cretaceous of America and Europe I shall, for the sake of compactness, limit them chiefly to the Potomac formation of the United States and the Wealden of England. Too little is known of the Lower Cretaceous of other parts of America to make it profitable to discuss it, while the deposits classed as Wealden in other parts of Europe are not always satisfactorily identified with the Wealden of England, and an attempt to describe them would add little to what can be gained without this. It is evident that in a comparison of this kind the term Wealden must be given a somewhat wider meaning than that which is now commonly applied to it by the English geologists. That is to say, the scope of the formation will depend upon the point of view from which it is considered. From its fossils alone it is restricted to those deposits which lie between the Purbeck below and the Atherfield and Punfield strata above. But when the subject is considered from the point of view of the origin of the beds and the manner in which they were laid down it becomes impossible thus to restrict it, and we are obliged to embrace under the term Wealden the whole of the Purbeck beds below, and those transition beds above, which do not properly belong to the true marine Neocomian or Lower Greensand. We thus have a clear and well-defined geological unit, although the fossils of the Purbeck indicate that these beds belong to the Jurassic, while those of the transition beds mentioned are very different from those of the Wealden. This affords another good illustration of the importance of the principle of "dual nomenclature" in geology, according to whether we are considering phenomena from the standpoint of age or time, or from the standpoint of geological integrity.

In reviewing the history of the Wealden it will be convenient to look at it from two points of view, viz, first, as to its mode of formation or deposition, including the question of whether the beds are of estuarine, fluviatile, or lacustrine origin; and secondly, as to its materials; under both of which heads I shall give descriptions that occur in works of the prominent geologists of England.

The earlier geologists, who were apt to be influenced by the broader considerations, generally inclined to class the Purbeck with the Wealden. This was notably the case with Dr. Mantell in his numerous works dating back to his Geology of Sussex, 1822; also with Dr. William Fitton in his extended paper on the Strata below the Chalk.[1] Mr. C. J. A. Meyer as late as 1872 also took substantially the same position.[2] Indeed, as

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[1] Trans Geol Soc London, 2d ser , Vol IV, 1835, pp 103-388* (see p 159).

[2] Quart. Journ Geol. Soc London, Vol XXVIII, 1872, p 243.

we shall see, all geologists when discussing the origin of the Wealden beds have been driven to this assumption.[1]

ORIGIN AND MODE OF DEPOSITION OF THE WEALDEN.

For a long period geologists were so intent on determining the age of formations by means of their contained fossils that very little attention was paid to beds in which such fossils were absent. And during about the same period animal fossils were considered to be almost the only ones of any value for this purpose. It is natural, therefore, that geological investigation should have been in the main restricted to marine deposits, and certain beds of great thickness which were not laid down in deep water were largely ignored. Such was the case with the Wealden of England, and but for the circumstance that this formation actually did yield a considerable number of animal remains it would have doubtless been still worse neglected. Dr. Mantell was almost the only one to lay stress on the vegetable remains and to insist that they had a geological importance. The history of American geology has even more strongly emphasized this tendency on the part of geologists to leave out of view the fresh-water deposits of the country, and it is only within quite recent times, and especially since paleobotanists have directed their attention to them, that they have begun to receive adequate consideration. Professor Huxley had observed this tendency, and in his paper on Hyperodapedon read before the Geological Society of London on January 13, 1869, he was led to make the following significant remark:

> At present our knowledge of the terrestrial faunæ of past epochs is so slight that no practical difficulty arises from using, as we do, sea-reckoning for land time, but I think it highly probable that sooner or later the inhabitants of the land will be found to have a history of their own—mixed up with that of the sea, indeed, but independent of it, in some such relation as the histories of England and that of France.[2]

Mr. Godwin-Austen, in the address already referred to, realizes this fact, and expresses himself in the following language:

> Great periods, during which wide marine conditions prevailed, alternated with others of wide terrestrial surfaces. The marine periods, as we measure them by the products of the agents which seas and oceans call into action, must have been of vast duration. In like manner we may feel assured that the great freshwater formations are not, as some geologists have supposed them, mere subordinate parts of the great marine groups, as our "Wealden" of the "Cretaceous," but rather true intermediate groups, of equal geological value with them in the estimate of past time [3]

We may next consider the various expressions of geologists relative to the origin of the Wealden. Dr. Fitton said that "The mode in which the Wealden is disposed, in the southeast of England, accords with the

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[1] See Topley, Geology of the Weald, 1875, p. 321, Godwin-Austen, Brit Ass Rept, 42d Meeting, Brighton, 1872, Pt II, p 93, Phillips's Manual of Geology, Pt II, by Robert Etheridge, London, 1885, p 505

[2] Quart Journ Geol Soc, London, Vol XXV, 1869, p 150

[3] Brit Assn Rept, 42d Meeting, Brighton, 1872, Pt II, p 91

hypothesis of its having originated in a lake of fresh water, or in the estuary of a large river."[1] Dr. Mantell regarded the Wealden as "the delta of a river, composed of the spoils of a vast continent, of which no other vestiges remain."[2] Messrs. Robertson, Murchison, Wood, and Meyer have further ably discussed this question, some maintaining that the Wealden is a purely lacustrine formation, but most of them admitting a greater or less connection of the Wealden waters with those of the sea. The last author named stoutly defends what he calls the fluvio-lacustrine character of the strata, and remarks:

> To the fluvio-lacustrine origin of the Wealden strata which I propose to advocate, many objections may of course be raised; but these I shall not anticipate, the objections to their purely fluviatile or estuarine origin appearing to me to be of greater weight. The exceedingly quiet deposition of much of the sedimentary strata, the almost total absence of shingle, the prevalence, both numerically and specifically, of such species of mollusca as delight most in quiet waters, the comparative absence throughout the greater portion of the series of broken shells such as always abound in tidal rivers, and, I believe I may say also, the total absence of any trace of drift-wood perforated by mollusca in either the Purbeck or Wealden strata, all seem to me to point to the same conclusion—namely, to the accumulation of such strata beneath the waters of a wide but shallow lake, whose superfluous waters during the middle Wealden era escaped, indeed, to the sea, but only by some narrow outlet, and whose area was perhaps occasionally, though rarely, invaded by the ocean[3]

Judging from these statements and many others that might be adduced, it seems sufficiently clear that the Wealden of England, in the broad sense in which I use the term, can not widely differ in its mode of deposition from the Potomac formation of the United States, which is usually referred to as of estuarine or fluviatile origin, and which is in fact undoubtedly a combination of these two, the waters of the Potomac sea having consisted chiefly of extended estuaries similar to the Chesapeake and Delaware bays, which may be regarded as simply the widening of the principal river systems (Susquehanna, Delaware, etc.) flowing into them. The evidence in the case of the Potomac formation points much more clearly to this condition than it does either to a purely lacustrine origin or to a delta formation; although there may have been at places bodies of waters which were not thus entirely open to the sea but which possessed a somewhat constricted outlet, while at other points the deposits may have been near the head of these great estuaries, where the conditions partake more nearly of the character of a delta.

The remarkable fact is that the two great deposits on the east and the west sides of the Atlantic were, so far as can be judged from all the evidence at hand, practically synchronous. It is true that in the Potomac formation we have thus far discovered no beds whose organic remains prove them to have been actually Jurassic in age correspond-

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[1] Trans Geol Soc , London, 2d ser , Vol IV, 1835, p 324

[2] Geology of the Isle of Wight, London, 1847, p 65

[3] Quart Journ Geol Soc., London, Vol XXVIII, 1872, p 243

ing to the Purbeck; but it is also probably true that we have never as yet found any exposures of the absolute base of the formation, and there is much evidence to show that the lowest beds known are still further underlain by thick deposits of unknown character which could only be discovered by borings farther out on the coastal plain than any that have yet been made. This is because the deposits were formed during a period of loading and consequent subsidence, as a result of which the landward margin has the form of a wedge, those deposits nearest the margin being of a later date than those formed farther out in the Potomac sea.

LITHOLOGICAL CHARACTER OF THE WEALDEN.

Having thus seen that the Potomac and the Wealden are not only practically of the same age but also of the same empeirogenic origin, we will next consider their stratigraphical and lithological character. The Purbeck beds, which constitute the lowest deposits of the greater Wealden, are best exposed on the Isle of Portland and the Isle of Purbeck. They have been so frequently described and are so well known to geologists generally that it scarcely seems necessary to dwell upon them, and it need only be said that they consist of fresh-water limestones, clays, shales, and sandstones, and include two very remarkable swamp deposits known as the "dirt beds," which have furnished the well-known trunks of cycads, and in which are inserted the roots of great coniferous trees, whose trunks rise above the overlying shales and have been an object of interest for ages. The apparent distinction between the Purbeck and any known deposit of the Potomac by the occurrence in the former of calcareous deposits is in a great measure removed upon the hypothesis that the lime occurring in these deposits is not the result of organic life at the period, but is merely derived by erosion from the underlying limestones of the Portland.[1]

The Wealden proper consists, as already remarked, of alternating beds of sands and clays, of which the sands predominate below and the clays above. The lowest beds were called the Hastings Sands by Dr. Fitton in 1824, as a substitute for the less correct names, "ferruginous sands" and "iron sands," which had previously been applied to them. These are now further subdivided and are found to contain clay seams of considerable thickness, notably the Wadhurst Clay, interstratified between the Ashdown Sand and the Tunbridge Wells Sand. Dr. Fitton says: "The Hastings sands in the Isle of Wight may be described as consisting of an alternating series of beds of sand,—more or less abundant in ferruginous matter, and containing courses, generally in concretional form, of calcareous grit,—with beds of clay, much mixed with sand, of a greenish or reddish hue, or of a mottled and variegated appearance."[2] Mantell's description of the Tilgate Grit and Hastings

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[1] See Godwin Austen in Brit Ass Rept, 42d Meeting, Brighton, Pt II, 1872, p 93

[2] Annals of Philosophy, Vol VIII, New Ser., London, 1824, p 377

Sands is as follows: "Fawn-colored sand and sandstone; with beds of calcareous grit; blue clay, marl, and lignite."[1]

It is remarkable that this basal sand of the Wealden, like that of the Potomac, is often indurated into a sand rock, which in both cases sometimes becomes a workable freestone and is used for building purposes; although in neither case is this building stone of a very excellent quality.

The so-called Weald Clay, which succeeds the lower and more sandy deposits, bears perhaps a still greater resemblance to the red and mottled clays of the upper portions of the Potomac than do the Wealden sands to the Potomac sands. It was this that particularly struck me on my visit to the Isle of Wight. Before examining the Wealden deposits I had seen the celebrated cliff at Alum Bay, which has been so often compared by American geologists with the cliff at Gay Head, Marthas Vineyard. The resemblance is certainly striking at first glance, but a careful examination quickly indicates radical differences. On the contrary, the more one studies the red clay of the Wealden on the southwest side of the island the greater the resemblance becomes, not especially with the beds of Gay Head, which are so considerably tilted as to render the comparison less exact, but with the vast masses of this highly-colored clay that occur in the Potomac formation in Delaware and Maryland. The principal distinction is in the greater degree of lamination in the Wealden strata; but almost complete identity presents itself in cases where these strata have been broken down and lie in the form of talus at the base of the cliff. Where this talus is of long standing an alteration has taken place which renders the mingled materials far more homogeneous, gives the clays a much more plastic character, and distributes the color in streaks and blotches precisely similar to those of the Potomac mottled clays. This fact strongly suggested to my mind that the greater part of our Potomac clays of this character may have undergone a secondary deposition, and there are many other facts that tend to confirm this view. The descriptions of the mottled clays of the Wealden that we find in the books are sufficient of themselves to suggest to the student of the Potomac formation a close relationship. It is often referred to as "variegated clay," but where more specifically described the numerous hues of red, pink, purple, etc., are always mentioned.[2]

It is not to be expected that the special subdivisions of the Wealden and Potomac could be made to correspond any more nearly than is indicated by the general statement already made that the sands predominate below and the clays above. Clay seams are found quite low down in the lowest members of the Wealden, but nothing would be

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[1] Geology of the Isle of Wight, 1847, p. 63

[2] See Fitton, Trans Geol Soc, London, 2d ser, Vol IV, pp 185, 199, 200, Mantell in Quart Journ. Geol Soc, London, Vol II, 1846, p 92, Frederick Drew, op cit, Vol XVII, 1861, p 273, Meyer, op cit, Vol XXVIII, p 247, Topley, Geol. of the Weald, 1875, pl v, facing p 4, p 96, Bristow, Geology of the Isle of Wight, 2d ed, 1889, pp. 3, 5, 6, 15, 16

GEOLOGIC MAP OF SOUTH EAST OF ENGLAND

A. Hoen & Co. Lith. Baltimore.

gained by attempting to compare these with the heavy beds of greenish and purplish clays that lie at the present known base of the Potomac.

If we assume that the Purbeck beds correspond to buried portions of the Potomac which have not yet been brought to light, the corresponding parts of the Wealden, looked at from below upward, are: (1) the Ashdown Sands, 400 or 500 feet; (2) the Wadhurst Clay, 120 to 180 feet; (3) the Tunbridge Wells Sand, 140 to 380 feet; and (4) the Weald Clay, 1,000 feet.[1]

My own estimate of the thickness of the Potomac formation, as made in the last Annual Report, footed up 1,175 feet,[2] of which over 500 feet are assigned to the lower or more sandy portions; but in the Potomac formation there is evidence of great erosion during the period, and if all could be measured there is no doubt that the thickness would be increased to 1,500 or 2,000 feet. The measurements of the Wealden have been increasing from year to year, that of Etheridge in 1885 bringing it up to 1,800 feet; the more elastic estimate of Geikie, just given, would make it range between 1,660 and 2,060 feet. In general, then, it may be safely said that so far as is at present known the Potomac formation of the eastern United States and the Wealden formation of England are of practically the same thickness.

So far as the Atherfield and Punfield beds are concerned, they may be compared with certain partially marine deposits, immediately succeeding the highest Potomac beds. There is much evidence that the process of deposition was not abruptly changed in passing from the one to the other. There are certain localities, as on the eastern shore of the Chesapeake and on the south side of Raritan Bay, where this gradual transition is very noticeable, the Clay Marl of the New Jersey geologists (Matawan formation of Clark) being, at least at its base, only slightly glauconitic, and containing abundant lignite and other vegetable remains and a very meager fauna. It must not, however, be inferred that these American transition beds are of the same age as the Atherfield and Punfield beds of England. They correspond more closely with the Upper Greensand, which is regarded as of Cenomanian age, or Upper Cretaceous, and there seems to be nothing in England at all analogous to our Newer Potomac, which is about the age of the Gault.

In searching for a map of the Wealden of England I have not been able to find one among the more recent works that seemed to serve the present purpose as well as that of Dr. Fitton, published in connection with the paper I have so often referred to on the "Strata below the Chalk."[3] The essential portion of this map is given in Pl. XCVII.

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[1] Archibald Geikie, Text Book of Geol, 1882, p 817

[2] Fifteenth Ann Rept U S Geol Surv, 1893-94, pp 339, 340, fig 3

[3] Trans. Geol Soc, London, 2d ser, Vol IV, 1835, pl ix

The Isle of Wight has entered so largely into the foregoing discussions that I have thought it appropriate to exhibit a small map of it. Here again I have found the more modern maps too detailed for my purpose and have used the excellent one that accompanies Dr. Mantell's Geology of the Isle of Wight (see Pl. XCVIII).

I have also reproduced from the same work his ideal section of the dynamic conditions attending the deposition of the Wealden beds (see Fig. 67).

COMPARISON OF THE FOSSIL FLORAS

The Lower Cretaceous of England, while much richer in animal remains, is far less rich in vegetable remains than that of America. In fact, so few of the former have been found in this country, and these few have so little significance for geology, that any comparison that might be undertaken would be of slight value. Still the few vertebrate remains found in the Potomac formation of Maryland are of Saurian types not widely different from those of the English Wealden. It will, therefore, be necessary to limit the comparison to the floras of these respective areas. In America nearly a thousand different forms of vegetable life have been brought to light, many of which remain to be described, but over eight hundred species are already recorded in the different memoirs thus far published and in preparation, more than seven hundred of which are embraced in the Potomac flora. These are from a considerable number of horizons extending from the Basal beds of the James River to the uppermost deposits of the Raritan formation, which must lie very close to the line that should mark off the Lower from the Upper Cretaceous. In these upper beds we have, as has been shown in the paper already referred to,[1] a great dicotyledonous flora which has no representative in the English Lower Cretaceous. The few forms that have been collected from the Upper Greensand and Gault in England are nearly all coniferous, and thus far not a single dicotyledonous form has been reported from that country below the Eocene. Our comparisons will therefore be practically with the Older and Middle Potomac, the Trinity of Texas, and the Kootanie of the Northwest. As a basis for the discussion I introduce here a table of the Wealden flora, as complete as I am able to make it at this date, showing its distribution not only in America, but in other parts of the

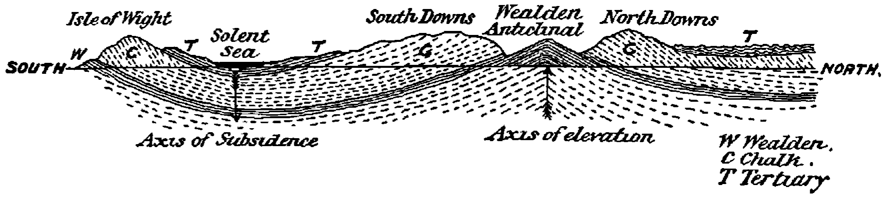

FIG 67 —Ideal section of the Wealden of England, from Mantell's Geology of the Isle of Wight, 1847.

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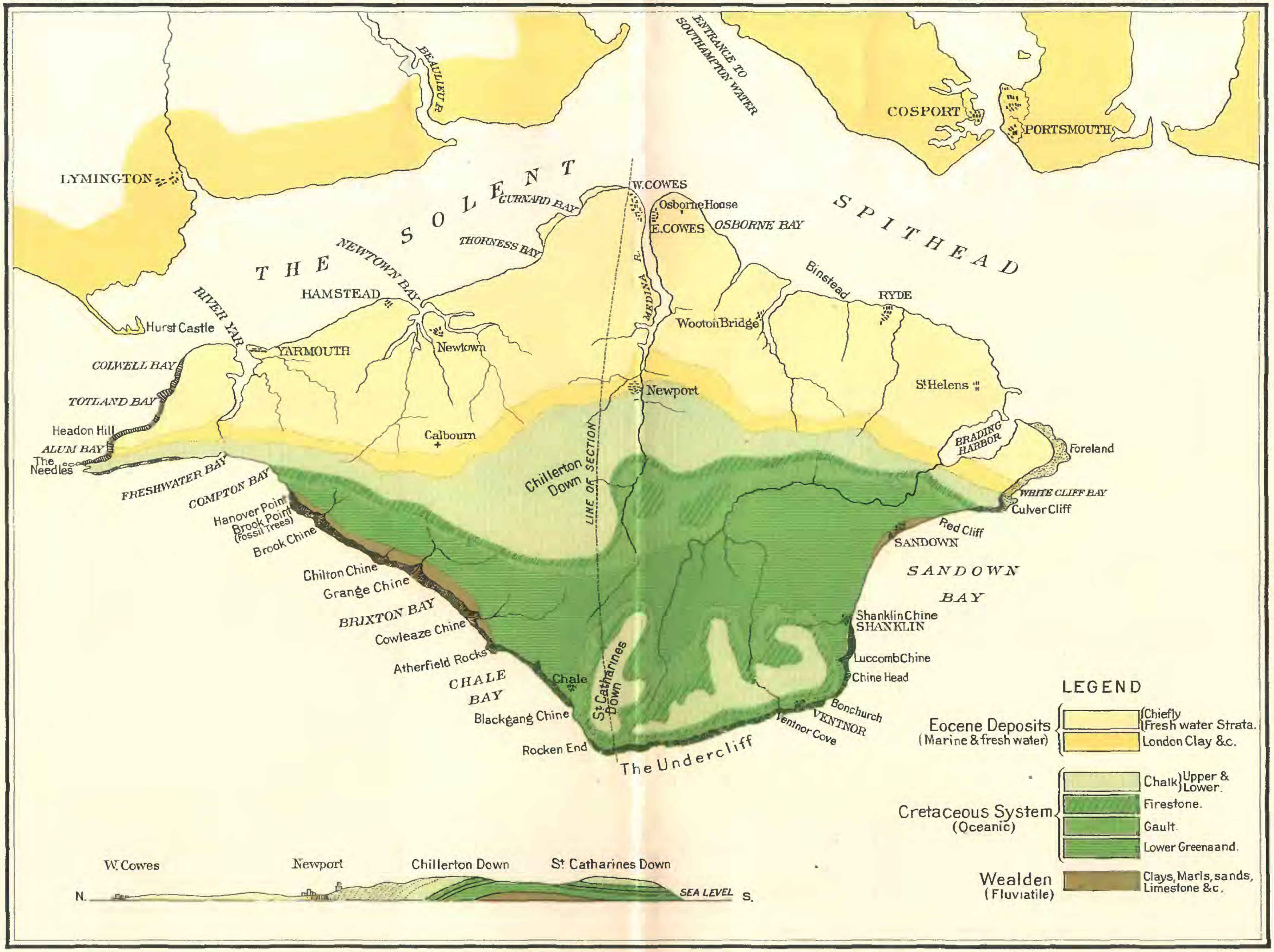
[1] Fifteenth Ann. Rept U S Geol Surv, 1893-94, pp 307-397



GEOLOGIC MAP OF THE ISLE OF WIGHT.

A. Hoen & Co. Lith. Baltimore

world. Eighty distinct forms are embraced in this list. They include 2 algæ, 2 fucoids, 1 hepatic (*Marchantites Zeilleri* Seward), 1 Chara (*C. Knowltoni* Seward), 3 equiseta, 23 ferns, 22 cycads, 24 conifers, 1 monocotyledonous plant (*Dracæna Benstedi* Koenig), and some undetermined seeds.

This list will probably be considerably extended when Mr. Seward shall have completed his studies of the Wealden flora, of which he has thus far published only the cryptogamic species.[1] He will doubtless also find reason for making extensive changes in the names here introduced, some of which are very old and badly in need of revision. Mr. Seward has confined himself exclusively to the Wealden in its restricted sense, and the bulk of the material at his disposal has been recently collected by Mr. P. Rufford from beds in the vicinity of Hastings. He has, however, worked over all the old material in the British Museum, and done the best that was possible with the older collections of Mantell, Webster, Fitton, and Buckland, and has embodied the later researches of Carruthers and Gardner. Unfortunately, however, many of the old types are lost, or at least their whereabouts are not now known, so that when not figured their identification is difficult.

I have in this table, as in the foregoing geological discussion, taken the broader view of the Wealden, and included the Purbeck beds below and the Atherfield beds above, and in order better to compare the flora with that of the United States I have included the Lower Greensand and the Gault. These constitute the first six columns of the table, in immediate juxtaposition with which I have placed the Lower Cretaceous of the United States, arranging the Potomac beds in their ascending order (James River, Rappahannock, and Aquia Creek), followed by the Trinity and the Kootanie, in all of which English Lower Cretaceous plants occur. The Kootanie of Canada is doubtless the same in age as that of Montana, and I have not therefore thought best to give it a separate column. In order to bring the most nearly related beds as close together as possible I have made the general distribution begin with the Wealden, and find it to include France, Germany, Austria, Moravia, and New Zealand. Then follow those deposits which are classed as Neocomian in Westphalia, Portugal, and Russia, the Urgonian of Portugal, Austrian Silesia (Wernsdorf beds), and Greenland (Kome beds), the Aptian and Albian (Gault) of Portugal, and the Gault of England (Folkestone), Belgium (Hainaut), and Westphalia, terminating the comparison with the equivalent Lower Cretaceous deposits. The distribution, however, extends to the higher Cenomanian deposits of England (Upper Greensand), Saxony (Niederschoena), Bohemia, and Greenland (Atane), and to the Senonian of Germany (Westphalia, Blankenburg).

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[1] Catalogue of the Mesozoic Plants in the Department of Geology British Museum (Natural History). The Wealden Flora, Part I Thallophyta Pteridophyta, by A C Seward, London, 1894

Table of distribution of the plants of the Lower Cretaceous of England (Purbeck to Gault, inclusive).

Species	Lower Cretaceous of England						Lower Cretaceous of the United States					Wealden					Neocomian			Urgonian			Aptian of Portugal	Gault or Albian			Cenomanian					Senonian of Germany	Buntersandstein of Alsatia	Rhetic of Bavaria	Lias			Lower Jurassic			Oolite		Upper Jurassic	
							Potomac																																					
	Purbeck	Hastings Sands	Weald Clays	Atherfield beds	Lower Greensand	Gault	James River	Rappahannock	Aquia Creek	Trinity	Kootanie	France.	Germany	Austria	Moravia	New Zealand	Westphalia	Portugal	Russia	Portugal	Austrian Silesia	Greenland		Belgium	Westphalia	Portugal	England	Saxony	Bohemia	Portugal	Greenland				England	Bornholm	Hungary	China	India	Australia	Yorkshire	Spitzbergen	Portugal	Japan
Acrostichopteris Ruffordi Sew.		+																																										
Algites catenelloides Sew.		+																																										
valdensis Sew.		+																																										
Araucaria pippingfordensis (Ung.) Schimp.		+	+										+																															
Araucarioxylon antediluvianum Ward	+																																											
Wallacei Kn.	+																																											
Webbii Kn.			+																																									
Bucklandia anomala (Stokes & Webb) Presl		+	?																								+																	
Mantelli Carr.		+																																										
Chara Knowltoni Sew.		+	+																																									
Cladophlebis Albertsii (Dunk.) Brongn.		+											+									+						+	+		+								+					
Browniana (Dunk.) Sew.		+					+	+	?		+		+					+	+									+															+	+
Dunkeri (Schimp.) Sew.		+					+	+			+		+					+		+			+	+																	+	+		+
longipennis Sew.		+																																										
Coniferous wood	+			+	+	+																					+																	
Cycadeoidea Carruthersi Ward	+																																											
Gibsoni (Carr.) Ward					+																																							
inclusa (Carr.) Schimp.					+																																							
maxima (Carr.) Solms					+																																							
megalophylla Buckl.	+																																											
microphylla Buckl.	+																										?								?									
Morierei (Ren.) Ward	+																																											
portlandica (Carr.) Solms	+																																											
Saxbyana (R. Br.) Moir			+																																									
Cycadeostrobus Brunonis Carr.			+																																									
crassus Carr.		+	+																																									
elegans Carr.			+																																									
ovatus Carr.			+																																									
truncatus Carr.			+																																									

tumidus Carr.			+																																									
Walkeri Carr.			+		+																																							
Dictyophyllum Rœmeri Schenk		+											+																							+								
Dioonites Brongniarti (Mant.) Schenk		+	+										+																															
Dracæna Benstedi Koenig					+																																							
Equisetites Burchardti Dunk.		+	+									+	+	+				+														+												
Lyelli (Mant.) Morr.		+						+			+																																	
Yokoyamæ Sew.		+	+										+																															
Fittonia squamata Carr.			+		?																																							
Fucoides bignoriensis Mant.					+	+																					+																	
sp. Bristow				+	+																																							
Marchantites Zeilleri Sew.			+																																									
Matonidium Gœpperti (Ett.) Schenk	+	+											+					+	+				+	+										+							+			
Microdictyon Dunkeri Schenk		+											+				+												+															
Nathorstia valdensis Sew.		+											+															+																
Onychiopsis elongata (Geyl.) Yok.		+											+																									+						+
Mantelli (Brongn.) Sew.	+	+							+	+			+	+	+			+		+			+	+				+											+				+	
Phyllopteris acutifolia Sew.		+																																										
Pinites Andræi (Coem.) Gardn.						+																		+																				
Benstedi (Mant.) Endl.					+																																							
Carruthersi Gardn.			+																																									
cylindroides Gardn.					+																																							
Dunkeri Carr.		+	+																																									
Fittoni (Ung.) Carr.	+																																											
gracilis Carr.						+																																						
hexagonus Carr.						+																																						
Leckenbyi Carr.					+							+																																
Mantelli Carr.					+	+																																						
oblongus (L. & H.) Endl.					+							+																																
patens Carr.					+	+																																						
pottoniensis Gardn.					+																																							
sussexiensis (Mant.) Brongn.					+																																							
valdensis Gardn.			+																																									
Protopteris Witteana Schenk		+											+																															
Pterophyllum schaumburgense Dunk.		+											+																															
Ruffordia Gœpperti (Dunk.) Sew.		+											+					+	+	+				+				+	+												+			+
Gœpperti latifolia Sew.		+																																										
Sagenopteris Mantelli (Dunk.) Schenk		+											+	+															+															
Seeds			+	+																																								
Sequoites Gardneri Carr.						+																																						
ovalis Carr.						+																																						
Sphenolepidium Kurrianum (Dunk.) Heer		+					+	+	+				+				+	+		+			+														+							
Sphenopteris Fittoni Sew.		+										+				+																											+	
Fontainei Sew.		+																																										
Tæniopteris Beyrichii (Schenk) Sew.		+											+																															
Beyrichii superba Sew.		+																																										
Dawsoni Sew.		+																																										
Tempskya Schimperi Corda		+	+										+																				+											
Thuyites sp. Bristow			+																																									
Weichselia Mantelli (Brongn.) Sew.		+	+	+	+							+	+	+			+		+		+			+	+			+				+												
Yatesia Yatesii (Carr.) Ward		+																																										

The Triassic and Jurassic distribution embraces the Buntersandstein of the Vosges, the Rhetic of Bavaria, the Lias of England, Bornholm, and Hungary, the Jurassic beds of China, India, and Australia, whose proper position it is difficult to assign, the Oolite of Yorkshire and of Spitzbergen, the Upper Jurassic beds of Portugal, which are perhaps the equivalent of the Kimmeridge clays, and those Mesozoic deposits of Japan from which Yokoyama and Nathorst have obtained so many fossil plants, and which may prove to belong to the Neocomian, but are probably extreme Upper Jurassic.

A glance at the table will show which plants possess a wide geographical distribution, and also which have an extended geological range. It will also make clear the relationships of the Wealden to the American floras. Mr. Seward has given this question special attention, and has shown that a number of Potomac ferns are common to the Wealden of England; such are especially the *Cladophlebis Browniana* (Dunk.) Seward, and *C. Dunkeri* (Schimp.) Seward, and the *Onychiopsis elongata* (Geyl.) Yok. (now made to include part of *Sphenopteris Gœpperti* Dunk.), *Dicksonia elongata* Yok., and *Thyrsopteris elongata* Geyl. He also maintains that the widely diffused *Thyrsopteris rarinervis* of Fontaine is identical with this species. In marking the distribution of this plant I have not accepted this decision as final. When he comes to discuss the coniferous species he will probably cause the connection between the Wealden and the Potomac to appear still more close by tracing in many cases the relationships of the English forms to those of America.

CYCADEAN TRUNKS.

Special attention should be called to the cycadean vegetation. Since the great cycad forest of the Black Hills of South Dakota was discovered,[1] and since the extraordinary development of cycadean vegetation in Maryland has been made known by Mr. Arthur Bibbins,[2] the interest in this group of plants has been greatly increased. As nearly all of this new American material had come into my hands for study, and as none of the Old World specimens, long ago described, were accessible for comparison, I felt the necessity of laying special stress upon this aspect of my work in Europe. Accordingly, I not only examined all the material in the British Museum, including the microscopic sections that had been prepared by Mr. Carruthers and those of Count Solms-Laubach, which Dr. Scott of the Jodrell laboratory at Kew kindly permitted me to see, but I also made an excursion to the Isle of Portland, and examined the celebrated "dirt beds" from which the original specimens first described by Buckland in 1828 were obtained. On this excursion I had the great pleasure of being accompanied by Dr. Alfred Russel Wallace, and we were so fortunate as to find a specimen of *Cycadeoidea microphylla* Buckl. in one of the quarries. It had been

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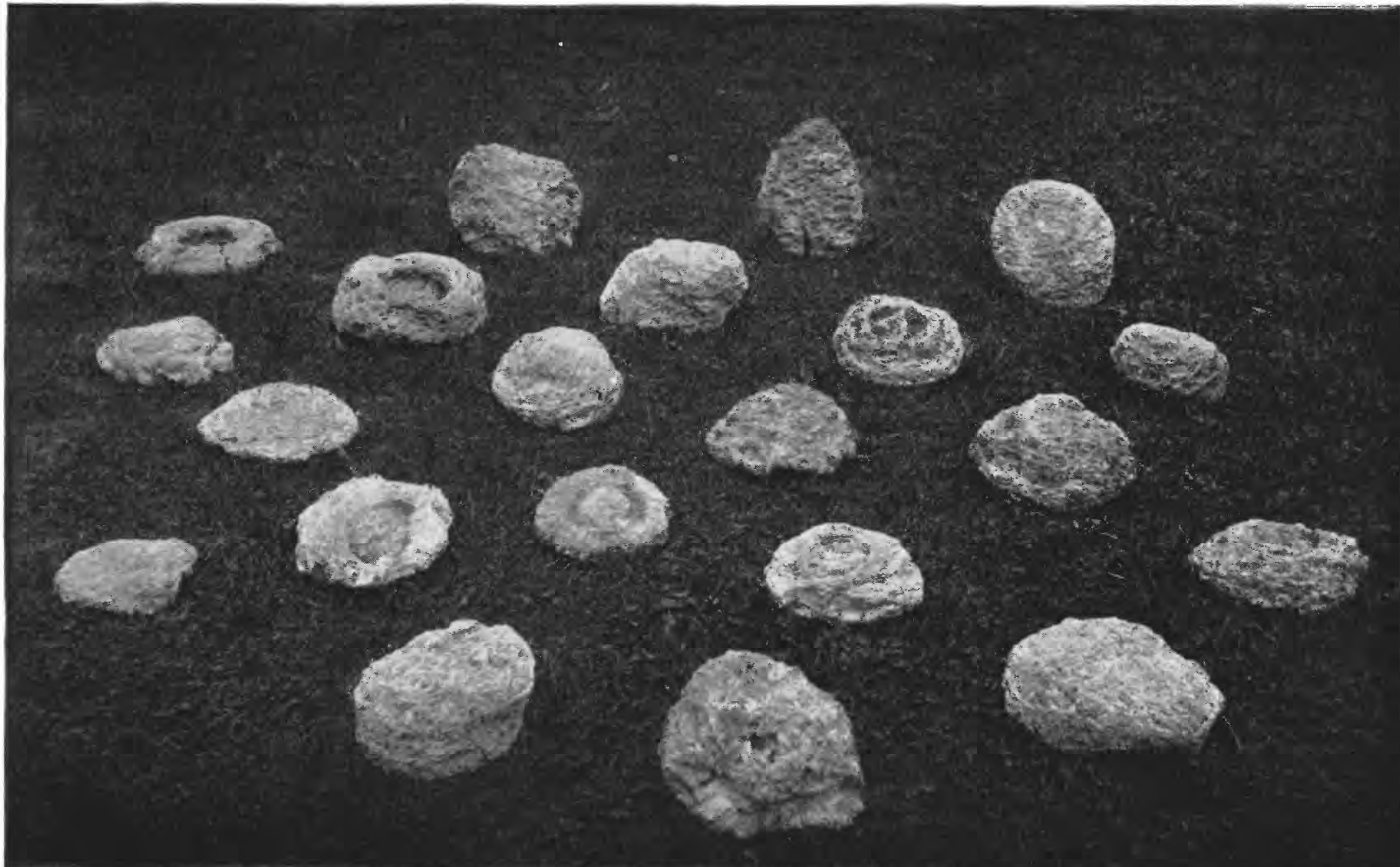
[1] Proc Biol Soc, Washington, Vol IX, 1894 pp 75-87

[2] Bull Torr Bot Club, Vol. XXI, No 7, July 20, 1894, pp 291-299.



GROUP OF 21 CYCADEAN TRUNKS FROM THE PURBECK BEDS OF THE ISLE OF PORTLAND removed from the immediate bed in which it was found and lay on the ledge of stratified rock almost immediately over the exposure. We subsequently met Mr. Joseph Sansom, superintendent of the quarries, who had been in the habit for a long time of laying aside any fossils that were taken from the quarries, and had placed a large number of objects of various kinds in a tunnel under Wide street between two quarries. Among these were a considerable number of cycadean trunks, some of them very perfect. We were much surprised to find this fine collection, of which nothing seemed to be known in London. On my return to America I represented this condition of things to the assistant secretary of the Smithsonian Institution, Prof. G. Brown Goode, and was able to give a rough estimate of what they would cost if purchased by the National Museum. Professor Goode warmly seconded my suggestion that they be ordered, and negotiations were immediately entered into for their purchase. The ultimate result has been that the entire collection, consisting of twenty trunks, is now the property of the United States National Museum. The specimen found by Dr. Wallace and myself was taken to his cottage in Parkstone, and when the shipment was made by Mr. Sansom, through the kindness of Dr. Wallace this specimen was included and arrived with the others. This group of twenty-one trunks has been photographed, and Pl. XCIX will afford a rough idea of a cycadean forest in Purbeck time. I have not yet had time to give this collection the careful study that it deserves, but it is certain that we have both the original species of Buckland (*Cycadeoidea megalophylla* and *C. microphylla*), and probably one or two other species. Most of them show the "crow's nest" distinctly, and those of the first-named species very closely resemble the original figured by Buckland.[1] None of the specimens of *C. microphylla* very closely resemble Buckland's figure (pl. xlix, fig. 1), and it may be said in general that the external surface in all these specimens is more obscure than his figures seem to indicate for the original ones. Most of them are of a light color, showing their contact with the limestone very distinctly, but in one or two cases they have the dark carbonaceous color of the "dirt beds." They are mostly much compressed vertically so as to appear squat and dwarfish. The smallest one is less than 3 inches high and more than twice that breadth. The one having the largest diameter, nearly 12 inches, is less than 4 inches high, and the large crow's nest makes a depression of nearly 2 inches on the upper side. This one was broken in transit into a number of segments, and the fracture affords the only opportunity I have had of examining the internal structure. Without polishing, the principal fact which it reveals is the course of the vascular bundles passing out from the center in fine white lines. There has not yet been time since the arrival of this collection for any sections to be cut or microscopic study made. They average considerably smaller than the specimens

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[1] Trans Geol Soc, London, 2d ser, Vol II, 1828, pl xlvii, fig 3

mentioned by Buckland and Fitton. The former says that "In the fossil specimens yet discovered, it [the trunk] varies from 5 inches to a foot in height, and from 8 to 15 inches in diameter";[1] and Fitton says that "The Cycadaceæ found in the 'black dirt' are generally from 9 inches to a foot in diameter, and about 9 or 10 inches high."[2] The ten specimens in this collection that certainly belong to *C. megalophylla* range from 3 to 6 inches in height and from 5 to 12 inches in diameter. Six or seven specimens, including the one found by Dr. Wallace and myself, doubtless belong to *C. microphylla*, and have a somewhat different shape, being considerably higher in proportion to their thickness. These range from 5 to 9 inches in height and from 7 to 10 inches in diameter. The smallest specimen weighs 5 pounds and the heaviest 29¼ pounds.

I should add that there are two specimens that certainly do not belong to the two original species; one of them is very well preserved, and though flattened laterally has a symmetrical conical shape. It is 13½ inches high and the two diameters are respectively 6 and 9 inches. I have no doubt that it belongs to *C. portlandica* of Carruthers, and his fig. 1, on pl. lxi of his memoir,[3] is a fairly correct representation of it, although Mr. Carruthers was able to show more definite structure on the external surface than can be seen on this specimen. Still, so far as the markings are visible, they agree substantially with those of his figure. This specimen is readily distinguished from the rest in the group (Pl. XCIX) in rear a little to the right of the center. The other specimen is smaller and much less perfect, but probably also belongs to the *C. portlandica*, although its internal structure may possibly prove to be that of *C. Morieri* Renault sp.,[4] which it resembles externally. In that case the collection would contain all the species of Cycadeoidea that have ever been described from the Purbeck beds, except the rare *C. Carruthersi*, of which no figures have appeared to indicate its form. As already stated, I saw at the British Museum on the occasion of my visit the greater part of these species, and judging from the notes taken and from my recollection of their appearance the new collection is fully equal in variety and importance to the one from this locality in that museum, as the originals of Buckland's species are not there and seem to be lost. These specimens are of special interest in comparison with the American forms, of which a similar group is exhibited on Pl. C, from the Potomac of Maryland, and another on Pl. CI, from the Black Hills; but the English forms cut a sorry figure by the side of our gigantic trunks, the largest of which stands 31 inches in height, measures 26 inches in diameter, and weighs 721 pounds.

Besides the two old species of Buckland above mentioned, three

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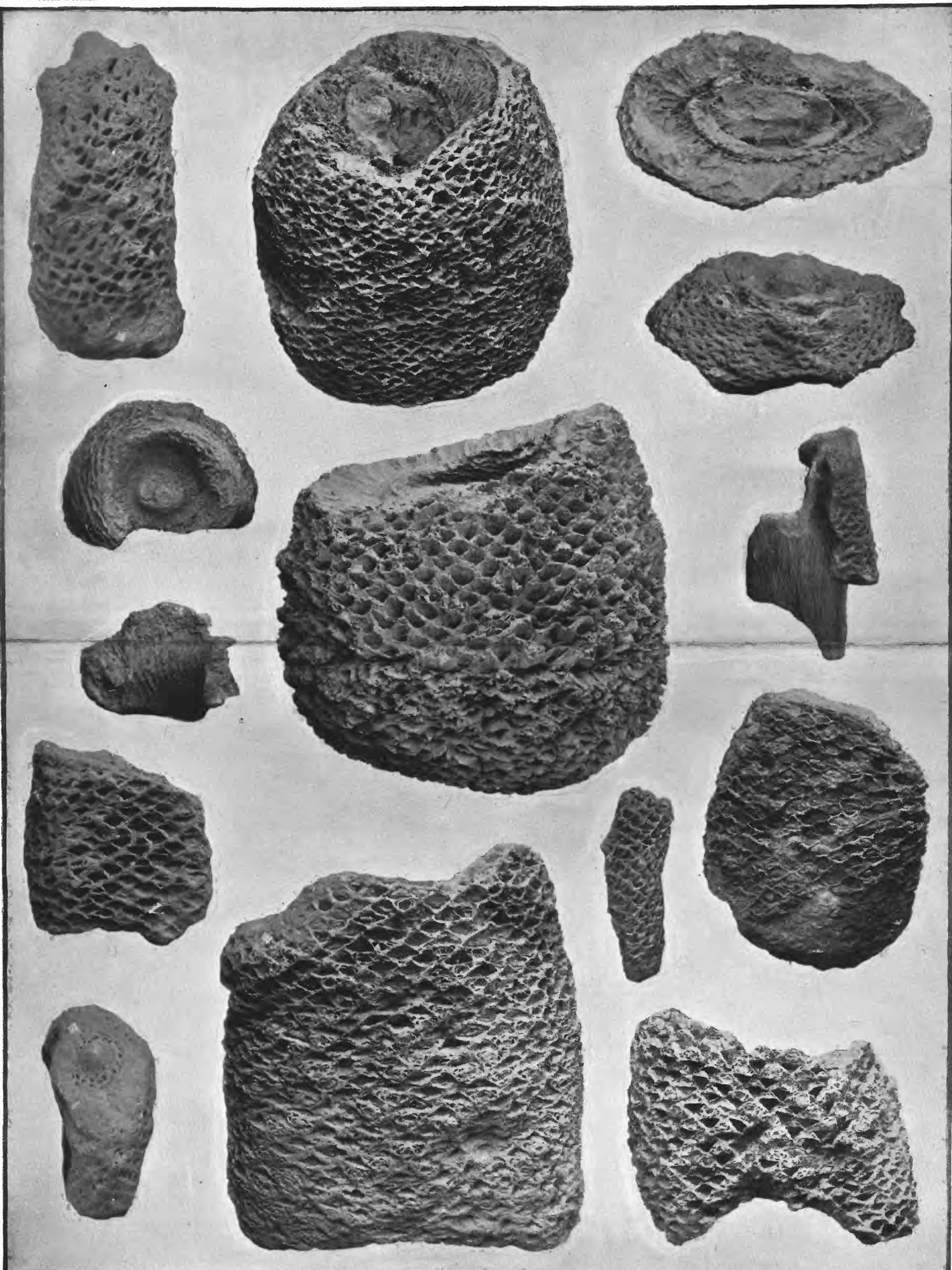
[1] Ibid., p. 397.

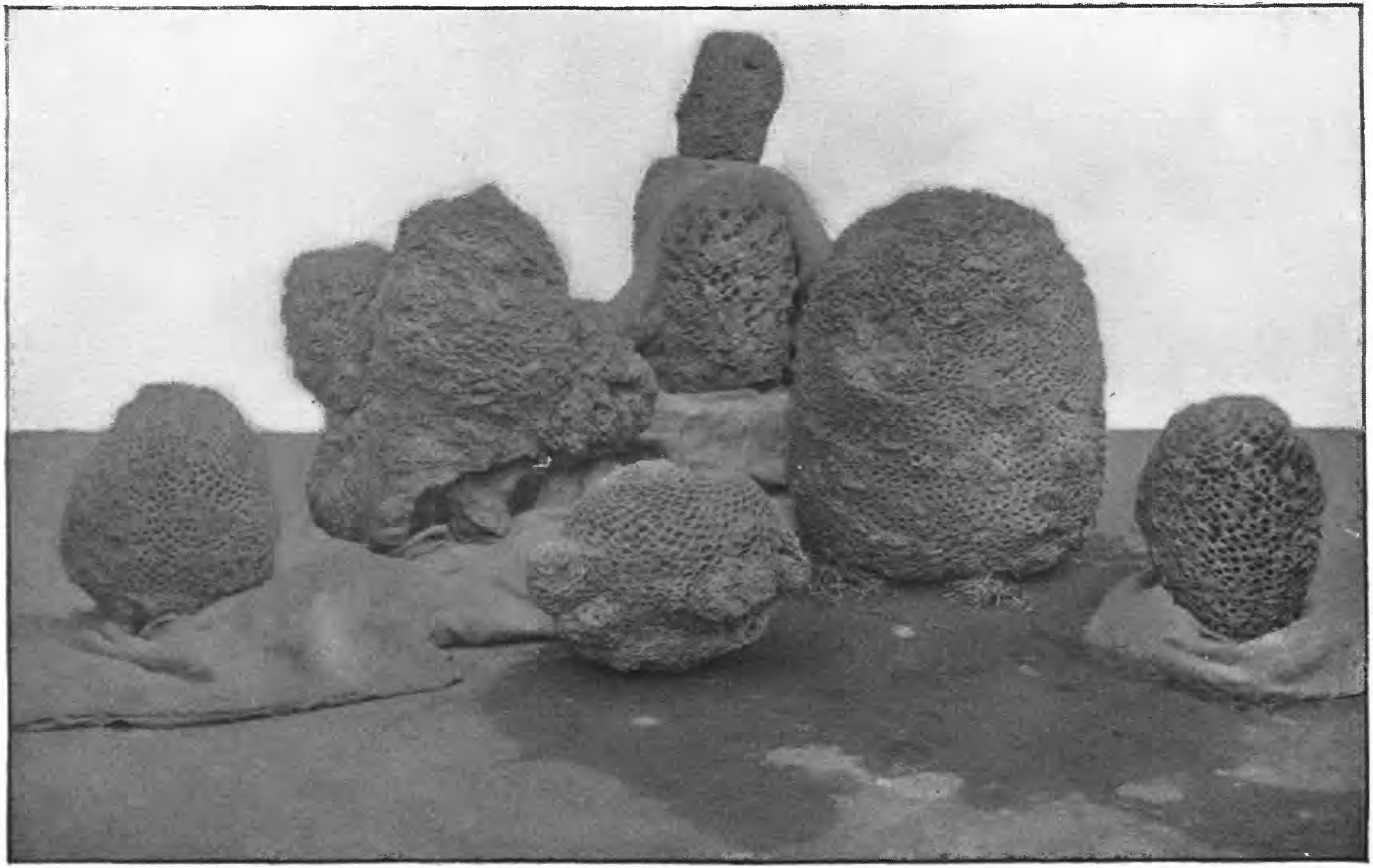
[2] Op. cit., Vol. IV, p. 222.

[3] On Fossil Cycadean Stems from the Secondary Rocks of Britain. Trans. Linn. Soc., Vol. XXVI, 1870, pp. 675–708, pl. liv–lxiii.

[4] Note sur le Clathrepodium Morieri, B. R. Bull. Soc. Linn. Normandie, 4e sér., Vol. I, Caen, 1887, pp. 143–151, pl. iv, v.



GROUP OF CYCADEAN TRUNKS FROM THE POTOMAC FORMATION OF MARYLAND.



GROUP OF CYCADEAN TRUNKS FROM THE BLACK HILLS OF SOUTH DAKOTA; LOWER CRETACEOUS.

others, as will be seen by the table, have been described from the Purbeck beds of Portland. Three of the species of Cycadeoidea are said to come from the Lower Greensand, including the celebrated *C. Gibsoni*, about which so much has been written, and which of all cycadean trunks exhibits the fruiting axes to the greatest perfection. In addition to these there is the *C. Saxbyana*, which is the only trunk thus far found in the Wealden proper. This is from Brook Point on the Isle of Wight, which is also the locality for the well known fossil forest, of which I shall soon speak. All of these trunks it was my privilege to examine in the British Museum. There are three specimens of the *C. Saxbyana*, but the labels were not sufficiently full for me to determine whether they were all from the same locality. One of them has a terminal leaf bud, and all of them closely resemble some of the smaller trunks from the Black Hills. The *C. Gibsoni* is disappointing when seen from without, as only by close study can the arrangement of the leaf scars and flowering axes be made out, but this lack is more than compensated for by the wonderful display of minute internal structure seen in the sections and visible even to the naked eye. This is not, of course, the place to discuss this remarkable phenomenon, but the occurrence of well-developed seeds far in the interior of a solid trunk certainly gives rise to a great number of questions as to their true morphology. I also saw the *C. Peachii*, from the Coral Rag of Helmsdale, Sutherlandshire, Scotland, which does not come within the purview of this paper, but which, notwithstanding its greater age, strikingly resembles one of our most perfect Maryland specimens. Of *C. inclusa* I was able only to see a model, the original being in the York Museum. This is from the Lower Greensand of Potton, Cambridgeshire, but does not widely differ from the forms farther south. With regard to *C. Gibsoni*, from the Greensand of Luccomb Chine, and *C. maxima*, from Shanklin, on the Isle of Wight, there is room to suppose that, although found in the Greensand, which is alone exposed at these localities, they may have both originally come from the Wealden, lying directly under these beds. At times of very low tide the Wealden strata have actually been seen at the base of the Greensand at Sandown and some distance farther to the southwest, and a little above Sandown, as is well-known, it comes to the surface, and rises many feet at the Red Cliff. The range of the cycadean trunks in England is, however, much greater, some having been found in the Lower Lias of Lyme Regis, but thus far none have been found higher than the Lower Greensand, and possibly may not have lived later than the close of the Wealden period. Their history in America is almost precisely similar, one species, *C. Emmonsi*, occurring in the Upper Trias of North Carolina, and another, *C. abequidensis* Dn., from nearly the same horizon on Prince Edward Island, while all the rest are from the Lower Cretaceous, and confined to the lower portion of those deposits, the Maryland beds, those of the Black Hills, and probably the Cheyenne Sandstone of Kansas not being widely different in age.

FOSSIL FORESTS.

In point of interest the fossil forests of this period may, perhaps, claim the second rank. Those of the Purbeck beds are among the most celebrated in the world. They have frequently been described and graphically portrayed by the older geologists of England. As early as 1829 Mr. Webster said of them:

> In it [the "dirt bed"] are found considerable numbers of fossil trunks of trees of the dicotyledonous class, which are from 1 to 2 feet in diameter The woody part is siliceous, and the longitudinal vessels are filled by, and surrounded with, radiated quartz; numerous veins of chalcedony and quartz also pass through these stems, but always following the direction of the concentric and radial structure In the cavities, and particularly on the outside, there is a small quantity of carbonate of lime, but this is only superficial, and has been a deposit subsequent to the silex I saw one of these trunks standing erect, and the workmen informed me they were frequently found in this position Its lower part was thickest, and being divided, it gave the idea of the commencement of roots; its upper part penetrated through the *soft burr* and terminated in the *ash*. The trunks are always broken off short, seldom exceeding 3 feet in length. This is the fossil wood which is so often brought from the Isle of Portland; and upon the most careful inquiry and examination, I could not discover that it was found in the oolite itself, nor in any other part of the series [1]

Dr. Mantell, in his Geology of the Isle of Wight, which contains a chapter on the Portland beds, makes the following allusion to them as well as to the cycadean trunks:

> Upon the uppermost oolitic stratum, is a layer a foot thick, of very dark brown, friable loam, which appears to have been a bed of vegetable mould It contains a large proportion of earthy lignite, and, like the modern soil on the surface of the island, waterworn stones, and pebbles. This layer is called the "*dirt-bed*" by the quarrymen, and in and upon it are stems and branches of coniferous trees and plants allied to the *Cycas* and *Zamia*. Many of the trees and plants are standing erect, as if petrified while growing undisturbed in their native forest Their roots extend into the soil of the dirt-bed, and their trunks into the superincumbent strata of limestone.
>
> As the Portland building stones lie beneath these beds, and the *cap* is only used for lime, the fossil trees are removed and thrown by as useless, and the dirt-bed cleared away to arrive at the more valuable material On one of my visits to the island the surface of a large area of the dirt-bed was exposed, preparatory to its removal, and the appearance presented by the fossil trees was most striking. The floor of the quarry was literally strewn with fossil wood, and before me was a petrified forest, the trees and the plants, like the inhabitants of the city in Arabian story, being converted into stone, yet still remaining in the places they occupied when alive! Some of the trunks were surrounded by a conical mound of calcareous earth, which had evidently, when in the state of mud, accumulated around the stems and roots. The upright trunks were in general a few feet apart, and but 3 or 4 feet high, they were broken and splintered at the top, as if the trees had been snapped or wrenched off at a short distance from the ground. Some were 2 feet in diameter, and the united fragments of one of the prostrate trunks indicated a total length of between 30 and 40 feet In many examples portions of branches remained attached to the stems The external surface of all the trees I examined was weather-worn, and resembled that of posts and timbers of groins and piers within the reach of the tides, and subjected to the alternate influence of the water and the atmos-

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[1] Trans Geol Soc, London 2d ser, Vol II, 1829, pp 41-42

phere. There were no vestiges of the bark in a carbonized state, nor of the natural external surface of the stems, as in the prostrate trees at Brook Point in the Isle of Wight.

The cycadaceous plants occur in the intervals between the trees, and the dirt-bed is so little consolidated that I dug up with a spade several specimens that were standing erect, in the position in which they originally grew. . . . The specimens are called *"crow's-nest"* by the workmen, who believe these plants to be bird's nests, originally built by crows in the fossil trees, which have become petrified. The largest specimens are about 2 feet high and 3 feet in circumference.[1]

The trees stand in the part of the series immediately above the upper "dirt-bed," locally termed the "soft burr," and project up through the several overlying deposits; but the erect portion is always comparatively short, not often exceeding 3 or 4 feet. They have their roots in the dirt bed itself. I have reproduced (Fig. 68) the excellent section

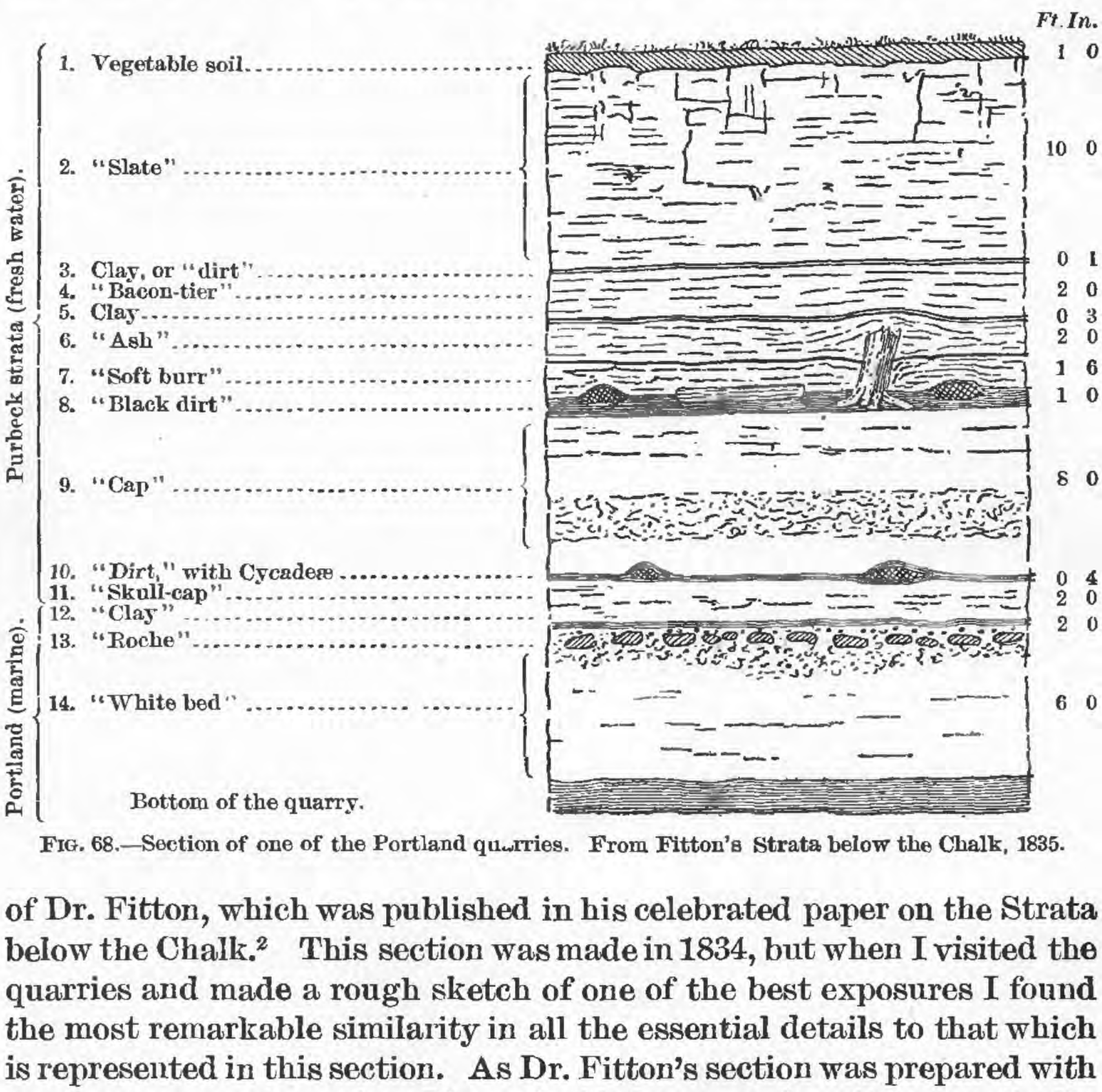

FIG. 68.—Section of one of the Portland quarries. From Fitton's Strata below the Chalk, 1835.

of Dr. Fitton, which was published in his celebrated paper on the Strata below the Chalk.[2] This section was made in 1834, but when I visited the quarries and made a rough sketch of one of the best exposures I found the most remarkable similarity in all the essential details to that which is represented in this section. As Dr. Fitton's section was prepared with much more care than mine, I have decided to reproduce it as practically representing the exact present state of things. He has introduced cycadean trunks at both the lower and upper dirt beds, where they are known to occur, and he also shows one of the erect trunks with its roots in the

[1] Geology of the Isle of Wight, London, 1847, pp. 395-398.
[2] Trans. Geol. Soc. London, 2d ser., Vol. IV, 1835, p. 219.

"black dirt," penetrating through the "soft burr" into the "ash," with a portion lying prone at its base; all of which is exceedingly true to nature. At the time of my visit none of these detached portions lay in position in the quarries, they all having been removed, but very short portions of the erect trunks still remained, from which I secured specimens. They were, however, too close to the roots to give the best results.

The specimens collected by us were from Kingbarrow quarry, and the cycad trunk above referred to lay on the same ledge only a short distance from the fossil stumps. There is every probability that it came from the dirt bed in which this trunk had its roots. In Mr. Sansom's tunnel under Wide street, besides the cycads and many other objects, there was an immense fossil trunk 26 feet in length and 4 feet in diameter at the lower end, diminishing to 2 feet at the upper end. At the extreme outer limit of the town of Portland proper, another fossil tree taken from these quarries has been fastened up against the side of a house. It was evidently taken out in sections, but in such a way as to admit of their being placed in their natural position one upon another so as to show nothing but the line of fracture. At the base it shows the enlargement preparatory to putting forth the roots. It is forked at the summit, the two branches being nearly equal, both in size, and in the length preserved. The house against which it stands is called the "Antediluvian House." It is No. 1 Fortune's Well street, Portland. We made a rough estimate of its height, and I recorded in my note-book that it was about 20 feet to the forks, and that the two branches were about 2 feet in length. It measured 11 inches in diameter above the enlargement at the base. On my return I found to my surprise that Dr. Fitton had described this same specimen in the memoir above referred to (p. 221), and in the following words:

> Some very fine specimens of the silicified trunks had been found not long before I saw them; one of which had been judiciously restored by joining the fragments and placing the whole erect against the wall of a house. The total height from one extremity to the other was above 20½ feet; the diameter of the stem where the roots went off, about 11½ inches The trunk was nearly straight and undivided for about 17 feet, and the branches slight in comparison with the main stem.

It will be seen that our estimate of the height was a little too great, and his measurement of the base was probably made at a point slightly lower than ours. It is a somewhat remarkable fact that this specimen should have been permitted to remain in the same position for so long a time. It had probably been there some time before Dr. Fitton described it, which he did in 1834, or sixty years prior to our visit. Dr. Fitton describes and figures on the same page another very similar but somewhat larger specimen from the Dungeness quarry, from which the first was also taken. This shows the beginnings of the roots and is, he says, elliptical in cross section. The two agree, however, in the important particular of being forked at the summit by a true dichotomy, which is rare in trees of so large a size. This at once indicates a peculiar type of vegetation. I reproduce here (Pl. CII, Fig. 1, facing p. 498)

Dr. Fitton's figure. As will presently be seen, all the fossil wood from the English Wealden, including the Purbeck, is of the Araucarian type, and in the absence of other parts must be referred to the genus Araucarioxylon. Assuming these two trunks to belong to the same species, I propose for them the name *Araucarioxylon antediluvianum*, the specific name referring, of course, to the "Antediluvian House," against which one of the specimens stands.

The fossil forests of the Isle of Wight are very different from those of the Purbeck beds. The principal ones occur on the southwest shore of the island near Brook Point They consist of loose trunks lying in a confused manner and bearing evidence of having been transported for some distance and stranded in their present position. They were first described by Mr. Webster in a contribution made by him to Sir Harry Englefield's Picturesque Beauties of the Isle of Wight, which appeared in 1816. Mr. Webster says:

> At Brook Point the cliffs interested me much. They were about 30 feet in height, and were composed chiefly of clay resting upon a bed of soft sandstone, which contained a considerable quantity of sulphur, arising from the decomposition of pyrites
>
> At this place I observed many masses of a coaly blackness, bearing the exact form and resemblance of trunks of trees that had been charred, lying on the beach, and embedded in the clay cliffs, and also in the rock.
>
> In some parts the ligneous fibre was still evident In other parts the wood had been converted into a substance much resembling jet; its blackness being intense, its cross fracture conchoidal, and its luster very great. Other parts of the trees were entirely penetrated by pyrites, and considerable groups of crystals of this substance were frequently attached to the outside
>
> They were embedded in clay of various colors, white, gray, yellow, and red, and lay in irregular horizontal strata of several inches in thickness, being often pressed flat by the incumbent weight Over this stratum of clay, which is about 8 or 10 feet thick, there is another of the same depth, of sand and gravel, highly ferruginous, and the water which filters from it is strongly impregnated with sulphate of iron.
>
> On lifting up some of the sea weeds which grew upon the shore between high and low water mark I was surprised to find almost all the rocks below them composed of petrified trees, which still retained their original forms They were of various sizes, from 8 or 10 feet long and 2 feet in diameter to the size of small branches The knotty bark and the ligneous fibre were very distinct, and they were frequently embedded in masses of clay now indurated and in the state of an argillaceous rock.
>
> Some parts of these trees were converted into ironstone, and other parts consisted of a great variety of substances, being partly calcareous, siliceous, ferruginous, pyritous, bituminous, and ligneous; and the whole exhibited a beautiful example of the astonishing processes of nature in converting vegetables into coal, and in filling their substance with solid rock.
>
> These changes have no doubt taken place at a period too remote for human conjecture, and whilst the trees were yet buried under the strata which still partially cover them; their present situation on the shore arises merely from the sea having made gradual inroads upon the land, and, after having washed away the soil above, exposed them to view.[1]

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[1] A Description of the Principal Picturesque Beauties, Antiquities, and Geological Phenomena of the Isle of Wight, by Sir Henry C Englefield, Bart , with Additional Observations on the Strata of the Island and their Continuation in the Adjacent Parts of Dorsetshire, by Thomas Webster, esq , London, 1816, pp 153–154

In a paper read before the Geological Society of London on December 3, 1845, Dr. Mantell gives the following account of the fossil forests of the Isle of Wight:

> The trees are lying confusedly one upon another. I saw no erect trunks, or any other indication that the forest had been submerged while growing in its native soil, like that of the Isle of Portland; but, on the contrary, the appearance, both of the trunks in the sand rock and of those exposed to view by the removal of the materials in which they were originally embedded, is that presented by the rafts that float down great rivers, as, for example, the Ohio and Mississippi Such rafts entangle in their course the remains of animals and plants that may happen to lie in the bed of the river, and at length subside and are buried in silt and sand The fossil trees in this cliff are associated with large river shells and with the bones of colossal land reptiles. The fossil forest at Brook Point we may therefore consider as a raft of pines which floated down the river of the country near which the Wealden beds were deposited, and had become submerged in the delta or estuary at its mouth, burying with it the bones of reptiles and the large freshwater mussels it had entangled in its course
>
> The trees when lying in the sandstone are invariably covered with their bark, which is now in the state of lignite, varying from 1 to 3 or 4 inches in thickness, according to the magnitude of the trunk. This carbonized cortical investment is quickly removed on exposure to the action of the waves, but the ligneous structure, the woody fibre, remains
>
> The trees are calcareous and not siliceous, like those of Portland They are more or less traversed by pyrites, and the delicate veins and filaments of this mineral which permeate the woody fibre impart a beautiful appearance to the polished specimens, particularly to those which exhibit a transverse section of the stems. The trunks are generally of considerable magnitude, being from 1 to 3 feet in diameter. I traced two upwards of 20 feet in length, and these were of such a size as to indicate a height of 40 or 50 feet when entire. They appear to have attained maturity
>
> In the conversion of the bark into lignite and in the smooth condition of the trunks this fossil forest presents a remarkable dissimilarity from that of the Isle of Portland, in which, so far as I have observed, the carbonized bark rarely, if ever, occurs, and the surface of the stems is similar to that exhibited by the trunks of old decorticated trees that have been much weathered by alternate exposure to air and moisture. At Brook Point, on the other hand, the trees appear to have been engulfed when fresh and vigorous, and when their bark and vessels were full of sap. The annular lines of growth are often very distinct, and I have traced from thirty to forty on some of the stems, but these circles are unequal, and indicate therefore a variation from year to year in the climate of the country in which they grew. The wood exhibits, under the microscope, coniferous structure of the type seen in the *Araucaria* (Norfolk Island Pine), the rows of glands or ducts being placed alternately, and the appearance being similar to that of the fossil wood of Willingdon in Sussex I observed no trace of the foliage of these trees, nor of their fruit, with the exception of a small cone, scarcely so large as that of the larch
>
> In the strata that overlie the fossil forest, thin interrupted seams and irregular masses of lignite are very abundant, and their substance is more or less impregnated with and permeated by iron pyrites. Fossils similar to these occur also in the clays of Tilgate Forest and at Hastings [1]

Very little additional information has accumulated with regard to these fossil forests since that date, as may be judged from the follow-

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[1] Quart Journ Geol Soc London, Vol II, 1846, pp 92-93

ing statements contained in the second edition of Bristow's Geology of the Isle of Wight, 1889:

> Below and partly imbedded in this rock lie the scattered trunks of coniferous trees, known as the "Pine Raft" They were first observed by Webster in 1811, but were more fully described by Mantell in 1846. The trunks lie prostrate in all directions, broken up into cylindrical fragments. They are covered by thin bark, now in the state of lignite, the wood having been converted into a black or grayish calcareous stone, with much iron pyrites Many of the trees still present traces of woody structure, and the annular rings of growth are clearly perceptible, but they are traversed also by numerous threads of pyrites The trunks are generally of considerable magnitude, being from 1 to 3 feet in diameter; two upwards of 20 feet in length, and of such size as to indicate a height of 40 or 50 feet when entire, were noticed by Mantell.
>
> The "Pine Raft" can be seen at low water only. During spring tides it may be observed to rest on variegated marls, but all attempts to trace it eastwards from Brook Point have failed, probably on account of its being of local development only. The purple marls forming the cliff above it are apparently the same beds that have made the great slip of Roughland, and the "Pine Raft," if it is continuous, should be found in the cliff near Sedmore Point; but though many large fragments of trunks are lying on the beach, there is no bed in the cliff exactly corresponding to that of Brook Point.
>
> As suggested by Mantell, the trees were probably drifted from a distance, in the same manner as the trunks, brought down by the Mississippi at the present day, are deposited in large rafts in the delta of that river It is not to be expected, therefore that the "Pine Raft" is of wide range, or that the horizon at which it occurs should be recognizable when the trees are not present There is no evidence that any of the trees in this or any other part of the Wealden series grew upon the spots where they are now found.[1]

At the time of my visit to the Isle of Wight the "Pine Raft," though many of the logs lay above the water, was inaccessible except by boat; but a little farther to the northwest, viz, at Hanover Point, there was a collection of prostrate trunks, some of them lying on the strand and others at about the elevation of high tide, projecting from the cliff. They were of a very dark color and contained much pyrites, but were not incrusted with marcasite, as is much of the lignite of the Potomac formation. I collected specimens from four different trunks, selecting from the parts which seemed most likely to show internal structure. One of these specimens was surrounded by a pyritiferous envelope, which has almost completely effloresced, leaving a mass of comminuted material, flakes, and chips in the box in which it was contained, and an ashy-white substance on the surface of what remains. The other three specimens have not suffered at all from this process. One of them has a jet-black coat of coaly matter, with a shining surface, to which there adheres in some places blotches of pure iron pyrites of a green color. This black coating varies in thickness from one-third to one-fourth of an inch, and seems in places to be divided into two obscure layers. It is very light, like charcoal, and shows scarcely any structure. This outer coating is in marked contrast with the light ash-colored interior, and it

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[1] The Geology of the Isle of Wight, by Henry William Bristow Second Edition, Revised and Enlarged, by Clement Reid and Aubrey Strahan London, 1889, pp 6-7.

is easy to see how it might be mistaken for the bark of the tree, but I see no evidence whatever that such was the case, and regard it simply as an illustration of the fact that under the conditions to which these trunks were subjected the interior was petrified, while the exterior remained in the condition of lignite.

Internal structure.—Although, in the papers relating to the fossil forests of the Wealden and Purbeck beds, reference has several times been made to the evidence furnished by the internal structure as to the botanical character of the trees that compose these forests, and although from these statements it is certain that thin slices have been from time to time prepared and studied, still, so far as I can learn, no figures showing this structure have ever been published. Relative to the Portland trunks, Dr. Fitton makes the following remarks: "From the evidence afforded by thin transparent slices both of the transverse and longitudinal sections, which have been examined under the microscope by Mr. Brown, the fossil trunks of Portland are found to possess the characters uniformly belonging to coniferous wood; but it must be observed that these characters are not absolutely confined to Coniferæ." And in a footnote he says: "One of the longitudinal slices examined by Mr. Brown was broken from the extremity of the left branch of the tree represented in the annexed woodcut."[1] He does not state whether the "longitudinal sections" were made tangentially or radially. In the latter case it would not be true that the characters represented are not exclusively coniferous.

Dr. Mantell, speaking of the same trunks, makes the following statement: "Slices rendered transparent by Canada balsam exhibit under the microscope, in the transverse sections, the cellular tissue as a reticulation of polygonal meshes; and in the radial, the ducts or glands characteristic of the Coniferæ, and arranged in alternate rows as in the Araucaria or Norfolk Island Pine."[2]

The Wealden trunks from the Isle of Wight possess the same general character as shown by their internal structure. Of these Dr. Mantell says: "The wood exhibits, under the microscope, coniferous structure of the type seen in the Araucaria (Norfolk Island Pine), the rows of glands or ducts being placed alternately, and the appearance being similar to that of the fossil wood of Willingdon in Sussex."[3] Here again he fails to show by any published figures what the internal structure was as evidenced by his microscopic sections.

In view of this great lack of evidence upon the question of internal structure it is of the utmost importance that this aspect of the subject be brought out. The material which I obtained was very limited in amount and deficient in quality. I placed it in the hands of Dr. F. H. Knowlton and requested him to examine it. He did so, and indicated the most advantageous directions for cutting sections, and a number of

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[1] Trans Geol Soc London 2d ser, Vol IV, 1835 p 222

[2] Geology of the Isle of Wight 1847, pp 282-283

[3] *Quart Jour Geol Soc London, Vol II, Dec 3, 1845 (Proceedings), p 93*

thin slices were prepared and mounted in Canada balsam. Dr. Knowlton has studied them, and while several of the specimens showed too little structure to be available, those from the Purbeck and one of the specimens from the Isle of Wight are sufficiently well preserved to form the basis of a report which he has placed in my hands. It is as follows:

DESCRIPTION OF TWO SUPPOSED NEW SPECIES OF FOSSIL TREES FROM THE PURBECK BEDS OF THE ISLE OF PORTLAND AND THE WEALDEN OF THE ISLE OF WIGHT, ENGLAND

ARAUCARIOXYLON WALLACEI n sp. Knowlton

Pl CII, Figs. 2-4

Habitat. Isle of Portland, England, Kingbarrow Quarry An erect stump in place in the "burr" overlying the upper "dirt bed" of the Purbeck Collected by Lester F. Ward and Alfred Russel Wallace, August 17, 1894

Diagnosis —Rings of growth broad (4 to 7 mm.), very indistinct, the fall wood consisting of 6 or 8 rows of thickened cells; other cells uniform in size; wood cells long, pointed, provided on the radial walls with a single row of contiguous, large pores; medullary rays in a single series of 1 to 8 superimposed cells, not very abundant

Macroscopic characters —The fragment submitted is about 7 cm. in length and about 4 cm in diameter It is a segment from a small trunk that was probably 12 or 15 cm. in diameter. It is white in color, being perfectly silicified and somewhat distorted by irregular bands of bluish-white chalcedony which cut through it in various directions The periphery of the segment is irregularly furrowed, as though it had partially decayed before fossilization

Microscopic characters —Thin sections when viewed under the microscope show that it is only fairly well preserved The structure is made out with some difficulty, especially in the vicinity of the bands of chalcedony. In detail the following characters may be noted

Transverse section.—It is not possible to distinguish the rings of growth with the naked eye, but under the microscope they are found to be present, although very faint The rings are broad and the actual area of demarkation between them consists of only 6 or 8 layers of cells with thickened walls and diminished lumen The ordinary cells, that is, those of the spring and summer wood, are of very uniform size and small The rays in this section are seen to be rather few in number

Radial section —The section in longitudinal-radial direction is the most satisfactory of all The wood cells are long, apparently pointed, but much distorted In only exceptional cases are the pits preserved They seem to be in a single series, which approximately covers the wall. They are too obscure to permit their size or the size of the inner pore to be made out with certainty.

Owing to the distortion it is possible to get only a very small area of the medullary rays in the plane of section Nothing can be made out regarding either their length or markings.

Tangential section.—This section is reasonably satisfactory It shows the medullary rays to be in a single series from one to eight or ten cells high, the average number being from three to six. They are not numerous, for there are often two or three contiguous wood cells that do not show rays within the range of a microscopic field

From this description it is not possible to make out with absolute certainty the proper generic reference The most important character, viz, the punctations on the radial walls of the wood cells, is so obscure that some uncertainty results. Yet these punctations, if correctly observed, are seen to be in a single contiguous series, which nearly or quite covers the wall This is a character of the genus Araucarioxylon, and I have so considered it Subsequent investigation of material better preserved may throw additional light on the matter.

ARAUCARIOXYLON WEBBII n sp Knowlton

Pl CII, Fig 5.

Habitat · Hanover Point, Isle of Wight, England. Fossil wood from prostrate logs at foot of cliff above tide. Wealden Collected by Lester F Ward and E A Webb, August 19, 1894.

Diagnosis.—Rings of growth absent, wood cells large, thick-walled, of uniform size; wood cells with a single series of contiguous pores; medullary rays in a single series of from 1 to 30 cells high, abundant.

Macroscopic characters.—The specimen submitted is a fragment about 10 cm. long, 5 cm. wide, and 3 cm thick, and appears as though broken from a log of some size It is dark, almost black in color, with a coaly outside layer 4 mm thick. This coaly layer is crusted in many parts with a thick layer of iron pyrites The specimen is thoroughly silicified and much distorted by secondary crystallization It is traversed in various directions by white bands of calcite

Microscopic characters —The distortion of the tissues by the processes of crystallization has been so great that the microscopic characters are made out with difficulty.

Transverse section.—(See fig. 5) This section is by far the best one The wood cells are of uniform size, with thick walls There is no evidence of annual rings The medullary rays are numerous as seen in this section, and have thick walls

Radial section.—This section is especially unsatisfactory. The plane of section is so much interrupted that no adequate idea can be gained of the appearance of the medullary rays. The same might almost be said of the punctations on the wood cells, yet by careful selection it appears that they are in a single contiguous series, which does not cover the entire wall. Their size can not be determined The inner pore is also too obscure to admit of measurement

Tangential section —This is obscure, yet shows in exceptionally well-preserved places that the rays are numerous, thick-walled, in a single series, and usually some twenty or more cells high.

At my suggestion and request Dr. Knowlton has given to the species from the Purbeck beds of Portland the name *Wallacei*, in honor of Dr. Alfred Russel Wallace, the celebrated traveler, scientist, and philosopher, who, as above stated, accompanied me and assisted in collecting the specimens. Similarly he has given to the specimen from the Isle of Wight the name *Webbii*, in recognition and remembrance of the delightful companionship of Mr. E. A. Webb, which I enjoyed on the occasion of my visit to that island, and who showed me not only where the fossil forests were to be found, but many other interesting things which I would otherwise have failed to see.

It is surprising that no one in England has thought to describe or name these fossil woods, and I would not have ventured to do this on the imperfect material in my possession if it had not seemed to be the only way in which they could be brought into their systematic position as an integral part of the fossil flora of the Wealden.

PLATE CII.

PLATE CII.

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Fig 4, transverse section.	
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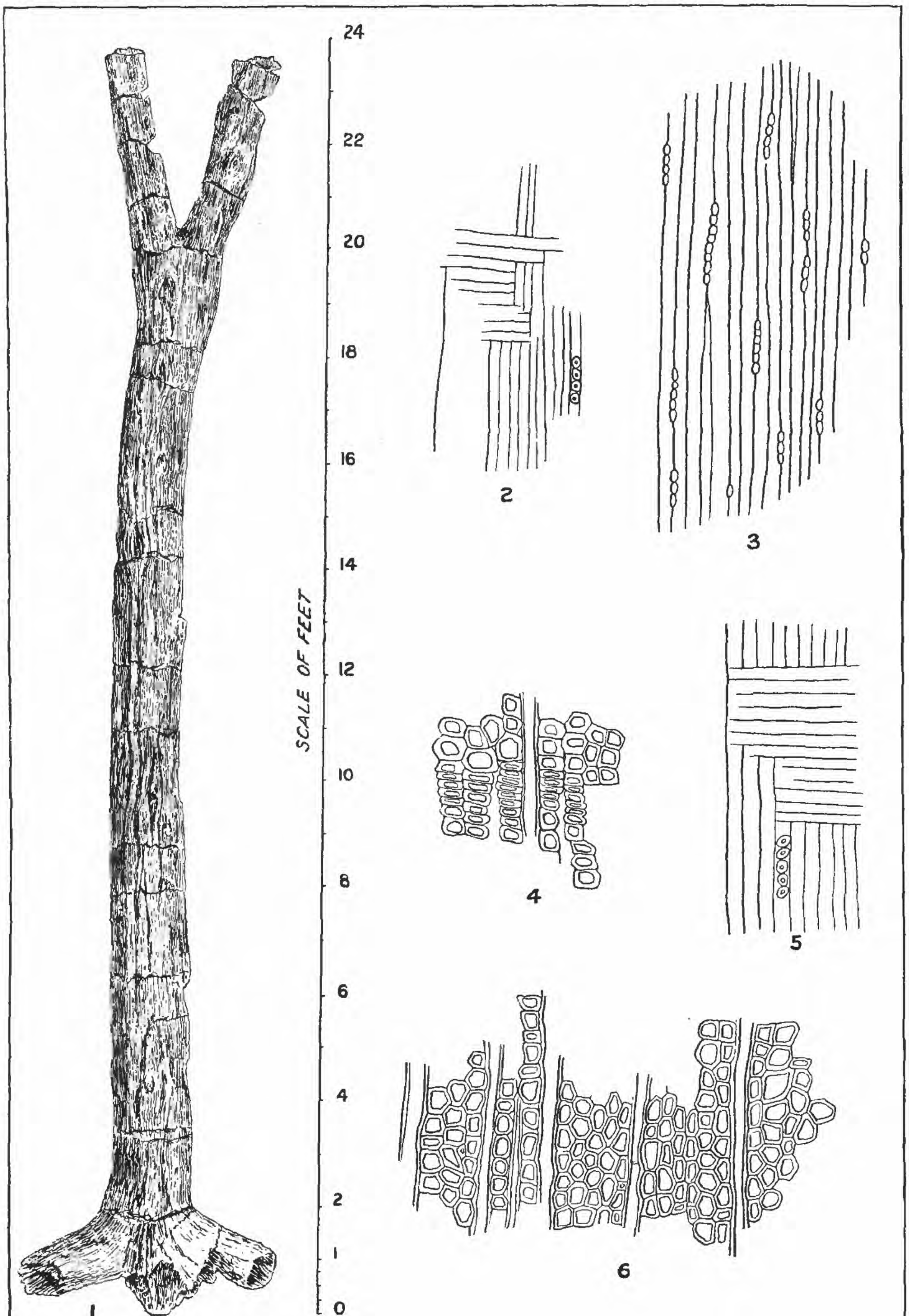

PETRIFIED WOOD FROM THE ISLE OF PORTLAND (PURBECK) AND THE ISLE OF WIGHT (WEALDEN).

As will be seen by the table, in addition to these specimens from the Purbeck and Wealden beds, "coniferous wood" has been reported from the Atherfield beds, the Lower Greensand, and the Gault. I have placed all these under one entry as "coniferous wood," although it will probably be found when they are subjected to scientific investigation that they represent several species and possibly more than one genus. It will be observed that while the structure of all the fossil wood thus far reported from the Potomac formation is of the Sequoian type, that of the Wealden deposits is of the Araucarian type. In America the Araucarian type is the only one that has thus far been detected in the Triassic deposits, either those of the Atlantic border (Connecticut Valley, Richmond and North Carolina coal fields) or those of the Southwest, the Shinárump formation of Major Powell. The celebrated Arizona woods, which yield such beautiful material for decorative objects, often show very perfect internal structure, and Dr. Knowlton, after examining a large number of specimens, was able to make only a single species, *Araucarioxylon arizonicum*,[1] which may be the same as the *Araucarites Mollhausianus* Göpp. described, but not figured by Goppert in Mollhausen's Reise (p. 492) in 1858, from specimens collected in the Rio Secco, near the Colorado Chiquito, Arizona, in 1853.[2] Those consulting Dr. Knowlton's description of the fossil wood and lignite of the Potomac formation[3] will observe an apparent exception to the statement made above. The *Araucarioxylon virginianum* is described by him as from the Potomac formation at Taylorsville, Va. A subsequent investigation of this locality by Mr. McGee, Professor Fontaine, and myself has proved that the fossil forest bed from which this specimen was taken really belongs to the Older Mesozoic or Upper Trias. This is one of the few regions in which the Trias and the Potomac formation are in contact, and without such a careful investigation as we made on that occasion it might be easy to confound these deposits, as the locality for the fossil wood lies close to the line of contact. It should, however, be remarked that some specimens of fossil wood collected by me in the Black Hills of South Dakota, at the same locality at which the great cycadean trunks occur, clearly exhibited the Araucarian structure. This locality is certainly Cretaceous, and therefore we have both types of structure in the Cretaceous of America.

I have dwelt thus fully on the fossil wood, partly because it is of great historic as well as scientific interest, and partly in order to emphasize the fact that, thanks to the labors of Nicol, Witham, Williamson, Renault, Felix, Knowlton, and other cultivators of this field, the vast quantities of petrified wood found at so many geological horizons and often constituting the only paleontological evidence of the

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[1] New Species of Fossil Wood (*Araucarioxylon arizonicum*) from Arizona and New Mexico Proc U S Nat Mus, Vol XI, 1888, pp 1-4, pl i

[2] Tagebuch einer Reise vom Mississippi nach den Kusten der Sudsee, von Balduin Mollhausen Leipzig, 1858

[3] Bull U S Geol Surv, No 56, Washington, 1889 (See p 50)

age of formations, is no longer the useless rubbish that it was formerly thought to be, and that in so far as it can furnish evidence that evidence is of the clearest and most reliable character.

The foregoing remarks, taken in connection with the table of distribution upon which they are based, render it obvious that the paleontological relations, especially those furnished by the plant remains, between the Wealden of England and the Potomac formation of the United States, and also more generally between the Lower Cretaceous of England and that of America, are as close and as much deserving of attention as are the geological relations treated at the beginning of this paper.

THE SCALY CLAYS OF ITALY.

Scarcely anything is said in the general works on the geology of Europe about the existence of the Cretaceous formation in Italy. It is entirely ignored in Geikie's Text Book of Geology and in the latest edition of Phillips's Manual of Geology. Little more can be said for Lapparent's Traité Géologique. In the second edition of that work (p. 1159) he treats the Scaly Clays under the Eocene system, and cites M. Mantovani[1] to the effect that it is tufaceous mud derived from below and sometimes contains blocks torn from more ancient formations. In another place (p. 1337) he speaks of their association with the *gabbro rosso.* Nevertheless a number of Italian geologists (De Stefani, Seguenza, Capellini, etc.) have recognized that formation within the last fifteen years. In a memoir by Capellini, which appeared in 1880,[2] he showed that Cretaceous rocks had been confounded with Eocene and Miocene ones, and referring to this paper in a later one, published in 1884,[3] he says (p. 536):

> As regards the Scaly Clays, I continued to maintain that they were of different ages I recognized as Cretaceous rocks the sands of San Martino and Salto di Montese, with Inocerami and cephalopods, and in default of decisive facts I did not say the last word as to the chronological value to be attributed to the Ammonites of the neighborhood of Porretta, and concluded that it could be maintained at that date that they were proofs of the Cretaceous in the Apennines of Emilia

Six years later the same author described a saurian fossil under the name of *Ichthyosaurus campylodon* from these same clays, and also treated of certain cycadean trunks out of the same beds in the Province of Bologna.[4] The saurian fossil was regarded as ample proof of the Cretaceous age of the strata in which it was found. In concluding his remarks upon it he says (p. 444):

> The fossils collected in the Scaly Clays of Emilia and of other parts of Italy have shown that in part they relate to the Senonian, but that there are also representatives of the Turonian, and that a great portion is certainly to be referred to the

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[1] Atti Soc Ital Sci Nat Milano, Vol XVIII, 1875, pp 28–62

[2] Il macigno di Porretta e le rocce a Globigerine dell' Apennino bolognese Mem Real Accad Sci Ist Bologna, Ser IV, Tom II, Bologna, 1880, pp 175–194

[3] Il Cretaceo Superiore e il Gruppo di Priabona, op cit , Tom V, Bologna, 1884, pp 535–550

[4] Ichthyosaurus campylodon e tronchi di Cicadee nelle Argille Scagliose dell' Emilia, op cit . Tom. X, Bologna, 1890, pp 431–450 two plates

Cenomanian. It is probable that specimens have also been discovered from the Infra-Cretaceous, and it is also probable that in general the Cenomanian Scaly Clays rest upon the Triassic rocks in the Northern Apennines.

The cycadean trunks described in this memoir were not supposed to furnish in themselves definite evidence as to their age. This part of his memoir is devoted especially to giving an account of a fine one collected in the Scaly Clays in the Province of Bologna. The following is the substance of that account:

> In the last days of November of the past year (1889) Signor Count Francesco Massei announced to me that he had collected in the Scaly Clays of the valley of the Idice, not far distant from his villa at Ozzano, certain stones which he suspected might be fossil cycads. Having been kindly invited to do so, I immediately repaired to his house in Bologna and ascertained that he really had reference to a wonderful specimen of a true cycadean trunk, but which had unfortunately been broken in order to enable him more easily to get it out of the field where it had been dug up. The Count having himself collected these important remains, kindly offered to guide me in exploring the locality, where I hoped to find some more fragments, in fact, on the 3d of December I went to Ozzano, and going up the right branch of the Rio Centonara, which traverses an important mass of typical Scaly Clays, 280 meters above the level of the Adriatic, the spot was pointed out to me where the fossil cycad had been exhumed. Count Massei related to me that on the 24th of November, in company with his foreman, Enrico Ghini, and Corporal Lucio Rocca, passing near an estate called La Torre, the property of Signor Engineer Cavalieri, in the parish Settefonti, on the road along the borders of a recently plowed field he found the four fragments of a cycad, which he recognized without difficulty as belonging to one and the same specimen.
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> I was then in condition to assure myself of the exact source, having succeeded, with careful search, in finding some additional pieces of the beautiful fossil, which, from its most perfect state of preservation and from the matrix which still adhered to it, permits me to exclude even the remotest doubt that it was just where it fell to the bottom of the Cretaceous sea before it became fossilized.
>
> This, then, is the first fossil cycadean trunk collected under such favorable conditions as to permit us to affirm with certainty once for all that the fossil cycads collected loose in the streams of Emilia incontestably come from the Scaly Clays, and these also serve to prove that the Scaly Clays in which they are entombed belong to the Lower Cretaceous.

In intimate connection with this description he very appropriately makes mention of another specimen discovered in the eighteenth century, which is now lost, but relative to which an extensive memoir by Giuseppe Monti is extant, including a figure.[1] A file of the Commentarii is preserved in the library of the University of Bologna, and Capellini was able to consult it. He saw at once from the figure of Monti, who had regarded the fossil as a heap of barnacles, that it was a cycadean trunk, and on comparing it with the one recently found he observed that they were similar in many respects. The following is his account of the manner in which he came to recognize this ancient figure and of his researches in bringing the subject to light:

> In 1865, when treating of the fossil Balænidæ of the Bolognese, I made known the fact that the first notices relative to remains of fossil Cetaceans were due to the

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[1] De quadam Balanorum Congerie. De Bononiensi Scient. et Artium Instituto atque Academia Commentarii, Tomus tertius. Bononiae, MDCCLV, p. 323.

> Bolognese naturalist Giacomo Biancani, who, at the end of 1757, described and figured vertebræ and remains of Balænidæ in his memoir published in the fourth volume of the Commentarii of our Academy under the title *De quibusdam animalium exuviis lapidefactis*.
>
> Two years before, in the same volume of the Commentarii, Giuseppe Monti published in the Opuscoli a work of his with the title *De quadam balanorum congeries*, and this work was illustrated by a plate drawn and engraved by the celebrated Ercole Lelli. A specimen collected in 1754 in a stream which is an affluent of the Idice under Castel de' Britti was found in a collection of Count Giuseppe Ippolito Grassi, and was sent by him to Monti for study. Monti saw in it the form of a pine cone, and at first suspected that it was an ornamental relic of some ancient building, but having shown it to B. Beccari was assured by him that it was a fossil. It was then that Monti thought of barnacles, and imagined that it might be a great mass of the remains of these animals, so he called it *lapideorum balanorum insignis congeries*, describing it accurately and comparing it with other specimens of barnacles, with which, however, he found that he could not in any way identify his large specimen. It is sufficient to read that description in order to perceive that it might very well adapt itself to a specimen of a cycad of the same species as the one found by the Count Massei, and equally fossilized.[1] I suspected that it was a cycad the first time that, when engaged on these fossils, I recalled the plate with fossil barnacles published in the old Commentarii.

At the conclusion of his paper he says: "Some transported fragments may have been found in the Post-Cretaceous conglomerates, but the original bed is in the Lower Cretaceous."

In 1892 appeared the important memoir on the Cycadean Trunks of the Italian Museums, of which Capellini wrote the historical and geological parts and Count Solms-Laubach furnished the botanical descriptions.[2] This work was largely stimulated by the discoveries above recorded. For an indefinite period specimens of cycads had been accumulating in the various museums of Italy, and Senator Capellini conceived the idea of getting this material all together and having it systematically elaborated. Count Solms had long been engaged in the study of the English material, and was well qualified to do the botanical part of the work. Capellini's historical introduction is very thorough, and forms a most interesting document. For the present I can only refer to his matured conclusions relative to the age in which the Italian cycads flourished. The numerous specimens that had been picked up from time to time mostly upon the surface furnish no positive proof upon this point, but on investigating the subject he came to the conclusion that, notwithstanding the fact that most of them had been referred by different geologists to a much later period, all the specimens were probably originally derived from the Scaly Clays and had been transported and redeposited by various agencies in the beds where they were found. The case already mentioned was almost the

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[1] It is not entirely improbable that the terminal portion of the cycad trunk found by Grassi was a part of the trunk of the specimen discovered by Count Massei, collected a short distance from the Castel de' Britti. In its measurements it corresponds to the missing upper part of the specimen recently found. [Footnote by Capellini.]

[2] I tronchi di Bennettitee dei Musei Italiani. Notizie Storiche, Geologiche, Botaniche dei Professori Senatore G. Capellini e Conte E. Solms Laubach. Con cinque tavole. (Mem. Real. Accad. Sci. Ist. di Bologna, Ser. V, Tom. II, Bologna, 1892, pp. 161-206, pl. i-v.)

only one in which they were actually found embedded in these clays; but a careful study of the surrounding conditions in nearly all the other cases showed that the clays were not far distant, and that such a secondary deposition would be very natural under the circumstances. He was struck by the close resemblance of these clays to the descriptions contained in American works of the beds in which the cycads of Maryland occur, and he concludes his account with the following remarks:

> In May, 1859, Mr Tyson had found two trunks of silicified cycads coming from the variegated clay of the Potomac group, Jurasso-Cretaceous formation, which he regarded as corresponding in part to the Wealden and in part to the Purbeck of English authors
>
> The specimens given to Tyson by Dr Jenkins and Mr Emack were found, the first near Coutee Station and the second near Beltsville, and were deposited in the Museum of Baltimore From the same clays, near Contee, Tyson obtained important specimens of saurians dug out of an iron mine, and through these the chronological correspondence could be better determined The discovery of Tyson (recorded by Dana in his Manual of Geology, speaking of Cretaceous plants) was also mentioned by Carruthers, who, through the aid of Dr. Dawson, who possessed a photograph of those fossils, referred them without doubt to the genus Bennettites, with scales a little smaller than those of *B saxbyanus*
>
> Fontaine, creating without necessity the new genus Tysonia, distinguished the fossil cycad of the Potomac with the name of *Tysonia marylandica*, referring to it the two above-mentioned trunks and the fragments The descriptions and figures are accurate, but in default of any kind of sections we think it impossible to enter into a discussion relative to their more intimate relations with any of our Cycadeoideæ
>
> The interesting fact which it has pleased me to note is that there is an almost perfect chronological correspondence and a very great lithological similarity between the beds of the Cycadeoideæ of Emilia and those of the Cycadeoideæ (Tysonia) of Maryland A part of the variegated clays of the Upper Potomac corresponds very well with our Scaly Clays, of which it sometimes even presents the fragmentary and scaly[1] character; and while, as to their fossils, the variegated clays of the Upper Potomac are made to correspond to the Cenomanian of Europe, it is also to be noted that even in America there is a species of hiatus in the superimposed chronological series, and that the Eocene or Oligocene immediately covers these clays In the Lower Potomac sandstones and ferruginous sands, sometimes true conglomerates predominate, and they are considered to be of the age of the Wealden, and it is presumed that the abundant specimens of Cycadaceæ and other Cretaceous plants of the upper member are derived from these.

In working up the collections of cycads from Maryland and the Black Hills I had, of course, familiarized myself with the memoirs of Capellini, and had become deeply interested in the large amount of similar material existing in Italy, derived, as it thus seems, from beds so closely analogous to our own. Fourteen species are described by Solms-Laubach, and from Capellini's account it appeared that the greater

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[1] I was at first inclined to translate the Italian term "argille scagliose" by the English *clay shales*, the more because, as stated above, I observed that where undisturbed they consist of shales, but in default of any allusion to them in English works I was very much in doubt as to the idea implied in the Italian designation "scagliose" (literally *scaly*) M Lapparent generally contents himself with using the Italian term, but in one passage (Traité, p 1159) he refers to them as "argiles écailleuses," which is not the French term for shales I conclude, therefore, that the scaly character must have some reference to the peculiar appearance of the disturbed portions as described above. There is very little to justify Capellini's comparison of it to anything in the American beds

part of all this material was at the University of Bologna in the geological museum. I therefore resolved, while on my vacation abroad, to visit Bologna if possible and examine these specimens. I was in correspondence with Senator Capellini, and before leaving America received from him a very courteous invitation to do so. This visit I made in the early part of September and enjoyed the fullest opportunities for satisfying my desires in this respect. My plan involved something more than merely to examine the material in the collections. Ozzano, near which place the large trunk, *Cycadeoidea Masseiana*, was found, is only a short distance from Bologna, and I expressed to Senator Capellini an ardent desire to make an excursion to this locality. This request was complied with in a manner that far exceeded my anticipations, for not only was I permitted to accompany the eminent Italian geologist to the place, but he had taken the pains to anticipate my arrival and to announce our coming to Count Massei, who discovered the specimen on his own estate and for whom it was named. It is needless to say that we were cordially received, and the Count accompanied us on the excursion over the Scaly Clays and pointed out to us the precise spot from which the specimen had been plowed out of the ground. The opportunity for examining the beds was all that could be desired. Count Massei after having discovered the specimen had frequently revisited the place and made careful observations in the vicinity. He had had the ground excavated in all directions and had found a few additional fragments. This work had been so thoroughly done that it was not of course to be expected that anything additional would be found on that occasion. But as I had seen the specimen at the museum this was a comparatively unimportant consideration. What I specially desired was to see the beds in which it had occurred and to make a general survey of the field.

The Scaly Clays present a very peculiar appearance; the rock has some resemblance to certain Potomac strata, but seems to consist chiefly of greatly disturbed and subsequently decomposed shales of a dark color, weathering whitish. At places there are ledges of these shales which are not decomposed, and these have the consistency of hard rock. They bear evidence of having been subjected to heat and sometimes have a tendency to be converted into slate. I was informed that fucoidal remains had been found in them and that *Chondrites intricatus* Sternb. had been described from them. They are probably of marine origin and intrusive rocks, probably gabbro, are mingled with them in irregular ways. Much pyrites and manganese and also crystals of calcite occur. It may be described as a calcareous sandstone, but very argillaceous. The region about Ozzano is very hilly, and the locality where the cycad was found is on the slope of a ravine leading down to the Rio Centonara. Everywhere on these slopes there has been extensive erosion of the decomposed shales, and the materials thus removed from their original position have a very different appearance from those in place. Notwithstanding the heterogeneity of the rock the erosion is practically uniform, and the sculpture has the same regular character that is always seen where soft homogeneous material has been subjected to the action of the elements, as in the case of the Columbia brick clay of the Potomac Valley. But the Scaly Clays when thus eroded assume a very dark color, appearing nearly black at a distance. The uneroded portions are much affected with slickensides. In some places the eroded, and even occasionally the uneroded, material takes on a red color and even assumes the peculiar mottled appearance so characteristic of the Potomac clays, and which was also remarked in the Wealden of the Isle of Wight. I would not lay too great stress upon this phenomenon, but after all it is one which is not exactly paralleled at any other horizon in any part of the world so far as I have been able to learn.

High up on the slopes of these hills the Cretaceous clay is seen to be unconformably overlain by Pliocene sands and sandstones, which contrast with it in a marked manner.

While at Bologna I of course paid special attention to the great collection of cycad trunks in the geological museum. The greater part of those described by Solms-Laubach are, as already stated, in this place, and many of his microscopic slides were also there. The great *Cycadeoidea etrusca* Cap. & Solms, which, as I have stated in a former paper,[1] is not only the largest but also the most ancient, so far as human knowledge is concerned, of all the Italian cycads, having been found on a tomb in the Etruscan Necropolis at Marzabotto, in the province of Bologna. Its original source is of course unknown, and Capellini believes that it was designed as an ornament or symbolic emblem. On many of the tombs large stones were found, having of course the same purpose, but this was the only one that proved to be a cycadean trunk. It is black on its external surface, but has been cut through transversely and longitudinally, the longitudinal section passing through the center. The cut surfaces have been polished, and the nature of the stone is such as to admit of this admirably. The portion represented on pl. IV of the memoir referred to is only a small part of this longitudinal section, but the details can be seen even better in the original than in the figure. There are also radial sections of fragments, and the model that has been made of the whole section, though very perfect, has not been colored. The exterior of the specimen shows large elongated or elliptical flower buds or axes of inflorescence, and also small ones; the leaf scars are subrhombic in shape, but with rounded angles, so as to appear almost elliptical.

There are a number of specimens of *C. Capelliniana*, which is the one that has been found at the largest number of localities. I was unable to detect the presence of axes of inflorescence on the surface of any of the specimens. The ramentum walls are unusually thin. These specimens are also dark colored.

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[1] Proc Biol Soc, Washington, Vol IX, 1894, p 84

C. Masseiana shows an abundance of flower buds, some of which project beyond the general surface. They have small perforations, being probably the scars of the surrounding bracts. These are features which are not well brought out in either of the figures published in Capellini's memoir.

C. Maraniana is too much worn to show the external characters distinctly. There are large openings on the surface which I would regard rather as indicating the existence of secondary axes or lateral branches than as flower buds. The cortex is unusually thick, even for cycad trunks, and the woody zones which it surrounds are much decayed.

The original specimen of *C. intermedia* scarcely justifies the definite structure shown on pl. iii, fig. 5. The scars are not depressions, but are level with the partitions, which, as the figure shows, are whitish on the general black ground. This specimen has been cut through longitudinally, and I am surprised that the inner surfaces were not figured in the memoir.

C. Pirazzoliana shows scarcely anything when viewed from without. Only the upper portion of the internal structure exhibited on pl. ii, fig. 1, was at the Geological Museum, but it fully justifies the figure.

C. Bianconiana shows the flower buds with large decayed centers much more clearly than would be supposed from the figure given (pl. ii, fig. 2).

Of *C. Scarabellii* only a model is to be seen in the Geological Museum, and this seems to be of the opposite side from that represented on pl. iii, figs. 2 and 3, and does not show the fine flowering buds seen in fig. 2, being much worn on that side. One large bud, however, was present, resembling the largest one shown in the figure. The polished surface of the cut brings out the structure very clearly, even more so than fig. 3, which was, of course, drawn from the original.

Also in the case of *C. Cocchiana* only a model could be seen. As no figure was given of the exterior of this fossil I would have been glad to see the trunk itself. From the model I judge that the outer parts had suffered much from wear.

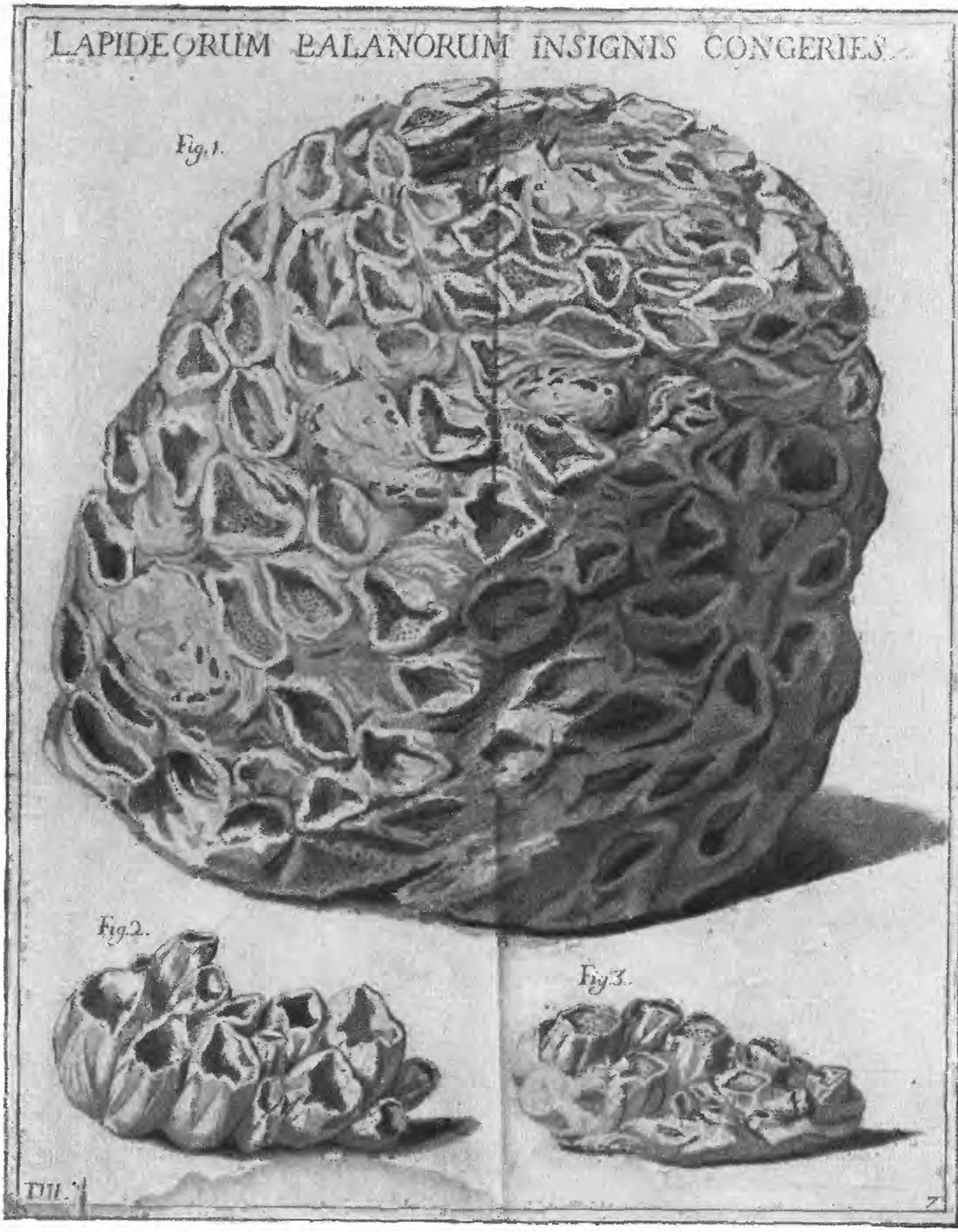
Count Solms made a new genus for a peculiar fragment found near Imola and called it *Cycadea imolensis*. I examined this fragment, and found that it had no external parts whatever, so that its relation to the remaining trunks must be judged entirely by the internal structure. It has been cut in three oblique directions, chiefly transverse. It seems to be a portion in the vicinity of a branch or near the forks of two branches, and shows two axes. A superficial examination would never suggest that it was a cycad, but Count Solms found ramentum hairs which differed in their structure and form from those of any cycad hitherto examined by him, and chiefly upon the strength of this he described it as a cycadean trunk and gave it this name. I still think it was unwise to do this, since the creation of a new genus should certainly be based on abundant material.

CYCADEAN TRUNK (CYCADEOIDEA MASSEIANA) FROM THE SCALY CLAYS OF ITALY.

PLATE CIV.

PLATE CIV.

	Page
FIG. 1. Cycadeoidea Montiana Cap., Scaly Clays of Italy	509, 510
FIGS 2, 3. Barnacles used for the purpose of comparison. (Copy of figure of Monti, 1755.)	501, 502



CYCADEAN TRUNK (CYCADEOIDEA MONTIANA) FROM THE SCALY CLAYS OF ITALY.

In looking over a large collection of cycads, such as that at the Geological Museum of Bologna, after having so long studied those of America, I could not fail to be struck by the general resemblance that holds among the forms in both countries, and considering the additional fact that both in America and England the remains of this class of vegetation are confined to the lower portion of the Cretaceous and older deposits, I can not help feeling that the paleontological evidence alone in favor of the Lower Cretaceous age of the Scaly Clays of Italy is strong. It does not appear that the animal fossils distinctly contradict this view, and as to the stratigraphy, a formation lying unconformably between the Trias below and the Pliocene above, may certainly be referred to any intermediate horizon which its flora and fauna require.

In view of the fact that *C. Masseiana* was actually found in the Scaly Clays and that I have myself examined the locality, I have thought it worth while to reproduce the figure that appears in the earlier of Capellini's two papers (see Pl. CIII). As Capellini inclines to believe that the original specimen of Monti may have formed a part of this same trunk, this also acquires peculiar interest. Capellini had the great kindness to hand me, on my departure from Bologna, the original plate published by Monti in the Commentarii, which he took from a duplicate volume in his possession. I have therefore thought best to reproduce the figure as it appears on that plate (see Pl. CIV). The following is the original description given by Monti, translated from the Latin:

> Its length in one direction is 7 inches, or about half a Parisian foot; but in the other direction it scarcely equals half a foot, which measurements are about the same as in the rest of its parts; for its form approaches roundness moderately compressed; but at the summit, where there is a flat space, even slightly concave,[1] it does not exceed 4 inches in width. Its base, in whatever direction measured, is found to be 7 inches, therefore the circumference of the whole stone near the base would be almost two feet, but at the summit only 18 inches Moreover, as regards the external form, although, as was stated, it may not improperly be compared to a truncated pine cone, yet it seemed to us rather to be not unlike a sailor's cap, although we could assert nothing with certainty concerning the base, since it appears to be broken and irregular on all sides. The material or substance, as well internal as external, of this stone is homogeneous, and indeed does not differ much from that of siliceous or igneous rocks, which are sometimes found to be of a dark or black color, for if it is struck at any place with flint it emits sparks Nevertheless it has this peculiarity, that it is altogether opaque, and if broken is not smooth like flint, but shows in many places streaks interspersed with white crystalline particles, nor is there wanting metallic matter mixed with it, for in various places small shining lines are detected imitating copper pyrites Its dark color and very great weight, exceeding 30 pounds, sufficiently convinced me when examining it that this stone also contains iron; so that it would not be surprising if it should be regarded by some as a lump of iron ore

Senator Capellini, after having worked up the literature of the subject, undertook to rediscover the locality at which the specimen was

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[1] The concavity observed by Monti and clearly expressed in the figure corresponds to the decayed portion noted by English authors in the trunk of Bennettiteæ referred to the genus *Mantellia* and described under the name of *crow's nest* [Note by Capellini, loc cit, p 165]

found. He made an excursion into the region, of which he gives the following account, which has considerable geological as well as historical interest:

> In June last (1891), in company with Signor Count Francesco Massei and Signor Bernardi, now proprietor of the foundry, I visited the Rio della Cavaliera, following it up a good distance to familiarize myself with the nature of those clays and of the minerals that are met with
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> The Rio della Cavaliera empties on the right side of the Idice, near the Molino delle Donne, and almost opposite the Cassola Canina. At the very entrance of the Rio, a short distance from Bernardi's house, there was found an interesting mass of limestone, containing *Lucina pomum*, which had been formerly in great part used by Bernardi in making lime, and which strongly reminds one of the similar mass that is observed in the grove of the Santagata, near Gesso Having passed this small Miocene bed, the Rio was found encased in ancient scaly clays, identical with those of the Rio Centonara, which descends toward Ozzano, on the opposite slope of the same hill from which the Rio Cavaliera takes its origin, immediately under the church of Ciagnano It is to be noted that about 200 meters east of Ciagnano, and in the direction of the course of the Rio della Cavaliera, the superb specimen of *C Masseiana* was found in the same mass of scaly clays
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> In the scaly clays of Rio della Cavaliera, as well as in those of the Rio Centonara, I have noted masses of yellowish-red and greenish clays, which recall certain jaspers and stannites of the Titonic and of the Cretaceous, besides aragonite, quantities of manganese-bearing concretions, masses of altered variolite, and traces of *calcareous and siliceous serpentine (oficalce e ofisilice), with calcareous and jasper* elements; which, in fact, suggest the Lower Cretaceous and Upper Jurassic of other regions Upon the whole, as well from its position as from the relations of fossilization, even from the dimensions and form, there is good reason to maintain that there are close relations between the specimen of Cycadeoidea from the Rio della Cavaliera, collected in 1745, for which I propose the name of *C Montiana*, and that of the Rio Centonara, found in 1890.

THE MESOZOIC OF PORTUGAL.

THE EARLIEST DICOTYLEDONS.

Prior to the year 1888 no dicotyledonous plants had been made known from any deposit older than the Cenomanian, with the sole exception of the *Populus primæva* of Heer from the Kome beds (Urgonian) of Greenland. The statement had therefore been frequently made, not only that the type of vegetation which now predominates throughout the world had its origin in the Middle Cretaceous, but that, in view of the great abundance of this type in the 'Cenomanian of Europe and of Greenland and in the Dakota group of the United States, supposed to be of Cenomanian age, the dicotyledonous flora had suddenly come into existence at that date.

It is a remarkable fact, though one paralleled many times in the history of science, that two persons independently of each other, and neither of whom was aware of the labors of the other, in regions separated by the entire breadth of the Atlantic Ocean, were simultaneously discovering the existence of this class of vegetable life at a much earlier age than that at which it had previously been found. Prof. William M.

Fontaine, of the University of Virginia, had at that date already been several years engaged in a careful study of what is now known as the Potomac formation, which he was then calling the Younger Mesozoic of Virginia; and, in view of the almost complete absence of other paleontological evidence, had been giving special attention to the fossil plants. He found these in many parts of this terrane, and although the great majority of them were ferns, cycads, and conifers, there were certain rare and obscure forms which he was unable to refer to any of these groups. They were for the most part broad expansions resembling fronds or leaves, with coarse reticulate nervation. It is due to his sagacity to say that he himself suspected that they might represent peculiar dicotyledonous leaves. Professor Fontaine wrote to me and described the forms which he had found. He subsequently came to Washington and showed me some of the specimens. I fully agreed with him that they represented dicotyledonous plants, and soon after he found localities on the James and Rappahannock rivers, and especially near Aquia Creek, in which these forms were much more abundant and better preserved. The question was definitively settled that they could not be, as was thought possible, ferns of the type of Dictyophyllum and Thaumatopteris, but must be in very truth dicotyledonous leaves. In his subsequent researches he made extensive collections of these forms and developed a rich flora in the Lower Cretaceous of Virginia.

So exceedingly important did I regard this discovery that I urged Professor Fontaine to publish a preliminary announcement of it in anticipation of his work on the flora of that formation, which did not appear until 1890, although it bears date 1889. He declined to do so, but gave me permission to mention the fact in a paper which I was then preparing.[1] It was then supposed that these beds were Jurassic, and at the close of a discussion of the origin of the dicotyledons I there remarked (pp. 302-303):

> It is to be hoped that we are at last approaching the beginning at least of a solution of this truly great problem of the origin of the dicotyledons. I have myself seen at least one slight, it may be, but very interesting sign of possible progress in this direction. Certain quite defective but very instructive specimens, collected in the Upper Jurassic of Virginia, by Prof. William M. Fontaine, and which he kindly brought to Washington for my inspection, certainly possess all the essential elements of dicotyledonous leaves, although at the same time bearing a certain recognizable stamp of the cryptogamic and gymnospermous vegetation that characterizes that earlier age. What is to be the final verdict of science upon these forms can not now be told, but it is to be hoped that the Mesozoic strata not only in Virginia, but in all parts of the world, may be diligently searched and the materials carefully studied, with a view to discovering these certainly merely "missing links" of a chain that can but have been once complete.

The manuscript of Professor Fontaine's Potomac or Younger Mesozoic Flora[2] was completed early in 1888 and submitted for publication.

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[1] On Mesozoic Dicotyledons. Amer. Journ. Sci., 3d ser., Vol. XXVII, April, 1884, p. 292-303.

[2] Monographs of the U. S. Geol. Surv., Vol. XV, Washington, 1889.

But, as is well known, from one to two years is required to bring out a work of this magnitude, and I again endeavored to prevail upon him to publish a popular statement of the dicotyledonous flora which it describes. With his characteristic modesty he still declined to do so. He, however, not only permitted but requested me to perform this duty. I brought the matter to the attention of Major Powell, Director of the Survey, and Professor Marsh, president of the National Academy of Sciences, from both of whom I received a courteous invitation to present these results to the National Academy at its meeting at Washington in 1888. I did so, and the paper was published in August of that year.[1] Relative to the question here under consideration I there ventured the following statements (pp. 129–131):

> It remains to consider the second question, as to the true significance of the dicotyledons. Their presence is supposed to indicate a later age than that denoted by the other groups of plants It was long supposed that the upper Quader beds of Blankenburg contained the earliest remains of plants of this class, but they were at length found in the considerably older strata of Niederschoena in Saxony Since then their occurrence in strata of about the same age in Bohemia and Moravia was made known, and it is the practice to treat the so-called Upper Cretaceous of Greenland, the Dakota group of Kansas and Nebraska, and the Raritan clays of New Jersey as homotaxially equivalent to these Continental deposits
>
> With but a single exception no dicotyledonous plants had been found lower than this horizon prior to the discovery of the Fredericksburg bed This exception was the occurrence among the collections from Kome in Greenland, a deposit whose animal remains are said to fix its age as Urgonian, of a single dicotyledonous species, the *Populus primæva* of Heer, all the other plant remains from that deposit belonging to the lower types Although this discovery has not been confirmed by subsequent research, and therefore remains subject to the doubt whether the collections may not have become mixed with those from higher beds made and sent at about the same time, still there is nothing antecedently improbable in it, and it may pass unquestioned It does not, however, invalidate the general proposition that up to this time the Cenomanian has furnished the most ancient forms of dicotyledonous plants
>
> This can not now be said, and we have in the Potomac formation a still earlier date at which to fix the observed origin of the type of vegetable life which is now the predominant one upon the globe What then does this dicotyledonous element in the Potomac flora prove as to the age of that formation? Can we argue from its analogy with other Cretaceous floras? In doing so great caution is required. As compared with these the Potomac flora is wholly anomalous in this respect In all the others, with the sole exception already mentioned, instead of those plants coming in gradually, as they would be expected to do if the formation represented an age at which their development was inchoate, and instead of presenting rudimentary transition and archaic types of that subclass, as such early deposits would naturally do, we find them to be the prevailing, sometimes, as in the Dakota group, almost the only form of plant life, and we also find them fully developed, and even when most unlike our modern vegetation, still exhibiting all the characters of highly organized plants of their rank In the Potomac formation, on the contrary, we find the dicotyledons behaving precisely as they ought to behave in a formation that represents an age close down to that at which this form of life first made its appearance in the geologic history of the globe. We find them to constitute the great rarities of the

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[1] Evidence of the Fossil Plants as to the Age of the Potomac Formation. Amer Journ Sci., 3d ser, Vol XXXVI, August, 1888, pp 119-131

> flora, absent from many of the most productive beds, scarce at all places in comparison with the lower types of vegetation, strange and peculiar in character, so vague and ill-defined as in some cases to cause doubts as to whether they really belong to this group of plants, possessing features that recall the ferns, cycads, conifers, and even the monocotyledons, and containing comprehensive types prophetic of many of the now fully developed families of dicotyledons. They therefore form just such a homogeneous and undifferentiated group of plants, combining in a scarcely distinguishable way all the elements of the later dicotyledonous flora, as we should expect to find existing during the early history of this type of vegetation. They are therefore not to be regarded as anomalous, but as normal, and the anomaly, if any there be, exists in *Cenomanian floras*, where this type occurs in such a predominant and highly developed form.
>
> In view of these facts I can not accept the conclusion that the dicotyledonous element of the Potomac flora argues a more recent age than that denoted by the other types. On the contrary, the immense difference between this and the Cenomanian floras clearly indicates that a vast period must have been required to produce so great a development.
>
> On numerous occasions, dating as far back as 1878,[1] I have expressed the opinion that the dicotyledons could not have had their origin later than the Middle Jura, and it will not surprise me if the final verdict of science shall place the Potomac formation, at least the lower member, in which the plants occur, within that geologic system. While the remaining types point strongly in this direction, I do not regard the dicotyledons as at all negativing, but even more strongly suggesting this view.

Since that date the flora of the Potomac formation has been greatly increased by further discoveries, and the older beds from which Professor Fontaine obtained his specimens have been connected in an almost unbroken series with higher ones in Maryland, New Jersey, New York, and Massachusetts—the Albirupean, Raritan (Amboy Clays), and Island series, as well as with the Tuscaloosa formation of Mississippi and Alabama, in all of which the dicotyledonous element largely predominates, amounting to 330 species out of a flora of 707 species. I regard all this as belonging to the Lower Cretaceous in the sense in which I have used that term in this paper, viz, from the Wealden and Neocomian to and including the Gault and Albian of Old World nomenclature.

As already remarked, a similar series of investigations was being carried on in Europe simultaneously with the ones just recorded. Not long after I had had the correspondence with Professor Fontaine to which reference has been made I began to receive letters from the Marquis Saporta, drawing my attention to the existence of peculiar forms in the Lower Cretaceous of Portugal, some of which he was obliged to refer to the group he had established under the name Proangiosperms, and others of which, he was quite sure, represented true dicotyledons. I acquainted him with the results reached by Professor Fontaine, and in 1888, or the same year as the publication of my paper last quoted, he came forward with his first statement of this peculiar

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[1] American Naturalist, Vol. XII, June 1878, p. 378, November, 1878, p. 734. In a lecture delivered February 24, 1883, at the National Museum, on Plant Life of the Globe, Past and Present (see Science, Vol. 1, May 4, 1883, p. 358). American Journal of Science, 3d ser., Vol. XXVII, April, 1884, p. 302. Proc. A. A. A. S., Vol. XXXIII, Philadelphia meeting, September, 1884, p. 497. Botanical Gazette, Vol. IX, Indianapolis, October and November, 1884, p. 174. Fifth Annual Rept. U. S. Geol. Surv., 1883-84, Washington, 1885, p. 449, diagram, pl. lviii, facing p. 452.

condition of things in Portugal.[1] In this paper are described, in a preliminary manner, certain collections made by M. Choffat from beds in Portugal of Lower Cretaceous age, but higher than those from which Heer, seven years earlier, had described an interesting flora, in which no dicotyledons appear. The present collections contained a number of undoubted dicotyledonous leaves. The age of the beds was probably about that of the Gault of England or Albian of France. With the exception of the American discoveries, this was therefore the lowest horizon from which such plants had been reported.

The following statement contained in this paper is directly in point (p. 1502):

> The only essential difference which distinguishes these beds from those with which Heer was acquainted consists in the constant presence in the former of a certain number of dicotyledons, a class of plants the date of whose introduction in Portugal is thus determined and circumscribed by the vertical space which separates the Urgonian from the Cenomanian. This supposed date is in fact entirely conformable to the observations made upon this same question in Central Europe, where the Wealden and even the Urgonian (Wernsdorf beds in the Carpathian mountains) are found to be devoid of dicotyledons, while the plants of this class are already numerous and varied in the Cenomanian of Bohemia, in that of Saxony (Niederschoena), and of Moravia (Moletein). In the present state of our knowledge and in view of the discoveries in Portugal it is therefore at the stage of the Almargem, that is to say, at the Aptian and Albian, more precisely at the Bellasian of the Portuguese,—Viaconnian of the Jura,—Upper Gault,—horizon of *Pterocera incerta* d'Orb., *Ostrea pseudo-africana* Choff., *Sphaerulites Verneuilli* Coq., *Sphenodiscus Uhligi* Choff., that it is necessary to place the moment at which the dicotyledons commenced to be introduced and to spread in Europe.

But soon after I learned from the Marquis that other collections from still older formations also contained dicotyledons, and in 1891 he published a second paper[2] calling attention to these earlier forms from the Urgonian of Cercal. This paper begins with the following significant statement:

> The appearance and first extension of the dicotyledonous angiosperms, long excluded from the terrestrial flora, of which they form at the present time the principal element, certainly constitute the most considerable event of which the annals of the vegetable kingdom have preserved any trace. How was this phenomenon produced, to what date should it be referred, and what were the characters of the most ancient plants of the new type? These are questions which it is natural to ask and which belong to the domain of those which paleontology has for its object to solve. Thus far, however, for want of proof, this science has not been able to answer them, and while the Urgonian flora of the Carpathians embraces no vestige of dicotyledons, those of the Cenomanian of Bohemia already include a rich series of them, coming without doubt within the range of still existing genera, or offering with these, in appearance at least, no well-marked contrast from the morphological point of view. The improbable idea of a sudden creation once rejected, it was necessary to have recourse to the hope of one day meeting, at stages anterior to the Cenomanian, with dicotyledons closer to their point of origin than those of the chalk

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[1] Sur les Dicotylees prototypiques du systeme infra-crétace du Portugal. Comptes rendus de l'Acad. Sci. de Paris. Tome CVI, 28 mai, 1888, pp. 1500–1504.

[2] Sur les plus anciennes Dicotylees europeennes observees dans le gisement de Cercal, en Portugal. Comptes rendus, etc. Tome CXIII, 3 Août, 1891, pp. 249–253.

of Bohemia Already the researches of the geological survey of Portugal, directed by M Delgado, with the cooperation of M P Choffat, had enabled me to indicate at Buarcos dicotyledons probably of Albian age More recently the flora of the Potomac in Virginia, published by M Fontaine, has brought to light dicotyledons still nearer to the extreme base of the Cretaceous series Prof L Ward, in a notice of these dicotyledons,[1] has not failed to set forth the synthetic characters and embryonic affinities of many of them, recognizing in such traits the indications of an evolution in process of accomplishment It is indications of the same nature, even more accentuated, that I meet with among the angiosperms of the flora of Cercal, a Portuguese deposit inclosed between the fossiliferous Cenomanian and the Neo-Jurassic upon which it rests The Commission des Travaux géologiques has succeeded in obtaining from this deposit a collection of plants, of which I shall here sum up the most salient characters.

In this paper he briefly discusses a few of the ancestral types (Protorhipis, Protolemna, Poacites, etc.), which will be more fully considered in the sequel.

It was evident from this that Saporta was monographing this flora, and the final report was awaited with much impatience. It arrived, as we shall see, late in the year which preceded his death.

In view of the special importance of the Mesozoic flora of Portugal, I have been to the trouble to prepare a somewhat complete history of the discovery in that field, which may be appropriately introduced in this place, in the course of which I have made careful comparisons with the similar conditions on this side of the Atlantic.

HISTORICAL NOTICE

The earliest studies in the Mesozoic deposits of Portugal seem to have been made by Mr. Daniel Sharpe, who read a paper before the Geological Society of London on April 11, 1832, describing certain beds in the vicinity of Lisbon and Oporto, in the former of which were included strata referred by him to the Oolite. On the 9th and 23d of January, 1839, he presented a second paper, describing more fully the secondary formation in the vicinity of Lisbon.[2] On November 21, 1849, Mr. Sharpe read still a third paper, before the same society,[3] of a much more extended nature and devoted entirely to the secondary formation. In this paper is a full list of all the fossils known down to that date, carefully determined by Mr. John Morris. Included in these was a single fossil plant regarded by Mr. Morris as a variety of a species of the Yorkshire Oolite, called by Phillips *Cycadites gramineus.* It was found at Cape Mondego, and from this circumstance was given the varietal name *Mundæ.* Mr. Morris referred Phillips's plant to the genus Zamites, and called the Portuguese species *Z. gramineus*, var. *Mundæ.* Schimper recognized in it an Otozamites, and Heer afterwards changed the name to *O. angustifolius.* By the correct rules of nomenclature it should be called *Otozamites Mundæ.*

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[1] Referring to the above mentioned paper in the Am Journ Sci, 3d ser, Vol XXXVI, August, 1888, pp 119-131

[2] Geol Soc London Proc, Vol I, p 395, Vol III p 31, Trans, 2d ser, Vol VI, p 115 ff

[3] Quart Jour Geol Soc, London, Vol VI, pp 135-201

In 1858 Sr. Carlos Ribeiro published a series of elaborate papers on the Geology of Portugal,[1] treating chiefly of the Carboniferous; but in two of these[2] he considers the Lias and Oolite, mentioning the plant above referred to from Cape Mondego and four other species from this and other localities.

Meantime other collections were being made, and in 1880 M. Paul Choffat published a somewhat elaborate report on the Geology of the Jurassic of Portugal[3] in which the fossil plants were considered as far as available. The collections were sent by Choffat to Prof. Oswald Heer, and a preliminary report upon them was received in time to be inserted as an addendum. Heer's full report appeared a year later[4] and constitutes the first important contribution to the Mesozoic flora of Portugal. It also includes a large number of Tertiary plants. The Mesozoic horizons are here regarded as embracing, first, the Rhetic; second, the Jurassic, subdivided into Lias, Oolite or Dogger, and Upper Jurassic or Malm; and third, the Cretaceous, which was largely compared with the Wealden of other parts of Europe. Heer found in these collections 5 Rhetic, 18 Jurassic, and 23 Cretaceous forms. The Cretaceous plants consisted chiefly of ferns, cycads, and conifers, but two of them were referred to the monocotyledons. No traces of dicotyledons were discovered.

M. Choffat continued his investigations, and after Heer's death sent the plant impressions to the Marquis Saporta at Aix. The latter was greatly interested in them and published three preliminary reports, two of which have already been mentioned; the other[5] relates to the Jurassic. Some of the horizons in the Cretaceous were the same as those containing the plants described by Heer, while others were considerably higher. The full report upon these interesting collections has been waited for with great impatience, especially by American geologists familiar with our Potomac formation, in which the case is so nearly paralleled. In fact I was so desirous of learning more in regard to them that by previous arrangement with the Marquis, and at his urgent request, I paid a visit to the veteran paleobotanist at Aix, in the south of France, and through his extreme courtesy was not only permitted to examine these collections, but enjoyed the great favor of discussing with him a large number of most interesting questions to which they gave rise. It was then that I learned that the final report was already in press and would soon appear, and proof sheets both of the text and plates were already in the possession of the author, so that it was possible

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[1] Mem Acad Real Sci de Lisboa, New Ser Vol II

[2] Mina de Carvão de Pedra do Cabo Mondego, and do Districto de Leiria, op cit, Pt II, Third and Fourth Memoirs (these memoirs are separately paged)

[3] Étude stratigraphique et paléontologique des terrains Jurrassiques du Portugal Premiere livraison. Le Lias et le Dogger au Nord du Tage Section des travaux géologiques du Portugal, Lisbonne, 1880

[4] Contributions à la flore fossile du Portugal par le Dr Oswald Heer Section des travaux géologiques du Portugal, Lisbonne, 1881

[5] Comptes rendus Acad Sci de Paris, Vol CXI, December 1, 1890, pp 812-815

to examine the work in immediate connection with the specimens. This work[1] appeared before the end of 1894, scarcely a month before his death, which occurred on January 26, 1895, so that he was unable to distribute it, as I know he intended to do, among his correspondents; but copies were sent out by the geological survey of Portugal and a few are in the hands of American geologists. It may as well be stated here that although a large and voluminous report, containing 288 quarto pages and 39 plates, it still comes far short of covering the material that was then in the author's hands. The collections were sent to him in installments almost every year and were still arriving, but it was necessary to fix some limit, and the work was closed at a certain date and sent to press, since which time other collections had been received, upon which he was at the time actively engaged, and these were also carefully examined on that occasion at the Château of Fonscolombe, the country residence of the Marquis, 16 kilometers north of Aix. These were to be reported upon in a subsequent memoir. The remarkable parallelism between the plant-bearing deposits of the west coast of Portugal and those of the eastern part of the United States, and especially between the Lower Cretaceous of Portugal and our Potomac formation, gives an especial interest to this memoir.

THE JURASSIC FLORA

In America there is a decided time hiatus between the lowest Potomac beds and the next plant-bearing horizon below, which is now regarded as belonging to the extreme Upper Triassic and as about the equivalent of the Keuper deposits of Lunz in Austria.[2] In Portugal, on the contrary, there appear to be no plant-bearing horizons in the Trias proper, but in the Jurassic a considerable number of such deposits have been found. M. Choffat, who prepared the geological part of this memoir, follows as closely as possible the nomenclature of the French geologists, and it is found that plant-bearing horizons occur in the Infralias, part of which may be as low as the Rhetic, and some of which is referred to the Sinemurian; in the Lias; in several of the properly Oolitic beds (Toarcian, Bajocian, Callovian, etc.); in several members of the Corallian; and especially in still higher beds classed as Neo-Jurassic, which are mainly correlated with the Kimmeridgian, but may extend into the Portlandian. The Jurassic deposits of Portugal consist of sandstones and limestones, the former predominating below; and while all of them may not be of marine origin, so large a part is fossiliferous that by the aid of the careful stratigraphical investigations of the Portuguese geologists it has been possible to fix the position of the plant beds with relation to those holding animal remains, a fact which is of the utmost importance in determining the validity of the evidence of

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[1] Flore fossile du Portugal Nouvelles contributions à la flore Mésozoique par le Marquis Saporta Accompagnées d'une notice stratigraphique par Paul Choffat (Avec 40 planches) Direction des travaux geologiques du Portugal, Lisbonne, 1894

[2] See Bull Geol Soc Am , Vol III, 1891, p 31

fossil plants in such countries as America, where for the most part no such guide exists.

The Jurassic flora of Portugal, as embraced in the present memoir and in that of Heer already mentioned, consists of 126 species, as follows:

List of the Jurassic plants of Portugal, with their distribution in that country.

Species	Jurassic					Cretaceous			
	Infralias	Lias	Oolite	Corallian	Neo-Jurassic	Valanginian	Urgonian	Aptian	Albian
Abietites fructifolius Sap					+				
Adiantum dispersum Sap					+				
distractum Sap					+				
longinquum Sap					+				
Alethopteris Choffati Sap					+				
? discerpta Sap					+				
Baiera dilatata Heer	+								
Brachyphyllum Delgadonum Heer			+						
lusitanicum Sap				+					
majusculum Sap					+				
microcladum Sap					+				
micromerum Heer				+					
Cheirolepis Munsteri Schenk	+								
Chondrites bollensis Heer			+	+					
Chrysodiopteris marchantiæformis Sap					+				
Cladophlebis angulata Sap					+				
Browniana (Dunk.) Seward					+	+			
microlepsina Sap					+				
micromorpha Sap					+				
minor Sap					+	+			
multipartita Sap					+				
obtusiloba Sap					+				+
parvula Sap					+				
sinuatiloba Sap					+				
undulatiformis Sap					+				
Clathropteris sp Sap	+								
Comptoniopteris dubia Sap					+				
incisa Sap					+				
sinuata Sap					+				
Cylindrites curvulus Heer			+		?				
lusitanicus Heer			+						
sp Heer		+							
Equisetum deperditum Sap					+				
lusitanicum Heer				+					
pseudo-hœrense Sap	+								
striatulum Sap	+								
tenue Sap	+								
Granularia repanda Heer				+					
Gutbieria angustiloba Presl	+								
Hymenophyllites ambiguus Sap					+				
crenilobus Sap					+				
gracilis Sap					+				
tenellinervis Sap					+				
Microdictyon parvulum Sap					+				
Neuropteridium lacerum Sap					+				
venulosum Sap					+				
Onychiopsis Mantelli (Brongn.) Seward					+	+	+	+	+
Otozamites Mundæ Morr sp				+					
Ribeiroanus Heer				+					
Terquemi Sap?	+								

List of the Jurassic plants of Portugal, with their distribution in that country—Continued.

Species	Jurassic					Cretaceous			
	Infralias	Lias	Oolite	Corallian	Neo Jurassic	Valanginian	Urgonian	Aptian	Albian
Pagiophyllum cirinicum Sap	...	...	...	+	+	...	...	...	...
Combanum Heer	+	...	+	...	...	...	...	...	...
Heerianum Sap	...	...	...	...	+	+	...	...	...
liasinum Sap	+	+	...	...	...	...	...	...	...
minus Sap	...	...	...	...	+	...	...	...	...
peregrinum (L. & H.) Heer	+	...	...	...	...	...	...	...	...
Palæocyparis flexuosa Sap	...	...	...	...	+	+	...	...	...
lusitanica Sap	...	...	...	...	+	...	...	...	...
vetustior Sap	+	...	...	...	...	...	...	...	...
Palissya Braunii Endl	+	...	...	...	...	...	...	...	...
lusitanica Sap	+	...	...	...	...	...	...	...	...
Pecopteris acutiloba Sap	...	...	...	...	+	...	...	...	...
obliquinervis Sap	...	...	...	...	+	...	...	...	...
stricta Sap	...	...	...	...	+	...	...	...	...
Poacites angustiformis Sap	+	...	...	...	...	...	...	...	...
antiquior Sap	...	...	...	...	+	...	...	...	...
binervius Sap	...	...	...	...	+	...	...	...	...
cyperaceus Sap	+	...	...	...	...	...	...	...	...
exiguus Sap	...	...	...	...	+	...	...	...	...
primordialis Sap	...	...	...	...	+	...	...	...	...
striatifolius Sap	...	...	...	...	+	+	...	...	...
Podozamites lacerus Sap	...	...	...	...	+	...	...	...	...
minutus Sap	...	...	...	...	+	...	...	...	...
? obtruncatus Sap	+	...	...	...	...	...	...	...	...
sp. Sap	...	...	...	...	+	...	...	...	...
Pteridoleimma lacerum Sap	...	...	...	...	+	...	...	...	...
residuum Sap	...	...	...	...	+	...	...	...	...
Rhizocaulon vetus Sap	...	...	...	...	+	+	...	...	...
Schizoneura hœrensis Heer	+	...	...	...	...	...	...	...	...
Scleropteris acutidens Sap	...	...	...	...	+	...	...	...	...
densior Sap	...	...	...	...	+	...	...	...	...
Pomelii Sap	...	...	...	...	+	...	...	...	...
proxima Sap	...	...	...	...	+	...	...	...	...
sinuata Sap	...	...	...	...	+	...	...	...	...
subdentata Sap	...	...	...	...	+	...	...	...	...
tenuisecta Sap	...	...	...	...	+	...	...	...	...
Zeilleri Sap	...	...	...	...	+	...	...	...	...
Sphenolepidium Choffati Sap	...	...	...	...	+	...	...	...	...
Sphenopteris acutidens Sap	...	...	...	...	+	...	+	...	...
adjuncta Sap	...	...	...	...	+	...	...	...	...
anticolobula Sap	...	...	...	...	+	...	...	...	...
breviloba Sap	...	...	...	...	+	...	...	...	...
deflexa Sap	...	...	...	...	+	...	...	...	...
Delgadoi Sap	...	...	...	...	+	...	...	...	...
densa Sap	...	...	...	...	+	...	...	...	...
dissectifolia Sap	...	...	...	...	+	+	...	...	...
fracta Sap	...	...	...	...	+	...	...	...	...
marginata Sap	...	...	...	...	+	...	...	...	...
microclada Sap	...	...	...	...	+	...	...	...	...
microlepisina Sap	...	...	...	...	+	...	...	...	...
minima Sap	...	...	...	...	+	...	...	...	...
odontoceras Sap	...	...	...	...	+	...	...	...	...
ovatiloba Sap	...	...	...	...	+	...	...	...	...
pallida Sap	...	...	...	...	+	...	...	...	...
palmifida Sap	...	...	...	...	+	...	...	...	...
pedicellata Sap	...	...	...	...	+	...	...	...	...
proxima Sap	...	...	...	...	+	...	...	...	...

List of the Jurassic plants of Portugal, with their distribution in that country—Continued.

Species	Jurassic					Cretaceous			
	Infralias	Lias	Oolite	Corallian	Neo-Jurassic	Valanginian	Urgonian	Aptian	Albian
Sphenopteris subtilinervis Sap	...	...	...	...	+	+	...	...	...
tenelliloba Sap	...	...	...	...	+	...	...	...	...
tenellisecta Sap	...	...	...	...	+	...	...	...	...
thinnfeldiæformis Sap.	...	...	...	...	+	...	...	...	...
trapezoidea Sap	...	...	...	...	+	...	...	...	...
tricholoba Sap	...	...	...	...	+	...	...	...	...
trifida Sap	...	...	...	...	+	...	...	...	...
Stachypteris litophylla Pom	..	...	..	...	+	...	...	...	...
minuta Sap	...	..	...	...	+	+	...	...	...
Taonurus procerus Heer	...	...	+	...	...	...	...	...	...
scoparius Heer	...	...	+	...	...	...	...	...	...
Thuyites Choffati Heer	...	...	+	...	...	...	...	...	...
leptocladus Sap	...	...	...	...	+	...	...	...	...
pulchelliformis Sap	...	...	...	...	+	+	...	+	...
Thyrsopteris minuta Heer	...	...	...	+	...	...	...	...	...
Voltzia pachyphylla (Zigno) Schimp	+	...	...	...	...	...	...	...	..
recubariensis (Mass.) Schenk	+	...	...	...	...	...	...	...	...
Widdringtonites debilis Sap	...	...	...	..	+	+	...	...	...
Yuccites fimbriatus Sap	+	...	...	...	...	...	...	...	...

As will be seen from this table this flora embraces 21 species from the Infralias, 2 from the Lias, 8 from the Oolite, 9 from the Corallian, and 91 from the Neo-Jurassic, which about corresponds to the Kimmeridgian of England, with 5 species occurring in two of these horizons. The table also shows that no less than 14 species pass up into the Cretaceous beds. Most of these are cases in which the range is only from the Neo-Jurassic to the Valanginian, or from the uppermost Jurassic to the lowermost Cretaceous, but a few reach the Urgonian, Aptian, or even the Albian, while the widely distributed and polymorphous *Onychiopsis* (*Sphenopteris*) *Mantelli* occurs at all these horizons as well as in the Upper Jurassic beds. These species will be more specially considered in connection with the Cretaceous.

As regards botanical affinity this flora is subdivided into 7 algæ, 6 equiseta, 71 ferns, 7 cycads, 26 conifers, 8 monocotyledons, and 1 species of Yuccites referable to the group Proangiosperms. Of the ferns, which so largely predominate, 26 species belong to the genus Sphenopteris, 10 to Cladophlebis, 8 to Scleropteris, and 4 to Hymenophyllites. Of the conifers, which come next in importance, 6 belong to Pagiophyllum, 5 to Brachyphyllum, and 3 to Thuyites. The cycads belong to the two genera Podozamites and Otozamites. Seven of the monocotyledons consist of small blades and culms of supposed grasses, grouped under the genus Poacites.

A comparison of this Jurassic flora with that of the American Trias reveals the fact that while only 3 species, *Cheirolepis Munsteri*, *Pagio-*

phyllum peregrinum, and *Palissya Braunii*, are common to the two, there are 14 genera that occur in both. In the number of species the two floras as now known are almost equal, that of the American Trias numbering 119, while that of the Portuguese Jurassic numbers 126. It is therefore important to note in what proportions these 14 genera occur in the two floras:

Genera common to the American Trias and the Jurassic of Portugal.

Genera	Number of species	
	American Trias	Jurassic of Portugal
Baiera	3	1
Brachyphyllum	1?	5
Cheirolepis	2	1
Chondrites	3	1
Cladophlebis	7	10
Clathropteris	2	1
Equisetum	6	5
Otozamites	4	3
Pagiophyllum	6	6
Palissya	3	2
Pecopteris	1	3
Podozamites	2	4
Schizoneura	5	1
Voltzia	1	2

When we consider that the two horizons do not at all overlap and that more than three-fourths of the Portuguese plants come from the uppermost members of the Jurassic, it is not to be expected that the correspondence will be very close; and accordingly we not only miss in the Portuguese flora some of the largest American genera, such as Acrostichites, Ctenophyllum, and Pterophyllum, but also some of the most striking and abundant forms, such as Macrotæniopteris, while on the other hand no monocotyledons occur in the American Trias so far as known, and the two largest genera of ferns in the Portuguese Jurassic, Sphenopteris and Scleropteris, are entirely wanting in the American Trias.

The remarkable feature of this Upper Jurassic flora of Portugal is the large number of ferns that are closely related to those of the Lower Cretaceous of the United States, and this alone would justify the above discussion of the Jurassic flora. The comparisons which Saporta makes are confined almost exclusively to the two genera, Sphenopteris and Cladophlebis, although he does note a close resemblance between his *Scleropteris sinuata* and Fontaine's *S. virginica.* In the genus Cladophlebis he compares his *C. angulata* with Fontaine's *C. parva;* his *C. sinuatiloba* with *C. crenata*, and also with *Aspidium fredericksburgense* Font.; his *C. obtusiloba* with *C. constricta*, and also with *Pecopteris strictinervis* Font. With this last species he also compares his *Pecopteris stricta*, showing that he, too, has difficulty in distinguishing

Pecopteris from Cladophlebis; and undoubtedly the movement which Mr. Seward has inaugurated in the direction of eliminating the genus Pecopteris entirely from Post-Paleozoic horizons will now go on until it becomes complete and the genus Pecopteris is restricted, as it should be, to the Paleozoic. The number of species of Sphenopteris compared with American forms is still greater. For example, he compares his *S. palmifida* with two of Fontaine's species of Acrostichopteris, *A. densifolia* and *A. longipennis*. His *Sphenopteris ovatiloba* he compares with Fontaine's *S. latiloba;* but most of his comparisons of Sphenopteris are with species that Fontaine refers to Thyrsopteris; for example, *Sphenopteris Delgadoi* is compared with *Thyrsopteris Meekiana* and *T. elliptica*. He also compares his *S. tenelliloba* with *T. elliptica* and with *T. densifolia;* and again his *S. marginata* is compared with Fontaine's two species, *T. insignis* and *T. pachyrachis*. These comparisons and some others that might be mentioned are sufficient to indicate the close affinities of these Mesozoic genera of ferns and the great difficulty that even the best authorities have in drawing clear lines of demarkation among them. It is probable that the genus Thyrsopteris, which is a rare type in the living flora, does not actually occur in the fossil state, and it will be better in the end to refer all these forms to extinct genera, such as Cladophlebis, Sphenopteris, Onychiopsis, Ruffordia, etc.

But the special interest which these comparisons have in this place is the intimate bond which they furnish between the late Jurassic of Portugal (supposed to correspond closely with the Kimmeridge clays of England, but perhaps running up into the Portland beds, and thus closely approaching the Purbeck, which has been treated in this paper as a part of the Wealden) and the oldest Cretaceous of America, which some geologists in this country make to extend some distance into the Jurassic, but which is here treated as a Cretaceous deposit.

THE CRETACEOUS FLORA

The Cretaceous flora of Portugal has, of course, a much greater interest for the student of American paleobotany than the Jurassic flora which has just been considered; first, because, as now known, it is considerably larger, numbering 204 species, but chiefly because we have in America a large number of plant-bearing deposits that correspond so closely with those of Portugal that a comparison may be legitimately made, and furnishes valuable results. It is true that our American Lower Cretaceous flora has been now so extensively worked that it has assumed relatively large proportions, numbering at the present date over 800 different species. The Potomac formation alone furnishes no less than 737 species. The interest is still further heightened by the fact that in the Lower Cretaceous of both Portugal and America the plant-bearing beds occur at a number of distinct horizons, which may not without profit be directly compared in the two countries. For example, the Potomac formation now furnishes at least five distinct horizons from which fossil plants have been obtained, the lowest being the James River series, which may extend as low as the top of the Jurassic. The next higher is the Rappahannock series, so well known at Fredericksburg, Va., and other points on the Rappahannock and Potomac rivers. The third is the Mount Vernon clays which directly overlie the last named and have furnished a distinct flora. The fourth is the Aquia Creek series which unconformably overlies the last, in some places at least. The fifth is undoubtedly much higher, and there appears to be a considerable thickness of nonfossiliferous deposits intervening between the last named and those plant-bearing beds that have been discovered on the eastern side of the District of Columbia and at other points near Washington, on the Severn River, and on the eastern shore of the Chesapeake Bay, which have furnished a flora substantially identical with that of the Amboy Clays on the Raritan River, and not widely differing from that of Staten Island, Long Island, and Marthas Vineyard, which I have called the Island series, nor from that of the Tuscaloosa formation of Alabama.

The Lower Cretaceous of Portugal is subdivided into a very similar series of plant-bearing deposits. One locality, Valle-de-Brouco, is referred by Choffat to the Infravalanginian, which is at the very base of the Neocomian, and corresponds well with our James River series. An important plant-bearing locality between Matta and Valle-de-Lobos, is regarded as Valanginian or Neocomian, as is also the series in the vicinity of Torres-Vedras, viz, at S. Sebastião, Quinta-da-Fonte-Nova, Forca, etc. This horizon may be compared with the Rappahannock series of the Potomac formation. Near Cercal and Zambujeiro a large flora has been obtained. The plants are of rather ancient types, but denote a horizon considerably higher than the one last mentioned. Saporta refers them to the Urgonian, and M. Choffat does not decidedly object to this, but says that the stratigraphy, so far as he can judge, would indicate a somewhat later age. This horizon may be nearly the same as that of the Mount Vernon series of the Potomac formation. The beds of Almargem, which have furnished many species, chiefly determined by Heer, overlie the recognized Urgonian and probably belong to the next one, called by the French geologists the Aptian. Certain other beds, as at Caixaria and Caranguejeira, are less definitely fixed geologically, but probably belong to about the same horizon. The Aptian of the French geologists lies between the Urgonian below and the Albian above, and corresponds in the main with the Lower Greensand of England. It may be compared with the Aquia Creek series of the Potomac formation, which has yielded a large number of fossil plants, including such well-marked dicotyledons as Celastrophyllum and Sapindophyllum.

Above these beds there is an abundant plant locality at Buarcos, which is classed as Albian, and still higher others at Nazareth, Alcanede, and Monsanto, also regarded as Albian, but as belonging to that uppermost member called Vraconnian. The Albian corresponds in a general way with the Gault and is the uppermost section of the Lower Cretaceous, the overlying beds being Cenomanian, which is the lowest subdivision of the Upper Cretaceous. These Albian plant-bearing beds may be roughly compared with what has been called in America the Amboy Clays, but which has recently been more correctly named by Prof. William B. Clark the Raritan formation. In America, as in Portugal, this deposit may also be divided into two parts, a lower and an upper, the former consisting of the beds along the Raritan, which themselves have a considerable thickness and show marked changes in the flora, while to the latter belong the deposits on Staten Island, Long Island, Marthas Vineyard, the Island series, which have yielded large collections chiefly from indurated nodules formed in red clay. If the Buarcos bed is correlated with the Raritan, the Vraconnian may correspond to the Island series.

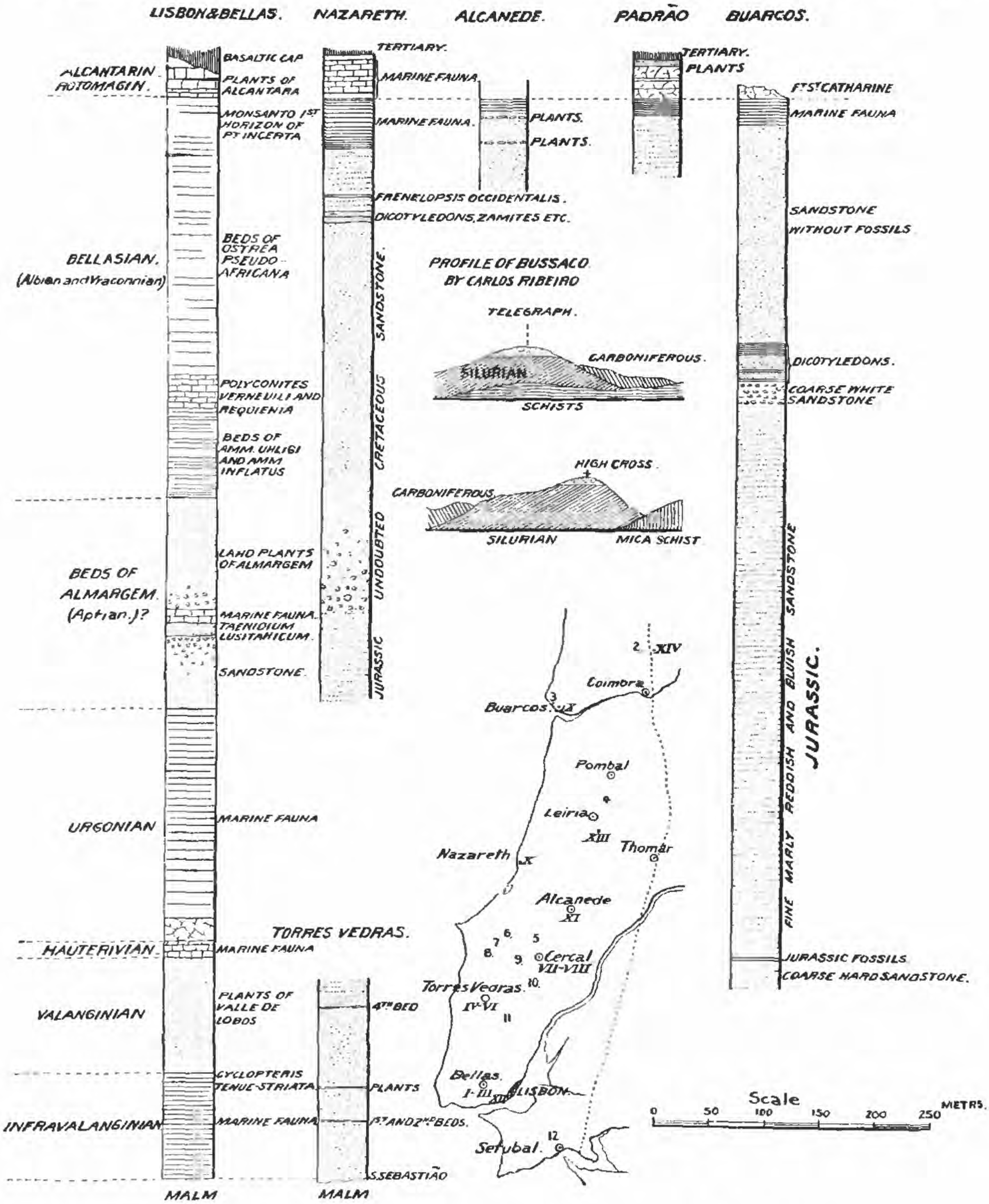
Finally, in the valley of Alcantara, at Padrão, Pombal, and Villa-Verde-de-Tentugal, there are plant-bearing beds belonging to the Cenomanian. It is possible that these latter may not be higher than those of Long Island and Gay Head.

In describing the lithological character of the strata in the vicinity of Torres Vedras, M. Choffat says:

> The sandstones of Torres are in general incoherent, they contain numerous worn quartzites either in grains or pebbles, sometimes attaining the size of the fist and giving place to conglomerates Some beds are fine and argillaceous, there are even clay masses and also beds of siliceous cement forming true quartzites The color of the whole is a yellowish-white, sometimes reddish, the clays are sometimes dark gray, but they are in too small quantity to influence the general aspect, the whitish color of which is chiefly due to the presence of kaolin

As regards the plant beds he almost always describes them as consisting of clay lenses ("lentilles d'argile"), and in much of his general description he might have been treating of the Rappahannock series of Virginia, so similar are these practically equivalent beds on opposite sides of the Atlantic.

I had had some curiosity to know how the fossil plants from the Portuguese beds occurred. Most of the fossil plants known are broken out of hard rock, the leaf impressions forming natural planes of cleavage; these may be sandstones or indurated clays, rarely limestones; but in the Potomac formation the case is entirely different. In all beds below the Island series the plants occur in clay, which is either laminated or regularly stratified between the sands, or else it occurs in lenses and pockets, the latter being the prevailing form in the older beds (James River and Rappahannock series), and the former being the regular mode of occurrence in all the Newer Potomac deposits (Albirupean, Raritan clays, etc.). In the Island series, however, the plants mostly occur in nodules, which are more or less completely lithified, but are formed within the clay after the manner of concretions by the action of iron and other minerals. I was therefore greatly interested to examine the



COLUMNAR AND PROFILE SECTIONS OF THE CRETACEOUS OF PORTUGAL.

matrix in which the Portuguese fossil plants occur. It evidently corresponds very closely with that of the great majority of the Potomac deposits. The plants occur in the clays, which are more or less soft and even plastic when first exposed, but harden on drying. In some of the Potomac beds the vegetable matter of the leaves remains as a thin, black film covering the clay, which, being damp when first exposed to the light, almost immediately cracks and crumples on drying, and is thus more or less completely lost. But in most cases the vegetable matter is reduced by compression and other influences almost to a mere stain, often of a brownish color, upon which the fine nerves are distinctly visible. This last seems to be the character of the preservation of these impressions in the Portuguese beds, and the similarity in the nature of the matrix is very marked.

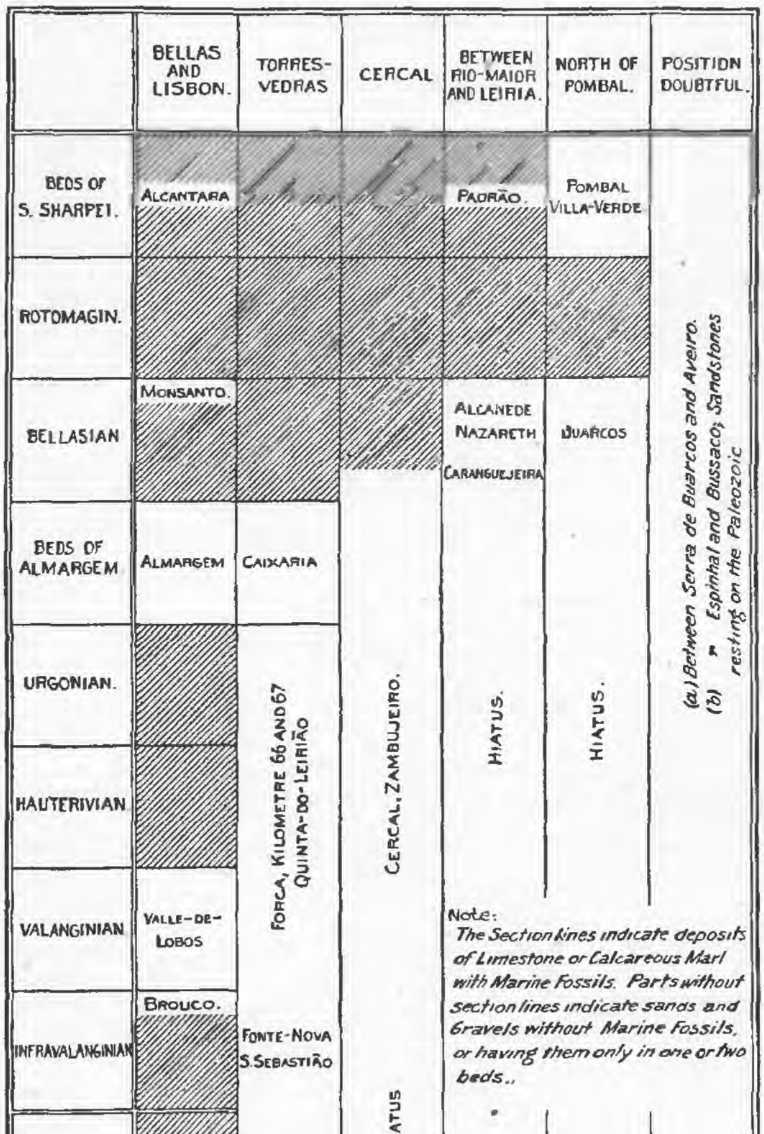


FIG. 69.—Correlation table of the Mesozoic deposits of Portugal. From Paul Choffat, 1894.

I give herewith (Pl. CV) the diagram of the Cretaceous plant-bearing beds of Portugal prepared by M. Choffat and published in the joint memoir of Saporta and himself. It embraces a small sketch map of the locality and profiles. I also give (Fig. 69) his diagram showing the correlation of these several beds.

Properly to illustrate the character of the Lower Cretaceous flora of Portugal I have prepared three tables of distribution.

The first embraces the entire flora of 204 species and shows their distribution in Portugal alone, but throughout not only all the Lower Cretaceous beds, but also the Jurassic below and the Cenomanian above.

The second contains only the 11 species that occur in the Lower Cretaceous of America. None of them are peculiarly American species, but nearly all have a wide distribution over the world. Their complete lateral and vertical range is given.

The third table embraces 12 of the new species of Saporta which he compares with American species, or with species occurring in America, with the full distribution not only of the Portuguese forms, but of the plants with which they are compared.

List of the Lower Cretaceous plants of Portugal with their geological distribution in that country.

Species	Mesozoic						
	Cretaceous						Jurassic
	Lower Cretaceous					Cenomanian	
	Neocomian	Urgonian	Aptian	Albian	Vraconian		
Abietites acicularis Sap	+	....	....	....	....	....	....
Adiantum aneimiæfolium Sap	+	...	....	....	....	....	....
dilaceratum Sap	....	....	....	+	....	....	....
eximium Sap	...	....	....	+	....	....	....
expansum Sap	....	....	....	+	....	...	....
subtilinervium Sap	+	....	....	....	....	....	....
tenellum Sap	....	....	....	+	....	....	....
Adoxa præatavia Sap	....	....	....	+	....	....	....
Alismites primigenius Sap	+	....	....	....	....	....	....
Aneimidium lobulatum Sap	....	+	....	....	....	....	....
minutulum Sap	....	+	....	....	....	....	....
tenerum Sap	....	+	....	....	....	....	....
Aralia calomorpha Sap	....	....	....	+	....	....	....
proxima Sap	....	....	....	+	....	....	....
Aristolochia Daveauana Sap	....	....	....	+	...	....	....
vetustior Sap	....	....	....	+	....	....	....
Baiera cretosa Schenk	....	....	....	+	....	....	....
Bambusium latifolium Heer	+	....	?	....	....	....	....
Blyttia infracretacea Sap	....	+	....	....	....	....	....
Brachyphyllum contusum Sap	....	....	+	....	...	....	....
corallinum Heer	?+	....	....	....	....	+	....
obesiforme Sap	....	....	....	+	....	....	....
obesiforme elongatum Sap	....	....	....	+	...	....	....
obesum Heer	+	+	+	....	+	....	....
Braseniopsis venulosa Sap	....	....	....	+	....	....	...
villarsioides Sap	...	....	....	+	....	....	...
Carpites burmanniæformis Sap	...	+	?	....	....	....	....
granulatus Sap	....	....	....	....	+	....	....
plicicostatus Sap	....	+	....	....	....	....	....
Caulinites atavinus Heer	+	....	+	....	....	....	....
fimbriatus Sap	+	....	....	....	....	....	....
Cedrelospermites venulosus Sap	+	....	....	....	....	....	.. .
Changarniera dubia Sap	+	....	....	....	....	....	....
Cheirolepis Choffati Sap	+	....	....	....	....	....	....
Choffatia Francheti Sap	....	+	....	....	....	....	....
Cissites obtusilobus Sap	....	....	....	+	....	....	....
sinuosus Sap	....	....	....	+	....	....	....
Cladophlebis argutidens Sap	+	....	....	....	....	....	....
Browniana (Dunk.) Seward	+	....	....	....	....	....	+
confusior Sap	....	....	....	+	....	....	....
derelicta Sap	+	....	....	....	....	....	....
Dunkeri (Schimp.) Seward	+	+	+	+	....	....	....

List of the Lower Cretaceous plants of Portugal with their geological distribution in that country—Continued.

Species	Mesozoic						
	Cretaceous						
	Lower Cretaceous						
	Neocomian	Urgonian	Aptian	Albian	Vraconnian	Cenomanian	Jurassic
Cladophlebis fissipennis Sap	+	....	....	....	....	....	....
Limai Sap	....	....	....	+	....	....	....
minor Sap	+	....	....	....	....	....	+
minutissima Sap	+	....	....	....	....	....	....
obtusiloba Sap	....	....	....	+	....	....	+
sinuatilobula Sap	+	+	....	....	....	....	....
subcycadina Sap	+	....	....	....	....	....	....
Comptoniopteris cercalina Sap	....	+	....	....	....	....	....
Ctenidium dentatum Heer	....	....	+	....	....	....	....
integerrimum Heer	....	....	+	....	....	+	....
Ctenopteris ultima Sap	+	....	....	....	....	....	....
Cussonia ? lacerata Sap	....	....	....	+	....	....	....
Cycadites pygmæus Sap	....	....	....	+	....	....	....
tenuisectus Sap	....	....	....	+	....	....	....
Cyclopitys Delgadoi Sap	+	....	....	....	....	....	....
Cyclopteris tenuestriata Heer	+	....	....	....	....	....	....
Czekanowskia nervosa Heer	....	....	+	....	....	+	....
Delgadopsis rhizostigma Sap	....	+	....	....	....	....	....
Dicotylophyllum cerciforme Sap	....	+	....	....	....	....	....
corrugatum Sap	....	+	....	....	....	....	....
hederaceum Sap	....	+	....	....	....	....	....
lacerum Sap	....	+	....	....	....	....	....
Dictyopteris anomala Sap	+	....	....	....	....	....	....
infracretacica Sap	+	....	....	....	....	....	....
tenella Sap	+	....	....	....	....	....	....
Eolirion lusitanicum Sap	....	....	....	+	....	....	....
Equisetites Burchardti Dunk	+	....	....	....	....	....	....
Equisetum, sp. Sap	....	+	....	....	....	....	....
Eucalyptus angusta Sap	....	....	....	....	+	....	....
Choffati Sap	....	....	....	....	+	....	....
proto-Geinitzi Sap	....	....	....	....	+	....	....
Frenelopsis leptoclada Sap	+	....	+	....	....	....	....
occidentalis Heer	+	+	?	+	+	+	....
Glossozamites brevior Sap	+	....	....	....	....	....	....
dilaceratus Sap	+	....	....	....	....	....	....
modestior Sap	+	....	....	....	....	....	....
Isoetes Choffati Sap	....	+	....	....	....	....	....
Jungermannites vetustior Sap	....	+	....	....	....	....	....
Laccopteris pulchella Heer	....	....	+	....	....	....	....
Laurus attenuata Sap	....	....	....	....	+	....	....
notandia Sap	....	....	....	....	+	....	....
palæocretacea Sap	....	....	....	....	+	....	....
Leguminosites intracretaceus Sap	....	....	....	....	+	....	....
Lonchopteris lusitanica Sap	+	....	....	....	....	....	....
Lycopodites Francheti Sap	....	+	....	....	....	....	....
gracillimus Sap	....	+	....	....	....	....	....
Limai Sap	....	+	....	....	....	....	....
Magnolia Delgadoi Sap	....	....	....	+	....	....	....
Marattia minor Sap	+	....	....	....	....	....	....
Matonidium Gœpperti (Ett.) Schenk	+	....	+	....	....	....	....
Menispermites cercidifolius Sap	....	....	....	+	....	....	....
Microlepia pluripartita Sap	+	....	....	....	....	....	....
Myrica lacera Sap	....	....	....	....	+	....	....
revisenda Sap	....	....	....	....	+	....	....

List of the Lower Cretaceous plants of Portugal with their geological distribution in that country—Continued.

Species	Mesozoic						
	Cretaceous						
	Lower Cretaceous						
	Neocomian	Urgonian	Aptian	Albian	Vraconnian	Cenomanian	Jurassic
Myrsinophyllum revisendum Sap	....	....	....	+	....	....	....
venulosum Sap	....	....	....	....	+	....	....
Neuropteridium spinulosum Sap	+	....	....	....	....	....	....
torresianum Sap	+	....	....	....	....	....	....
Oleandridium tenerum Sap	+	....	....	....	....	....	....
Onychiopsis Mantelli (Brongn.) Seward	+	+	+	+	....	....	+
Osmunda retinenda Sap	+	....	....	....	....	....	....
Pagiophyllum Heerianum Sap	+	....	....	....	....	....	+
Palæocyparis flexuosa Sap	+	....	....	....	....	....	+
obscura Sap	....	....	....	+	....	....	....
Palæolepis bicornuta Sap	....	....	....	+	....	....	....
emarginata Sap	....	....	....	+	....	....	....
Pecopteris Choffatiana Heer	+	....	....	....	....	....	....
dilacerata Sap	+	....	....	....	....	....	....
dispersa Sap	....	....	....	+	....	....	....
minutula Sap	....	....	....	+	....	....	....
Peucedanites primordialis Sap	....	....	....	+	....	....	....
Phlebomeris? falciformis Sap	+	....	....	+	....	....	....
spectanda Sap	....	....	....	+	....	....	....
Willkommi Sap	....	....	....	+	....	....	....
Phyllites inflexinervis Sap	....	....	....	....	+	....	....
problematicus Sap	+	....	....	....	....	....	....
triplinervis Sap	....	....	....	....	+	....	....
Pinites cyclopterus Sap	....	....	....	+	....	....	....
Poacites acicularis Sap	....	+	....	....	....	....	....
cerealinus Sap	....	+	....	....	....	....	....
gemellinervis Sap	+	....	....	....	....	....	....
lævis Sap	....	....	....	+	....	....	....
paucinervis Sap	+	....	....	....	....	....	....
plurinervius Sap	....	....	+	....	....	....	....
plurinervulosus Sap	....	+	....	....	....	....	....
striatifolius Sap	+	....	....	....	....	....	+
tenellus Sap	+	....	....	....	....	....	....
Podozamites ? acutus Sap	+	+	....	....	....	....	....
Podozamites ellipsoideus Sap	+	....	....	+	....	....	....
gracilior Sap	....	....	....	+	....	....	....
Henriquesi Sap	....	....	....	+	....	....	....
linearis Sap	+	....	....	....	....	....	....
modestior Sap	....	....	....	+	....	....	....
oviformis Sap	+	....	....	....	....	....	....
Proteophyllum daphnoides Sap	....	....	....	....	+	....	....
demersum Sap	....	....	....	....	+	....	....
dissectum Sap	....	....	....	+	....	....	....
leucospermoides Sap	....	....	....	+	....	....	....
oblongatum Sap	....	....	....	....	+	....	....
oxyacanthæmorphum Sap	....	....	....	+	....	....	....
truncatum Sap	....	....	....	....	+	....	....
Protorhipis Choffati Sap	....	+	....	....	....	....	....
Pteridoleimma phycomorpha Sap.	....	....	....	+	....	....	....
spoliatum Sap	+	....	....	....	....	....	....
tripartitum Sap	+	....	....	....	....	....	....
Ravenalospermum incertissimum Sap	....	....	....	....	+	....	....
Rhizocaulon elongatum Sap	+	+	....	....	....	....	....
vetus Sap	+	....	....	....	....	....	+
Ruffordia Gœpperti (Dunk.) Seward	+	+	....	+	....	....	....

List of the Lower Cretaceous plants of Portugal with their geological distribution in that country—Continued.

Species	Mesozoic						
	Cretaceous						Jurassic
	Lower Cretaceous					Cenomanian	
	Neocomian	Urgonian	Aptian	Albian	Vraconnian		
Salix assimilis Sap	....	...	....	....	+	....	....
infracretacica Sap	....	....	...	+	....	...	....
retinenda Sap	....	...	....	+	- ..	....	....
Sapindophyllum brevior Sap	....	..	....	....	+	....	....
subapiculatum Sap	....	...	....	....	+	....	....
Sassafras protophyllum Sap	....	...	....	+	- ..	....	....
Scleropteris debilior Sap	+	....	....	....	....	....	....
Sequoia lusitanica Heer	+	...	+	....	....	+	....
subulata lusitanica Sap	....	....	....	+	....	....	....
Sphæria phylostichoides Sap	....	....	....	+	....	....	....
Sphenolepidium debile Heer	+	+	+	+	....	....	....
Kurrianum (Dunk.) Heer	+	+	+	+	+	+	....
Sternbergianum (Dunk.) Heer	+	+	+	+	+	....	....
Sphenopteris acutidens Sap	....	+	....	....	....	....	+
aneimiæformis Sap	....	+	....	....	....	....	....
angustiloba Heer	...	+	+	....	....	+	. ..
capillaris Sap	+	...	....	....	....	....	....
cercalensis Sap	....	+	....	....	....	....	....
Choffatiana infracretacica Sap	+	.. .	....	....	...	....	..
Cordai (Dunk.) Schenk	....	+	....	....	....	....	....
crenularis Sap	...	....	....	+	....	....	....
cuneifida Sap	+	+	....	....	....	....	....
debiliformis Sap	+	....	....	....	....	....	....
debilior Sap	...	....	....	+	....	....	....
dissectifolia Sap	+	....	....	....	....	....	+
dissectiformis Sap	+	....	....	....	....	....	....
flabellina Sap	...	....	....	+	....	....	....
flabellinervia Sap	+	....	....	....	....	....	....
flabellisecta Sap	+	....	....	....	....	....	....
ginkgoides Sap	•+	....	....	....	....	....	....
Gomesiana Heer	+	....	....	....	....	....	....
involvens Sap	....	....	....	+	....	....	....
linearisecta Sap	....	+	....	....	....	....	....
lobulifera Sap	+	+	....	....	....	...	....
lupulina Heer	+	....	....	....	....	....	....
plurinervia Heer	+	+	?	....	....	....	....
polyclada Sap	....	+	....	....	....	....	....
pseudo-Cordai Sap	.. .	....	....	+	....	....	....
pseudolepida Sap	+	....	....	....	...	....	....
pygmæa Sap	....	+	....	...	....	....	....
recurrens Sap	....	....	....	+	....	....	....
subtilinervis Sap	+	....	....	....	....	....	+
tenuifissa Sap	.. .	....	+	+	....	....	....
Stachypteris minuta Sap	+	....	....	....	....	....	+
Tæniidium lusitanicum Heer	....	....	+	....	....	....	....
Thuyites debilis Sap	....	....	+	....	....	....	....
densior Sap	+	....	....	....	....	...	....
pulchelliformis Sap	+	....	+	....	....	....	+
Viburnum vetus Sap	....	....	....	....	+	....	....
Widdringtonites debilis Sap	+	....	....	....	....	....	+
pygmæus Sap	+	....	....	....	....	....	....
Williamsonia minima Sap	+	....	....	....	....	....	....
Yuccites fractifolius Sap	+	...	....	....	....	....	....

Table of distribution of the eleven species of fossil plants from other beds that occur in the Lower Cretaceous of Portugal.

Species	Lower Cretaceous of Portugal					Lower Cretaceous of America							Wealden					Neocomian		Urgonian				Cenomanian							Oolite			Kimmeridgian		
						Potomac																														
	Valanginian	Urgonian	Aptian	Albian	Vraconnian	James River	Rappahannock	Mount Vernon	Aquia Creek	Trinity	Kootanie	Purbeck of England	England	France	Germany	Austria	Moravia	Westphalia	Russia	Silesia	Spitzbergen	Greenland	Gault of Belgium	Portugal	Saxony	Bohemia	Senonian of Blankenburg	Rhetic of Bavaria	Lias of Hungary	Ipswich beds of Australia	Yorkshire	Spitzbergen	Corallian of France	Portugal	France	Upper Jurassic of Japan
Baiera cretosa Schenk				+																+	+	+														
Cladophlebis Browniana (Dunk.) Sew.	+					+	+		?		+		+		+				+						+									+		+
Cladophlebis Dunkeri (Schimp.) Sew.	+	+	+	+		+	+				+		+		+								+								+	+				+
Equisetites Burchardti Dunk.	+												+	+	+	+											+									
Matonidium Gœpperti (Ett.) Schenk	+			+								+	+		+				+				+					+			+					
Onychiopsis Mantelli (Brongn.) Sew.	+	+	+	+					+	+		+	+		+	+	+						+		+					+				+		
Ruffordia Gœpperti (Dunk.) Sew.	+	+		+									+		+				+				+		+	+					+					+
Sphenolepidium Kurrianum (Dunk.) Heer	+	+	+	+	+	+	+		+				+		+			+						+					+							
Sphenolepidium Sternbergianum (Dunk.) Heer	+	+	+	+	+		+	+							+	+		+																		
Sphenopteris Cordai (Dunk.) Schenk		+													+																					
Stachypteris minuta Sap.	+																																+		+	

Table of distribution of twelve species of plants from the Lower Cretaceous of Portugal, and of the Potomac species to which they are related.

Portuguese species	Lower Cretaceous of Portugal				Lower Cretaceous of the United States									Cenomanian					Senonian		Oolite			Potomac species
					Potomac																			
	Valanginian	Urgonian	Albian	Vraconnian	James River	Rappahannock	Mount Vernon	Aquia Creek	Albirupean	Raritan	Island Series	Kootanie	Cape Lisburn	Saxony	Bohemia	Moravia	Greenland	Dakota Group	Germany	Greenland	Spitzbergen	Siberia	Persia	
Aralia calomorpha Sap			+							+				+	+	+		+						Aralia formosa Heer
Cladophlebis fissipennis Sap	+					+																		Asplenіopteris pinnatifida Font
Cladophlebis subcycadina Sap	+				+							+												Cladophlebis distans Font
Dicotylophyllum corrugatum Sap	+					+	+	+ +																Populophyllum reniforme Font Proteæphyllum reniforme Font
Eucalyptus Choffati Sap				+						+	+			+	+	+	+	+						Eucalyptus Geinitzi Heer
Podozamites? acutus Sap	+	+			+ +	+ +		+																Nageiopsis ovata Font zamioides Font Phyllocladus heterophylla Font
Podozamites Henriquesi Sap			+									+ +	+		+		+		+					Podozamites latipennis Heer nervosus Newb
Podozamites linearis Sap	+									+								+				+	+	Podozamites angustifolius (Eichw.) Schimp
Podozamites oviformis Sap	+					+																		Nageiopsis obtusifolia Font

Table of distribution of twelve species of plants from the Lower Cretaceous of Portugal, and of the Potomac species to which they are related—Continued.

Portuguese species	Lower Cretaceous of Portugal				Lower Cretaceous of the United States									Cenomanian					Senonian		Oolite			Potomac species
					Potomac																			
	Valangınian	Urgonian	Albian	Vraconnian	James River	Rappahannock	Mount Vernon	Aquia Creek	Albirupean	Raritan	Island Series	Kootanie	Cape Lisburn	Saxony	Bohemia	Moravia	Greenland	Dakota Group.	Germany	Greenland	Spitzbergen	Siberia	Persia	
Salix assimilis Sap				+						+	+							+						Salix proteæfolia Lx
Sassafras protophyllum Sap			+					+																Sassafras cretaceum heterolobum Font
Sequoia subulata lusitanica Sap			+		+	+			+	+							+			+				Sequoia subulata Heer

As will be seen from the first of these tables, the floras of the several horizons in the Lower Cretaceous of Portugal differ less in their abundance than those of the Jurassic. The largest is that of the Valanginian, amounting to 88 species, or over 43 per cent; the Urgonian has yielded only 45 species, or 22 per cent; the Aptian, 25 species, or over 12 per cent; the Lower Albian, 64 species, or nearly 32 per cent; the Upper Albian or Vraconnian, 26 species, or nearly 13 per cent. The striking coincidence of the parallelism between these horizons and those of the Potomac formation in America is still further heightened by the circumstance, accidental perhaps, that the numerical proportion existing between the species now known at the corresponding horizons in America is very nearly the same. The Basal Potomac, corresponding to the Valanginian, has yielded 329 species, or a little over 44 per cent; the Mount Vernon clays, which were compared with the Urgonian, 42 species, or somewhat less than 6 per cent; the Aquia Creek beds, corresponding to the Aptian, 137 species, or rather more than 18 per cent; the Raritan beds and their equivalents, compared to the Lower Albian, 264 species, or nearly 36 per cent; and the Island series, compared to the Vraconnian, 133 species, or 18 per cent. These results may be put in the following tabular form:

Comparative table of percentages.

Lower Cretaceous of Portugal.		Potomac formation of the United States	
Horizons	Per cent	Horizons	Per cent
Vraconnian	13	Island series	18
Lower Albian	32	Amboy Clays, etc	36
Aptian	12	Aquia Creek series	18
Urgonian	22	Mount Vernon clays	6
Neocomian	43	Basal Potomac	44

The Mount Vernon clays have been very little developed as yet, and when this florula is thoroughly known it will probably fully equal that of the Urgonian beds of Portugal relatively to the total flora.

Taking the Cretaceous flora of Portugal as a whole, exclusive of the Cenomanian, it is found to consist of 2 algæ, 2 Hepaticæ, 1 species of Isoetes, 3 of Lycopodites, 2 equiseta, 79 ferns, 15 cycads, 29 conifers, 5 anomalous types classed by the author under the head of Proangiosperms, 16 monocotyledons, 47 dicotyledons, and 3 forms of uncertain affinity.

It will be seen that, as in the Jurassic, so in the Cretaceous, the ferns predominate, and of these 30 species belong to the genus Sphenopteris, and 12 to Cladophlebis. Seven of the cycads belong to the genus Podozamites, and 3 to Glossozamites. The conifers are much more evenly distributed, there being 5 species of Brachyphyllum, and 3 each of Sphenolepidium and Thuyites, while a large number of genera have only one or two species. Among these are Frenelopsis, Palæocyparis, Palæolepis, Sequoia, and Widdringtonites. The genera referred to the Proangiosperms are Changarniera, Eolirion, Yuccites, Delgadopsis, and Protorhipis, some of which will require special mention further on. Nine of the monocotyledons consist of grass-like objects referred to Poacites, some of which Saporta classes under the Proangiosperms and others as true monocotyledons, but I prefer to group them together. The dicotyledonous flora is here well developed, but most of the forms occur in the Albian. Seven species are referred to a new genus, Proteophyllum, a name too near to both Proteæphyllum of Fontaine and Protophyllum of Lesquereux, but the forms are different from both of these; four to the new genus Dicotylophyllum, and 3 each to Eucalyptus, Laurus, and Salix.

In comparing the Cretaceous flora of Portugal with that of America it is true that we find only a few species that are common to the two countries, really only five, as follows:

Cladophlebis Browniana (Dunk.) Seward
Cladophlebis Dunkeri (Schimp.) Seward
Onychiopsis Mantelli (Brongn.) Seward
Sphenolepidium Kurrianum (Dunk.) Heer
Sphenolepidium Sternbergianum (Dunk.) Heer

These are all plants of wide distribution, and argue very little for the identity of the particular horizons in which they occur. The comparisons which are indicated in the third of the above tables are much more significant from this point of view, and it is altogether probable that if all the material from both countries could be studied together there would be a large number of specific identifications.

We should not, of course, expect the species to be common to any great extent, and the comparison is practically limited to the genera. Looked at from this point of view, we see that the resemblance is indeed close, a great number of the important genera occurring in both floras. There are no less than 46 of these common to the two, though in some cases the author's individuality is probably alone responsible for slight differences of termination in the names. For example, forms referred to Baiera by one would be referred to Baieropsis by the other, and so with Ctenis and Ctenidium, Myrsine and Myrsinophyllum, Oleandra and Oleandridium, Salix and Saliciphyllum, Thuya and Thuyites, etc.

Many of these genera, when we consider the difference in the size of the two floras (about as 1 to 4), occur in both countries in nearly the same proportion. For example, of Aralia we have in Portugal 2 species, in America 11; of Brachyphyllum, in Portugal 5, in America 9; of Cladophlebis, in Portugal 12, in America 25; of Frenelopsis, in Portugal 2, in America 6; of Laurus, in Portugal 3, in America 8; of Myrica, in Portugal 2, in America 11; of Podozamites, in Portugal 7, in America 15; of Sphenolepidium, in Portugal 3, in America 9, etc. There are, of course, some cases in which the proportion is not the same. Thus, only 1 species of Magnolia occurs in the Portuguese beds, while in America we have 12, and on the other hand the largest Portuguese genus, Sphenopteris, represented there by 30 species, counts in America only 8 species. But here it may be supposed that the true representative in America of the Sphenopteris type of Portugal is really that exceedingly abundant genus Thyrsopteris, which numbers 40 species in the American beds. This would somewhat restore the relative proportions. On the whole, then, it may be considered that the Lower Cretaceous flora of Portugal is, botanically speaking, a very close repetition of that of America; and in view of the fact that in both countries a number of distinct horizons showing the progressive change in the flora throughout that period have yielded fossil plants in such a way that, if the Portuguese beds were as fully developed as are the American ones, each of these florules might also be compared, the subject becomes rather fascinating.

ARCHETYPAL ANGIOSPERMS.

Space will only permit the consideration of one other important aspect, viz, a comparison of the dicotyledonous forms in the two countries together with those ancestral types which Saporta regards as prophetic of that great group of plants. This last question may be considered first. He finds among the specimens certain forms which he refers to the genus Protorhipis of Andræ. This genus was founded in 1853 upon some remarkable forms from the Lias of Steierdorf in Banat, Hungary,[1] which Andræ regarded as a fern and placed under the Pecopterideæ. He compares it with Jeanpaulia, which has since been proved identical with Baiera and correctly referred to the Coniferæ; also to Cyclopteris, Comptopteris, Diplodictyum, and Thaumatopteris, among fossils, and to Platycerium, among living ferns.

When I first saw the figure of his *Protorhipis Buchii*, I had grave doubts of its being a fern and inclined to believe that it represented some higher type of vegetation. I am therefore not surprised that Saporta has arrived at the same conclusion, and am highly gratified that he has had the courage to give it publicity, notwithstanding the fact that Schimper, Schenk, Heer, and Nathorst have all been content to regard it as a fern of the type of Drynaria, Platycerium, Allosorus, Clathropteris, and the other living and fossil forms already mentioned. I have reproduced Andræ's figure (Pl. CVI, Fig. 1) for purposes of comparison.

In 1865 Zigno discovered another species which, however, differs in a marked manner from the original of Andræ, having the margins entire. It is a small, deeply kidney-shaped leaf resembling that of some species of Asarum, and was named *P. asarifolia*. This comes from the Oolite of Italy.[2]

The forms described by Nathorst in 1878,[3] though much smaller, are

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[1] Lias Flora von Steierdorf im Banate, by K J Andræ, Abhandl d k k geol Reichsanst, Vol II, Abth 3, No 4, 1853, pp 35-36, pl viii, fig 1

[2] Fl Foss Form Oolithicæ, Vol I, 1865, p 180, pl ix, figs 2, 2*a*

[3] Fl v Bjuf, Pt 1, p 42, Pt 2, p 57, pl xi, figs. 2, 4

otherwise similar to *P. Buchii*, and Nathorst at first proposed to refer one of them to that species, but later concluded that it was distinct and made two species, *P. integrifolia* and *P. crenata*.

In 1880 Heer described another small cordate form from the Oolite of Siberia. It is similar to Zigno's species and was named *P. reniformis*.[1] Two years later, however, he found another similar form in the Kome beds of Greenland, Urgonian, which is rather cordate than reniform and which he called *P. cordata*.[2] Both these forms have the margins entire.

Saporta in this work has revised all these forms and comes to the conclusion that they can not be ferns, and although the original *P. Buchii* and both of Nathorst's species, though lacking the distinction of midrib and secondary nerves, so closely resemble dicotyledonous leaves and are somewhat comparable in nervation to Credneria and some fossil Viburnums, as well as to such living genera as Glechoma and Chrysosplenium, still he hesitates to class them in that group. He has carefully refigured both of Nathorst's specimens, and these revised figures are here reproduced (Pl. CVI, Figs. 4 and 5). All these he carefully compares with the Portuguese form, which he names *P. Choffati*, two of the most perfect figures of which are here shown (Pl. CVI, Figs. 2 and 3), and classes the whole in the special group which he long ago created and denominated the Proangiosperms, as representing the forerunners of both the monocotyledons and dicotyledons. The Portuguese species comes from the beds at Cercal, which, as we have seen, may be referred to the Urgonian. It is therefore probably of about the same age as the Kome beds of Greenland from which Heer derives one of his species; all the others, of course, are of far more ancient origin, viz, Jurassic, and it is not to be wondered at that no one should have ventured to refer them to any modern type.

Of the other four genera referred to this group, viz, Changarniera, Yuccites, Delgadopsis, and Eolirion, the first two come from the Valanginian (Neocomian) of S. Sebastião, the third from the Urgonian of Cercal, and the last from the Albian of Buarcos. They all seem to be ancestral monocotyledons. Delgadopsis occurs in two forms, first as a sort of culm or broad striate stem, and secondly in the form of a jointed rhizome, the swollen joints emitting innumerable rootlets, which when absent leave peculiar scars.

Choffatia Francheti from Cercal, regarded by the author as a dicotyledon, is also a very remarkable plant, and has been aptly compared by him to certain euphorbiaceous forms, such as Phyllanthus. It also resembles some species of Euphorbia. It seems to be a floating aquatic, and specimens with the fibrous roots occur in the collection. In some of these, descending fibers occupy one side of the stem or rachis, while the floating or aerial leaves occupy the other.

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[1] *Fl Foss Arct, Vol VI, Abth 1, Pt I, p 8, pl i, fig 4a*

[2] Ibid , Abth 2, p. 10, pl iii, fig 11

PLATE CVI.

PLATE CVI.

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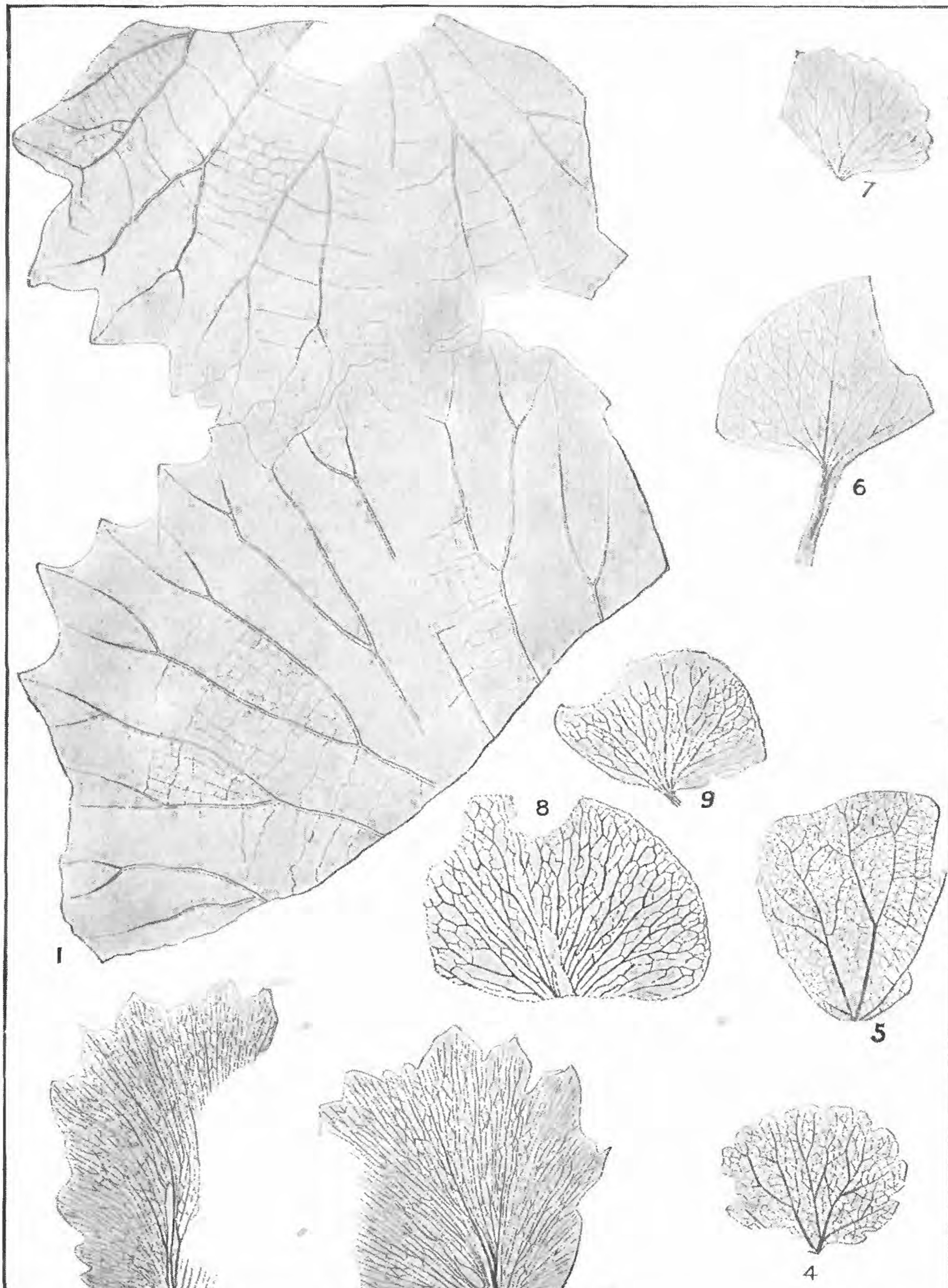

ARCHETYPAL ANGIOSPERMS FROM THE MESOZOIC OF EUROPE AND AMERICA.

Upon the whole it can not be said that any of these higher types, found below the Albian and corresponding in age to our Middle and Older Potomac, very closely resemble the plants of the same general class from the American beds of that age, and yet there are certain Potomac forms referred by Professor Fontaine to Menispermites, Hederæphyllum, Proteæphyllum, and Populophyllum, whose areolate nervation somewhat resembles that of *Protorhipis Choffati.* The new genus Dicotylophyllum, of which he finds four species in the Urgonian of Cercal, and which he very properly regards as a true dicotyledon, somewhat resembles the Protorhipis, but lacks the peculiar areolate nervation. These leaves are all quite small, but show a somewhat distinct midrib and usually 2 to 4 lateral primaries. In form they recall some species of Vitis or Cissites, and *D. cerciforme*, while not resembling Cercis, as the specific name would imply, has many of the characteristics of Hedera. It may be roughly compared with Professor Fontaine's Vitiphyllum, from the Potomac of Baltimore, and except in size *D. hederaceum* and *D. corrugatum* are fairly comparable with *Populophyllum reniforme* Font. and *Proteæphyllum reniforme* Font. Several of the American forms are reproduced here for comparison (see Pl. CVI, Figs. 6–9).

In the Albian beds of Buarcos, and especially in the Vraconnian of Nazareth, we begin to find some of the higher types. But the genus Proteophyllum has still a very ancient appearance, with a more or less areolate nervation. It is a narrowly-lobed leaf, remotely recalling in its general form some species of Dewalquea. It may be possible to trace this form into his *Aralia calomorpha* from the same beds. His *Adoxa præatavia* is a very peculiar plant, which also reminds one of Vitiphyllum Font., although species of the latter genus which show the branching character have not yet been figured. His *Braseniopsis venulosa* has some of the characteristics of Protophyllum of Lesquereux, but is usually smaller and always entire; the nervation is also different except at the base of the leaf, which has a large expansion below the summit of the petiole, as in Protophyllum. *Myrsinophyllum revisendum* will doubtless have to be revised. It is much like Potomac forms that have been referred to Myrica (e. g., *M. brookensis*) and Celastrophyllum. It is entirely different from the *Myrsine borealis* of Heer, which, with two other species, occur in the Amboy Clays and Tuscaloosa formation. His *Cissites obtusilobus*, of which I give one figure (Pl. CVII, Fig. 1), is very close to Fontaine's *Vitiphyllum* (*Cissites*) *multifidum* (Pl. CVII, Figs. 2–5). His *Menispermites cercidifolius*, though much smaller, is not unlike Professor Fontaine's *M. virginiensis*, especially the smaller forms which I have found in the Mount Vernon clays. His *Aralia proxima* can scarcely be distinguished from *A. Wellingtoniana* of the Dakota group, more common in the Newer Potomac.

It is only in the Nazareth beds (Vraconnian) that we find the typical Amboy Clay flora. Here we have the Eucalyptus, Laurus (Laurophyllum), Salix, Myrsinophyllum, Sapindophyllum, etc., some of which are doubtless specifically identical with forms described by Newberry, and it is altogether probable that if the posthumous work of Dr. Newberry, now in press, had been in the hands of the author a large number of the species would have been identified with American forms.

I will notice only one other significant fact. In the Cenomanian beds which overlie these last, as it would seem unconformably, but which may not be so widely separated from them as has been supposed, there occurs a large elongated leaf which the Marquis has called *Chondrophyton laceratum.* It agrees only in its finer nervation with *C. dissectum* Sap. & Mar , the only other species.[1] It has a very delicate nervation with small polygonal meshes, and an entire paryphodrome margin, but the remarkable fact is that it seems to have a deeply retuse summit. It is evident that from the specimen the author was unable to make this latter out with certainty; but he has drawn the marginal lines so as distinctly to indicate it. So desirous was he that this leaf should be correctly represented that he has given us two interpretations from drawings made at different times (figs. 4 and 5 of pl. xxxviii). He states that he considers fig. 5 to represent the form better than fig 4, and it is in this that the terminal lobation is most clearly shown. A comparison of this figure with the numerous specimens of *Liriodendropsis simplex* of Newberry, leaves no doubt whatever that the Portuguese plant is at least a congener of the American plant, and it is just possible that it may belong to the same species. As this form has been three times published,[2] it is a little surprising that Saporta did not think to compare it with the Portuguese plant. There are differences in the finer nervation, but this is also perceptible between his two drawings of the same specimen; these also differ in different specimens of the American plant, and one or two other species remain to be published. When all the material is illustrated most of these differences will disappear. If any remain they can be ascribed to difference of age and geographical position. I do not, therefore, hesitate to refer this plant to the American genus and to rename it *Liriodendropsis lacerata.* On Pl. CVII, Fig. 6, Saporta's best figure is here reproduced, by the side of which (Figs. 7 and 8 of the same plate) is shown our *L. simplex* from the Amboy Clays. I had expected to use some of the published figures above referred to, but thinking that possibly Dr. Hollick might have some drawings that would be available for the purpose I sent him Saporta's plate and requested him to inform me whether he knew of any specimens of Liriodendropsis that approached any more closely to the Portuguese plant than those already published. He investigated the matter and made drawings of two forms, both of which deviate slightly from the type of *L. simplex.* That represented by Fig. 7 seems to be nearest to Saporta's figure. It is what Dr. Newberry distinguished as the variety *angustifolia.* The other form, Fig. 8, is nearer the type, but belongs near a group that Dr. Hollick proposes to regard as forming the variety *constricta.* It shows the summit better than the other.

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[1] L'Évolution du Règne Végétal Les Phanérogames, par G de Saporta et A F Marion, Vol II, Paris, 1885, p 120, fig 126

[2] Bull Torr Bot Club, Vol XIV, New York, January, 1887, p 6, pl lxii, figs 2, 3 4, Am Journ Sci, 3d ser, Vol XXXIX, New Haven, February, 1890, p 98, pl ii, figs 6, 7, Trans N Y Acad Sci, Vol. XI, 1892, p 102 pl ii, figs 2-7, 9.

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PLATE CVII.

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Fig.	7.	Liriodendropsis simplex angustifolia Newb., Amboy Clays, New Jersey	540
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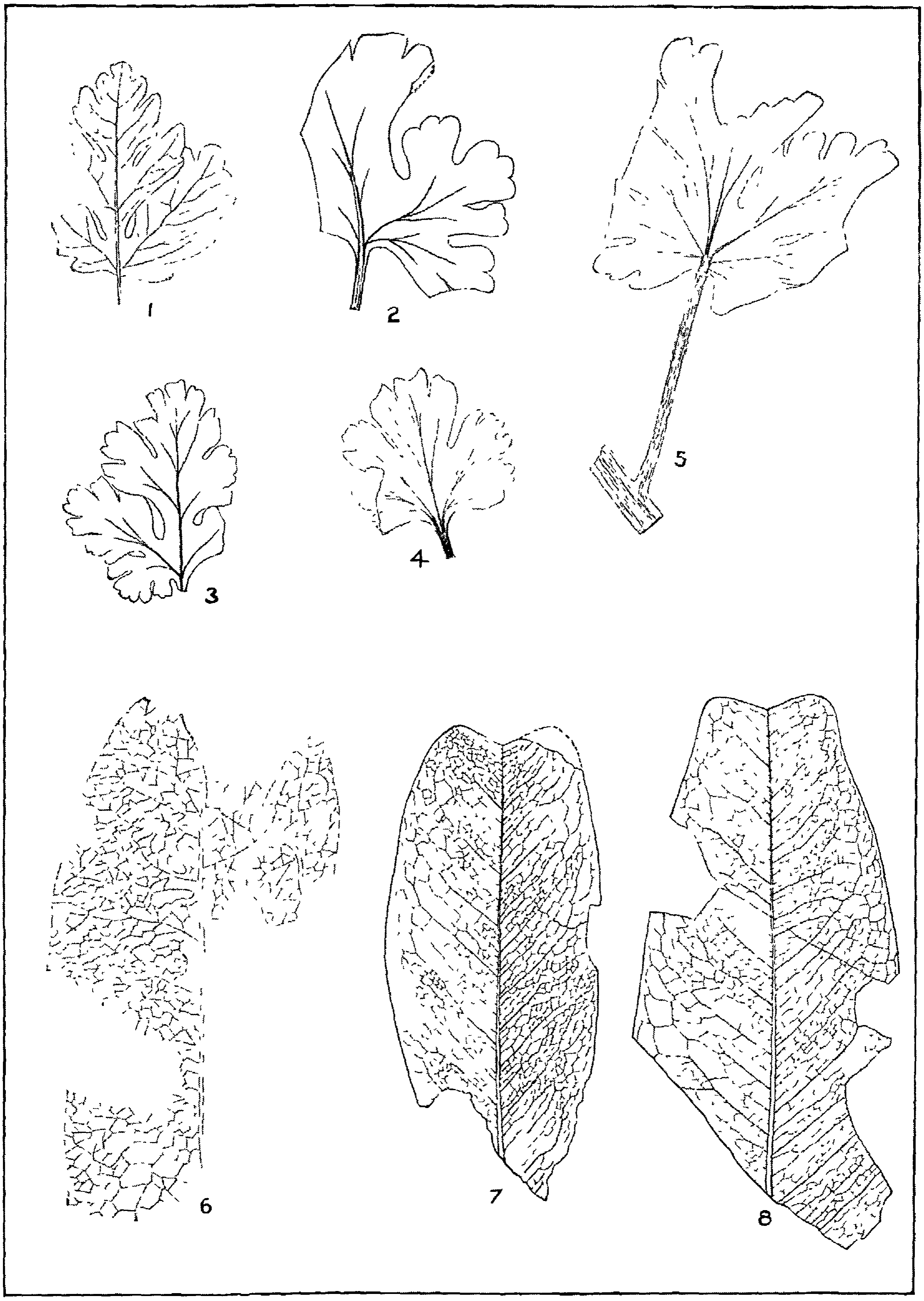

DICOTYLEDONS FROM THE CRETACEOUS OF PORTUGAL AND THE UNITED STATES

STRUCTURAL DETAILS IN THE GREEN MOUNTAIN REGION AND IN EASTERN NEW YORK.

BY

T. NELSON DALE.

CONTENTS

ILLUSTRATIONS

STRUCTURAL DETAILS IN THE GREEN MOUNTAIN REGION AND IN EASTERN NEW YORK.

By T. Nelson Dale.

INTRODUCTION.

After several years of field work in a region and the publication of its more important results, there may yet remain scattered in a geologist's note-books descriptions and sketches of details at disconnected localities which either illustrate in a fresh way well known geological laws or throw a little more light on less familiar ones.

The great movements which have produced what Sir William Dawson fitly calls "mountains of crumpling" are apt to leave their record on every cubic foot of the region affected by them whenever its materials are sufficiently fine grained. For this reason the characteristic features of such mountain-making movements are often quite as truly shown by single ledges, or even hand specimens, as by whole mountain sides.

This is particularly true of the Green Mountain ranges and their western foothills in New York. In this paper a number of observations of such minor objects in that region have been brought together and made to tell their own story in few words. In each case the observations have been, as far as possible, brought into relation with the geological principles which they illustrate. These chips from a geological workshop may prove useful to teachers; some of them may afford hints to field geologists in other but similar regions, and a few may find application in economic geology.

INCLINED AND OVERTURNED FOLDS.

In an old limestone quarry at Lenox, Mass., a narrow cart road has been cut through an anticline, thus giving two transverse sections of it (figs. 70, 71). A system of east-and-west vertical joints probably facilitated the operation. The anticline has the prevailing strike of the region, north 20° east, and dips 40° east on its eastern side and about 75° east on its western. It is compressed and overturned so that its axial plane dips about 50° east. The usual thickening and pinching out of the beds along the apex of the fold is well shown. In one of the upper beds (fig. 70) a slight faulting has resulted. The southern face (fig. 71) has suffered more weathering, and shows a very low easterly cleavage crossing all the beds and evidently subsequent to the folding. In limestone, weathering often brings out structural features which could otherwise hardly be detected. Overturned folds, i. e., with axial planes

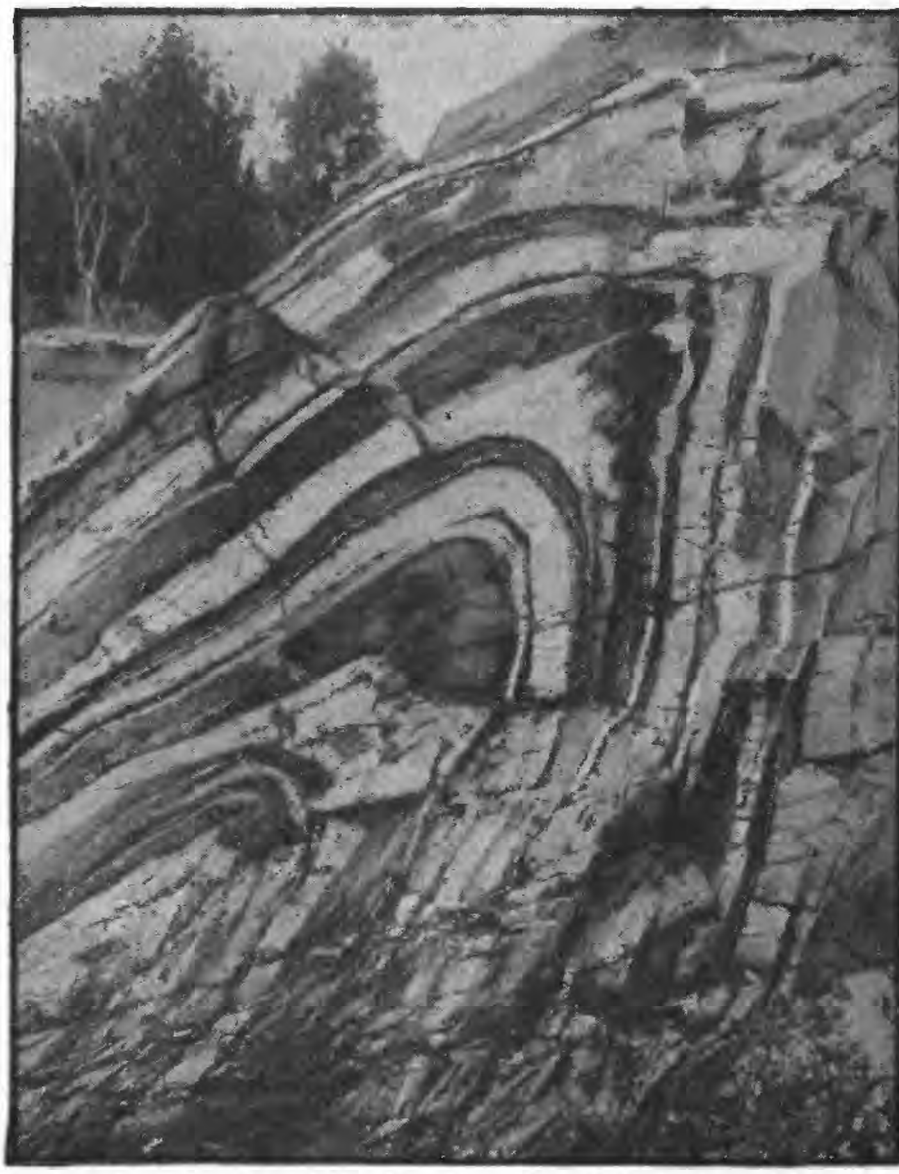

FIG. 70.—Overturned anticline of crystalline limestone with easterly dipping axial plane, Lenox, Mass. Photograph taken looking south. Height, 15 feet. The dark layers are due to yellowish weathering. The folds are thickened at the top and drawn out. Some faulting has occurred here in the upper layers.

dipping east or west—more frequently, however, to the east—are well known as typical of the western part of the northern Appalachian region.

Within a few hundred feet of this is another limestone fold (fig. 72), in which the overturn has proceeded a step farther. We have either the eastern or the western limb of a syncline folded over onto itself so as to form a minor anticline and syncline.

A cliff of Silurian shale along the gorge of the Hoosick at Schaghticoke, Rensselaer County, N. Y., 5 miles west of the Hudson (fig. 73), shows how misleading a series of such similarly overturned folds may be to one making estimates of thickness, even when cleavage phenomena are absent. In crossing the upper edges of such a series the observed dips would all be easterly at various angles. This series of small, acute folds

FIG. 71.—Same anticline as in fig. 70, but 10 feet farther north. Photograph taken looking north. The face has suffered erosion, bringing out a very low easterly dipping cleavage.

with easterly dipping axial planes probably forms part of the side of a broad fold, and the dip to be entered in the geologist's note-book in such a locality ought to be "low west, in small folds."

On the Lebanon Springs Railroad a little south of Stephentown, Rensselaer County, N. Y., the Silurian slates contain a small, extremely compressed anticline so overturned that its axial plane dips only 10° (fig. 74). It is traversed by a slaty cleavage parallel to its axial plane.

Slightly overturned folds may be confined to certain zones of strata and also have pitching axes. Thus at Ashley Hill, near Rayville, in the northern part of Columbia County, N. Y., there are beds of red shale 5 to 6 inches thick alternating with beds of very quartzose limestone 1 to 3 inches thick (fig. 75). The axes of the folds pitch 60° south. This folding seems to be confined to some 10 feet or so of strata, for a few feet east and west the beds resume their usual northerly strike and easterly dip, and the folding disappears. The shale beds have a cleavage which strikes and dips conformably to the unfolded beds on both sides of the folded zone (see fig. 76).

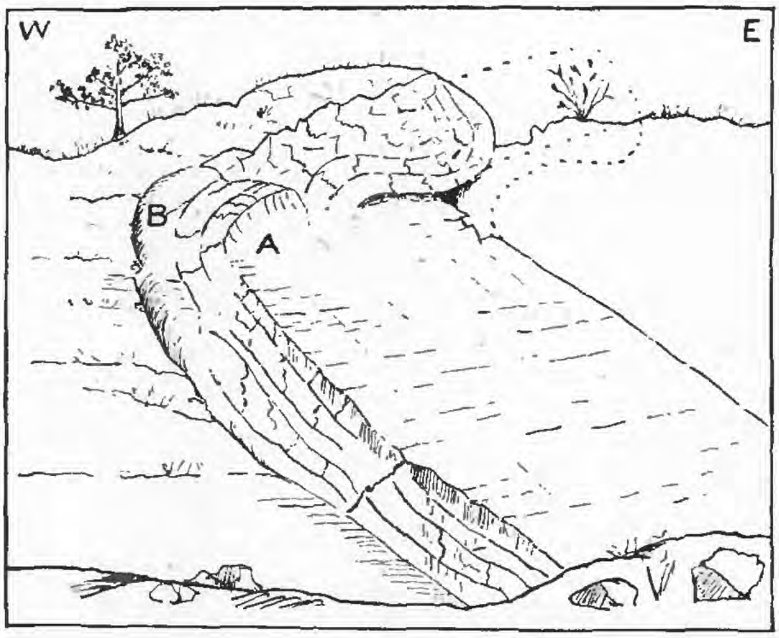

FIG. 72.—A fold within the limb of a syncline of crystalline limestone, Lenox, Mass. Sketch taken looking north; area 15 by 15 feet. At A the upper side of the bed; at B the lower side reflexed.

Such small belts of strata plicated along the strike within a mass of strata which is broadly folded in a direction across the strike are not of very frequent occurrence. They may, perhaps, be accounted for by the unequal plasticity of different beds, the softer ones thinning out under pressure more than the harder ones, that is, becoming longer. The plication of such beds along the strike would then be the result of the taking up of their surplusage in that direc-

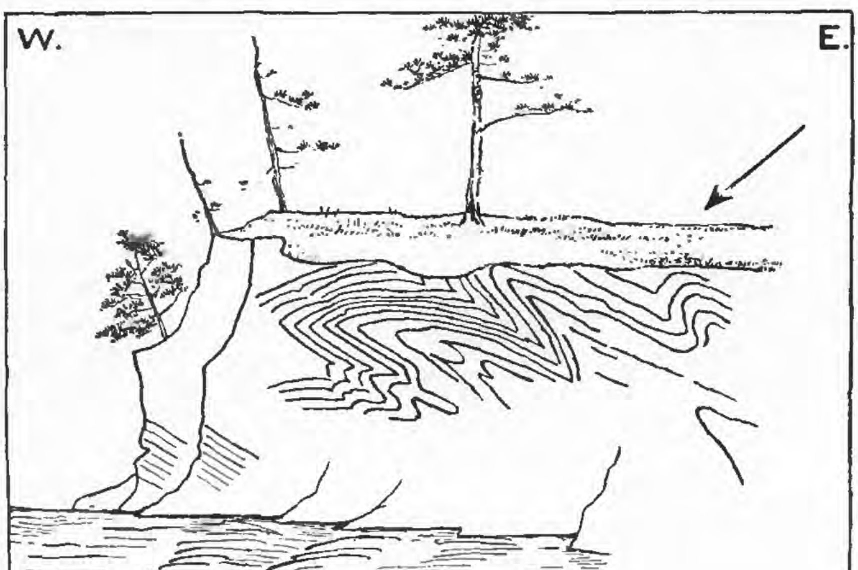

FIG. 73.—Sketch of a series of overturned folds of shale, with easterly dipping axial planes, on the right bank of the Hoosick, at Schaghticoke, N. Y.

tion.[1] In this instance this plication, instead of acting directly along the strike, seems to have acted in a direction between it and that of the general dip of the entire series, thus giving a southerly pitch to the subordinate folds.

FIG. 74.—Overturned compressed anticline of slate with axial plane dipping 10°, and with slaty cleavage parallel to it. Length, 6 feet. Stephentown, Rensselaer County, N. Y. Photograph.

TRANSVERSE FOLDS.

In Dr. J. E. Wolff's section of Hoosac Mountain[2] the folding of a great mass of beds in two directions at right angles to each other, i. e., with and across the strike, is finely shown.

The anticline is 1½ miles broad at the surface from east to west, and the transverse anticline, i. e., the one in the axis of the fold, is about 4½ miles long at the surface from north to south.

At the foot of the Taconic Range, near the west end of the village of Williamstown, about 8½ miles northwest of the great complex Hoosac anticline, is a hillock of quartzite and limestone of Cambrian and Silurian age[3] in which the Hoosac structure is repeated in miniature, the whole structure being exposed within about one-third of a mile square. Further study may show that this structure is characteristic of the Green Mountain region.

On the north, the east, and the southwest sides of the hillock the limestone crops out, overlying, as it should, the quartzite of the Vermont formation, which constitutes its center and top. Similar relations, if one may judge from the outcrops along the strike to the south, probably

[1] See Archibald Geikie's report on recent work of the Geological Survey in the Northwest Highlands of Scotland, etc.: Quart. Jour. Geol. Soc., London, Vol. XLIV, p. 397, where he describes a similar overfolding of small micaceous layers. This structure also occurs in Cambrian schists and quartzites at Clarendon in Vermont.

[2] Mon. U. S. Geol. Survey, Vol. XXIII, Pl. VI, Secs. V, X, XII.

[3] See Ibid., Pl. I (map).

recur on the west side, which, however, is covered with drift. The dips on the east are about 30° east, on the north about 30° northeast, and on the southwest about 45° southwest. Fig. 77 represents a section crossing the hill nearly in the direction of the axes of the folds of the region; fig. 78, one crossing it at right angles to them. In fig. 77 the parallelism between the faulting and the cleavage is noticeable, also the partial protection afforded to the limestone synclinal cores by the quartzite anticlines.[1] Such longitudinally folded anticlines show that the compression which was concerned in the formation of the Green Mountains operated both in a northwest-southeast and in a northeast-southwest direction. On the theory of the contraction of the earth's interior as the cause of mountain systems, and even on that of the expansion of the crust, it seems more rational that the corrugation of the sedimentary beds should have occurred simultaneously in two directions at right angles to each other than that it should have been confined to one. It must be admitted, however, that the Hoosac structure is probably uncommon in the Green Mountain region. That the northeast-southwest folding was the result of a secondary movement seems difficult to believe, on account of the great rigidity which the first folding and its accompanying metamorphism must have imparted to the masses.

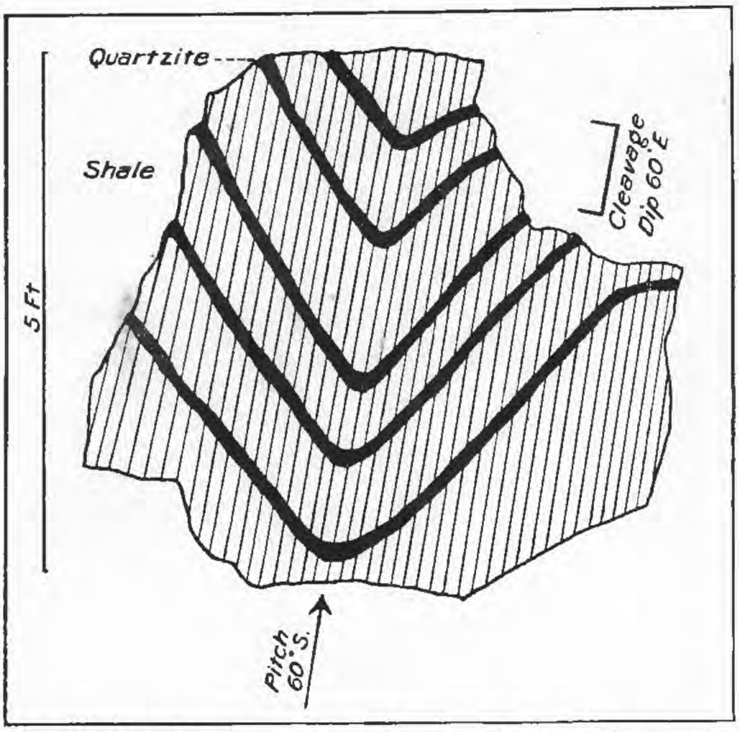

FIG. 75.—Belt of folded and pitching strata of shale and quartzose limestone, with a slaty cleavage confined to the shale. Sketch taken looking down along the pitch. Ashley Hill, Columbia County, N. Y.

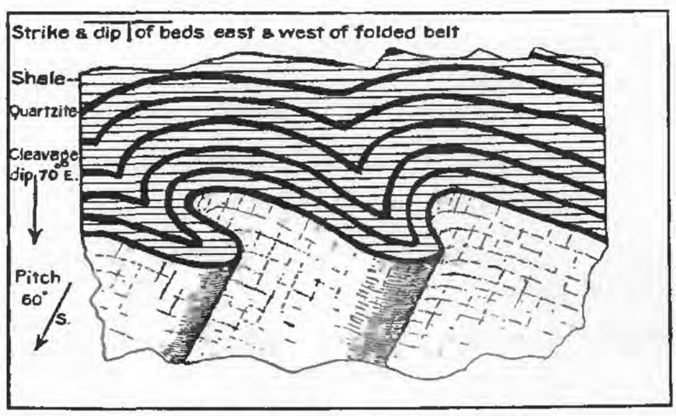

FIG. 76.—Diagram of above, looking across the strike. The cleavage in the shale is parallel to bedding east and west of folded belt.

[1] In gathering material for this section the author has availed himself to some extent of the labor of a former student of his, Mr. Alexander Sloan.

VERTICAL DISAPPEARANCE OF FOLDS.

A specimen, fig. 79, from the Taconic Range, about 6 miles west of Pittsfield and a mile north of Perry Peak, illustrates a familiar fact in stratigraphical and experimental geology, namely, that crumpling in a

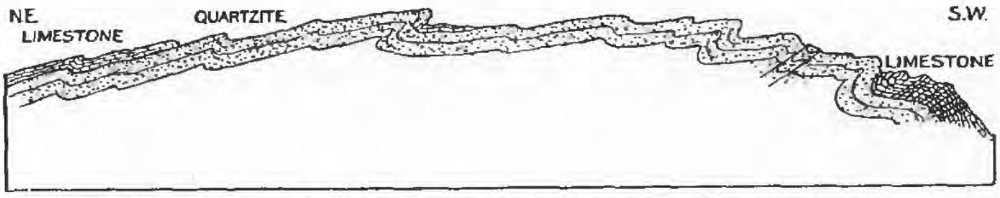

FIG. 77.—Longitudinal section of hillock ("Bullock's cobble") at west end of Williamstown village, Mass., showing longitudinal folding, faulting, and cleavage. Looking southeast.

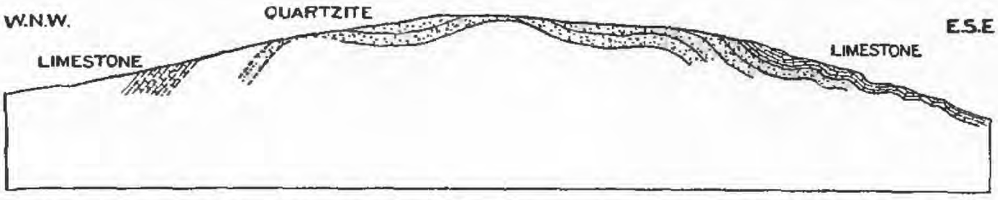

FIG. 78.—Cross-section of same hillock (fig. 77), looking north-northeast along the strike; the portion at the left taken from supposed relations south along the strike. The limestone may be overturned and, for a space, dip easterly under the quartzite.

series of superposed strata can not be uniform for any great vertical distance, even where there is no change in the material of the strata.

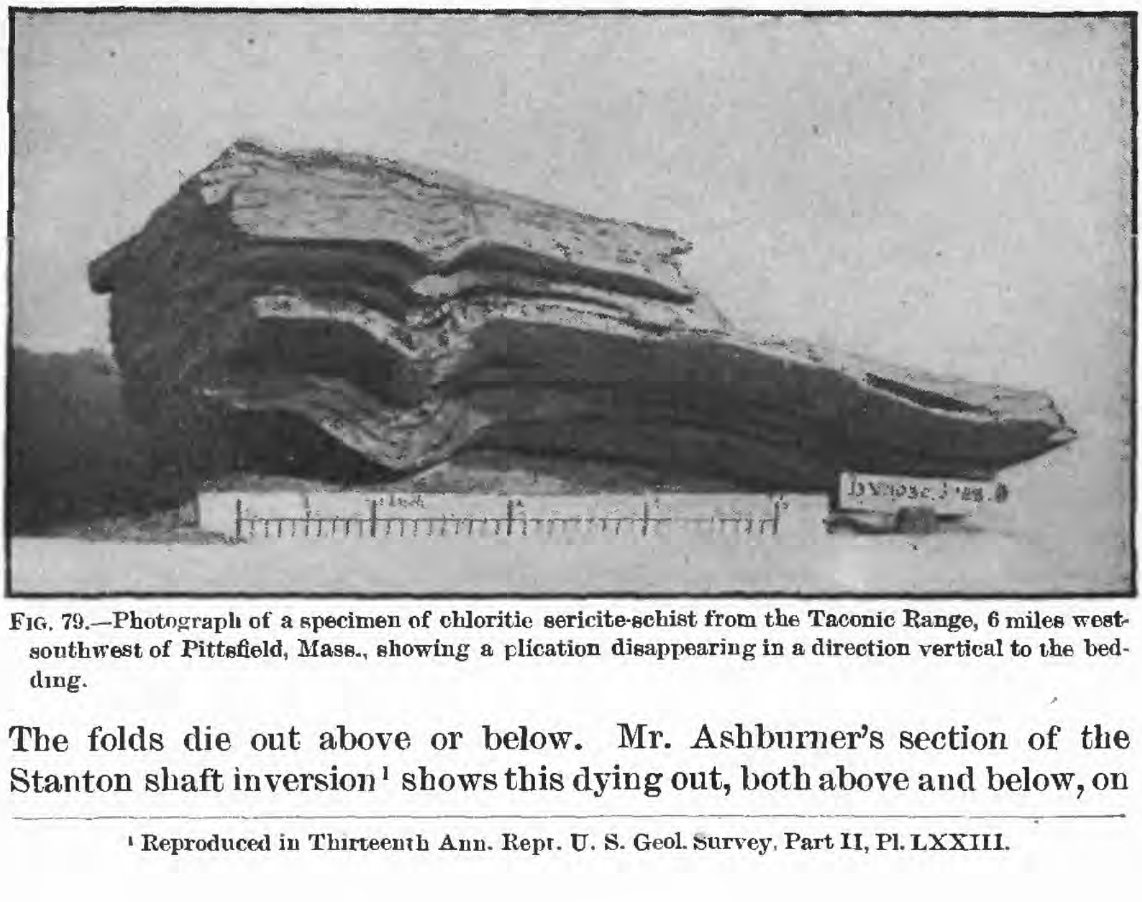

FIG. 79.—Photograph of a specimen of chloritic sericite-schist from the Taconic Range, 6 miles west-southwest of Pittsfield, Mass., showing a plication disappearing in a direction vertical to the bedding.

The folds die out above or below. Mr. Ashburner's section of the Stanton shaft inversion[1] shows this dying out, both above and below, on

[1] Reproduced in Thirteenth Ann. Rept. U. S. Geol. Survey, Part II, Pl. LXXIII.

a large scale. The same occurs on a small scale in fig. 80. In such cases the cause may lie in the different tenacity of the material, as was supposed in explaining fig. 76. These possibilities should be taken account of in the construction of sections.

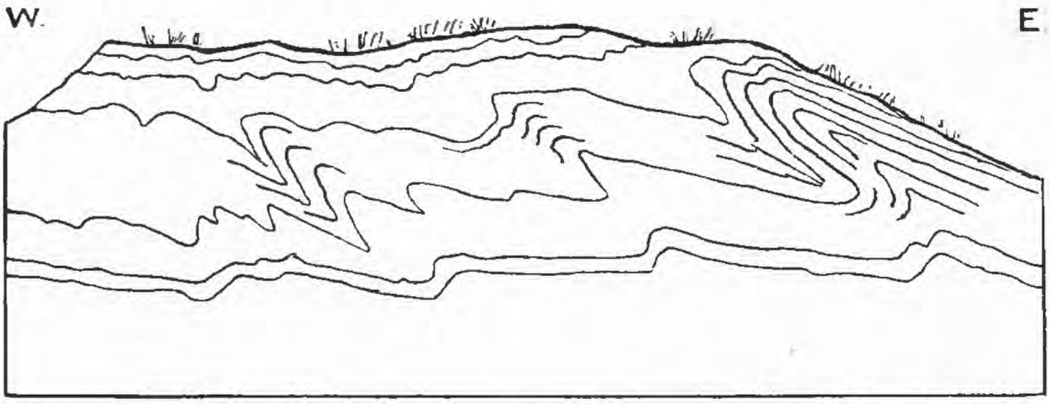

FIG. 80.—Sketch of a ledge of micaceous quartzite on the west side of Rattlesnake Hill, Stockbridge, Mass., 25 by 8 feet, showing the folds diminishing both above and below.

ORIGIN OF QUARTZ LENSES IN THE BEDDING-PLANES OF SERICITE-SCHIST.

Quartz veins and lenses occur almost everywhere in the sericite-schist of the Taconic Range in Vermont and Massachusetts, and also characterize the Cambrian-Silurian schist mass of Hoosac Mountain.[1]

FIG. 81.—Photograph of a ledge of plicated sericite, chlorite, quartz-schist in the Taconic-Greylock mass, New Ashford, Mass., showing quartz lenses and laminæ in the bedding; in lower part, quartz in cleavage. Size of ledge, 14 by 10 feet.

Some of them are evidently in bedding planes; others, however, lie in cleavage planes crossing the former, and others again occur in joints (see fig. 81).

[1] See Mon. U. S. Geol. Survey, Vol. XXIII, figs. 7, 31, 41, 46, 47, 50, 51, 58, 70.

The question arises whether those which lie in the bedding planes are silica which has filtered into partings between the strata formed during their plication and metamorphism, or whether they are replacements of sedimentary material.

In traveling westward from Shaftsbury and Arlington, in Vermont, across the Taconic Range into Washington County, N. Y., one crosses a great schist mass, part of which is of Silurian and part of Lower Cambrian age; as a whole, therefore, it seems to correspond to the Hoosac schist of western Massachusetts. In the western portion the typical quartz veins and lenses give place to small beds, $\frac{1}{2}$ to 3 inches thick, of quartzite, which in places is more or less calcareous, and instead of the schist we have a fine-grained slate.

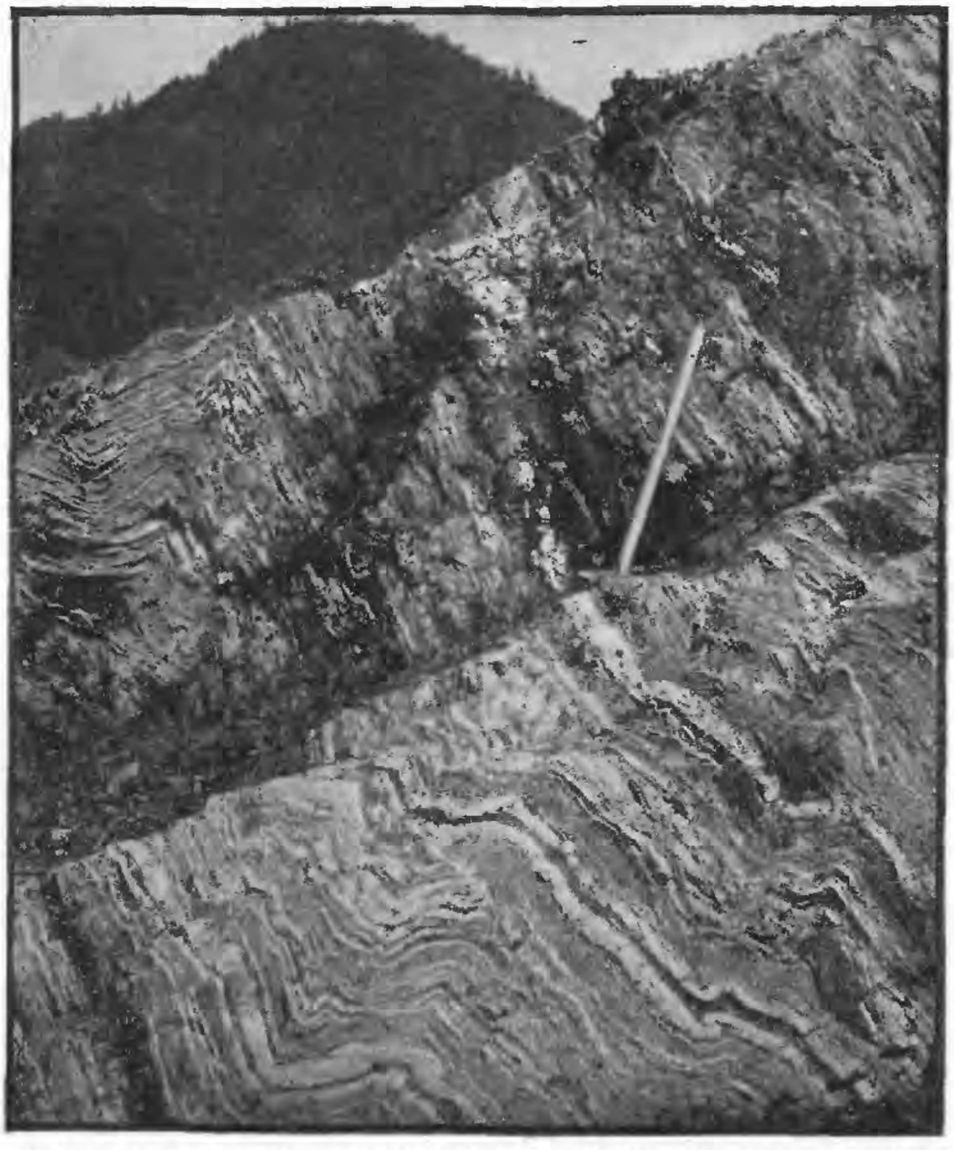

FIG. 82.—Photograph of the southern side of a ledge of small alternating beds of plicated slate and quartzite, the latter weathering white. Two miles west of the Vermont line, in White Creek, Washington County, N. Y. A mile off, along the strike of the folds, is seen the top of Goose-egg Hill, which consists of similar rocks. Hammer handle, 30 inches long.

Fig. 82 shows a plicated mass of such alternating beds of slate and quartzite. Under the microscope the quartzite consists of interlocking quartz areas, with here and there a grain of plagioclase or a plate of muscovite or a fiber of sericite.

About a quarter of a mile west of this locality the slate is finely and sharply plicated, and contains small beds of quartzose material. Under the microscope these are found to consist of quartzite similar to that just described, but with cavities lined with limonitic staining from the decomposition of some ferruginous mineral. These beds, even when only one-fourth of an inch thick, are traversed by vein quartz, and particularly at the sharp turns where fractures would be likely to occur, so that it is difficult in the field to determine where the quartzite ends and the quartz begins. On the whole it seems probable that the quartz lenses of the bedding originated in either of the following three ways:

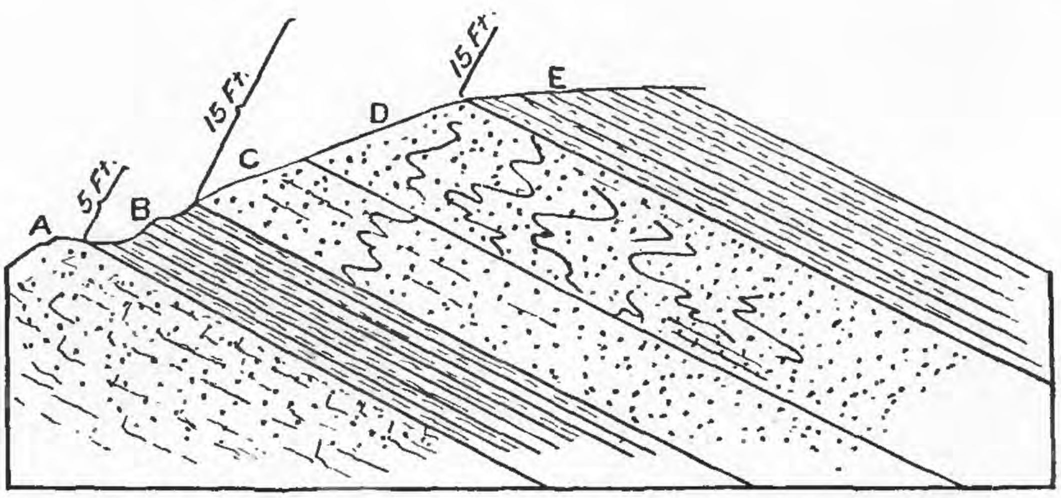

FIG. 83.—Section of crystalline limestone, mica-schist, and quartzite, 1½ miles south of Jamaica village, Windham County, Vt., showing false bedding. A, white and pink marble; B, feldspathic biotite-schist, 6 feet; C, quartzose limestone; D, micaceous quartzite; (C and D together, 15 feet); E, feldspathic biotite-schist, 15 feet.

1. As infiltrations in partings parallel to the bedding during plication and metamorphism.[1]

2. As infiltrations in small, plicated, stretched, and fractured beds of quartz sandstone or quartzite.

3. As replacements of calcareous beds after their plication and stretching.

A case like that figured on page 147 of Monograph XXIII, where the quartz of the bedding has suffered cleavage, points to movement subsequent to the cleavage and the metamorphism which attended the formation of the lenses. A large quartz vein in the pre-Cambrian granitoid gneiss of Stamford, Vt., is thus minutely cleaved. Careful observation and coordination of such instances in veins of segregation may lead to interesting inferences.

[1] Mr. C. L. Whittle, in a paper on "The occurrence of Algonkian rocks in Vermont and the evidence for their subdivision," Jour. of Geol., May–June, 1894, considers the secondary quartz in the bedding and cleavage planes of mica-schist to have originated in "the excess of silica resulting in great part from the decomposition of silicates originally in the rock, the alumina and potassium going to form the muscovite."

FALSE BEDDING.

Besides all the structural difficulties arising from complex folding and metamorphism, there occurs now and then false bedding, or "contorted false bedding."

On the east side of the Green Mountain range, about 1½ miles southeast of Jamaica village, the Brattleboro and Whitehall Railroad cuts a series of alternating beds of feldspathic, quartzose biotite-schist and of crystalline limestone, here and there of a delicate pink.

Two of the beds of limestone, more quartzose than the rest, and about 15 feet thick, with the mica-schist both above and below them in conformable contact, have the structure shown in fig. 83. The plicated structure can hardly be ordinary stratification. It may be a cleavage foliation originally diagonal to the bedding, but plicated in a secondary movement, or we may have to do here with such minor unconformities as are caused by the deposition of the limestone along a sloping bottom with currents occasionally eroding portions of the small beds, creating a plunge-and-flow structure, and this may have been plicated in the general compression of the mass. Someone may suggest a thrust plane between B and C, and another between D and E.

CLUES TO BEDDING.

Wherever bedding is obscured by cleavage one of the first things to be done is to distinguish, if possible, the bedding by tracing out the continuity of some minute line of sedimentary grains.[1] When the sediment is homogeneous this becomes impossible. In the Cambrian-Silurian shales and slates of Washington County, N. Y., lines of holes occur now and then on transverse joint faces (see fig. 84, A, B, C). Upon a closer inspection these are found to be due to a very slight calcareousness of the shale along certain bedding planes. Weathering attacks these planes more readily, but at irregular intervals, and the effect is as though small limestone pebbles had been dissolved out. Again, sometimes, in weathering, a slight parting in the stratification is sufficient to arrest vertical erosion for a time and expose the actual

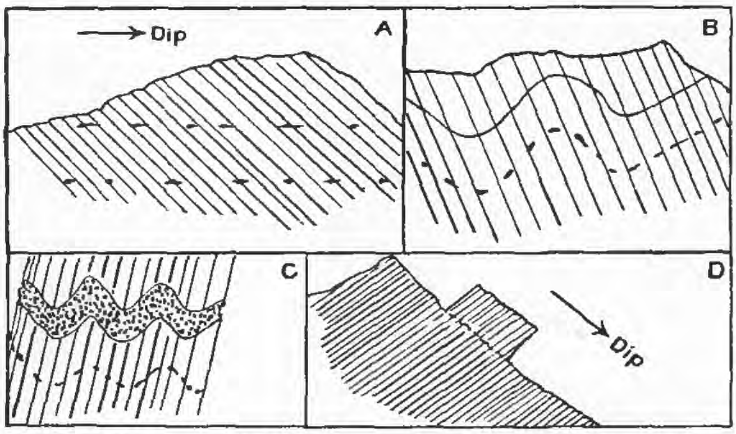

FIG. 84.—Diagrams of shale ledges showing obscure traces of bedding, Washington County, N. Y. A, bedding shown by lines of holes (due to dissolution of calcareous matter) crossing the cleavage; B, C, proof of interpretation of A; lines of holes parallel to small calcareous bed; D, bedding shown by uneven surface continuous with a delicate parting in the stratification.

[1] See Thirteenth Ann. Rept. U. S. Geol. Survey, Part II, pp. 322-323, figs. 28, 29, 31.

surface of a stratum, even where the cleavage foliation is the dominant one. (See fig. 84, D.)[1]

In fig. 85 is shown a plicated bed of limestone in a mass of shale. In determining the dip of such a mass neither the dip of the cleavage nor that of the separate limbs of the step-like folds of the limestone should be taken, but the general course of the limestone bed.

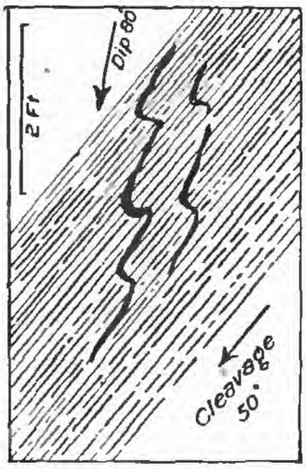

FIG. 85.—Diagram of ledge of cleaved shale inclosing small bed of limestone in step-like folds. Height, 10 feet. Locality, 1½ miles southeast of North Greenwich, Washington County, N. Y.

DIFFERENTIAL CLEAVAGE.

Where a bed of shale or other fine-grained rock is inclosed in a coarser-grained one cleavage foliation is apt to be confined to the former (fig. 86). Where the adjoining strata are not plicated such localities may afford a clue to the relation between the dip of the cleavage and the direction of the pressure which produced it. If we suppose the cleavage in fig. 86 to have originated at the time of the folding, the force which produced the fold would seem to have operated in a direction nearly at right angles to the cleavage; but if the cleavage was produced while the beds were still horizontal, the direction of the pressure would be about 45° to the dip of the cleavage.

How slaty cleavage may be confined to particular beds is also well shown in figs. 75, 76, 85. J. Gosselet gives a fine illustration of this in a section of certain slate quarries in northeastern France.[2] That the angle of the dip of the cleavage is determined in part by the physical character (tenacity) of the rock materials is shown at the locality represented in fig. 87. Different materials diffract, as it were, the cleavage differently. Here the cleavage, in crossing alternating beds of shale and limestone, changes its dip, being almost vertical in the limestone and only 40° in the shale,

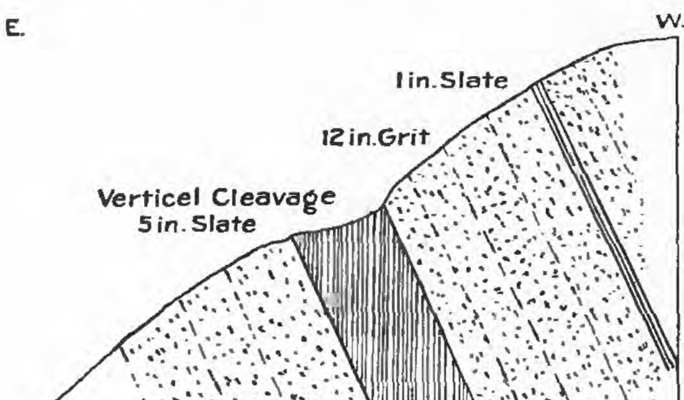

FIG. 86.—Diagram of ledge of grit and red slate in Grafton, Rensselaer County, N. Y. One of the beds of slate has a vertical cleavage which does not extend into the grit.

[1] Compare William W. Mather, Geology of New York, Part I, Pl. X, fig. 6, 1843.

[2] J. Gosselet, L'Ardenne, Mémoires pour servir à l'explication de la carte géologique détaillée de la France, p. 41, fig. 7, Paris, 1888. See, also, Mather, op. cit., Pl. X, figs. 7 and 8.

a difference of over 50° within a mass which must have been subjected to a uniform pressure. This is what Sir Archibald Geikie has termed "differential cleavage," and about which he says: "In fact, there seems to be a constant relation between the inclination of the cleavage planes and the texture of the strata; the fine flags and shale behave, so to speak, like lines of weakness, their constituent particles having been drawn out or dragged much farther than those of the grits."[1] But in the locality which he figures the cleavage planes, instead of merely altering their dip angle in passing from one material to another, as in fig. 87, form in the coarser beds "sigmoidal curves," which seem to be the result of a continuance of the motion after the formation of the cleavage. Fig. 87 represents simple differential cleavage, but Sir Archibald Geikie's, a more complex thing, a flexed or slightly plicated differential cleavage.

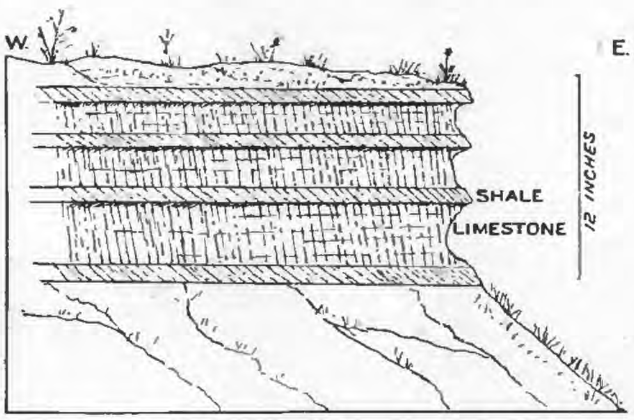

FIG. 87.—Sketch of ledge of alternating beds of limestone and shale, showing the different effect of these materials upon cleavage ("differential cleavage"). Erosion has in turn also affected these materials differently. Jackson, Washington County, N. Y.

In fig. 87 the effect of the more tenacious or brittle material, limestone, upon the cleavage has been similar to that of a denser medium upon a ray of light—the cleavage has been, as it were, refracted toward the perpendicular.

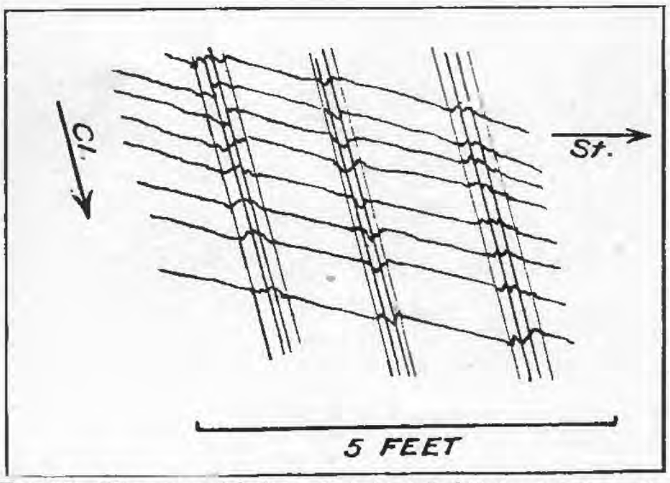

FIG. 88.—Diagram of ledge of slate (phyllite), showing slip cleavage confined to the tops and shorter limbs of the plications, giving the rock a banded structure across the bedding planes. On the Battenkill, 1½ miles west of Vermont line, in Salem, Washington County, N. Y.

CLEAVAGE BANDING.

One of the more interesting developments of slip cleavage is shown in figs. 88 and 89, from the schist and slate region of Salem and White Creek, in Washington County, N. Y. In fig. 89 the weathered bed of coarsely plicated quartzose limestone indicates plainly the direction of

[1] Archibald Geikie, Report on the recent work of the Geological Survey in the northwest Highlands of Scotland, etc.: Quart. Jour. Geol. Soc., London, 1888, Vol. XLIV, p. 432, fig. 23. See, also, his Text-Book of Geology, 3d ed., 1893, p. 706, fig. 335.

the bedding. The slippage due to cleavage seems to have been mostly confined to certain narrow belts or bands, which recur at intervals of a foot or so. This appears to be the result, in some cases, of the inequality of the limbs of the plications and of the slippage occurring at the apex of the fold and within the shorter limb (see fig. 88). The effect is to give the rock a somewhat stratified appearance in the cleavage direction, i. e., across the stratification. My assistant, Mr. Louis M. Prindle, recently found in Bennington County, Vt., 1½ miles west of Rupert and one-fourth of a mile east of the Hebron (N. Y.)

FIG. 89.—Photograph of slate ledge (phyllite) on the southeastern foot of Goose-egg Hill, in White Creek, Washington County, N. Y., looking north along the strike, showing, in upper part, a coarsely plicated easterly dipping bed of quartzose limestone eroded so as to leave a series of small caves in which ferns are growing. Above and below and parallel to this bed are the coarse plications of the noncalcareous slate, with a coarse slip cleavage, forming here and there cleavage bands. One of these traverses the calcareous bed, having withstood erosion. Hammer handle, 30 inches long.

line, some shales in which this structure is still more highly developed (see fig. 90).

The rock is plicated in roundish folds measuring in places about an inch in diameter. Each fold is gently arched for a space of one-half inch to 2 inches, and this portion of the rock appears massive; but under the microscope it shows about 360 imperfectly developed slip cleavage planes to the inch, which are vertical to the tops of the arches. The shanks of the folds are very long (measuring at least 1½ inches in about one-fourth of an inch thickness of rock), and make an angle of only about 20° to 40° with the cleavage. The cleavage within that part of the rock traversed by the shank of the folds, although not any more minute than in the arches, is much more continuous, and there breaks up the rock into slaty laminæ. Along these shanks, therefore, most of the motion has taken place. The general appearance of the rock is that of a series of alternating beds measuring about one-fourth of an inch and three-fourths of an inch, respectively, or even more, but running transversely to the actual bedding. The change in the course of the cleavage is here not due to a change of material, but to a change of motion in the same material.[1]

Furthermore, there appears under the microscope a ferruginous staining along the cleavage of the more slaty bands (see fig. 91). Under higher magnifying powers the muscovite scales, which, together with quartz fragments, largely make up the rock, lie nearly all with their axial planes in the bedding planes of the rock instead of in that of the cleavage.[2]

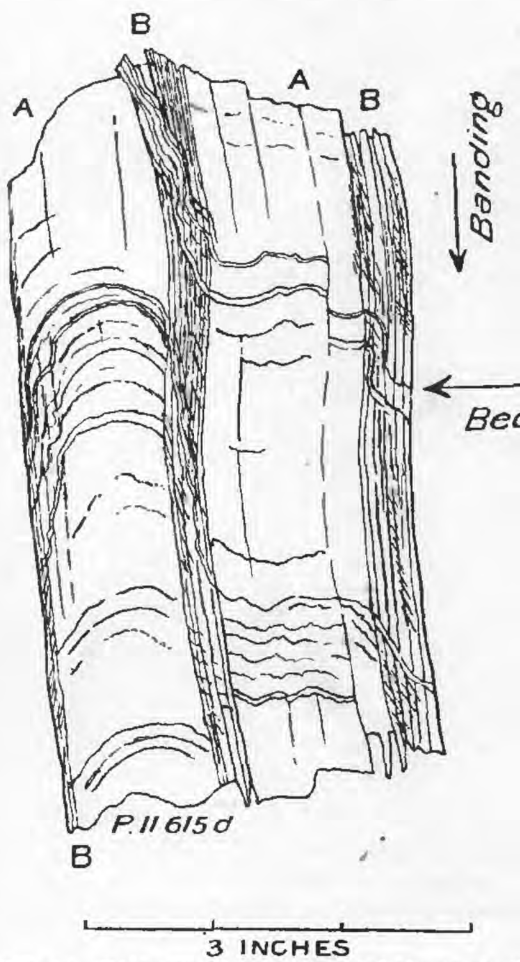

FIG. 90.—Diagram of specimen of shale, or phyllite, from near Rupert, Bennington County, Vt., showing the development of cleavage banding along the shanks of the plications, giving the rock the appearance of being stratified across the real bedding.

This cleavage banding may explain some perplexing localities where there appears to be a distribution of different coloring materials in parallel belts across the bedding. Such color bands seem to be due to the unequal development of cleavage. The more highly cleaved belts more readily admit percolating waters holding various iron compounds in solution, which they deposit within the cleavage foliation, while the less highly cleaved belts, being less permeable, show less staining or preserve the original color of the rock. The result is a rock striped in two colors or in several

[1] Since the preparation of this paper this locality has been revisited and photographed, for future publication. Cleavage banding is not infrequent in Washington County and the adjacent parts of Vermont.

[2] This rock possesses the character of a shale (mica scales and numerous quartz fragments), and in places that of a phyllite or slate (sericite fibers).

shades across the bedding. Such alternations of color or shade are naturally taken as indications of bedding, and the stratigraphy is confused. See fig. 92.

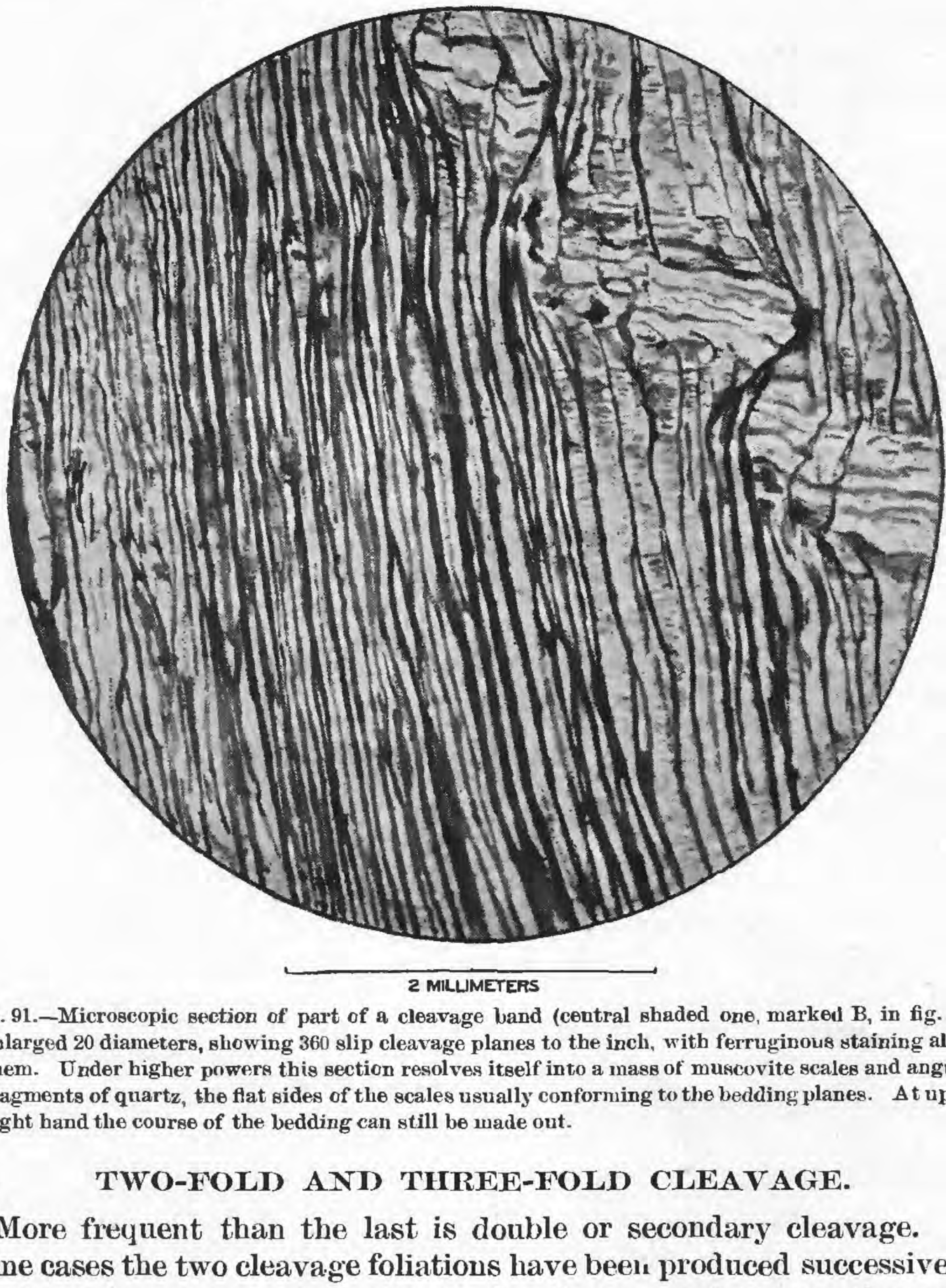

FIG. 91.—Microscopic section of part of a cleavage band (central shaded one, marked B, in fig. 90), enlarged 20 diameters, showing 360 slip cleavage planes to the inch, with ferruginous staining along them. Under higher powers this section resolves itself into a mass of muscovite scales and angular fragments of quartz, the flat sides of the scales usually conforming to the bedding planes. At upper right hand the course of the bedding can still be made out.

TWO-FOLD AND THREE-FOLD CLEAVAGE.

More frequent than the last is double or secondary cleavage. In some cases the two cleavage foliations have been produced successively, as shown by microscopic sections. In other cases, however, they may have arisen simultaneously by complex pressure. In fig. 93 both cleavages are distinct. The bedding is shown by the course of the quartz veins. The difference in the size and number of the plications in the same vertical series is noticeable here, the broad fold of the thicker material corresponding to several smaller folds of the thinner material. This accords with numerous observations that the less tenacious the material the smaller the folds.

In fig. 94 a hand specimen of slate from Petersburg, Rensselaer County, N. Y., shows three cleavage foliations crossing the bedding, which is distinctly marked by changes in sediment. Of these, Cleavage I is the usual slip cleavage, striking with the bedding. Cleavage II, striking at right angles to the bedding, is what the French call "longrain,"[1] and is analagous to much of the coarse jointing observed in our slate regions, and probably to the "grain" of our Welsh quarrymen. Cleavage III is diagonal to the other two. There need be no limit to the number of foliations which may be set up in such a fine-grained rock by pressure from varying directions and the resultant motions of the particles. At Cavendish, Vt., a mass of limestone at its contact (a fault plane) with a gneiss has five foliations crossing the bedding plane. English geologists have long ago described similar instances.

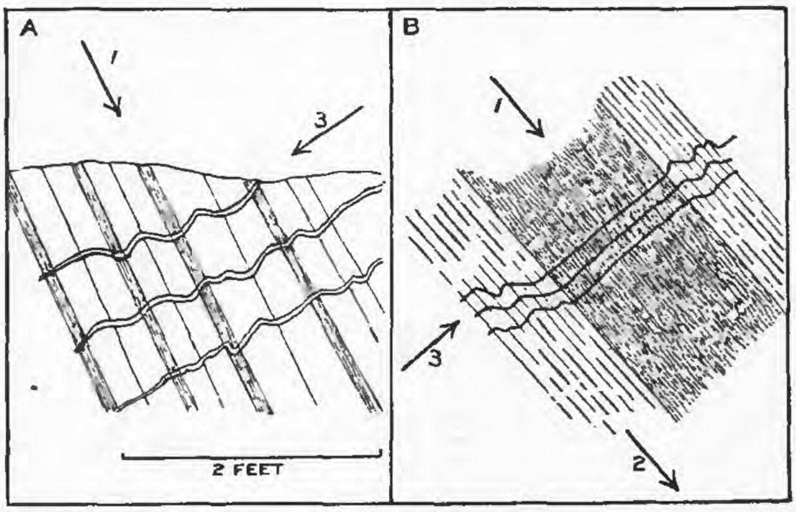

FIG. 92.—A. Diagram of ledge of micaceous slate near Ash Grove in White Creek, Washington County, N. Y., showing plicated quartz veins (3), dipping west across light and dark bands of shale (1 and 2). If the quartz is in a plicated cleavage then the bands represent bedding; otherwise the bands are cleavage bands. B. Microscopic section of slate from Conanicut, R. I., showing plications crossing greenish (2) and reddish (1) bands. Unless the plications represent cleavage the banding originated as in fig. 90. Compare A. Geikie, Text-Book of Geology, p. 546, fig. 258, which shows a plication of the cleavage at contact of two dissimilar rocks.

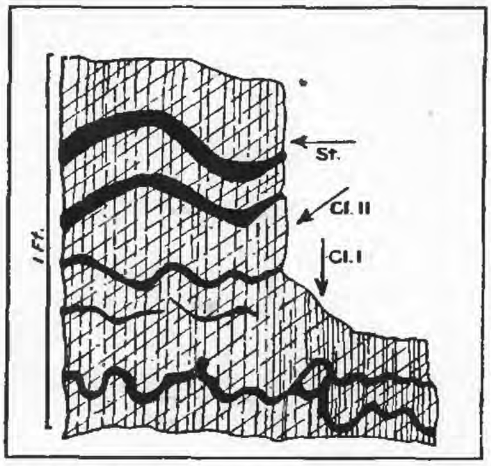

FIG. 93.—Diagram of part of a ledge of chloritic sericite-schist in the southwestern part of Salem, Washington County, N. Y., showing quartz laminæ in the stratification and two cleavage foliations across it. The two upper laminæ may be quartzite.

CLEAVAGE ALONG FAULT LINES.

The beds near a fault have usually been exposed to great compression, and in them, if the material be favorable, cleavage may be expected. Where the cleavage has originated with the faulting, it will usually be found to be parallel with the fault plane. When the actual fault plane

[1] Ed. Jaunetaz, Mémoire sur les clivages des roches (schistosité, longrain) et sur leur reproduction: Bull. Soc. Géol. France, ser. 3, Vol. XII, p. 211, 1884.

has not been exposed the strike and dip of the cleavage adjacent to it afford indications of its probable direction. This parallelism is shown in fig. 95.

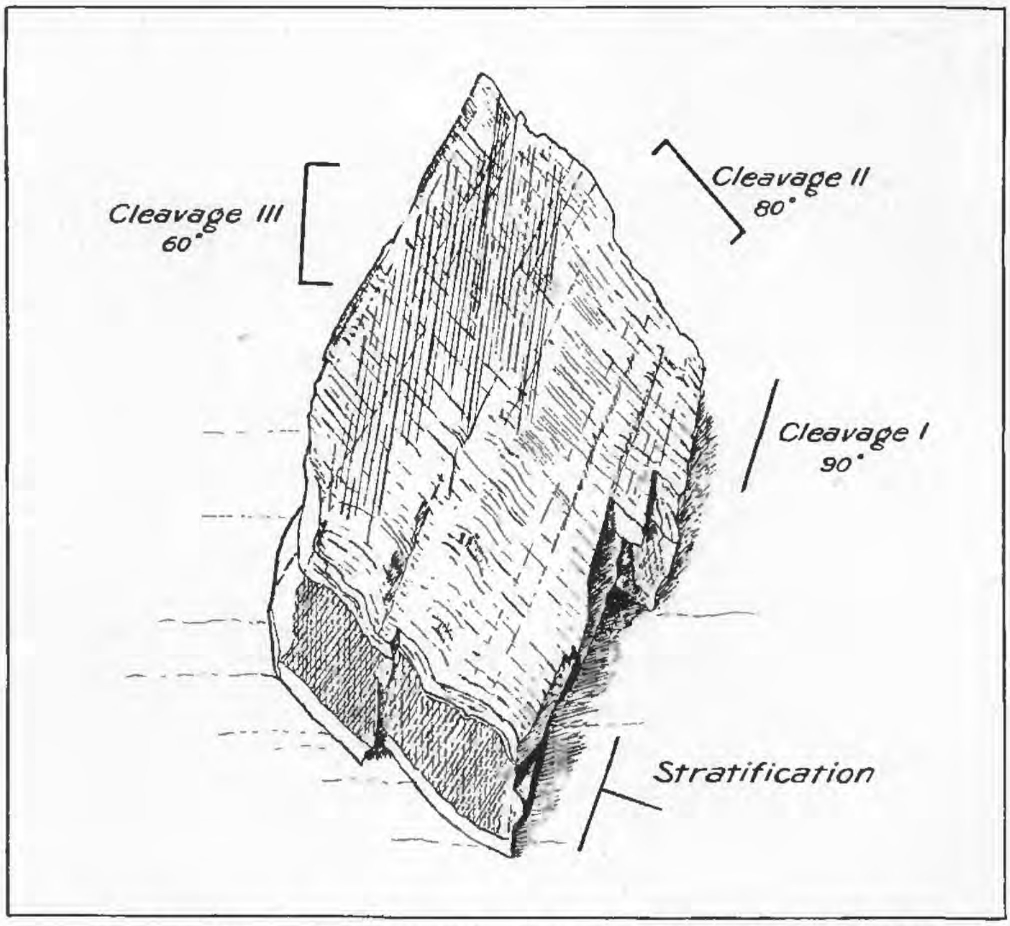

FIG. 94.—Sketch of specimen of phyllite (slate) from Petersburg, Rensselaer County, N. Y. Size, 4 by 3½ inches. The bedding, indicated by small calcareous beds, is crossed by three cleavage foliations. The dips of Cleavages I and III are seen crossing each other on the front end.

THE BEGINNING OF A CLEAVAGE PLANE.

As the microscopic study of massive crystalline rocks impresses one with the chemical changes which their constituent minerals have undergone, so the microscopic study of sedimentary rocks in such a folded region as that of the Green Mountains impresses one with the movements which have affected their particles. Indeed, the evidences of motion are so clear that it requires but little imagination to conceive of the particles as moving into their present relations on the stage of the microscope. Figs. 96 and 97 show how the undulatory motion imparted

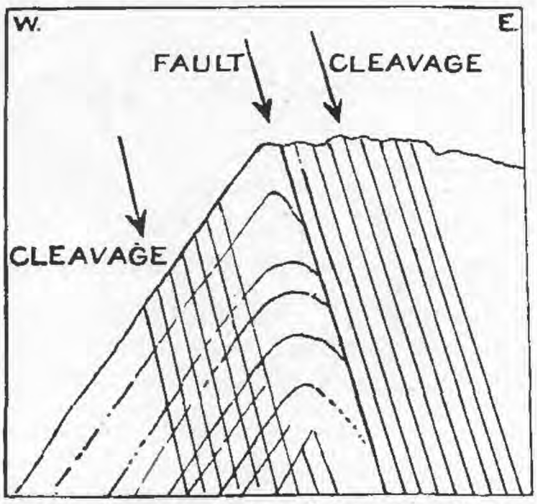

FIG. 95.—Diagram of ledge of shale, 3 by 4 feet, in Brunswick, Rensselaer County, N. Y., showing relation of cleavage to faulting.

to the stratification laminæ and sericitic fibers became so sharp as to fracture them and start a plane of slip cleavage.

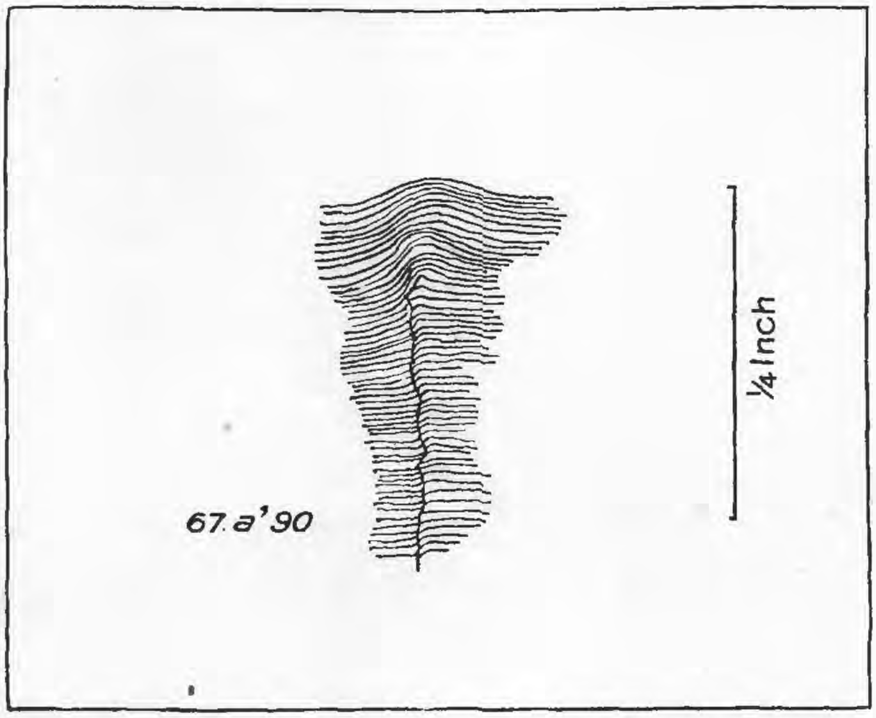

FIG. 96.—Microscopic section of phyllite (slate) made across the bedding from near North Stephentown, Rensselaer County, N. Y., showing a fold giving rise to a plane of slip cleavage.

EVIDENCES OF STRETCHING.

Every geologist is familiar with the fact that in the great mountain-making movements rocks have not only been powerfully compressed, but stretched. Indeed, stretching is one of the results of compression. The elongation of pebbles in conglomerate, the separation within the rock of the fragments of a crystal, or of the fragments of an elongated fossil, are all evidences of stretching. Fig. 98 represents a horizontal surface of grit in which appear bedding, cleavage, and joint planes intersecting one another at various angles. In the direction of the cleavage a series of more or less parallel openings has been formed and filled with quartz. While these openings may have been produced

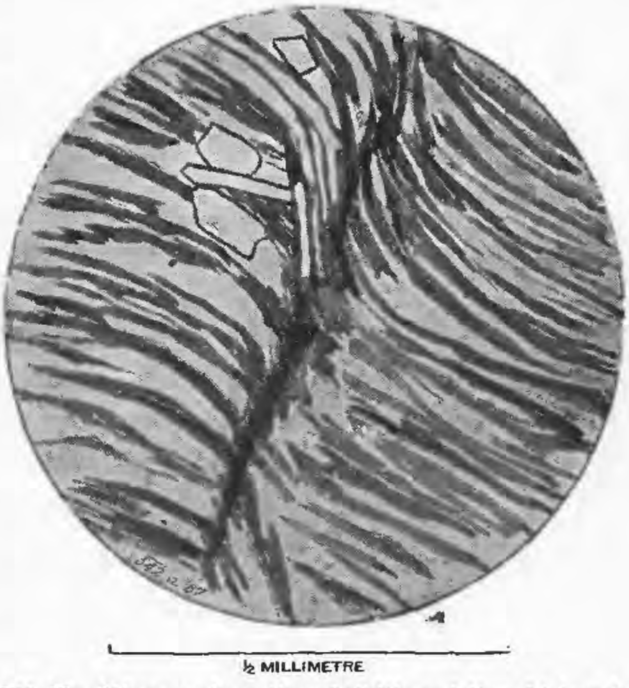

FIG. 97.—Microscopic section of albitic sericite-schist made across the bedding from Mount Greylock, Mass., showing a fold giving rise to a plane of slip cleavage. Enlarged 80 diameters.

by a shearing pressure, the result, in any case, has been to open the rock in the direction of the double arrow and permit the infiltration of quartz. The rough parallelism of the quartz lenses and their shapes convey a notion of the strain to which the rock must have been subjected.

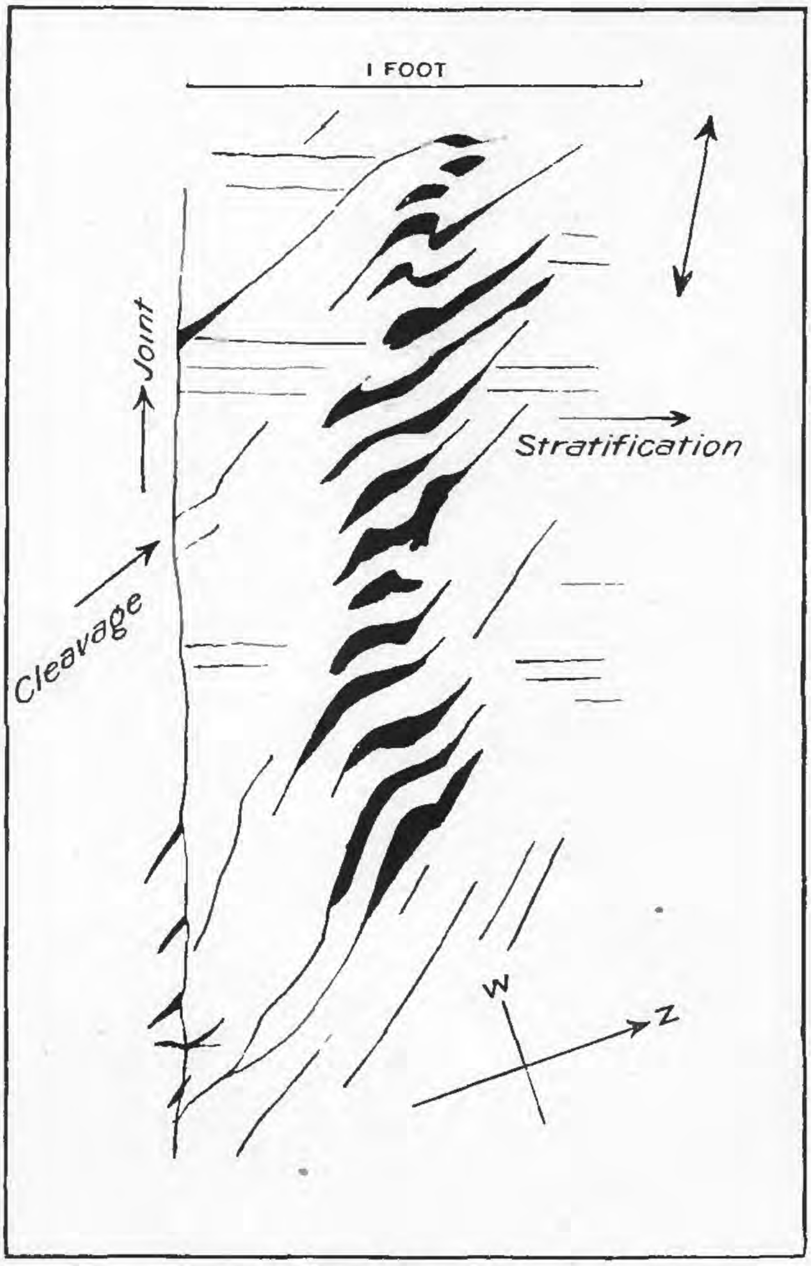

FIG. 98.—Sketch of horizontal surface of ledge of grit in Grafton, Rensselaer County, N. Y., showing bedding, jointing, and cleavage. A series of parallel gaps has been formed in the cleavage foliation and filled with quartz, showing the direction in which the rock has been stretched.

BRECCIATION AND BRECCIATION-PEBBLES.

In the Cambrian-Silurian belt, between the Hudson and the States of Massachusetts and Vermont, conglomerates and breccias are of frequent occurrence. Fig. 99 represents a Cambrian calcareous sandstone in which the grains of quartz sand are mostly spherical. The sandstone was evidently once interbedded with small layers of limestone. The relations of the fragments, however interpreted, show a horizontal, if not also a vertical, compression. Some of the fragments may have suffered from solution within the rock mass since the brecciation.

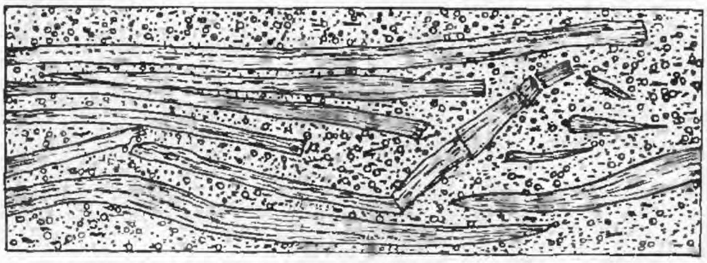

Fig. 99.—Sketch of specimen of calcareous sandstone, about one-third natural size, from south of Lake Aries, in North Greenbush, Rensselaer County, N. Y., showing several small beds of limestone broken up and pushed across one another.

Mr. Aug. F. Foerste, in a manuscript report on the geology of the vicinity of Troy, N. Y., made in 1892, gives a diagram, reproduced in fig. 100, illustrating his observations there. This shows the conversion of a small bed of limestone within a mass of shale into roundish pebbles by means of pressure. It is really the process of slip cleavage isolating the longer limb of each fold.[1] The rounding of the fragments thus formed may have been completed by the dissolving action of acid waters under pressure. Beds of such "pebbles" inclosed in shale form extensive deposits in Columbia, Rensselaer, and Washington counties, N. Y. These brecciation-pebbles might be taken for concretions or beach pebbles. True conglomerates, however, also occur in the region

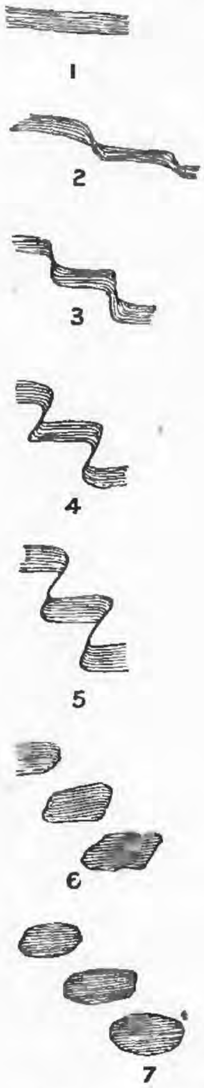

FIG. 100.—Diagram showing the development of nodules (brecciation-pebbles) of limestone by the plication and cleavage (slip cleavage) of a small bed of limestone within a mass of shale, as observed near Troy, N. Y., by A. F. Foerste.

CONCLUSION.

All the phenomena described—inclined, overturned, and transverse folding, unequal folding, false bedding, obscuration of bedding by cleavage, differential cleavage, cleavage banding, two-fold and three-fold cleavage, cleavage along fault lines, stretching, brecciation and the formation of brecciation-pebbles by slip cleavage, and various siliceous replacements or infiltrations—these may characterize any region of crumpled, more or less metamorphic, argillaceous, calcareous, and quartzose sediments. Although the modes of stratigraphic deformation are many, and

[1] Compare J. E. Marr, On some effects of pressure on the Devonian sedimentary rocks of North Devon, Geol. Mag., Dec. III, Vol. V, p. 219, London, 1888.

some of its results quite complex, they are all traceable simply to the various motions of rock particles into which the compression of the sedimentary masses has resolved itself.

INDEX TO AUTHOR'S DESCRIPTIONS OF RELATED STRUCTURAL PHENOMENA IN PUBLICATIONS OF THE UNITED STATES GEOLOGICAL SURVEY.

For the assistance of readers interested in such problems, the following index to the author's descriptions of kindred structural features in the same region is added:

Cleavage, how distinguished from bedding. Mon XXIII, p 158
Cleavage in quartzite Fourteenth Ann Rept., pp. 562, 563, figs 70, 71.
Cleavage, literature of Mon. XXIII, pp. 137, 138; Thirteenth Ann Rept, p. 321
Cleavage, relation of, to faults Mon. XXIII, p. 154, fig. 55; Fourteenth Ann Rept, p 537, fig. 56
Cleavage, secondary Thirteenth Ann Rept, p. 322, figs 28; 30; Mon XXIII, pp. 151, 152; fig 52, p 158
Cleavage, slaty, nearly horizontal Thirteenth Ann. Rept., p. 319, Pl CI
Cleavage. slip, extreme Mon XXIII, pp 149, 156, 158, Fourteenth Ann Rept, p 537, fig 57
Cleavage, slip, in limestone Mon XXIII, pp. 140–143, figs 35–39
Cleavage, slip, in sericite schist. Mon XXIII, pp. 139, 140, figs. 32–34, pp. 144–147, figs 41–46; pp 153, 154, figs 53, 54; p 188, fig 73
Cleavage, slip, nearly horizontal Thirteenth Ann. Rept, p. 319, fig. 25
Cleavage, slip, plicated. Thirteenth Ann. Rept, pp. 322–324, figs. 28–33
Cleavage, strike and dip of, in relation to stratification Mon XXIII, pp 155–157, figs 56, 57, 59
Faulted slate slab (faults in two directions) Thirteenth Ann Rept, p 320, fig 26.
Faults Mon XXIII, p 168, Pl XX; Fourteenth Ann Rept, p 538, fig 58, p 542, fig 62, p. 546, figs 63, 64, and Pl LXIX
Folds, acute Mon XXIII, p 155, fig 56; Fourteenth Ann. Rept, p 536, fig. 55; p 538, fig 59
Folds, anticlinal Mon. XXIII, p 202, fig 77; Thirteenth Ann Rept, p 325, fig 34.
Folds in gneiss Fourteenth Ann Rept, p 539, fig 60
Folds, pitching Mon XXIII, p 157, fig 60
Impressed limestone pebbles Thirteenth Ann Rept, p 313, fig 24
Mica, secondary, in cleavage foliation Mon XXIII, p 143, fig. 40
Quartz vein, cellular. Thirteenth Ann Rept., p 303, Pl C, fig 5
Quartz veins in bedding. Mon XXIII, pp 148, 151, figs 47–51, p 156, fig 58.
Quartz veins in cleavage Mon XXIII, pp 148, 149, 151, figs 48, 49, 51
Quartz veins in joints Thirteenth Ann Rept, p. 321, fig 27
Torsional grooving Fourteenth Ann Rept, p 541, fig 61.

PRINCIPLES OF NORTH AMERICAN PRE-CAMBRIAN GEOLOGY,

BY

CHARLES RICHARD VAN HISE,

WITH

AN APPENDIX ON FLOW AND FRACTURE OF ROCKS AS RELATED TO STRUCTURE,

BY

LEANDER MILLER HOSKINS.

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Metamorphic sedimentary rocks—Continued.

Rocks modified mainly by metasomatism, cementation, and consolidation, but assisted by mashing—Continued.

PART II.—HISTORICAL GEOLOGY—Continued.

PART II.—HISTORICAL GEOLOGY—Continued

ILLUSTRATIONS

PRINCIPLES OF NORTH AMERICAN PRE-CAMBRIAN GEOLOGY.

BY CHARLES RICHARD VAN HISE.

INTRODUCTION.

The design of this paper is (1) to give a partial discussion of principles applicable to geological work among the pre-Cambrian rocks of North America, and (2) to give an historical account of the North American pre Cambrian, and to point out the principles illustrated in the various regions. The first is considered in Part I, the second in Part II.

The discussion of principles is not complete A knowledge of the principles of geology, as found in the text-books, is assumed In Part I the purpose is to emphasize and amplify those principles which have a special bearing upon pre-Cambrian stratigraphy and which have hitherto been somewhat neglected. The paper is therefore a supplement rather than a full treatment of principles. There is no claim of newness for parts of the paper, except in the manner of presentation, but it is believed that in certain directions an advance is made. Just as in a text-book, I have freely used any published information which could be of service to me, and from my own papers I have taken without quotation any parts which could be used to advantage While the paper is written primarily with reference to the pre-Cambrian, it will be apparent that the principles discussed are general.

By the term "pre-Cambrian rocks" is meant all formations which are older than those containing the Olenellus or Lower Cambrian fauna. As to the length of time represented by the pre-Cambrian, we have two points of view from which an approximate inference may be made. Accepting the nebular hypothesis, (1) we may look forward from the time when a crust first formed upon the globe, and (2) we may look backward from the broad domain of facts furnished us by the Lower Cambrian.

(1) After the first continuous solid crust of the earth formed there must have been an exceedingly long time before the conditions were such that life could exist. It is highly probable that this first outer crust was of an igneous character. After solidifying, this first shell must have thickened steadily by inward solidification. Much or all of

the first crust may have been removed by subsequent erosion, but this is not true of its inward crystallization; that is, it can not be assumed that erosion has anywhere overtaken inward solidification. It is therefore to be expected that there exists in various parts of the earth the first outer crust or its inward continuation.

(2) The fauna of the Lower Cambrian is varied, complex, and abundant. It comprises all of the great classes of animals except the vertebrates, and it is by no means certain that these did not exist. One biologist says that if the differentiation of life since the Cambrian were represented by a line of a certain length the differentiation before the Cambrian would be represented by a much longer line. Another says that the amount of differentiation of life forms before the Cambrian is at least nine times as great as the amount of differentiation since the Cambrian. Believing, as we now do, that this complex and varied life was produced by slow development under a definite order set in the universe, rather than by special creations, the Cambrian life implies that the time of pre-Cambrian life was very long, although it does not necessarily imply that it is nine times as long as post-Cambrian time, for it can not be assumed that the development of life was at a uniform rate. So far as we know the laws of development, it appears to be true that higher forms differentiate more rapidly than lower forms. If this law were applied it would follow that the time of pre-Cambrian life was more than nine times as long as Cambrian and post-Cambrian time, but unknown factors may enter into the problem of the earlier phases of development, and hence we can not assume any such time ratio as nine to one. However, it seems reasonably certain that the time of pre-Cambrian life was as long as or longer, probably much longer, than all subsequent time.

If the conditions were such that life could exist, they were also such that ordinary sedimentary rocks could be deposited. Therefore it is reasonable to think that in pre-Cambrian time there were eras in which vast groups of sedimentary rocks of essentially the same character as the Paleozoic sediments were deposited. Such rocks may have since been profoundly modified.

Between the time when all the rocks forming on the earth were igneous and the time when ordinary pre-Cambrian sediments began to form, there may have been a great length of time in which the conditions were materially different from those that we now know. The waters of the ocean may have been at a high temperature, and the rocks deposited by this early ocean may have been different in character from ordinary sediments. Thus a third possible group of rocks may have formed, which bridged the time interval between the early igneous rocks and the ordinary sediments. If portions of such rocks still exist, it is probable that transition phases unite them with the igneous rocks on the one hand and with the ordinary sedimentary rocks on the other hand.

From our forward and backward views we then conclude that in pre-Cambrian time, at least two great classes of rocks were produced, and may, perhaps, now be found: first, those of igneous origin, representing the earliest outer crust of the earth or its inward crystallization, or both combined; second, those of sedimentary origin, deposited during the vast length of time in which life was growing from the first rudimentary form to the highly complex and varied life of the Cambrian; and, third, there may be a group of rocks intermediate in position between these two, in character and origin unlike any rocks which we now know to be forming, but connected by gradations with the later sediments. The first conclusion is a probable inference, based upon the truthfulness of the nebular hypothesis. The second conclusion is a certain one, based upon the known facts of the Cambrian life. Turning now to the field, do we find phenomena corresponding to these conclusions?

One who has worked long among the pre-Cambrian rocks in areas where the conditions are favorable for a structural study is usually impressed by the dual character of the pre-Cambrian. First, he finds a great series of gneissoid granites, gneisses, and schists, all completely crystalline, having the most intricate relations with one another, and showing the effects of repeated strong dynamic actions. These are injected by many undoubted igneous rocks of different characters and different ages. This group is always below the most ancient sedimentary rocks found. Without at present saying anything in regard to the origin of this Basement Complex, or as to the relations which obtain between it and the sedimentary rocks, it may be said that it is possible that it or some part of it corresponds either with the original crust of the earth and its inward crystallization or else with the transition rocks between these and the ordinary sediments which were deposited later. Second, he finds another great group of pre-Cambrian rocks, having all of the characteristics of ordinary sedimentary rocks. In many places these are divisible by unconformities into two or more different series. These rocks comprise conglomerates, sandstones, grits, shales, limestones, and their altered equivalents. These rocks may be reasonably regarded as occupying some part of the second great division of time, that in which life existed before the Cambrian, and as a matter of fact within these rocks we are not without evidence of the existence of life. This is demonstrated by the presence of undoubted fossils, which occur in Newfoundland, in the Grand Canyon region, in the Lake Superior country, in Great Britain, in Belgium, in Brittany, and in other places. Further, within these rocks are great beds of carbonaceous and graphitic shales, from some of which hydrocarbons may be distilled, and are rarely so rich in nongraphitic carbon as to be combustible with difficulty. That these hydrocarbons were produced by any other than organic agencies is exceedingly improbable. Also, there exist great beds of limestone and gneiss through which are disseminated particles of graphite. Finally, beds of iron carbonate and other rocks which are by many regarded as products of life are abundant.

If the position be correct that abundant life existed for eras before Cambrian time, the rarity of recognizable fossils needs explanation. This Darwin mentioned as a serious difficulty in his theory of the origin of species. Recently Brooks has given a plausible answer to this difficulty. From his biological study, and particularly from the facts of embryology, he concludes that the great stems of animal life were established when all animals were free swimming and pelagic. When the conditions became favorable, certain of the forms of the different classes availed themselves of the advantages of location at the bottom of the sea. As a consequence, these animals were limited in their habitat to length and breadth rather than length, breadth, and depth. Hence there at once arose a far keener struggle for existence than had been known before. One of the great crises in life had come. There resulted the rapid development of the hard parts, such as are found in the Cambrian rocks. Professor Brooks suggests that this change from pelagic forms to those found in basal Cambrian formations may have taken place in a time no longer than the Tertiary. This may be an underestimate of the length of the time; and doubtless future geological work will find a fauna below the Cambrian, just as the Cambrian fauna was found below the Silurian. However, it is hardly to be hoped that the earliest life will ever be known from fossils. For the absence of recognizable forms during this era or these eras, Professor Brooks's explanation[1] of free swimming, pelagic animals devoid of hard parts is the most plausible one yet offered.

In a treatment of the pre-Cambrian rocks the object of which is mainly to determine the principles of stratigraphy and rules to carry them out, the question arises in what respect these rocks differ from the post-Cambrian rocks, and what are the criteria which are especially applicable to them. Why should the pre-Cambrian rocks have a treatment separate from later formations? As has been seen, the first great point in which these rocks differ from later formations is in the apparent absence of abundant fossils. Abundant life may, indeed must, have existed in some of them. Remains of this life, however, have not yet been found in sufficient quantities to serve for the purposes of correlation from district to district and region to region. Among post-Cambrian formations paleontology is the chief reliance in homotaxis and correlation. Upon paleontological data have been based nearly all inferences as to the intercontinental equivalence of strata, and even upon the same continent the equating of one set of strata with another set in a different region has been usually based npon their fossil contents. It then follows that in the pre-Cambrian there is an almost entire absence of the most important criterion upon which stratigraphical and struc-

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[1] The origin of the oldest fossils and the discovery of the bottom of the ocean, by W. K. Brooks Jour of Geol, Vol II, pp 455-479, 1894

tural work has been done among the post-Cambrian formations. We are thus driven to the use of physical data only. Being thus restricted, it becomes necessary to scrutinize them and to consider their limitations, in order that a judgment may be formed of the reliability of work done and correlations made. But the pre-Cambrian problem is still more complicated because the rocks are so old. They have been subjected to all of the constructive and destructive geological forces which have been at work during the whole of Cambrian and post-Cambrian time. Vast areas of pre-Cambrian rocks have been destroyed by the process of erosion. Other areas are hidden by later rocks. The major portion of the remnants at the surface have been profoundly modified by the processes of metamorphism.

The folding of the pre-Cambrian rocks is, upon the whole, of a more complicated character than that of the post-Cambrian, for not only have the former rocks been subjected to all of the earth movements which have affected the Cambrian and post-Cambrian sediments, but before Cambrian time they were affected by earlier movements; and if we are correct in supposing that some of these pre-Cambrian sedimentary rocks may be twice or thrice as old as those of the oldest Cambrian, the movements to which they have been subjected must have been upon the average twice or thrice as many, even if the law of uniformity applies, and it is wholly possible that the disturbing forces have increased in frequency and in power as we go backward in time, thus making the amount of folding even greater. This does not imply that there are no areas of post-Cambrian rocks which have been folded to an equal or greater degree than any pre-Cambrian rocks, but merely that in the same province the pre-Cambrian rocks are usually folded to a greater degree than later rocks; or, stated differently, the pre-Cambrian rocks have, upon the average, been subjected to more periods of folding. Hence, in treating of pre-Cambrian stratigraphy we must consider the effects of this exceptional folding—what new structures have been developed, what interior alterations have occurred.

Following the same line of argument, it is plain that the jointing and faulting through which pre-Cambrian rocks have gone are, upon the whole, greater than in post-Cambrian rocks. Also, as a consequence of the folding, faulting, and jointing, brecciated or autoclastic rocks have been more extensively produced. A greater proportion of the rocks have become metamorphosed. Secondary structures have been more extensively developed in them. There have been intruded among them more numerous and abundant masses of igneous rocks; for the pre-Cambrian rocks have been subjected not only to all post-Cambrian intrusions, but to many pre-Cambrian intrusions and extrusions. It may also be that extrusive rocks were more widespread and abundant in pre-Cambrian than in post-Cambrian time. As a consequence of these various causes, producing profound effects upon the pre Cambrian sedimentary rocks, it is inevitable that the problem of pre-Cambrian stratigraphy, even apart from the absence of fossils, is, upon the whole, a more difficult one than the problem of post-Cambrian stratigraphy, and the problem becomes increasingly difficult as we go back from the base of the Cambrian

In the face of these difficulties, upon what criteria are we to depend in pre-Cambrian stratigraphy?

The first and most important of the criteria, as giving common horizons from which to work in comparison, is unconformity. If an unconformity is marked it must have a wide extent, for an unconformity implies an orogenic movement which raises the land above the sea, implies faulting or folding of the strata, implies truncation by means of epigene forces, and, finally, implies another orographic movement, which depresses the area below the sea. Later, evidence will be given to show that such a break can hardly be less than regional, while it may be continental or, perhaps, intercontinental in its effects. For instance, the great Appalachian revolution at the close of Paleozoic time not only caused a profound unconformity between the Paleozoic rocks and the post-Paleozoic rocks along the whole length of the Appalachian Mountains, but produced great physical changes throughout the central and western part of the continent

Secondly, we may use the sequence of beds of the same character as guides in equivalency, that is, if a set of beds of peculiar lithological character occur in like order in different districts of the same geological province, it is probable that they are parts of a once-continuous series, and if such a series of beds is separated by an unconformity from a set of beds below and another set of beds above, the supposed equivalency has an increased degree of probability Then, with proper restrictions, the lithological character of a single bed itself may have some value in comparative work. It is necessary that we consider carefully how an unconformity may be established, and in correlation what value may be placed upon unconformity, upon sequence of beds, and upon lithological character.

Finally, the very phenomena which make the pre-Cambrian stratigraphy a difficult problem may also give us assistance. If a lower series has been more extensively folded, or folded in a different way from a superimposed series, the question may be asked whether the two are not separated by a time interval; for if the upper series existed in the same district when the lower series was folded in the first instance, it should be folded in the same manner Absence of folding, or a less complicated folding, indicates that the upper series was not present when the lower series was first folded. In using this criterion it must be certain that we have a case of superposition of the two series, not lateral position, for intense plications may die out rapidly transverse to the directions of the folds, and thus leave beds unaffected or little affected which were very close to those that are intensely folded In the same way, faulting, jointing, brecciation, metamorphism, cleavage, fissility, and the relations of igneous rocks are criteria by which we may separate one series from another. For instance, in the case of igneous rocks, if a lower series is cut through and through by dikes which nowhere penetrate a superior series, the inference is that this superior series was not present at the time of the injection of the igneous rocks. Thus we see that the very causes which increase the difficulties of pre-Cambrian stratigraphy—that is, the greater amount of folding, faulting, jointing, brecciation, metamorphism, etc., to which they have been subjected—may be of assistance to us in particular cases in working out the structure. Because of the importance of these phenomena and of unconformity, sequence of beds, and lithological character, it is necessary that each be taken up in order and be separately considered.

PART I.

DISCUSSION OF PRINCIPLES.[1]

SECTION I.

MOVEMENTS OF ROCK MATERIALS UNDER DEFORMATION.

Rock units under thrust act very differently, depending upon their thickness, strength, and other characters, upon the character and thickness of the rock units above and below, and upon the closeness of folding.

It is believed that the outer part of the earth may be divided into three zones: (1) An upper zone of fracture; (2) a middle zone of combined fracture and plasticity; (3) a lower zone of plasticity.

(1) *Rocks under less weight than their ultimate strength when rapidly deformed are in the zone of fracture.* That is, when rocks under such conditions are deformed they break, and crevices small or great separate the broken parts (fig. 145 and Pl. CXIV). The fractured rocks may be jointed, faulted, or brecciated in a simple or a complex manner. The fractures may be far apart and of great size and extent, or near together and of small size and extent. Innumerable parallel fractures may occur in the same direction, when, as shown later, the rocks develop a parting, or fissility. In extreme cases of fracture the rocks become autoclastic, or are broken into innumerable fragments by the forces of deformation. These fragments may be rounded, and such rocks resemble ordinary clastic rock. In this case the rock becomes a pseudoconglomerate (Pl. CXIII); and there are all gradations between such a rock and one in which the cracks and crevices become subordinate, the deformation being chiefly that of flowage. In the case of a soft shale, but a small thickness of superincumbent strata, possibly 500 meters or less, may prevent any considerable fractures and crevices from forming. In the case of the strongest massive rocks, a great thickness of

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[1] In the preparation of this paper I have been greatly indebted to the article by Prof L M. Hoskins which appears herewith as an appendix This has been of especial assistance to me in the preparation of Sections I and III

To Willis's paper upon the Appalachians I am equally indebted (The Mechanics of Appalachian Structure, by Bailey Willis, Thirteenth Ann Rept U S Geol. Surv , pp 211-281) This has helped me particularly in the preparation of Sections I, II, and V

I should also mention Heim's great work, "Mechanismus der Gebirgsbildung," from which I have absorbed many ideas superincumbent strata, possibly nearly 10,000 meters, may be necessary to prevent cracks and crevices from forming.

Heim states that it is impossible for crevices and cracks to exist at so great a depth as 5,000 meters.[1] From geological observations, I have for some time been convinced that a greater depth than this is required to close crevices under some conditions. The depth at which a cavity of any definite size begins to close will depend upon its form, upon the strength of the rock, upon whether the rock is saturated with water, upon the increased plasticity of the rock due to the rise of temperature with increased depth, upon the amount of lateral thrust, and upon the length of time during which the rock is subjected to stress.

So large an opening as the St. Gothard tunnel, 6.4 meters high and 8 meters wide, exists with no observed tendency to close under an irregular dome of rock which for some distance is more than a mile thick and has a maximum thickness of 1,830 meters. The thickness of the superincumbent rock diminishes from the maximum to nothing at the ends of the tunnel. However, it would appear from this case to be highly probable that in order to close cavities the maximum number must be multiplied by a factor of considerable magnitude.

It would seem that mathematicians and physicists, after experiments upon the plasticity of rocks of different kinds, ought to give an approximate solution of the problem as to the depth at which cavities in any kind of rock would begin to close. We need long-continued experiments upon the plasticity of different rocks at various temperatures and pressures, and while the rocks are saturated with superheated water. We also need a satisfactory theory of the flow of viscous liquids or plastic solids.

In the absence of these data a first approximate solution of the problem has been made by Prof. L. M. Hoskins, of the Leland Stanford, Jr., University, based upon the elastic limit and the ultimate strength of rocks. The most carefully conducted experiments agree with theory, and seem to show that rock masses of the same form have the same crushing strength per unit of area whether in large or in small masses. In experiments on cubes running from 1 to 12 inches in diameter, in each set there are irregular variations per unit area on each side of the average, but these are probably explained by the unavoidable variations in the strength of the different pieces tested and the impossibility of obtaining exactly similar conditions.[2]

Professor Hoskins, after a comprehensive discussion (see Appendix), reaches the following general conclusions upon the closing of cavities in rocks.

I If the three principal stresses in any region of a rock mass are equal, a spherical cavity can not exist permanently if the normal stress in the rock exceeds the pressure within the cavity by as much as two-thirds the elastic limit or the ultimate strength.

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[1] Mechanismus der Gebirgsbildung by Albert Heim, Band II, 1878, p. 110

[2] Tests of metals and other materials for industrial purposes, made with the United States testing machine at Watertown Arsenal, Mass , by S V Benét, Chief of Ordnance Rept of Chief of Ordnance for year ending June 30, 1884, pp 126, 166-167, 188-199, 212, Washington, 1886

II. If two of the three principal stresses are equal, a cylindrical cavity of considerable length whose axis is parallel to the third direction can not exist permanently if either of the equal principal stresses exceeds the interior pressure by as much as half the elastic limit or the ultimate strength, or if the third principal stress exceeds the interior pressure by as much as half the elastic limit or ultimate strength

Although the discussion has been confined to these special cases, it seems safe to state the following general proposition as at least probably true.

III. No cavity can exist permanently in a rock throughout a considerable portion of which the normal stress in any direction exceeds the pressure within the cavity by as much as the elastic limit or ultimate strength of the rock.

Professor Hoskins further says:

The intensity of stress upon a horizontal plane at any depth is equal to the weight of a column of rock of unit cross-section extending to the surface

In applying these results to ascertain the depth at which cavities would close, the following additional assumptions are made· Some of the cavities are supposed to have a form best adapted to resist closing. In most cases, as shown by Professor Hoskins, this is probably spherical. The cavities are supposed to be very small as compared with their depth below the surface, so that the pressure due to gravity is practically the same for all parts of a cavity. The rocks are assumed as being among the strongest—that is, having a crushing strength of 1,700 kilograms per square centimeter. This amount somewhat exceeds the average crushing strength of the ordinary crystalline rocks, such as granite and schist, but is surpassed by about one-fifth in some of the very strongest hornblende granites and basic rocks. It is probable that the stronger, and perhaps the strongest, rocks should be chosen, for the minute cavities in the interstices are concerned, and these can be closed only by the crushing or flowing of the individual mineral particles. Upon the one hand, it is natural to suppose that some of the minerals composing rocks are stronger than any rock. Upon the other hand, the cavities may be largely closed by the flowage or fracture of the weaker minerals of a given rock. However this may be, for the purposes of the present discussion it is plain that sandstones are to be placed upon the same basis as quartzites, and possibly shales upon the same basis as slates and schists.

The specific gravity of the outer crust of the earth is assumed to be 2.7.[1] As openings in the earth are usually filled with water, in obtaining a maximum depth at which cavities can exist permanently it is probably necessary to suppose that cavities are supported by the hydrostatic pressure of a column of water reaching to the surface, and therefore that 1 should be subtracted from the specific gravity of the rock in determining the depth at which the closing of cavities occurs. Under the slowly acting orographic forces it is probable that the water must be considered as free to escape, and that the viscosity of water in minute crevices plays no part.

If it be supposed that the rocks above the cavities are solid to the

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[1] This estimate of 2 7 was kindly furnished me by Mr G K Gilbert as a close approximation to the specific gravity of the continental masses It is the same as my own best guess of the specific gravity of the pre Cambrian rocks

surface, and therefore that they are not supported by the hydrostatic pressure of a column of water to the surface, the problem is reduced by Professor Hoskins's solution to finding the height of a column 1 square centimeter in area, with a specific gravity of 2.7, which weighs two-thirds of 1,700 kilograms for Conclusion I, and weighs 1,700 kilograms for Conclusion III. This gives for I about 4,200 meters; for III, about 6,300 meters.

If the more probable supposition be made, that the rocks are porous, and therefore that the cavities are supported by the hydrostatic pressure of a column of water extending to the surface, it is necessary to subtract 1 from the specific gravity of the rocks, and the effective pressure is 1.7 grams per cubic centimeter. Applying Professor Hoskins's solution, the question is reduced to finding the height of a column 1 square centimeter in area, with a specific gravity of 1.7, which weighs two-thirds of 1,700 kilograms for Conclusion I, and weighs 1,700 kilograms for Conclusion III. This gives for I, 6,667 meters, and for III, 10,000 meters. For the very strongest rocks the above numbers should perhaps be increased by one-fifth, and this gives a maximum of 12,000 meters.

These conclusions do not apply to rock-inclosed, liquid-filled cavities. So far as one can understand the conditions, such cavities might exist at an indefinite depth, or at least at a depth where the liquid and rock may be miscible in all proportions.

The above numbers fall within the various limits—roughly, 2 to 8 miles—assigned for the "level of no strain," or, as it shonld perhaps be called, more properly, the level of no lateral stress, and thus make it probable that the lateral stress is less than the vertical stress of gravity.[1] Therefore it is probable that the conditions upon which Conclusion III are based more nearly represent the truth for the greater part of the earth than do those of Conclusion I. However, in mountain-making regions the lateral stress may be so great as to comply with the conditions of Conclusion I, and therefore cavities may close at the minimum depth.

The maximum result reached by the calculation is probably in excess of the truth, for all of the assumptions excepting that concerning the free escape of water are those favorable to requiring a great depth for the closing of cavities. However, it is believed that the result is valuable, because it is certainly large enough, and we may be sure that at depths greater than 12,000 meters no cavities can exist. Also it is reasonably certain that in the weaker rocks cavities are closed much nearer the surface than this. As more accurate data for the solution of the problem become available, it may be possible to obtain reasonably accurate results for the rocks of greatest strength and also for weaker rocks of different kinds. For instance, if the crushing strength of ice be determined for various temperatures at and somewhat below

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[1] Manual of Geology, by James D Dana, 4th ed , 1895, pp 384–385

zero centigrade, the greatest possible depth to which crevasses in glaciers extend at such temperatures may be readily calculated.

It is highly probable that the very greatly increased plasticity of rocks when saturated with superheated water, due to the rise of temperature with depth, would lead to the closing of the deeper lying crevices by flowage and welding rather than by fracture. If the increase in temperature is 1° C. for 30 meters, at a depth of 10,000 meters the material would have a temperature of 333° C. above the average temperature of the level where climate produces no influence. To this in mountain making regions would have to be added any increase in temperature due to dynamic action. Under gravity alone, rocks at such a depth would be subjected to a vertical pressure of 2,550 kilograms per square centimeter. As has been seen, the lateral pressure might be less than this if the rock was not in mountain-making areas and near the level of no lateral stress, or it might be as much or more than this if in mountain-making areas and therefore subjected to great lateral pressure. It is probable that at such temperatures and pressures even brittle rocks, under these great and very slowly acting forces, when saturated with superheated water, obey the laws of hydrostatics, for plastic solids when strained beyond the limit of elasticity follow the same laws of deformation as do liquids. It is probable that the above considerations should reduce the estimated depth for the closing of cavities in the strongest rocks to 10,000 meters or less.

It therefore appears highly probable that at a depth of 10,000 meters, not only do no crevices permanently exist in the earth, but the rocks are in such a condition that actual welding of the fractured parts would soon take place, supposing fracture to occur.

Such was apparently the case in the deepest lying gneisses and anorthosites of the original Laurentian area, described by Adams.[1] Here in certain areas each of the individual mineral particles is broken into many fragments. No extraneous or infiltrated material is discovered between the granules, and yet the rocks are exceedingly strong and tough, showing in all probability that the broken particles were welded. However, there may possibly be a zone in which the deformation occurs by minute fractures of the individual particles, these being held together without interspaces, and yet where the temperature and pressure are not sufficient to cause welding.

The conclusions as to the depth at which cavities close accord well with observations in the field and with the microscope. It is only in material from the cores of the great mountain masses or in regions subjected to vast denudation that the microscope is unable to discover crevices caused by great deformation. The large secondary cracks and crevices which may have formed during the time when the rocks were nearing the surface by denudation are not here referred to, but the

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[1] A further Contribution to our Knowledge of the Laurentian, by Frank D Adams Am Jour Sci. (3), Vol L, 1895, pp 62-63

innumerable minute crevices affecting the individual grains, which were plainly produced by the deep-seated deformation of the rock. In many instances in which such crevices are found it appears probable from the geology of the region that the rocks were buried under well-nigh 10,000 meters of material, although this is difficult to demonstrate.

Whether rocks flow or fracture is in many cases largely dependent on the rapidity of deformation. As pointed out by Professor Hoskins under "Conditions of flow and of fracture" (see Appendix), a rock under a certain pressure in two directions, when rapidly deformed by a greater pressure in a third direction, may be fractured, and when less rapidly deformed may flow. This results from the fact that the elastic limit of a rock is always less than its ultimate strength. During the time of rapid deformation the rock may be fractured and crevices and cracks formed which are subsequently closed by plastic flow, even if the stresses decrease in amount. Also, as the stresses were slowly increasing, there may have been very considerable flowage before any fractures were produced. Hence, even in homogeneous rocks, the zone of fracture and the zone of flowage are not sharply separated from each other, and the upper part of the zone of flowage is at different depths under varying conditions of stress. This principle is illustrated by the distortion of rocks in ancient buildings, such as the Alhambra, and by slabs of marble suspended by their ends in cemeteries.[1] This latter case shows how important the element of time is in the deformation of rocks, and that, given a sufficient time, a stress much below the ultimate strength may surpass the elastic limit and result in flowage. It thns becomes clear that there may be a very considerable thickness for any given rock in which it may be in the zone of fracture or in the zone of flowage, depending upon the amount of differential stress.

(3) *Rocks buried to such depth that the weight of the superincumbent strata exceeds their ultimate strength are in the zone of plasticity and flowage.* These are the conditions of folding, for permanent perfect flexure is possible only by flowage of material. It is a contradiction to suppose that cracks and crevices can form under these conditions. Were it possible for an opening to be made in any way, under the hypothesis the rock would flow toward the opening and close it. All of the rocks concerned are everywhere under compressive stress. The material at any given moment, when deformed, moves from places of great compression to places of less compression. In other words, there is always a tendency for the rocks to approach equilibrium under the forces applied, or to obey the laws of hydrostatics. In order that deformation shall occur, the difference between the greatest and the least stresses must equal or surpass the elastic limit of the rock in question, under the conditions in which it exists. In rocks which were bent when so deeply buried that no cracks or crevices could form even tempo-

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[1] An Illustration of the Flexibility of Limestone, by Arthur Winslow Am Jour Sci. (3), Vol XLIII, 1892, pp 133-134

rarily, it is probable that the material flowed to its new position quietly, without shock, under the enormous stress to which it was subjected.

Even if in the zone of flowage, the relative thickness and strength of the members folded will play their part. If the mass were exactly homogeneous it would flow in the direction of least resistance, like a mass of tallow. But the rock masses are heterogeneous, and the alternating layers of different plasticity may retain their individuality, there being no considerable commingling of the materials of one layer with others (Pl. CXI). The strong, thick beds will greatly vary the direction of movement of the material at a given place, and thus, as explained by Willis, develop folds of great length and amplitude.

FIG. 101.—Thin section of a mashed quartz-porphyry.

On account of their relatively resistant character when bent into anticlines and synclines, the anticlines will be able to carry part of the superincumbent load, and thus relieve to some extent the softer beds below, which, however, as a consequence, promptly flow in the direction of relief or least resistance, and ever press against the confining arch, and thus do their part, which may be the major part, of carrying the superincumbent load. In a similar manner the strong formations bent into synclines because of the thrust transmitted along their limbs, furnished in part by the weight carried by the adjacent anticlines, will give increased pressure to the softer beds below and add to the ordinary thrust which is already forcing the material to follow the arches of the adjacent anticlines. However, if the superincumbent strata be but sufficient, the strongest and most brittle rock beds, such as quartzite and jaspilite, may be crumpled or bent upon themselves within their own radius without any macroscopic sign of crevice or fracture. In extreme cases the microscope is unable to detect any evidence of crevices or cracks, but it shows in a most remarkable manner that the mineral particles have been greatly flattened (fig. 101).

The thinner and softer the beds the less potent are they to control the movement of any considerable amount of material. Therefore, under given conditions, the thinner and softer the beds the shorter and steeper are the folds and the more nearly does their material approach in its movement to the flowage of tallow. In soft, homogeneous shales the approximation is closest. Therefore, in a series or group of beds of different lithological character, the thick, strong beds are less closely folded than the thin, weak beds. The softer layers are greatly thickened here and greatly thinned there, as demanded by the stronger layers. The folding of the first may be comparatively simple, and the second may be closely plicated (fig. 133). These principles are finely illustrated in the Hiwassee section of the Ocoee series of the Southern Appalachians.

In any great anticlinorium, even if the strongest rock be at the bottom—for instance, a massif of granite (figs. 112 and 116)—it yields to the force of thrust, under the law of normal plastic flow, moving toward the places of least compression, and ever presses against and helps to raise and support the overlying arch of sedimentary and other rock. If a massif were absolutely homogeneous without reference to its strength, its movements would be analogous to that of wax. Consequent upon such movement, as explained on a subsequent page, it is believed that uniform cleavage is often produced. But no massif is homogeneous. It is composed of mineral particles of different kinds and of different sizes. In a larger way it is composed of rock masses of different character. Frequently these masses of different character and strength are divided by vertical or steeply inclined planes of weakness, rather than horizontal ones, as in the sedimentary rocks; hence, major movements take place along the major inclined planes and minor movements along minor planes and between the mineral particles. Complex minor folding and shearing therefore occur in the readjustment of a massif to its new position. The major planes of shearing may be called fault planes, but they differ from ordinary faults in that the parts moved over one another are always in close contact, and probably are also always welded.

When a set of rock beds are bent even slightly, readjustment and rearrangement of the material must occur to some extent, and the amount increases in proportion as the rocks are closely folded.

If a steel bar be bent the molecules are separated to some extent upon the convex side and compressed upon the concave side. When released from stress the bar, by virtue of elasticity, springs back to its original position. While to some slight degree rocks are elastic when subjected to forces continuing for a short time, it may be doubted whether this property is of importance in considering the slowly acting and long-continued forces of rock folding, except perhaps in the slight flexures of great extent. Single rock beds, when much deformed, are rather to be compared to a wrought-iron bar, which when bent takes a permanent set. In this case there is an actual flowage of material or rearrangement of the particles to the new conditions. The half of the bar on the convex side, subjected to tension, is lengthened, and, to compensate it, is of less cross-section than originally. The half of the bar on the concave side, subjected to compression, is shortened, and, to compensate it, is of greater cross-section than originally. Each homogeneous rock stratum when bent acts like the iron bar to a certain extent. There is rearrangement of its material to new positions, and when the bending occurs without fracture the movements of the rock particles may be like those of the particles of the compressed part of the iron bar. But rock beds are usually composed of different mineral constituents, which differ from one another in strength, in hardness, in

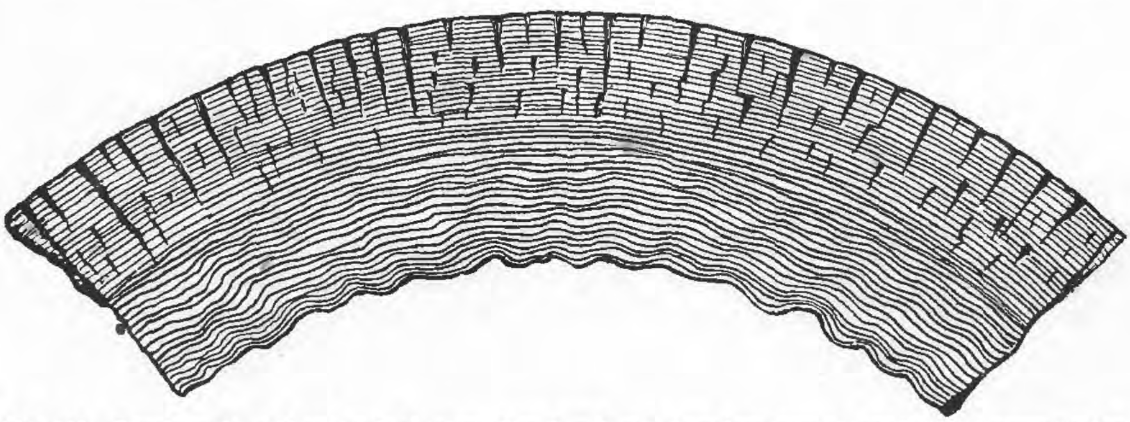

FIG. 102.—Ideal section of bent rock stratum showing fracturing along convex surface and compression along concave surface.

brittleness, in elasticity, and in size. The necessary rearrangement of the mineral particles will more largely affect the weak, small particles than the large, strong ones. However, as shown by microscopical study, when a district is closely folded, no particle of a rock stratum, small or great, simple or complex, weak or strong, escapes the effects or fails to take part in the necessary readjustment of folding (fig. 101).

If a rock stratum could be bent without fracture in such a position that the superincumbent weight were slight, about one-half of the bed, like the iron bar, would be elongated, and the other half would be compressed. Between the two there would be a neutral plane.

As rock beds are brittle they act differently from an iron bar when bent to any considerable degree. Beginning at the middle of the mass in the trough or crest of the fold and passing toward the convex surface, the first lamina is under tension, the second under greater tension, and so on, each stratum being stretched more than the preceding. The tensile force may go beyond the limit of elasticity and radial cracks will be formed (fig. 102). Beginning again at the center and passing toward the concave surface, the first layer is under compression, the second under greater compression, and so on, each stratum being more severely squeezed than the preceding. This may go beyond the limit of elasticity and produce minor plications.

But the majority of strata which have been closely folded when bent were deeply buried beneath other strata. If the superincumbent weight was greater than the strength of the rock all parts of it were under compression, increasing, it is true, from top to bottom in an anticline, and, if the mass was not too thick, from bottom to top in a syncline. In this case there was no neutral plane. The rearrangement which took place were therefore those of varying compression, flowage away from the places of greatest compression and flowage toward the places of least compression. The crenulations in an anticline may mean that the part of the fold seen was in the compressed area, the stretched and fractured part being removed by erosion. Where both the anticlines and synclines show plications throughout, it follows that the superincumbent strata were so thick that no zone of stretching could be formed, the weight being beyond the supporting strength of the rocks, and the movements being those of a heterogenous plastic body.

Just as there is rearrangement of the particles within a bed, so there is readjustment of the beds over one another. This may be illustrated by a bunch of paper (figs. 118 and 119). If straight lines be drawn at the ends of a bunch of horizontal sheets, and then the whole be bent into folds, it will be found that the straight lines become curved. In other words, the sheets were moved over one another. An examination of the curved lines shows that on opposite sides of an anticline or syncline the movement for any given stratum is in opposite directions; therefore at the anticlines and synclines the forces are directly opposed, and hence the stretching or plication at these places, as already explained. But on the limbs of the folds the forces are in the same direction for each lamina, but in opposite directions for laminæ upon opposite sides of any layer thus constituting a couple. Each stratum moves up as compared with the one next below it, and each stratum moves down as compared with the one next above it. In the case of much inclined and overturned folds this statement needs modification. (See p. 624.)

The axial lines also show that at the crests of the anticlines and at the troughs of the synclines there was comparatively little movement, while at the middle of the limbs of the folds the movements were at a maximum. From this experiment and from fig. 103 we would expect that in folded rock strata the effects of readjustment would be least at the crests of the anticlines and troughs of the synclines and most at the middle of the limbs, and such are the facts. On subsequent pages it will be seen that clastic rocks become crystalline in proportion to the degree of shearing and the intensity of the pressure. The former is at a maximum on the limbs of folds and at a minimum on the crests and troughs.

Further, secondary structures nearly parallel to the beds may develop on the limbs, while upon the anticlines and synclines the secondary structures form across the beds. It follows that on the anticlines and synclines, where there is most crenulation and puckering of the laminæ, the original structures will be less altered, and the clastic characters in sediments, such as sandstones and conglomerates, are likely to be preserved. Upo the other hand, upon the limbs of the folds the obliteration of fragmental characters may be complete. We therefore have the paradox that where there is most crenulation there is least meta-

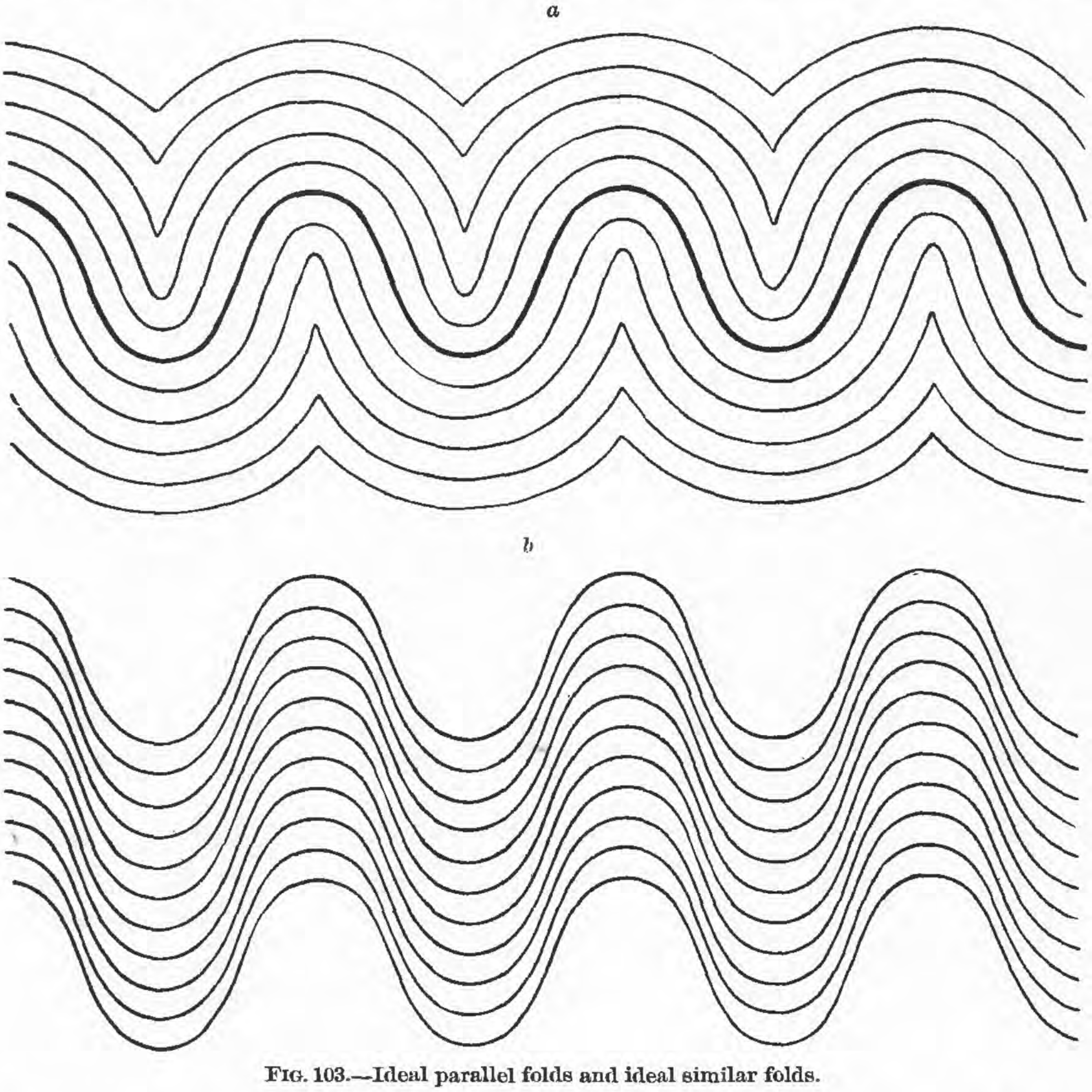

FIG. 103.—Ideal parallel folds and ideal similar folds.

morphism; where least crenulation, most metamorphism. This of course applies only to the different positions of the rock in the fold, not to a gently folded district as compared with a more closely folded area.

But rock beds as they occur in nature differ from the bunch of paper in that they are of varying thickness and strength. The major readjustments of the rock beds occur between the thick and strong strata, and within the weak and soft strata (fig. 133). In these latter, therefore, the rearrangement of the particles is far more profound than would be the case if such beds were folded alone. The polishing effects of the readjustments between the beds may often be seen in the slickensided surfaces of the major and stronger beds, and in cases of implicated folding the same phenomena are observable between the thinnest laminæ. A most striking instance of this polishing is seen in the Jura Mountains, where at many places both sides of the strong, thick layers of Jurassic limestone are polished as smoothly as if glaciated. They reflect the sun like an imperfect mirror. At some places where the folds are steep layers have fallen down along these movement planes, exposing great surfaces of beautifully polished rock. In the folded Cambrian quartzites of Doe River, Tennessee, the polishing of the layers by accommodation is scarcely less strikingly illustrated.

If a given bed in the center of a rock formation be plicated and the layers above and below be folded in a strictly parallel manner, in passing away from the central bed in either direction those on either side are less closely folded, and finally the crenulations become slight. If the folds are close in the center they die out with great rapidity. The above follows directly from the laws of deformation of solid masses, and is illustrated by fig. 103*a*. It should be observed that the more crenulated lines are longer than the less crenulated ones. In so far as this is imitated in nature this implies that there is differential movement between the layers, for originally all of the beds must be supposed to have been of the same length. Such differential motion doubtless does occur in strata in which the folds differ in character, for the more closely folded beds must be subjected to severer thrusts or have been originally weaker, so that the thrust is more effective, or have been in a position in which friction gave less resisting power. The ideal figure probably more nearly illustrates the effects of nature in passing downward from the central line than in passing upward, for the deformation in superficial strata may be accomplished by jointing, faulting, and brecciation.

If beds above and below the central one be folded in a similar fashion, the limbs of the different layers will be closely pressed together or thinned, or both, and at the anticlines and synclines there will be spaces between the layers, or thickening, or both (fig. 103*b*.) But this result can be accomplished only by plastic flow of the material of the limbs toward the areas of relief. This often produces minor plications at the crests and troughs (fig. 133). Even where the folding is only moderately close the limbs of folds may be only one-half as thick as the troughs and crests (fig. 103*b*; see also fig. 70, Dale, in the previous paper, p. 550). Where the folding is very close the troughs and crests must be several times as thick as the limbs in order that they may have similar forms. This is shown in some layers in fig. 133. (See also fig. 74, Dale, in the previous paper, p. 553.)

Without fully realizing the above principles many geologists have drawn sections which are a compromise between figs. 103*a* and 103*b*, and to the structure shown thereon the facts of nature usually correspond.

It is evident from the above that close folds can persist in depth with similar forms only by great differential movement of material, for the readjustment will go only so far as demanded by the differential stresses. It is therefore to be expected that the close folds of mountain districts die out rapidly with increasing depth. This would certainly be true if the lateral stresses diminish, as they must do if the theory of "level of no strain" at very moderate depth be correct. The foregoing doubtless partly explains the open folding often observed in the center of the mountain masses as contrasted with the closely folded flanks, although in many cases other causes undoubtedly enter.

This rapid disappearance of folds with increased depth is beautifully illustrated in a section along the Schuylkill River near Philadelphia, between Lafayette and Spring Mill, shown me by Miss Florence Bascom. In the center of the section is gently undulating gneiss. In passing toward the outer parts of the gneiss it is closely folded. The gneiss is flanked on either side by still more closely folded mica-schist. Not only is the principle illustrated by the entire section, but at various places close local folds may be seen, above and below which the folds rapidly become more open. The same is illustrated in the crumpled gneisses of the Ottawa River (lower left-hand corner of Pl. CXI). The disappearance of folds in depth is also illustrated by fig. 135. The plications in slate rapidly die out and the limestone below is simply folded. (See also Dale's figs. 79 and 80 in previous paper, pp. 555, 556.) The same principle is illustrated upon a much larger scale by the section along the Doe River west from Cranberry, N. C. The folding of the schistosity of the pre-Cambrian granitoid gneisses is gently composite, while the overlying Paleozoic quartzite shows many close minor folds. This case is a particularly good one, for it can hardly be supposed that the quartzite is much less rigid than the gneissoid granite.

It follows from the above that where different beds are in folds of similar forms rearrangement within the beds, adjustment between the beds, and distortion of the beds all work together to shear the limbs of the folds parallel to the bedding and to develop plications in the crowns and troughs.

(2) *Since the boundary between the zone of fracture and the zone of flowage is at a different depth for two rocks of unequal strength, and for the same rock under different conditions of stress, there is a zone of combined fracture and flowage.* In a set of heterogeneous beds upper, weak strata may be in the zone of folding, while lower and stronger strata may be in the zone of fracture. Also, as pointed out by Willis, if strong folded strata at anticlines are competent to carry much of the load, as they often are if the arches are not too long, weaker strata below may be so relieved from weight so as to be partly deformed by fracture. Thus, between an upper horizon where all the rocks of a district fracture when deformed, notwithstanding the weight of the superincumbent

beds, and a lower horizon where the effective weight of the superincumbent beds is so great that no rock fractures, is a zone of combined folding and fracturing. This central zone is one of great thickness, and is of the first importance.

A soft shale may be in the zone of folding, far above a strong quartzite or jaspilite, and the latter be in the zone of partial deformation by fracture (Pl. CXIV). This difference in strength is at many places certainly equal to the weight of 2,000 or 3,000 meters of strata, and probably equal to the weight of 5,000 meters or more. Thus this middle zone is probably at least 5,000 meters thick, and it may be considerably thicker than this.

In heterogeneous rock strata in this middle zone irregular fracturing, brecciation, jointing, faulting, and folding and the development of secondary structure may occur together in a most complex manner. A deeply buried, brittle formation may be under such stress that as a whole it folds without major fracturing, but in a minor way it may be faulted, fractured, or brecciated (fig. 133 and Pl. CXIV, fig. 1). The *fracturing may leave no permanent openings, as the softer material may* promptly flow and fill the openings between the more brittle, broken layers. Such is the case in some of the jaspilite beds of the Lower Marquette series of Michigan. Such is also the case at many places where beds of shale or limestone are interstratified with beds of grit or sandstone. The first may pass to its new position by homogeneous flow, the second by repeated fractures, which in extreme cases may break the harder beds into fragments and bury them in the softer rocks. The same relations often are seen between mobile marble and brittle gneiss. Whether fracturing always implies at least temporary crevices is an undetermined point.

The weight of the superincumbent material may have been so great that the rock beds as a whole bent without macroscopic fracture, and yet the microscope may show that the individual grains were broken and that minute crevices were formed which have been subsequently filled by secondary infiltrations. At many places the massive beds of the quartzites of Doe River, Tennessee, are bent upon themselves within their own radius, with no macroscopic evidence of crevice or fracture. But the microscope shows that the fracturing and resultant flattening of the quartz grains was almost universal.

This illustration shows that for a given kind of rock the zone of fracture passes gradually into the zone of flowage. Even where so deeply buried that all large fractures are absent and the rocks are practically in the zone of flowage, the microscope may still show fractures. It has already been indicated that the zone of flowage is much deeper for some rocks than for others. Also for the same rock mass it may be less deep when gently folded than when closely folded. It is therefore clear that there are gradations between the three zones—of fracturing, of fracturing and flowage, and of flowage. In the placing of a rock mass in one of the three zones it is to be considered as belonging to the one to which it most closely corresponds. If the rocks are everywhere broken and show comparatively little folding, they are in the zone of fracture; if they show much fracturing and also are folded they are in the zone of fracture and flowage; if the fractures are subordinate or microscopic they are in the zone of flowage.

SECTION II.

ANALYSIS OF FOLDS.

As ordinarily treated, folds are considered as simple flexures in two dimensions. As they occur in nature, folds are complex flexures in three dimensions.

Folds in rocks may be compared with the waves of the sea. Each large wave has superimposed upon it waves of the second order; upon these are waves of the third order, and on these waves of the fourth order, and so on. Moreover, running across the most conspicuous waves at various angles up to perpendicularity may be other waves of an equally composite character. As observed from a ship at sea the waves of the first order are so large and have such gentle slopes that they are often overlooked, while the steeper waves of the second order are noticed, because more conspicuous. Upon account of their small size the waves of a higher order than the second are usually unnoticed, as are also the waves of all orders which are transverse to the more conspicuous set.

If when stirred by a great storm the surface of the sea could in an instant be frozen we should obtain some idea of the complexity of the waves. We should see primary elevations and depressions of circular, oval, and lenticular horizontal sections, in different sets, crossing one another in various directions, and upon these would be other sets of waves of like complexity of the second, third, and fourth orders, and so on.

The rock waves of the earth are of greater size and of equal or greater complexity than the waves of the sea. The rollers of the sea, when not wind forced, may be compared with the long, gentle folds of rock. At first sight they seem simple, but, like the rock folds, when observed closely they are found to possess secondary crenulations. At the other extreme are the highly complex waves running in various directions at the same time, formed by the shifting winds of a great storm, by currents and tides together. The sea in this condition may be compared with the rocks in which each set of primary folds has superimposed upon it folds of the second order, and upon these those of a higher order to the *n*th order (Pl. CXI). The smaller orders of folds are microscopic (fig. 162). Such complex rock folds are called crumpled, plicated, or implicated.

In this comparison it is not meant to imply that the forces which produce rock folds are the same, or that they work in the same manner, as the forces which produce sea waves. Nor is it meant that the forms of the folds are the same as the forms of the waves. The only purpose of the comparison is to give at the outset some idea of the complexity of rock folds.

Tangential thrust and gravity are assumed to be the causes of folds. No attempt will be made here to show this or to explain the cause of thrust, although in the last analysis it is probable that thrust is dependent upon gravity. At all times and in all positions rocks are subject to the force of gravity. Thrust and gravity act upon rocks of heterogeneous character. Rock heterogeneity, therefore, modifies the forms of folds. Folds are further modified by igneous rocks. In what follows, the effects of igneous rocks are at first excluded.

We shall now attempt to analyze the rock waves or folds. For convenience, they will first be considered in two dimensions.

SIMPLE FOLDS.

Simple folds are classified by de Margerie and Heim[1] as follows: A fold is upright or symmetrical when the axial plane is vertical, or nearly so, and the limbs have nearly equal dips in opposite directions at corresponding points (fig. 104).

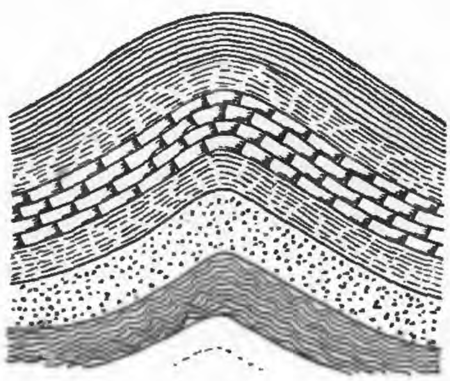

FIG. 104.—Simple upright fold.

A fold is inclined or unsymmetrical when the axial plane is inclined and the limbs have unequal dips in opposite directions at corresponding points (fig. 105).

A fold is overturned or overfolded when the axial plane is inclined and the limbs have equal or unequal dips in the same direction at corresponding points (fig. 106). An overturned fold is lying or recumbent when its axial plane is horizontal, or nearly so (fig. 107). The different parts of an overturned fold are the arch limb, reversed limb and trough limb (*a*, *b*, *c*, fig. 107).

As to closeness of compression, folds are described by de Margerie and Heim as follows: An ordinary fold is one in which the strata diverge from the crest of the anticline and the trough of the syncline (figs. 105–107). Ordinary folds may be described as gentle, open, or close. In close folds, according to Willis, the process has gone so far that the strata are perceptibly changed in

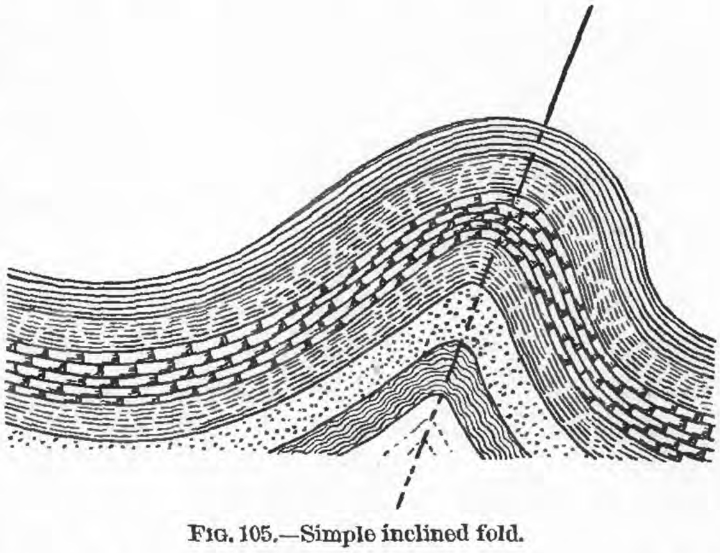

FIG. 105.—Simple inclined fold.

[1] Les dislocations de l' écorce terrestre, par Emm. de Margerie et Albert Heim, Zürich, 1888, pp. 49–63.

thickness in different parts of the fold. An isoclinal fold is one in which the strata are parallel, or nearly so (fig. 108). A fan fold is one in which the strata converge downward from the crest of the anticline (fig. 112). In this case the strata at the limbs of the fold are always greatly thinned, and in some instances the central strata are absent, the material having flowed up and down, forming detached arch cores and detached trough cores. An ordinary, isoclinal, or fan fold may be upright, inclined, or overturned.

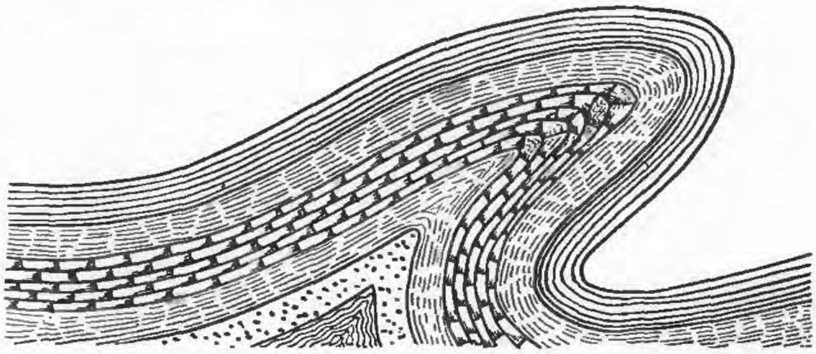

FIG. 106.—Simple overturned fold.

In the formation of the simple fan-shaped anticline the rocks are extremely compressed on the limbs of the fold, while on the anticline the compression is not so severe. This is doubtless due to the partial escape from pressure of the material which rises into an arch, as compared with the deeper-seated material in the limbs of the folds, which constitutes a part of the continuous crust of the earth in which the major thrust must have been transmitted. Another factor is the relative strength of the layers. A strong stratum may deform weaker layers, geologically below, into the fan form by producing

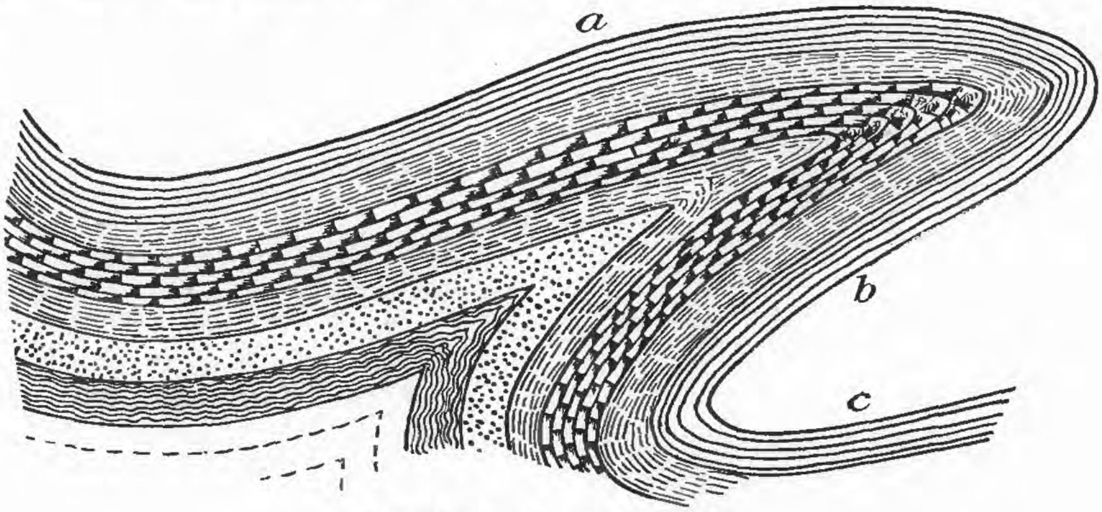

FIG. 107.—Simple recumbent fold.

flowage in them. The formation of the fan fold may be further assisted by the tendency of rocks to bend farther at a place where deformed rather than to bend in a new place. The different phases of the formation of fan folds are illustrated in the Jura. In the folds of certain parts of the Jura one is impressed with the flatness of the anticlinal domes and the synclinal troughs, the steepness of the limbs, and the rapidity of the change from flat dips at the anticlines and synclines to nearly vertical dips on the limbs of the folds (fig. 109*a*). So quick is the change that the folds may be said to have corners, where the beds are bent in a circular fashion almost within their own radius. In the more closely compressed folds the beds constituting opposite limbs of the folds are overturned in opposite directions, thus producing a true fan fold (fig. 109*b*). It is clear that the material of the domes partly escaped the thrusts which were transmitted in the solid rocks below. This thrust from both directions pressed the lower parts of the limbs closer

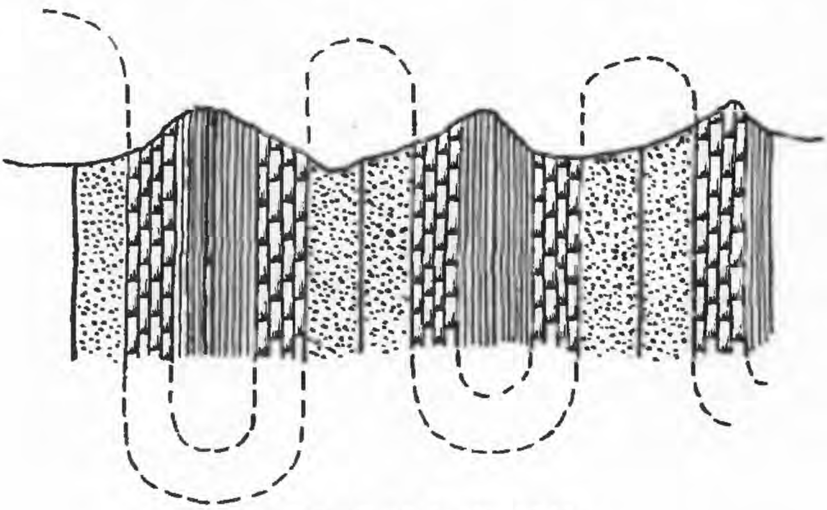

FIG. 108.—Simple isoclinal folds.

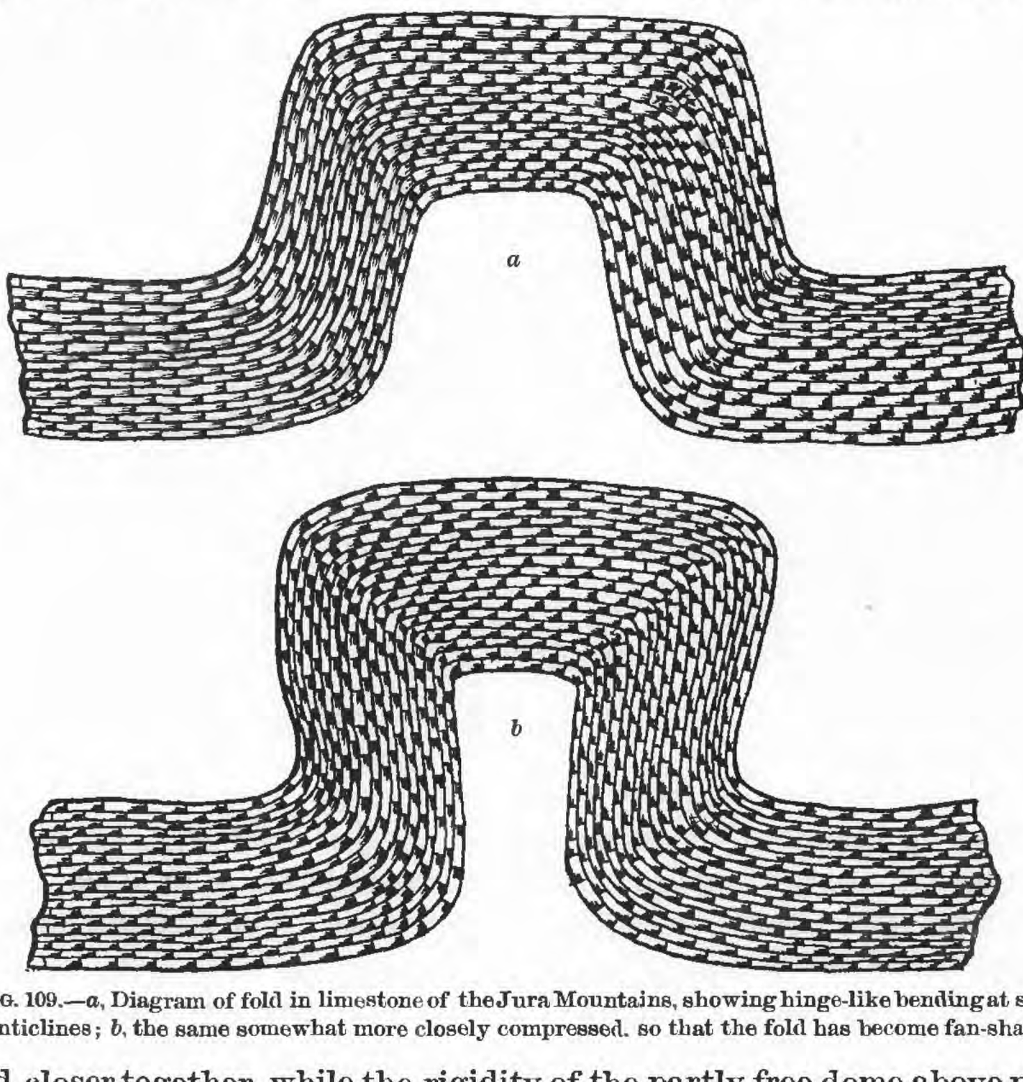

FIG. 109.—*a*, Diagram of fold in limestone of the Jura Mountains, showing hinge-like bending at sides of anticlines; *b*, the same somewhat more closely compressed, so that the fold has become fan-shaped.

and closer together, while the rigidity of the partly free dome above prevented the upper part of the legs from following, and thus the limbs were overturned in opposite directions. It is probable that the folds in the Jura represented by fig. 109 were not very deeply buried, and that had the material been much deeper the more regular form of fan fold shown by fig. 112, and characteristic of the Alps, would have been produced. It may be suggested that the Jura and the Alps belong to the same great geological province, and since the types of folding are the same in both mountain ranges it is not improbable that if the Jura were uplifted sufficiently and more deeply denuded the ordinary fan-shaped fold of the Alps would be revealed.

It follows from the above that the mechanics of the formation of fan-shaped synclines are not the same in all respects as those of anticlines. It can hardly be assumed that synclines are of such magnitude that the lower parts reach a level in which the thrusts are less than at a higher level. In other words, it can not be assumed that the lower part of the trough of a syncline is under less lateral compression than the center of the fold. This may, however, be the case if a "level of no strain" is so near the surface as 2 miles. Even if this supposed level is not at a greater depth than 7 or 8 miles, Davison's later estimate, the thrust may be considerably less at the deeper parts of the fold than at the places of greatest lateral force. We therefore do not know whether the first and probably the most important cause of the production of fan-shaped anticlines—difference in amount of thrust—may also apply to the production of fan-shaped synclines. A difference in the strength of layers and a tendency for layers to continue to bend at certain places when bending has begun, rather than at other places, may tend to produce fan-shaped synclines. For instance, if a very strong layer is between two weaker layers, and this stronger layer becomes bent more decidedly at the outer, upper parts of the syncline, it may continue to bend at these places, and by its strength deform the softer material above and below it, so as to force the whole into a fan form. That minor fan-shaped synclines are thus produced is highly probable, but it may be doubted whether fan shaped synclines of the first order would be thus formed, although they may be produced by differential thrust if the theory of a "level of no strain" be true.

COMPOSITE FOLDS.

The greatest flexures of the earth's crust are termed by Dana *geanticlines* and *geosynclines*. Generalizing from his illustrations, it appears that these may be defined as flexures which are predominantly due to the force of gravity in its tendency to produce isostatic adjustment. The deforming force is therefore mainly vertical. When rocks are subjected to strong lateral forces they are also deformed, and mountain ranges are produced. All folds, of whatever magnitude, thus made by the work of great lateral thrust and gravity combined, when not simple, are called, following Dana, *anticlinoria* and *synclinoria*. An anticlinorium or synclinorium of the first order of magnitude is one which comprises an entire mountain range. Illustrating this usage of the terms, the great geological province or basin of deposition of which the Jura, the great valley of Switzerland, and the Alps occupy a part, was a geosyncline. When subjected to orogenic forces the mountain ranges now seen were produced. The Alps and Jura taken as wholes are anticlinoria of the first order, and the great valley between is a synclinorium of the first order.

The various kinds of simple folds may be united to produce a great variety of composite structures. A composite fold may be an anticlinorium or a synclinorium. An anticlinorium or synclinorium, like a simple fold, may be upright, inclined, or overturned, but it is probable that in composite folds of the first order of magnitude the last rarely if ever occurs.

Taking as axial planes the radial planes of the primary fold, the secondary folds may be upright, inclined, or overturned, or on different parts of the same primary fold each form may occur. The radial positions of the axial plane give the proper basis in comparing the dynamic processes and effects of folding, but because we rarely see the whole

FIG. 110.—Ideal section of an upright normal anticlinorium.

of a great anticlinorium or synclinorium at a single view, it is perhaps best to treat both the primary and secondary folds in reference to the plane of the horizon.

Some of the special cases of composite folds are as follows:

NORMAL COMPOSITE FOLDS.

The upright normal anticlinorium.—The primary fold of the upright normal anticlinorium has a vertical or nearly vertical axial plane, and the limbs at corresponding points have nearly equal average dips in opposite directions.

(*a*) The primary fold is composed of a set of secondary folds, each of which is upright or nearly so, taking the radial planes of the primary fold as axial planes of the secondary folds. Referring the axial planes to the horizon, at the crest of the anticline the secondary folds are upright, and in passing in either direction transverse to the primary axial plane the secondary folds are inclined, but not overturned. The two sets of secondary axial planes on opposite sides of the crest of the primary fold diverge upward and converge downward (fig. 110).

(*b*) Composed fan fold. The primary fold is composed of a set of secondary folds which at the crown are upright, and in passing in either direction transverse to the primary axial plane the secondary folds are first inclined and then overturned. The secondary folds may be ordinary, isoclinal, or fan-shaped. The two sets of secondary axial planes on opposite sides of the crest of the primary fold diverge upward and

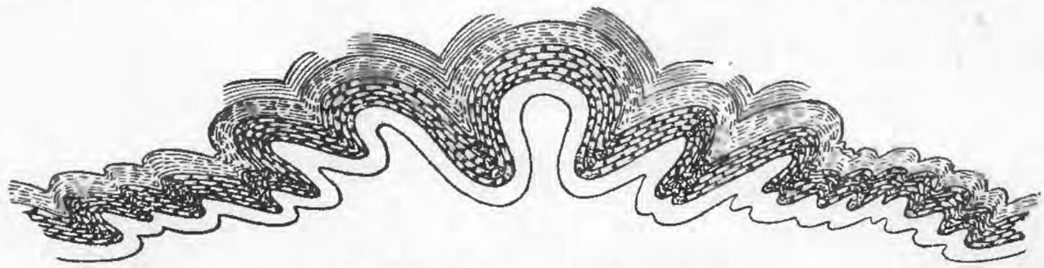

FIG. 111.—Ideal composed fan fold.

converge downward (figs. 111 and 112). Often in extreme cases of compression at the crest of the primary anticline the secondary folds are fan-shaped, and passing in either direction these grade into isoclinal and then into ordinary folds. Such are many of the composite folds of the Alps.

The inclined normal anticlinorium.—The primary fold of the inclined normal anticlinorium has an inclined axial plane and the limbs at corresponding points have unequal average dips in opposite directions. The primary fold is composed of a set of secondary folds which are inclined or overturned. The two sets of secondary axial planes on opposite sides of the crest of the primary fold diverge upward and converge downward. The secondary folds may be ordinary, isoclinal, or fan-shaped.

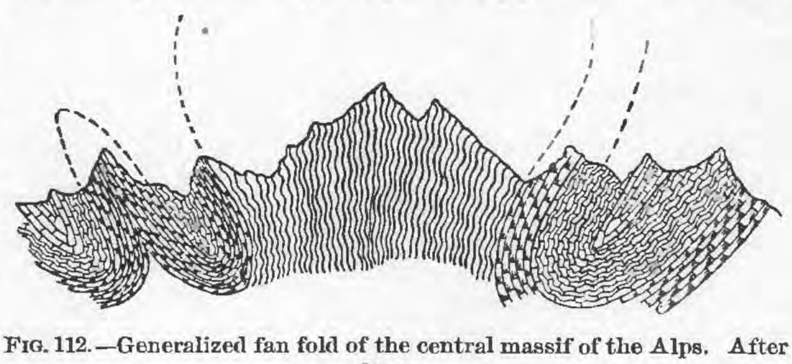

FIG. 112.—Generalized fan fold of the central massif of the Alps. After Heim.

The overturned normal anticlinorium.—The primary fold of the overturned normal anticlinorium has an inclined axial plane, and the limbs at corresponding points have equal or unequal average dips in the same direction. The primary fold is composed of a set of secondary folds, which are overturned in the same direction as the primary fold. The two sets of secondary axial planes on the opposite sides of the crest of the major fold diverge upward and converge downward. The secondary folds may be ordinary, isoclinal, or fan-shaped.

The upright normal synclinorium.—The primary fold of the upright normal synclinorium has a vertical or nearly vertical axial plane, and the limbs at corresponding points have nearly equal average dips in opposite directions.

(*a*) The primary fold is composed of a set of secondary folds, each of which is upright, or nearly so, taking the radial planes of the primary fold as axial planes of the secondary folds. Referring the axial planes to the horizon at the trough of the synclinorium, the secondary folds are upright, and in passing in either direction transverse to the primary axial planes the folds are inclined, but not overturned. The two sets of axial planes on opposite sides of the trough of the major fold converge upward and diverge downward (fig. 113).

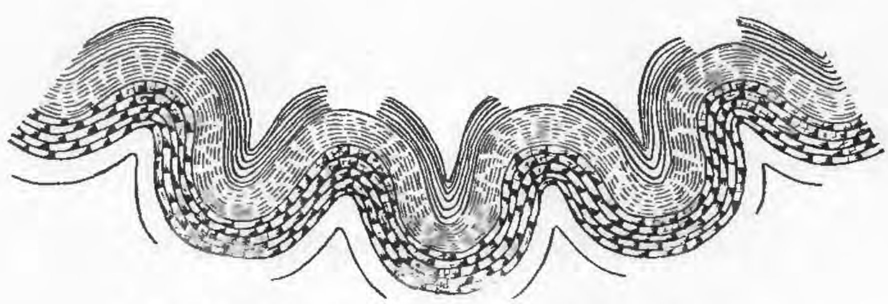

FIG. 113.—Ideal section of an upright normal synclinorium.

(*b*) Inverted intermont trough.[1] The primary fold is composed of a set of secondary folds, which at the center of the trough are upright, and in passing in either direction transverse to the primary axial plane the secondary folds are first inclined and then overturned. The two sets of secondary axial planes on opposite sides of the trough of the major fold converge upward and diverge downward. The secondary folds may be ordinary, isoclinal, or fan-shaped (fig. 114).

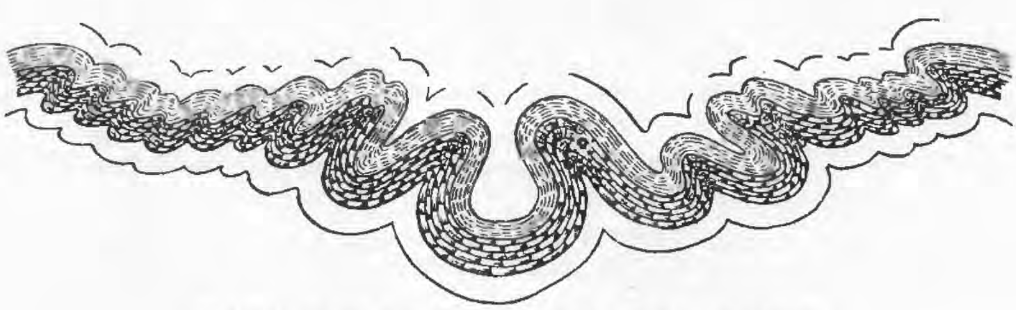

FIG. 114.—Ideal section of an inverted intermont trough.

The inclined normal synclinorium.—The primary fold of the inclined normal synclinorium has an inclined axial plane, and the limbs at corresponding points have unequal average dips in opposite directions. The primary fold is composed of a set of secondary folds, which are inclined or overturned. The two sets of secondary axial planes on opposite sides of the trough of the major fold converge upward and diverge downward. The secondary folds may be ordinary, isoclinal, or fan-shaped.

[1] Les dislocations de l'écorce terrestre, par Emm. de Margerie et Albert Heim, p. 83. Zürich, 1888.

The overturned normal synclinorium.—The primary fold of the overturned normal synclinorium has an inclined axial plane, and the limbs at corresponding points have equal or unequal average dips in the same direction. The primary fold is composed of a set of secondary folds, which are overturned in the same direction as the primary fold. The two sets of axial planes of the secondary folds on the opposite sides of the trough of the major fold converge upward and diverge downward. The secondary folds may be ordinary, isoclinal, or fan-shaped.

ABNORMAL COMPOSITE FOLDS.

The upright abnormal anticlinorium.—The primary fold of the upright abnormal anticlinorium has a vertical, or nearly vertical, axial plane, and the limbs at corresponding points have nearly equal average dips

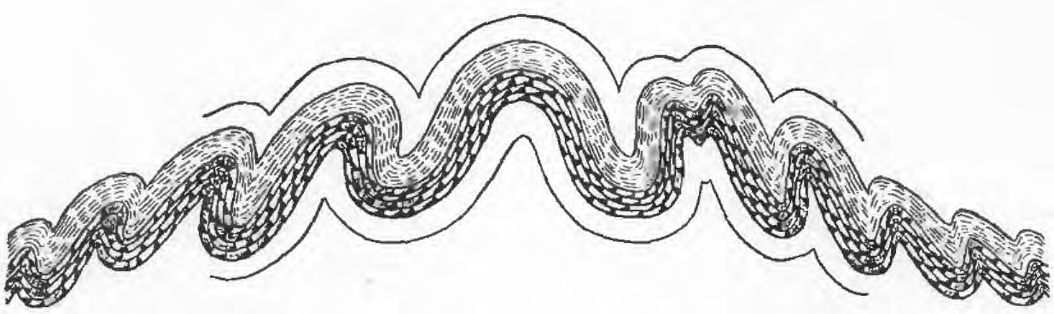

FIG. 115.—Ideal section of an upright abnormal anticlinorium.

in opposite directions. The primary fold is composed of a set of secondary folds, which at the crest are upright, and in passing in either direction transverse to the primary axial plane the secondary folds are first inclined and then overturned. The two sets of secondary axial

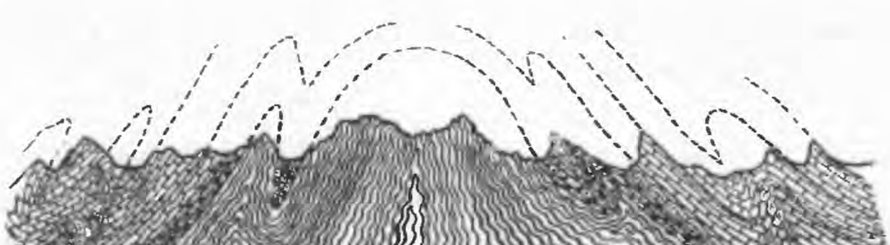

FIG. 116.—General section of roof structure in the central massif of the Alps. After Heim.

planes on opposite sides of the crest converge upward and diverge downward. The secondary folds may be ordinary, isoclinal, or fan-shaped (figs. 115 and 116).

The inclined abnormal anticlinorium.—The primary fold of the inclined abnormal anticlinorium has an inclined axial plane, and the limbs at corresponding points have unequal average dips in opposite directions. The primary fold is composed of a set of secondary folds, all of which are inclined or overturned. The two sets of secondary axial planes on opposite sides of the crest converge upward and diverge downward. The secondary folds may be ordinary, isoclinal, or fan-shaped.

The overturned abnormal anticlinorium.—The primary fold of the overturned abnormal anticlinorium has an inclined axial plane, and the limbs at corresponding points have equal or unequal average dips in the same direction. The primary fold is composed of a set of secondary folds, which are overturned in the same direction as the primary fold. The two sets of secondary axial planes on opposite sides of the crest converge upward and diverge downward. The secondary folds may be ordinary, isoclinal, or fan-shaped.

The upright abnormal synclinorium.—The primary fold of the upright abnormal synclinorium has a vertical, or nearly vertical, axial plane, and the limbs at corresponding points have nearly equal average dips in opposite directions. The primary fold is composed of a set of secondary folds, which at the trough are upright, and in passing in either direction transverse to the primary axial plane the secondary folds are first inclined and then overturned. The two sets of secondary axial

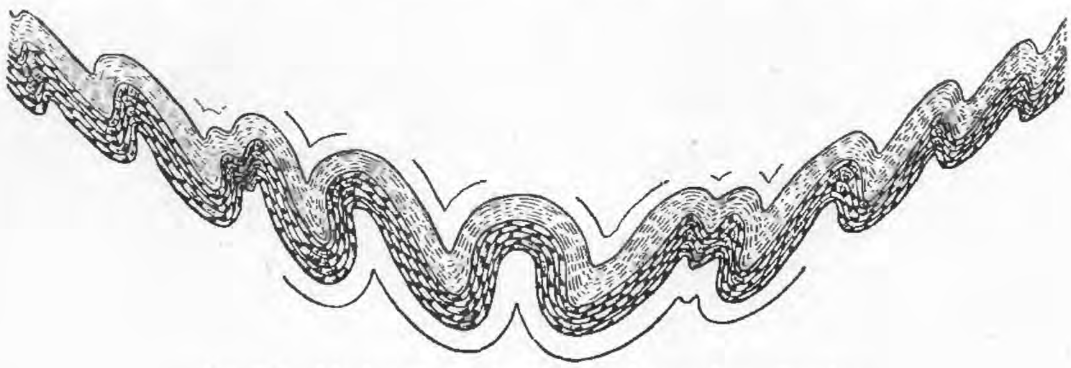

FIG. 117.—Ideal section of an upright abnormal synclinorium.

planes on opposite sides of the trough diverge upward and converge downward. The secondary folds may be ordinary, isoclinal, or fan-shaped (fig. 117).

The inclined abnormal synclinorium.—The primary fold of the inclined abnormal synclinorium has an inclined axial plane, and the limbs at corresponding points have unequal average dips in opposite directions. The primary fold is composed of a set of secondary folds, all of which are inclined or overturned. The two sets of secondary axial planes on opposite sides of the trough diverge upward and converge downward. The secondary folds may be ordinary, isoclinal, or fan-shaped.

The overturned abnormal synclinorium.—The primary fold of the overturned abnormal synclinorium has an inclined axial plane, and the limbs at corresponding points have equal or unequal average dips in the same direction. The primary fold is composed of a set of secondary folds, which are overturned in the same direction as the primary fold. The two sets of secondary axial planes on opposite sides of the trough diverge upward and converge downward.

OCCURRENCE AND ORIGIN OF COMPOSITE FOLDS.

Higher orders of folds.—In all of the above cases the secondary folds of the primary anticlinoria and synclinoria may themselves be anticlinoria and synclinoria. The tertiary folds of the secondary anticlinoria and synclinoria may also be anticlinoria and synclinoria, and so on to the nth order. The higher orders of the anticlinoria and synclinoria are microscopic. Each higher order of anticlinorium and synclinorium may be described with reference to the anticlinorium and synclinorium of the next lower order in a manner similar to the description of the primary anticlinorium and synclinorium with reference to the simple folds of the first order of magnitude.

Even in regions of gentle folding, looked at in a large way, anticlinoria and synclinoria are the rule rather than the exception. In regions of moderately close folding the secondary anticlinoria and synclinoria, as a rule, are themselves anticlinoria and synclinoria. However, it is in such regions as the Alps, Canada, eastern United States, and Lake Superior that occur the complex anticlinoria and synclinoria composed of folds of different orders up to the nth order (Pls. CX, CXI, CXII, CXIV).

The primary anticlinoria and synclinoria are usually upright or slightly inclined. The higher orders of anticlinoria and synclinoria are usually inclined or overturned. The very large synclinoria and anticlinoria on the flanks of the massifs of the Alps, in the Green Mountains of Massachusetts, in the southern Appalachians, and many other mountain ranges, many of them miles in length, are to be considered as secondary folds composing a part of the primary anticlinorium, which includes in each case the central massifs and both its flanks. By an examination of the published transverse sections of the Alps and Green Mountains (Pls. CIX, CXVI, and figs. 157, 158) it will be seen that they are usually complicated fan-shaped anticlinoria, which are composed of complex normal and sometimes abnormal anticlinoria and synclinoria. In each normal anticlinorium, of whatever order, the axial planes of the folds of the next higher order diverge upward and converge downward, while in each normal synclinorium the axial plane of the folds of the next higher order converge upward and diverge downward. In the abnormal anticlinoria and synclinoria the reverse is the case.

Origin of normal folds.—As has been stated, the forces which act upon rocks when being folded are assumed to be tangential thrust and gravity. In the smaller folds, thrust may be thought to be the dominant force, the other being the modifying force of varying strength. In the great folds of the earth, gravity may be thought to be the dominant force, which by differential depression relatively raises a great anticline or depresses a great syncline, while thrust may play a subordinate part, being the dominant force in the production of folds of the second and higher orders. In folds of intermediate size, each of the forces may be about equally important. The relative value does not matter so far as the foregoing analysis is concerned, as in all three cases the resultant forms fall within the classes given. As long as we are so far from agreeing upon the forces which produce mountain ranges, and their manner of work, it seems best to classify the forms of folds as we find them, and to explain their origin so far as we are able. If thrust and gravity be conceived as acting uniformly upon horizontal homogeneous rocks, which are under such conditions as to bend without breaking, normal anticlinoria and synclinoria will be produced. Because of initial dips (as explained by Willis), or unequal superincumbent weight, or other causes, or one or more of these together, rocks when subjected to thrust and gravity rise into an anticline here or fall into a syncline there. But there is unequal weight upon the different parts of each anticline and syncline. The large basins of deposition are not simple, but undulating. These secondary undulations are composed of smaller ones, and so on until ripple-marks are reached, and even these are composite. Each curve is composed of rhythmical curves of a higher order. Hence the arch or trough which forms is not simple, but is composed of a number of minor folds, and these again of those of a higher order.

At first the anticlinorium is upright, or nearly so, as are also the folds of a higher order which compose it, but the secondary folds on the flanks of the primary point slightly outward, although the accommodations between the beds compensate in part for this (figs. 118 and 119. As the limbs of the anticlinorium become steeper the secondary folds on the limbs are thrown farther and farther away from the axis of the primary arch (fig. 110). If unaffected by other forces, when the primary fold becomes steep the secondary folds on the limbs become much inclined or overturned. When the limbs of the primary folds become vertical, the secondary folds on the limbs become lying or recumbent. In all cases, therefore, the axial planes of the secondary folds diverge upward and converge downward. The force of gravity may enter to further modify the forms of the folds. When a fold is inclined, its own weight and that of the superincumbent beds tend to push it over still farther. The effectiveness of gravity in this work is doubtless in part due in many cases to partial escape from thrust because of the relative rise above the deep-seated beds largely transmitting the horizontal force. (See p. 606.) The farther the secondary folds are inclined, either by the increased steepness of the primary fold or by the effects of superincumbent weight, the more effective is gravity in pressing them down still farther (fig. 111). When the weight of the superincumbent material is great, these folds may be pressed into a recumbent position, even where the primary anticlinorium is a gentle fold. Thus are explained the composite normal anticlinoria of the Alps (Pl. CIX).

At first a synclinorium is upright, or nearly so, as are also the folds of the next order which compose it, but the secondary folds on the primary point slightly inward, although the accommodations between the beds compensate in part for this (figs. 118 and 119; see p. 598). As the limbs of the synclinorium become steeper the secondary folds on the limbs are thrown farther and farther toward the axis of the primary trough. If unaffected by other forces, when the primary fold becomes steep the secondary folds on the limbs become much inclined or overturned. When the limbs of the primary fold become vertical, the secondary folds on the limbs become lying or recumbent. In all cases, therefore, the axial planes of the secondary folds converge upward and diverge downward. But the force of gravity enters to further modify the form of the folds. When a fold is inclined, its own weight and that of the superincumbent beds tend to push it over still farther. The effectiveness of gravity in this work is doubtless in part due in many cases to partial escape from thrust because of the relative rise above the deep-seated beds largely transmitting the horizontal force. (See p. 606). The farther the secondary folds are inclined, either by the increased steepness of the primary fold or by the effects of superincumbent weight, the more effective is gravity in pressing them down still farther (fig. 114). When the weight of the superincumbent material is great, these folds may be pressed into a recumbent position, even when the primary synclinorium is a gentle fold. In the synclinoria on the flanks of the Alps, which are secondary to the great primary anticlinorium, the crests of the recumbent secondary folds sometimes nearly meet, thus almost closing the synclinorium (Pl. CIX).

The question may be raised as to the effectiveness of superincumbent weight in pressing down inclined folds. It has been explained that zones of folding of rock masses are necessarily zones of readjustment or of partial rock flowage. The flowage is from the place of great compression to the places of less compression. Where the weight of the superincumbent strata is so great as to equal or surpass the strength of the rocks folded, it appears clear that gravity must be an important force, which may greatly modify the forms of folds. The particular form of fold in a given case is of course the resultant of all the forces which work upon the rock stratum composing it.

So far as I am aware, Dana,[1] in 1847, was the first geologist to call attention to the principle that folds may be modified by the force of gravity. As is well known, this idea has been recently emphasized by Reyer.

Origin of abnormal folds.—In the abnormal anticlinorium and synclinorium new factors enter to modify the result. The first is readjustment between the beds. Fig. 118 represents a drawing of a number of upright folds made upon the ends of a bunch of smooth sheets of paper

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[1] Geological results of the earth's contraction in consequence of cooling, by James D Dana, Am Jour Sci, 2d ser, Vol III, p 185, 1847

three-fourths of an inch thick. The sheets may be taken to represent thin beds in a nearly homogeneous rock. Fig. 119 represents this same drawing as it was distorted when the bunch of papers was folded into anticlines or synclines between blocks of wood. It will be seen that, consequent upon the readjustment of the sheets over one another, rendered necessary by the folding, the secondary folds at the crests and the troughs remain upright, although compressed if a secondary anticline or syncline corresponds with a primary fold of the same kind, and dilated if a secondary anticline or syncline corresponds with a fold of the opposite kind, and vice versa. If the secondary folds were slight, the opening might go so far as to obliterate them and the only

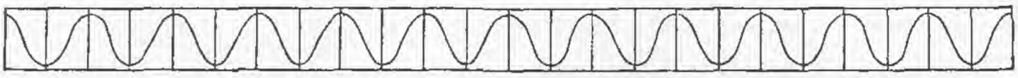


FIG. 118.—Representation of simple symmetrical folds, with their axial planes drawn on the ends of a bunch of smooth paper three-fourths of an inch thick.

remaining effect be to flatten the primary anticlines or synclines. The secondary folds on the limbs of the primary folds are distorted. The readjustment therefore mainly affected the forms of the fold upon the limbs. Taking as their axial planes the radial planes of the primary folds, the secondary folds on the limbs are seen to be inclined. In reference to a primary anticline, the axial planes of opposite folds converge downward; in reference to a primary syncline, the axial planes of opposite folds diverge downward, but both less than they would were it not for readjustment. The above experiment does not exactly represent the conditions in nature, for the accommodations between the beds, instead of occurring parallel to the primary folds, would take place parallel to the secondary folds. However, an examination of the distortion of the axial planes of fig. 118, shown in fig. 119, shows beyond question that when a set of beds are folded which are free to adjust themselves parallel to bedding, the movement of the material in the upper half of the beds is relatively away from a syncline toward an anticline, and the movement of the lower half is away from an anticline toward a syncline; or, stated more generally, the differential movements between the beds on the legs of folds are relatively up in a higher bed or relatively down in a lower bed. It can not be doubted that the sum total of the readjustments between the beds, although they follow the crenulations instead of being exactly parallel to the primary fold, would give the same effect. Therefore there is a tendency in

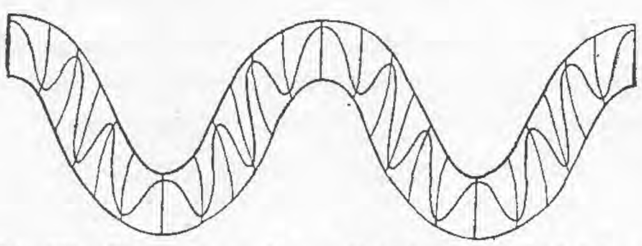


FIG. 119.—The same, as it was distorted when folded into anticlines and synclines.

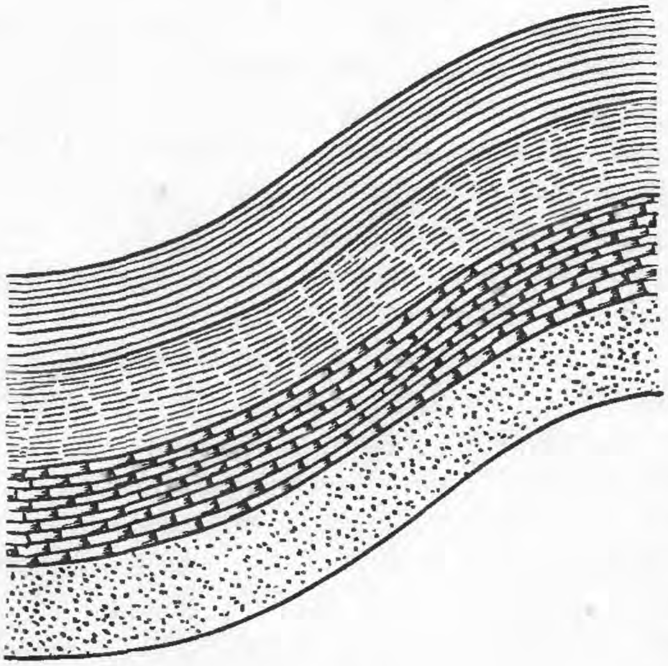
anticlinoria and synclinoria, due to normal differential movement, for secondary folds to become inclined, taking the radial planes of the primary folds as axial planes of the secondary folds. However, when the readjustment is uniformly distributed this tendency does not so far affect the secondary folds but that they fall within the class of normal composite folds. But if the major readjustment of a great set of formations were largely concentrated along a single one in it, anticlinoria might have the axial planes of the secondary folds converge upward and diverge downward, and synclinoria might have the axial planes of the secondary folds diverge upward and converge downward, and thus both become abnormal. This readjustment along the beds, as explained later, may in many cases be considered as movements along shearing planes. (See pp. 656–657.)

The second new factor in the production of abnormal folds is the great strength of the older rocks. For a given region, upon the average, rocks become stronger with increase of age. There are innumerable exceptions to this if too small a portion of geological time be considered, as period by period, but taking era by era such exceptions are rare or altogether absent. The Archean rocks are usually stronger than the Proterozoic, the Proterozoic rocks are stronger than the Paleozoic, the Paleozoic rocks are stronger than the Mesozoic, and the Mesozoic rocks are stronger than the Cenozoic. This in the sedimentary strata is due to the indurating effects of various geological forces. In mountain ranges, where complex anticlinoria and synclinoria mostly occur, a great thickness of strata is concerned in the major folds, usually more than the deposits of an era; so that upon the whole in great mountain masses the lower groups of rocks are stronger.

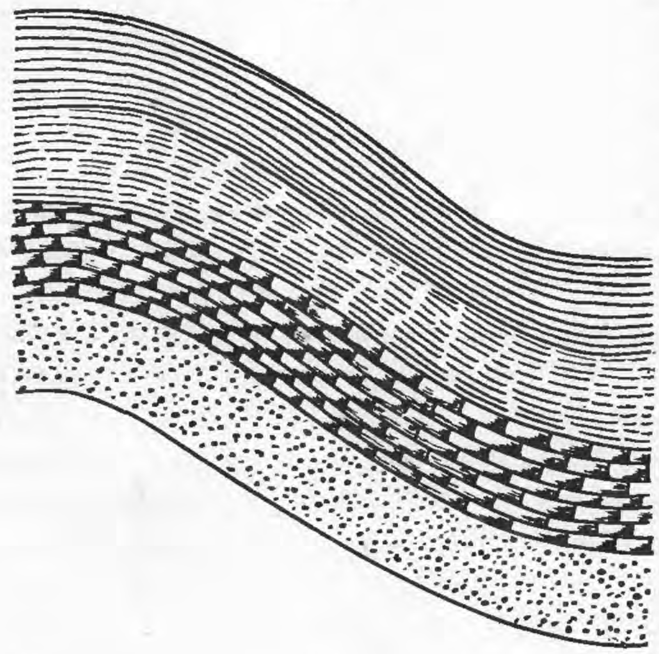
The third cause of the production of abnormal folds may be decreasing lateral stress with increasing depth. That such variation in stress is a general fact must be true if the theory of the level of no lateral stress at a moderate depth be correct. It has been pointed out (pages 600–601) that folds must die out with increasing depth unless there is great rearrangement of material. If it be supposed that the opposing stresses upon opposite sides of an anticline or syncline decrease with depth, there will certainly be more decided folding of the higher strata than of the lower. This implies upward differential movement of a higher stratum as compared with a lower beyond that required for normal readjustment. (See p. 598.) Consequent upon this there will be a tendency for the axial planes of secondary folds on anticlinoria to diverge downward, and for those on synclinoria to converge downward.

Another factor in the production of abnormal composite folds is the position of the fold in the group of rocks folded. The farther the rocks are below the surface the greater is the weight of superincumbent strata and the more forceful is gravity in pressing to a recumbent position the inclined secondary and tertiary folds of great anticlinoria or synclinoria. As has been seen, the inferior strength in the upper strata and the lessened weight to which the upper strata are subjected are not usually sufficient to prevent thrust and gravity from acting in the ordinary way and producing normal anticlinoria and synclinoria.

In both the abnormal anticlinorium and synclinorium the application of the above causes to their formation are identical. To make this clear the following figures are drawn: Figs. 120 and 121 each represent four strata, the lower two of which are strong and the upper two of which are weak, each figure comprising one-fourth of a wave and the other being its complement. In each case the figure ends on one side at the crest and on the other at the trough of the flexure. There is nothing to indicate whether either is a part of an anticline or a syncline. Each, in fact, may be half of either, for, put end to end in one way, they form an anticline; in the other, a syncline. In both cases the lower rocks constitute a relatively rigid inclined plane. If the superincumbent weight is not too great when thrust occurs, in certain cases the softer rocks above may yield to the forces to a greater degree than do the rigid rocks below, and thus tend to flow over them, and in case the upper strata be much weaker than the lower, or there be a plane of weakness, the differential flow will be largely concentrated along the contact or weak zone, and normal secondary folds which have before developed may be inclined in an opposite direction from their first position, so as to become abnormal. In this case the parts of the composite folds may be represented by figs. 122 and 123.



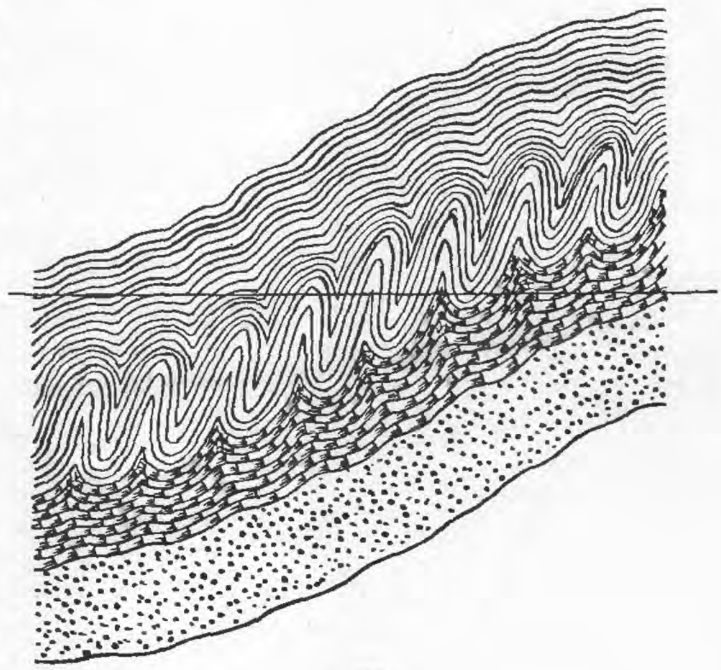
120.



121.

FIGS. 120 and 121.—Obverse halves of an anticline or syncline.

Put together end to end in one way the prominent secondary folds form an abnormal anticlinorium; in the other, an abnormal synclinorium. It will be noted that in passing away from the central zone of plications either into the more rigid rocks below or into the softer rocks above the secondary folds become normal. Considering the two figures put together to represent a great flexed mountain mass, and supposing erosion to truncate the layers to the horizontal line drawn, there would be exposed normal folds at the center of the anticline, abnormal ones upon the flanks, and normal ones at the outer parts of the mountain mass. In nature we can never hope to see such a great composite fold in all its parts. It is only in the great mountain masses where such folds have been dissected that we can get at their character. In such cases the older strata would be expected to show the normal forms, the newer strata the abnormal forms, and the intermediate strata alternations of the two. The change from normal to abnormal and to normal again is apparently that which actually occurs in the Alps from the St. Gothard massif south to the great valley of Switzerland. (See pp. 624–625, and Pl. CIX.)



122.

123.

FIGS. 122 and 123.—Obverse halves of composite folds, showing development of abnormal folds and their relations to normal folds.

The manner in which the more rigid rocks escape large plications while the weaker beds are strongly plicated, producing abnormal folds, is well shown by fig. 116, given by Heim as a general section showing roof structure in folded sediments and a central massif. In the production of actual abnormal anticlinoria and synclinoria it is probable that accommodations as illustrated by figs. 118 and 119 are largely concentrated as illustrated by figs 120–123. Therefore the production of abnormal anticlinoria and synclinoria may be summarized as follows:

When two groups of rocks of unequal strength, not deeply buried, are folded into an anticline, on account of the natural readjustment of strata, of the relative weakness of the upper, newer group of rocks, and probably of decreasing differential stress with increasing depth, there may be differential flow on either side toward the axis of the anticlinorium over the lower, older rocks, thus producing secondary folds, the axial planes of which converge upward and diverge downward. Had the rocks been of equal strength, or had the weight of the superincumbent strata been sufficient to more than overbalance the difference in strength and difference in stress tending to produce folds pointing crestward, normal secondary folds pointing outward would have developed.

When two groups of rocks of unequal strength, not deeply buried, are folded into a syncline, on account of the natural readjustment of the strata, of the relative weakness of the upper, newer group of rocks, and probably of decreasing differential stress with increasing depth, there may be differential flow of the rock material on either side away from the axis of the synclinorium over the lower, older rocks, thus producing secondary folds, the axial planes of which diverge upward and converge downward. Had the rocks been of equal strength, or had the weight of the superincumbent strata been sufficient to more than overbalance the difference in strength and difference in stress tending to produce folds pointing troughward, normal secondary folds pointing inward would have been developed.

Crystalline or core rocks are apt to be more massive and stronger than the little-altered sedimentary beds, and therefore the core rocks usually act to a certain degree as a unit when subjected to thrust. Secondary abnormal folds are frequently found at the contact of massifs and the overlying rocks. However, even in these cases the folds will be normal if only the thickness of the superincumbent beds be sufficient. At a considerable depth the different strength of rocks is not so potent as gravity in giving form to folds. From the above it does not follow that the massifs or portions of them do not take part in the folding. That they do in many regions is certain, as is shown by infolding of core rocks with sedimentary beds, even when the massifs were originally granite. Also that massifs may take part in the folding is shown by the minor and major folds of their parts, which in form are like those of the associated sedimentary rocks.

It is recognized, however, as explained upon a subsequent page, that massifs, because of their homogeneous character, because they are underlain by no definite stratum of rock of a different character, and because they are often so deeply buried, may act in quite a different fashion, under the forces of folding, from ordinary sedimentary layers.

Causes modifying the forms of folds.—The foregoing discussion has been carried on as though the active forces of deformation are equal in opposite directions, and are acting in the same zone from opposite sides of the deformed area. If this were the case, if the strata affected were of the same thickness and strength, if the initial dips were equal in opposite directions, and if the other conditions were the same, a strictly symmetrical arrangement of folds might be expected. But these conditions are never true. In the great majority of cases the facts do not depart so far from them but that the folds which form fall within some of the classes given. However, there are a number of ways in which the forms of folds may be modified.

Major faulting may interfere with their forms. Minor slip-faulting, as explained upon a subsequent page, may dominate an entire area. Igneous intrusions may disturb beds in many ways. Where these modifying effects are found the structure is the resultant of all the movements. One of these cases, that of the fold fault, is considered under Section V, Faults, p. 672.

Finally, it often happens that there is a tendency for the axial planes upon one side of an anticlinorium or synclinorium to be steeper than those upon the other. In some cases the axial planes of all the folds throughout a mountain mass may be inclined in the same direction. Such folds may be called *monoclinal.* (Fig. 148.) In such cases the force, and consequently the movement of the strata, have usually been supposed to be more largely from one direction than from the other, and the axial planes of the folds have usually been regarded as dipping toward the force.

Various explanations have been offered as to how the forces act upon the strata in the actual production of monoclinal folds. Of these explanations, that offered by Rogers appears most probable for piles of strata of like rigidity. Believing as he did that the folds of the Appalachians were analogous to the waves of the sea, he naturally concluded that the tendency to a southeastward inclination of the folds of the Appalachians was due to the fact that the center of disturbance and resultant waves came from the southeast. While not following him in his explanation of folds as great waves suddenly formed, the idea seems reasonable that the "forward thrust operating upon the flexures * * * would steepen the advanced side * * * precisely as the wind acting upon the billows of the ocean forces forward their crests and imparts a steeper slope to their leeward sides."[1] For we now regard folded rocks as plastic when bent. The compressive stresses do not

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[1] On the Physical Structure of the Appalachian Chain as exemplifying the Laws which have regulated the elevation of great mountain chains generally, by W. B. Rogers, Proc. Assn. Am. Geol. and Nat. for 1840–1842, p. 512, Boston, 1843.

extend to an indefinite depth, but are limited by the level of no lateral stress. They therefore affect the outer skin of the earth, just as does the wind the superficial water of the ocean. As a result there is a differential movement due to friction, the amount of movement upon the average gradually decreasing below the zone of maximum movement. Of course the sums of the forces, including friction, are always equal in opposite directions, but they constitute a vertical couple, i. e., "Two equal and parallel forces opposed in direction, but not in the same straight line." As a result there is differential movement of the material of the upper zone as compared with the lower, the former being thrust over the latter.

Other things being equal, where the differential thrust is greatest the first inclined fold is formed. The folding piles up the strata. After a time the increased thickness of material is sufficient to present a larger total resistance to deformation than the thinner strata in advance. The stress will then be transmitted forward. On account of the greater stress per unit of area, a second fold, similar to the first, will then be formed, but this results in again thickening the mass subject to the force couple, and again the stress is transmitted forward. A new inclined fold is then produced, and so on.

It is not necessary that one inclined fold shall be completely formed before others begin to develop. Indeed, this is not to be expected, for as soon as any thickening of the deformed mass occurs the conditions are favorable for the forward transmission of the effective stress. Thus many folds may be in process of formation at the same time. Indeed, so far as I can understand, there is no reason why differential movement should not be initiated at the same time wherever the conditions are favorable throughout the area in which monoclinal folds are observed.

It is to be noted that, under the assumption that the effective stress moves the upper strata over the lower, the vertical component of deformation is upward rather than downward. In other words, it is in the direction of easiest relief, and this is the kind of deformation one would expect, and which doubtless prevails in the majority of movements of the first order, in which thrust is the dominant force, for it has been seen (p. 617) that, upon the average, rocks are stronger with increasing age, and hence there is greater resistance centerward than surfaceward. Folds thus produced by upward differential movement may be called "overthrust folds." The axial planes dip toward the effective stress, hence *overthrust folds are those in which the axial planes dip toward the force producing them.*

While the development of overthrust folds is the general law, it may not infrequently happen that under favorable conditions beds or formations may be thrust forward and downward. Folds thus produced by downward differential movement may be called "underthrust folds." The axial planes dip away from the effective stress, hence *underthrust* *folds are those in which the axial planes dip away from the force producing them.*

In the rocks of a system or group strong formations may be above weak formations. In this case the strong formations are able to transmit the forces to a greater degree than the beds above or below. As pointed out by Willis, a forward downward movement may be directed by initial dip, and thus underthrust folds be produced. In a second case the strata pile up as a result of the folding. The relatively raised masses may then to a certain extent escape active thrust. (See fig. 109 and pp. 606–607.) The strata largely transmitting the thrust in front of the folded material may under these conditions be pushed under the higher mass. Underthrust folds are most likely to occur if the two conditions above given favorable to their formation are combined, i. e., weak formations below and piling up of strata.

In considering the force couples in normal and abnormal composite folds, each composite limb between trough and crest must be separately analyzed. (See figs. 120–123.) In normal anticlinoria and synclinoria gravity has been seen to be the efficient force which causes differential movement (pp. 614–616). Gravity works down the slope. The axial planes of the secondary folds dip toward the force (see figs. 111 and 114), and the secondary crenulations are therefore overthrust folds. In abnormal composite folds it has been explained (pp. 616–620) that the differential movement may be caused by (1) normal readjustment, (2) increased strength of the rocks with increasing depth, and (3) the possible decreasing lateral stress with increasing depth. The first of these is eliminated for the present purpose. The second and third, either singly or together, must be sufficient to overcome gravity and to give a resultant force directed up the slope, in order that abnormal folds may be formed. (See figs. 115 and 117.) The axial planes therefore dip toward the force, just as in normal composite folds, and the secondary crenulations are therefore overthrust folds.

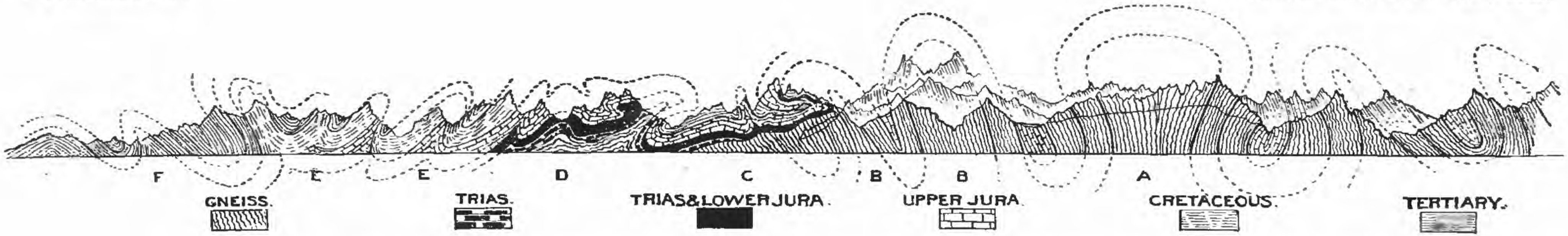
By the above it is not meant to imply that underthrust folds may not be produced in either normal or abnormal composite folds, for if the conditions given on previous pages favorable for underthrust folds locally occur, crenulations of this type may be formed.

The formation of monoclinal folds is sometimes well illustrated by the crenulations of a lava bed in which there was differential flow down a slope, the upper layers moving faster than the lower. Monoclinal folds thus formed are usually not large. The directing force was gravity, and the axial planes dip toward the force. The crenulations are therefore overthrust folds. Since ordinary folds, which form without fracture, develop in the deep-seated zone of flowage, the analogy with contorted lava currents is believed to be closer than might be at first thought, although it is not meant to imply by this that the folded rocks are really fluid, but merely that a plastic solid under sufficient differential stress is deformed in the same fashion as is a viscous liquid.

It has been pointed out (p. 598) that in ordinary folds the movement is relatively up for a higher stratum as compared with the one next below it. In the case of overturned monoclinal folds (figs. 106, 107, and 148) the later differential movements of the strata on the longer limbs of the folds may continue quite to and past the crests of the anticline, so that the differential movement on the shorter limbs of the folds is relatively down for the superior stratum geologically as compared with the inferior. However, in this case, when the folds are overturned, with reference to the horizon on the inverted limb, the movement of the higher stratum would still be upward, as compared with the one below it. This may be called *reverse differential movement*, and it may continue so as to more than compensate for the normal differential movement, but the resultant differential movement would be less on the steeply inclined or overturned limbs of the folds than on the longer, flatter limbs, since on the latter the motion is continuously in the same direction.

In the case of monoclinal folds it will be later shown (see p. 658) that the shearing is greater on the longer, more gently inclined limbs than on the shorter, more steeply inclined limbs. As a result of this the former are not so thick as the latter and are usually more metamorphosed.

Examples of composite folds.—As a first instance a cross-section of the Alps through the St. Gothard massif may be taken (Pl. CIX). This is a great anticlinorium. No complete section of the south limb has been published, so we can consider only the northern limb. The St. Gothard massif (A) is an upright secondary fan fold. To the south follows a set of normal, outward-pointing, isoclinal, secondary folds (BB). Then comes a great normal secondary synclinorium, containing Triassic, Jurassic, and Cretaceous rocks (C). Then follows a composite anticlinorium which is near the border line between a normal and abnormal composite fold, but upon the whole belongs with the former (D). This character is explained by the fact that the anticlinorium stands between normal and abnormal folds. Still farther south is a nearly upright abnormal synclinorium, composed of Jurassic, Cretaceous, and Tertiary rocks (EE). The last two are very weak as compared with the strong Jurassic limestone; hence differential flow and major readjustment have occurred between them, thus producing an abnormal composite fold. To the southward there follows a normal outward-pointing fold composed of Tertiary rocks (F). The difference in strength of the beds is not great, and hence their normal character. Beyond these are very gentle upright folds. If these great secondary folds be analyzed into lesser elements, it will be found that these also accord with the principle given as to the production of normal and abnormal folds. Also, if the same great set of folds be considered as a part of a great synclinorium, the trough of which is the valley of Switzerland and one flank of which is the Jura and the other the Alps, an analogous



SECTION OF THE ALPS FROM THE SAINT GOTHARD MASSIF, SOUTH: SHOWING RELATIONS OF ABNORMAL AND NORMAL COMPOSITE FOLDS.

After Heim.

explanation will be found to apply, and the conclusions as to the character of the folds will be the same.

In the United States, Mount Greylock, the Taconic range, and the valley between constitute a great normal anticlinorium (Pl. CXVI). The same is true of Mount Washington, in Massachusetts (fig. 158). A cross-section of the central part of the Marquette district furnishes an example of a great abnormal synclinorium (fig. 146). The abnormal character is due to the very great difference in strength between the Archean granite and the Algonkian Lower Marquette formations. At the east end of the Marquette district, where the Archean rocks are relatively weak schists, the synclinorium is normal. The detailed discussion of the above normal and abnormal folds in America is given on subsequent pages at the places where the respective districts are described.

Limit of term fold.—By the above analysis and examples it is not meant to imply that, where sediments were deposited off a land area and the land and sea areas were afterwards compressed, producing undulations in the sedimentary rocks, and often in those also of the original land areas, the terms anticlinorium and synclinorium are properly applicable to the primary flexures. Following Dana, as indicated on a previous page, such flexures are more properly described as geoanticlines and geosynclines. In such cases, however, there is a differential uprising or subsidence, in many cases producing a composite flexure. It is believed that the principles applied to primary folds of true anticlinoria and synclinoria apply to the secondary folds in question, just as though they together constituted a part of an ordinary fold. When gravity controls their form they are normal. When the difference of strength of the rocks controls their form they are abnormal.

As a matter of fact, it is often difficult to determine in a given mountain range whether the so-called core rocks were deeply buried under a great thickness of sediments, being, perhaps, in or near the center of the trough of deposition, or whether they were, and continued to be, land areas. It is thought that it is one of the advantages of the treatment given that it is not necessary to decide this question before working out the structure of the district. In either case the types of folds formed on the great flexures and the laws controlling them are the same.

Movements continuous or discontinuous.—Composite folds may be the result of forces acting continuously or discontinuously. The different secondary folds may develop at different times. The higher orders of folds may begin to form only at a late stage of development. Usually it is impossible to determine whether thrust was continuous or discontinuous. However, as will be explained later, if the intervals between the successive movements were sufficiently long and the conditions were such that crevices could be formed and these were filled with secondary minerals, or if cementation or metasomatic changes produced new minerals, or if within the strata igneous rocks were intruded, the later dynamic effects upon such new material may enable us to determine the fact of different movements.

In the Hiwassee section of the Ocoee series, in the southern Appalachians, in the more closely folded part of the section quartz veins have formed in a first set of crevices. The rocks have been subsequently folded so as to closely plicate these veins, and after this folding a second set of unfolded quartz veins has formed. In other parts of the section only unfolded quartz veins are seen. This shows that certain parts of the area were affected by two periods of folding separated by a long interval.

COMPLEX FOLDS.

ORIGIN OF COMPLEX FOLDS.

Thus far folds have been considered in two dimensions only and have been treated as though they were continuous and had continuous axial lines, each one being a great circle of the earth. Such is not the case in nature. In a given fold, in passing from place to place the direction and inclination of the crest-line are different, and it is rarely, if ever, a part of a great circle. Its deviation from the horizontal at any point gives the inclination of the fold at that point. This inclination, measured in degrees, is known as the pitch. Also when a fold is followed longitudinally, or in the third dimension, it changes continuously in size and character. A fold of the greatest magnitude may be followed along the third dimension until it dies out. The most closely compressed and intricately composite fold may be followed in the third dimension until it becomes a gentle composite fold, or even disappears. When a primary fold is traced in the third dimension it may be found to grade into a secondary fold. At the same time a secondary fold on the flank of a primary fold may itself become the primary fold. On any fold a new secondary fold may appear, and when followed longitudinally may become more and more important until it is the dominant fold. In short, in a composite set of folds each fold of any order is constantly changing in character and importance.

In a given fold all of the changes may occur, and thrust may have acted only in a single direction. The initial dip of the beds may have been different. The thickness and strength of the beds may have varied from place to place. Thrust may not have been equal along the border of the entire area affected. It may not have continued to act as long in one place as in another. Therefore there is great variation in the character and size of folds at their different cross-sections. Gravity is always toward the center of the earth; therefore variation in its direction does not enter as a modifying force.

Further, in the folding of rocks thrust is rarely, if ever, in a single direction. Usually, when complex thrusts are decomposed into two directions at right angles to each other, one is more powerful than the other.

The greater force may be called the major thrust, and the lesser force may be called the minor thrust.

Major and minor thrusts may unite in a resultant effect and produce a set of folds in a position intermediate between those that the two sets would have if each thrust had been alone. It is possible, and even probable in many cases, that after a thrust in one direction has produced a set of folds, a new thrust at an angle less than a right angle to the first may be decomposed into two forces and result in further folding the first set of folds, and perhaps in the production of transverse folds, rather than in producing a new diagonal set, for when rocks are once bent in a given place they bend farther much easier at this place in the same direction than at a new place in a new direction. This principle is well illustrated by the folds of the Jurassic limestone of the Jura Mountains (fig. 109). The transverse component of the lateral thrust may be too weak to produce any considerable effect. In such cases it would be difficult or impossible to discriminate a set of folds thus formed by two diverse thrusts from a set formed by simultaneous or successive thrusts in a uniform direction. However, if there be sufficiently strong thrusts in two or more diagonal directions, or two thrusts at right angles, two sets of folds are produced which intersect each other. Such a district may be described as one of complex folding. The more important set of folds, corresponding to the major thrust, may be called the major or longitudinal folds, and the cross folds, corresponding to the minor thrust, may be called the minor or transverse folds.

CHARACTER OF COMPLEX FOLDS.

From analysis, as well as from observation, it is found that cross folds are usually nearly at right angles to each other; for, as already explained, if the diverse thrusts be inclined to one another, they will be resolved into two forces, one of which forms the major folds, and the other of which produces cross folds in a direction at right angles, or nearly so, to the first set of folds.

Major and minor cross folds may each be produced by continuous forces in both directions, or in each direction each force may be continuous or discontinuous. To ascertain these points the same criteria are available as in the case of thrust in a single direction (see p. 625–626).

Longitudinal and transverse folds may be classified into upright, inclined, or overturned. Each of these may be ordinary, isoclinal, or fan-shaped. Simple folds may unite to form composite folds. The composite folds may be normal or abnormal, and each synclinorium or anticlinorium under each class may be upright, inclined, or overturned.

As complex folds actually occur in the field, usually the compression is not close in both directions. Cases are known, however, in which a set of longitudinal overturned folds have transverse folds with vertical dips, and the dips of the transverse folds in intricately folded districts are in many cases as steep as 45° or 60°.

When the major folds are close, as compared with the minor folds, the complex folds have great length as compared with the breadth, and are canoe-shaped. The Appalachians in the closely folded districts may be taken as a type of such complex folding. That initial dip is not sufficient to explain the pitch of the folds in this region is shown by the following facts: A stratum or set of strata may rise at one end of a synclinal canoe. Beyond this for a distance the strata are removed by erosion, but farther on appear again plunging downward at the end of another canoe. Corresponding phenomena are observed in reference to anticlines.

In proportion as the major and minor thrusts approach each other in power, the canoes become shorter and broader. Where they are nearly equal the folds are domes or basins. Usually these domes and basins are associated with canoes, which may be in one or both directions in the same region. Where the two sets of cross folds are about equally conspicuous the strikes and dips of the rocks vary constantly, their directions depending upon what part of the complex folds is under observation.

Where the complex folds are also composite the canoes, domes, and basins are fluted or crenulated, being composed of secondary canoes, domes, and basins. Similarly, these may be composed of canoes, domes, and basins of the third order, and so on.

OBSERVATIONS IN COMPLEXLY FOLDED DISTRICTS.

From the relations of cross folds, as above explained, it is clear that where there are complex folds the axes of one set of folds and their pitch give the direction and dip of the cross fold at that point. Therefore, to fully understand a district complexly folded it is necessary to make the following observations:

(1) Determine the strike and dip of the strata at the given point. These give the resultant position of the strata as tilted by the forces of folding in both directions.

(2) Determine the direction and pitch of the axes of the major folds. The first is the direction of dip and the second is the amount of the dip of the minor or cross folds. The average strike is, therefore, determined.

(3) Determine the direction and pitch of the axes of the minor folds. The first is the direction of dip and the second the amount of the dip of the major folds. The average strike is, therefore, also determined.

Of these three observations, the first is the only one ordinarily taken, and it is the one of the least importance in regions of close, complex folding. It is only by making the second and third observations that an adequate idea of the structure can be obtained. While the first observation may be made at any point, the second and third observations can be made accurately only along the crests of the anticlines or troughs of the synclines of the various orders of folds. Therefore, it may be necessary to work over a considerable area in order to obtain the required data. Some practical suggestions may be offered as to the manner of determining whether the rocks of a district are complexly folded, and the direction and pitch of the axes of each set of folds, and therefore the strikes and dips of the two sets of cross folds.

(1) It is advisable to look for the ends of canoes. These may be frequently found at the ends of ridges; hence especial study should be made of the folds where a topographic breaks appear across the ordinary ridges, either at a right or an acute angle (fig. 160). When once the end of a canoe is found, an observation can be made as to the direction and pitch of the axes of the fold, and thus the strike and dip of the cross fold be determined.

(2) The tops of ridges should be examined. These may be the crests of anticlines or the troughs of synclines, depending upon the topographic development of the region. Along the little cross breaks which are sure to occur the direction and pitch of the axes of the folds may be determined. In some instances ridges are longitudinally inclined, following hard layers, and in this case there is an exceptionally fine opportunity to determine the direction and pitch of the folds.

(3) In case the two sets of cross folds are about equally conspicuous, there may be a double set of ridges and valleys cutting each other at right angles, or nearly so, and this may give a clue to the character of the folding of the district.

(4) In some cases the beds are closely plicated in one direction so as to give nearly uniform strikes. Unless closely observed it may not be noted that there are really minor rapid deviations of strike, which indicate a set of pitching folds and a complexly folded district. The major and more important folds may be transverse to the minor plications. From what has gone before, it is plain that in such cases the important observations are not the strikes and dips of the strata of the minor folds, which vary momentarily, but the direction and pitch of the axes of the minor folds, which give the direction and amount of the dip of the major fold, and therefore the average strike (fig. 147).

(5) Pumpelly has called attention to the fact that discordance between strike of bedding and that of secondary structures indicates pitching folds. Where a secondary structure develops at right angles to the greatest normal pressure, or nearly so, it in many instances has a nearly uniform direction for an extensive area. In case the folds are horizontal, or the district is simply folded, this direction is the same as the strike of the rocks or the strike of the axes of the folds. Where the forces producing the folds are in two or more directions, and consequently form complex folds, the minor component, producing pitch, does not develop cleavage at right angles to itself; and the relations between the strike of bedding and that of the secondary structure vary from near parallelism on the limbs of the longitudinal folds to a direction at right angles to each other at the ends of the canoes and on the crests of

the anticlines and in the troughs of the synclines. In passing from one place to the other there are found all relations between parallelism and perpendicularity. Because the area where the two are parallel, or approximately so, is greater than the area where there is an important discordance between the two, it has been customary for text-books to speak of the strike of bedding and the strike of cleavage as usually parallel. This, as has been seen, is wholly true only where the folds are horizontal, and the statement becomes more and more a partial truth as the pitch of the folds increases in amount—that is, as the less conspicuous folds become more important. Hence it is that where a secondary structure exists the relations which obtain between its strike and that of bedding should be ascertained, and if discrepancies are found this indicates a complexly folded district.

(6) Pumpelly also formulated the principle that "The degree and direction of the pitch of a fold are indicated by those of the axes of the minor plications on its sides." This statement must be understood to apply to the direction and pitch of the primary fold at the point where the secondary fold is observed. This principle is a direct corollary from the relations of cross folds as given on a previous page, and it is of the greatest service in determining the structure of very complexly folded districts, because in them minor plications are so numerous. They may be seen in their entirety, and may therefore give the required determination of the character of the cross folds. The principle is, however, only approximately true. It would be wholly true if the secondary folds upon the flanks of the primary fold were exactly of the same character. But since the forces locally vary in direction and amount, and the rocks vary in rigidity, the direction and pitch of a secondary fold may vary somewhat from those of a primary fold. Usually this deviation is so small that the principle is invaluable in field work in regions of complex folding, and gives data of sufficient accuracy for ordinary purposes.

It is evident that in the application of all the above criteria we must consider bedding and not secondary structure. The criteria upon which this discrimination is made will be considered later. (See pp. 716–719.)

Very often in regions of complex folding observers note only the most conspicuous folds in a single direction. The fact that folds are composite may be overlooked, and that they are complex is even less likely to be seen. The difficulty is further increased because of faults and secondary structures, such as slatiness, schistosity, and banding, which may be mistaken for bedding. The development of these structures and their relations to folds and bedding will be considered later. (See pp. 656–659.)

In ordinary districts where there are cross folds the more conspicuous set is generally chosen as giving the direction of folds, while the less conspicuous set in the other direction is considered as giving the pitch of the folds. It does not follow that the folds giving the pitch, in the magnitudes of their vertical components, are less important than the more conspicuous longitudinal folds, for the lowness of the dips of the transverse folds may be more than compensated by their greater lengths, and the cross folds may be of the first order of magnitude in a district. Usually it is possible to work out the structure of such a district without particular attention being directed to transverse folds. They are so gentle that the changes of strike and dip are not rapid, and a satisfactory map may be made without recognition of the existence of cross folds. It is suspected that the largest folds of a district have often escaped the attention of the geologists who did the mapping.

The more complex the folding of a district the more necessary it is in determining its structure to consider the character of both sets of folds, and for very complex districts this is imperative.

By means of maps and sections it is difficult to represent the structure of a very complexly folded district, and even a dissected model does not represent it completely, as it is impossible to show in true proportion the different orders of folds, and especially those of the higher orders. It is plain that cross-sections in a single direction at long intervals fail to give any adequate idea of the structure of such a district, although these combined with geologic and topographic maps may do so. In reports the structure can best be represented by combining the geologic and topographic maps with two sets of cross-sections made at frequent intervals and at right angles to each set of folds.

It will be noted that in the foregoing treatment of folds they are classified as they occur, no ultimate theory of their origin being offered. No conception of the cause of mountain ranges enters into the analysis. It is true that an explanation is attempted of the difference between normal and abnormal composite folds. The fact that this explanation apparently accords with the forms and distribution of folds in all of the many different districts to which it has been applied, and at the same time accords with the principles of mechanics, appears to me to give to it a considerable degree of probability. Even if the explanation be not accepted, the forms of folds and the principles applicable to their study remain the same. Thus we have a classification of folds and an outline of methods for their study which will assist in determining the structure of the complexly folded districts and in preparing areal maps of them.

CHANGES ACCOMPANYING FOLDING.

Contemporaneous with rock folding, and in a large measure dependent upon it, other changes occur in rocks. As has been seen, crevicing and brecciation largely depend upon the same forces as does folding. During the process of folding old minerals are transformed into new ones. New mineral material enters from the outside. The minerals are rearranged and mechanically modified. Secondary structures, such as cleavage, fissility, joints, and faults may develop. In short, during the folding process the rocks are to a greater or less degree metamorphosed. In succeeding pages each of these phenomena will be separately considered.

RELATIONS OF FOLDING TO UNCONFORMITY.

The folding of a set of inferior formations in a more complicated manner than that of another set of superior formations may indicate a structural break between the two, and consequently that the two sets of formations belong to different series. In order that this criterion may be applied, it must be conclusively shown that the supposed upper formations are really above the others. It must not be assumed that a formation at one side of an axis of plication is in a superior position because less folded, for in many regions close folds die out within a comparatively short distance in a direction transverse to them. This is the case along the Green Mountains, where the closely folded Lower Paleozoic rocks pass quickly, to the westward, to unfolded or very gently folded ones. The change here takes place so rapidly that it has been supposed by many geologists that the more closely folded rocks are really the older and belong to a series prior to their unfolded westward continuation. The failure to appreciate the above principle has been to a large degree the cause of the Taconic controversy.

It is believed that the cause of the frequent sudden change from closely folded to very gently folded rocks across the strike of the folds is due to the principle explained on pages 621-623. This is: Strata when once bent at a certain place continue to bend at this place rather than to form a new fold. This bending continues until, as a result of the folding, the strata are greatly thickened and the inclinations become steep, so that resistance to further folding at this place is greatly increased. The force is then transmitted forward and a new area is affected by folding, but as soon as the strata are here bent they continue to bend easily until they are closely folded, so that there is the same sudden transition as before from the closely folded to the very gently folded or unfolded districts.

In the first and simplest case the lower formations have been subjected to either simple or complex folding, while the upper formations are undisturbed or very slightly disturbed. In this case the upper formations are likely to be found as inliers upon the other, and the structural break between the two is comparatively easy to determine. Phenomena of this kind are found at many localities between the Paleozoic and pre-Paleozoic sediments, and less frequently they are found wholly within the pre-Paleozoic formations.

The second case is that in which the lower formations were folded by one or more movements before the upper series was deposited, and subsequently the two were again folded. If the second folding was of a comparatively simple character, and the earlier was rather complex, it is usually comparatively easy to separate the two series. For instance, the lower formations may have been rather closely folded by the first orogenic movement, and the two sets of formations together may have been gently folded by the second movement. The discrepancy between the two may often be detected, even when the movements were in the same direction, as they so frequently were. But the discordance may be more easily discovered if the second movement was in a different direction from the first, so that the first folds of the lower formations became complexly folded at the second period of folding, the newer formations at the same time being simply folded.

Third, in more complicated cases the lower formations were folded one or more times before the upper series was deposited, and after the deposition of the latter the two series were again folded in a complex fashion, either by a single orogenic movement or else by successive movements. In proportion as the folding of the later formations becomes complicated the criterion of folding for separating series is more and more difficult to apply, and where the folding of the upper formations is at all intricate it is usually of little value. The criterion of folding for separating unconformable series is to be considered in all cases in connection with other criteria given upon subsequent pages.

SECTION III.

CLEAVAGE AND FISSILITY.[1]

DEFINITION OF CLEAVAGE AND FISSILITY.

The property of cleavage in rocks is here defined as a capacity present in some rocks to break in certain directions more easily than in others. By virtue of this property rock masses may be split into slabs or into leaves. The term cleavage is taken from a property in minerals, and is here confined to a strictly parallel usage. This definition does not agree with that ordinarily given in the text-books, but it is believed that the restriction is a gain for accurate discussion. The structure corresponds to Sorby's "ultimate structure" cleavage.[2]

Fissility is here defined as a structure in some rocks by virtue of which they are already separated into parallel laminæ in a state of nature. The term fissility thus complements cleavage, and the two are included under cleavage as ordinarily defined. Where a rock is finely fissile it may be called foliated. Fissility corresponds in part to Sorby's "close joints" cleavage.[2]

The terms slate and schist, slaty and schistose, slatiness and schistosity, are retained with their usual significations. A slate may be defined as a rock having the property of cleavage or fissility, or both combined, the rock parting into layers with relatively smooth surfaces. In slates the mineral particles are usually of small size. A schist is a rock having the property of cleavage or fissility, or both combined, the rock parting into layers with rough or wavy surfaces. In schists the mineral particles are larger than in slate. As is well known, there are all gradations between slates and schists. In origin and essential

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[1] Before reading this section it will be better to read the last part of Professor Hoskins's article in the Appendix, on Flow and Fracture of Rocks as Related to Structure, beginning with "Strain and Stress"

[2] On Some Facts Connected with Slaty Cleavage, by H C. Sorby, Rept. British Assn. Adv. Sci., 27th meeting, 1857, pp 92–93 of Transactions

characters the two have many properties in common. Schistosity, however, indicates more severe metamorphism than slatiness. It follows, from the above definitions, that a slate or a schist may have the property of cleavage or of fissility or of both combined. When both are present they may be parallel or intersecting. Both may occur in the same slate or schist in more than one direction.

It is not the aim here to inquire fully as to the manner of development of cleavage and fissility. The treatment here given will be supplemented to a certain extent on a subsequent page under the subject of mashing. Starting with the results reached by Phillips,[1] Sharpe,[2] Sorby,[3] Tyndall,[4] Heim,[5] Daubrée,[6] Harker,[7] Becker,[8] and others, it is the purpose to inquire into the attitudes of cleavage and fissility, the causal difference between the two, and the relations which these structures have to others. The investigators mentioned have shown that cleavage and fissility are usually closely connected with folding, being one of the results of compression. It has been held (pp. 589–603) that there are great differences in the manner in which masses of rock respond to compression, depending upon depth and upon whether they are homogeneous or heterogeneous.

Sorby explains rock-cleavage as mainly caused by the rotation of mineral particles, and especially mica, so that their longer diameters and the cleavage of the mica particles are normal to the greatest pressure. The rock readily parts along the greater dimensions and cleavage of the mineral particles. The minute mica plates were supposed to be fragmental particles deposited in the plane of bedding, and to have been rotated by the movement of the rock to a position normal to the pressure. Sorby also showed that the laminar hydrous silicates, such as chlorite, develop in situ parallel to the cleavage. He did not think that this was true of mica in slates, but believed that the parallel mica flakes of mica-schist formed in situ during the recrystallization of the rock.

Sharpe and Tyndall explain cleavage as due to the flattening of the mineral particles by pressure, so that they have a parallel arrangement with their shortest axes in the direction of greatest pressure.

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[1] Report on Cleavage and Foliation in Rocks, and on the Theoretical Explanations of these Phenomena, John Phillips, British Association for the Advancement of Science, 26th meeting, 1856, Proceedings, pp 369–396

[2] On Slaty Cleavage, Daniel Sharpe, Quar Jour Geol Soc Lond, 1846, vol 3, pp 74–105, vol 5 1849, pp 111–129

[3] Anniversary Address of the President, Henry Clifton Sorby, Quar Jour. Geol Soc Lond, 1849 vol 36, Proceedings, pp 68–92

[4] The Development of Slaty Cleavage, John Tyndall, Philosophical Magazine, 4th Ser, Vol XII, pp 35–48, 1856

[5] Mechanismus der Gebirgsbildung, Albert Heim, Band II, 1878, pp 51–74, mit einem Atlas

[6] Géologie Expérimentale, by A Daubrée, Vol I, pp 391–432, Paris, 1879

[7] On Slaty Cleavage and Allied Rock Structures, with Special Reference to the Mechanical Theories of their Origin, Alfred Harker, British Association for the Advancement of Science, 55th meeting, 1885, Proceedings, pp. 813–852

[8] Finite Homogeneous Strain, Flow, and Rupture of Rocks, by G F Becker, Bull. Geol Soc Am., Vol IV, 1891, pp 13–90

This cause and the causes given by Sorby have ordinarily been regarded exclusive of each other, but it is believed that they may be mutually supporting.

My microscopical study of both cleavable slates and schists has convinced me that in the interstices, and by the decomposition of the larger particles, new minerals, and especially mica, abundantly develop with similar orientation and with their longer diameters or cleavage, or both, parallel to the flattened or rotated original particles. The innumerable parallel minute flakes of cleavable minerals in slate, especially mica and chlorite, which are almost universally present, are in no case detrital, so far as observed by me, but have developed in situ. Usually it is easy to discriminate the large, comparatively sparse fragmental mica plates, if any are present, from those which are autogenic. As soon as a new mineral particle has developed it is subjected to flattening and rotation precisely as is an original mineral particle. This parallel arrangement of minerals developed in situ is probably the most important single cause of cleavage.

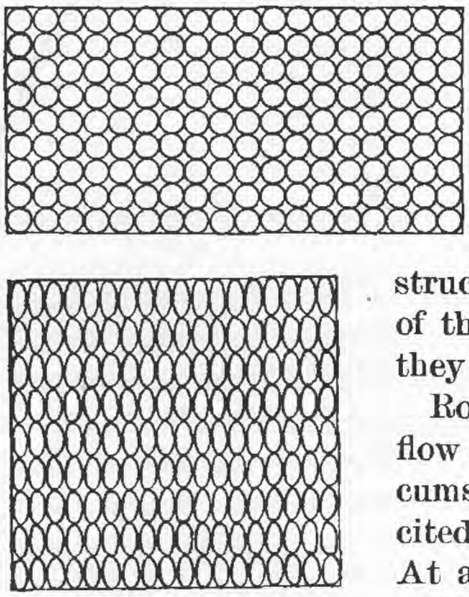
Not infrequently unmodified igneous rocks have the property of rift or cleavage more or less perfectly developed. In all cases observed by me this capacity is due to the arrangement of the mineral particles with their longer diameters in a common direction or to their similar crystallographic orientation, or both. In the case of cleavable minerals, the particles which are similarly orientated give the rocks a capacity to part parallel to the direction of readiest mineral cleavage, and this tendency is more marked if the greater dimensions of the mineral particles accord with their cleavage. In some cases, in which there is a rift in two directions, this is due either to cleavage in the mineral particles in two directions or to cleavage of them in one direction and their parallel arrangement with longer axes in the other direction. Hornblende is one of the minerals which sometimes produces a cleavage by having very numerous crystals with their longer diameters in a common direction. Feldspar is one of the minerals which produces cleavage on the same principle as hornblende, but which also in some cases gives a rock-cleavage as a result of the cleavage of the mineral particles.

From the foregoing it is believed that *rock-cleavage is due to the arrangement of the mineral particles with their longer diameters or readiest cleavage, or both, in a common direction, and that this arrangement is caused, first and most important, by parallel development of new minerals; second, by the flattening and parallel rotation of old and new mineral particles; and third, and of least importance, by the rotation into approximately parallel positions of random original particles.* The propriety of the definition of rock-cleavage as first given is therefore evident. It is always due to a capacity to part, and very frequently the parting does occur by the actual cleavage of the mineral particles.

DEVELOPMENT OF CLEAVAGE IN HOMOGENEOUS ROCKS.

Becker has recently rediscussed the origin of cleavage, and concludes that it always develops in the shearing planes rather than in the normal planes. Even in the case of the experimental development of a cleavage structure in wax, which is strictly normal to the pressure, the structure is explained as developing in the shearing rather than in the normal planes.

As will be seen below, it is my own conviction that a structure develops in the normal planes under certain conditions, and that under other conditions structures develop in the shearing planes, as advocated by Becker. The first is believed to be a deep-seated phenomenon of the zone of flowage; the second is believed to be a more superficial phenomenon in the zone of fracture. In other words, as already stated, it is thought that under the term cleavage two entirely distinct structures of different origins have been confused. Theories which explain or partly explain one of these structures have been extended to cover both of them, because it was not understood that they are different.



FIGS. 124 and 125.—Diagrams showing theoretical change in arrangement and form of particles when uniformly shortened by hydrostatic plastic flow.

Rocks when deformed under great weight flow as a plastic solid, and under these circumstances, as shown by the geologists above cited, the property of cleavage is developed. At all times the particles of the rock are welded together (fig. 101). Fissility will not form, for by the supposition the rocks are so deeply buried that no crevices can exist. In the formation of flowage cleavage, or cleavage proper, as the term is here used, the thrust may be from one or more than one direction. It may vary in force both horizontally and vertically. In any case there is flow of the rock mass in the direction of least resistance. If the force be applied so that there is uniform shortening in one direction, as in the case of a rigid piston, the elongation is at right angles to the direction of thrust, or in the normal planes. This may be called *pure shortening* (figs. 124 and 125). By pure shortening is meant the particular kind of nonrotational distortion illustrated. The volume remains unchanged, the shortening in one direction being compensated by equivalent elongation at right angles to this. In this kind of deformation, while there is no differential movement or shearing in the normal planes, shearing does occur along all of the intersecting diagonal planes. It makes no difference whether the movement is wholly from one end of the mass or in part from both ends. But when the lateral force varies greatly at varying depths the deformation may vary from pure horizontal shortening to a nearly horizontal differential movement combined with shortening (figs. 127 and 128). Such inclined differential movement is dependent both upon the varying force of thrust in passing from higher to lower horizons and upon increased friction with greater depth, due to gravity, which acts as an opposing force. In the case last illustrated the deformation is a simple shear.[1] The deformation here called pure shortening is defined by Becker[2] as a shear, and a shear, as just defined, is called by him scission.

Ordinarily, at any place in the rock mass the three principal stresses are unequal. If the differential stress surpasses the elastic limit of the rock it produces shortening in the direction of greatest stress, elongation in the direction of least stress, and shortening or elongation in the direction of mean stress, depending upon whether the latter is nearer the maximum stress or the minimum stress. The phenomena subsequently described appear to show that there is more frequently elongation than shortening along the direction of mean stress. It follows that as a result of flowage there is usually one direction of shortening and two of unequal elongation. The plane of the minimum and mean stresses is believed to be the plane of cleavage.

A coherent slate, which has the unmodified property of cleavage as here defined, shows but a single marked structure. This structure in the dense slates is often nearly normal to the direction of the greatest shortening of the strata. In the many instances in which cleavage is everywhere nearly parallel to intrusive igneous masses, there seems to be no escape from this conclusion. In such cases a zone of slate or schist surrounds a granite or other mass, the secondary structure varying in direction through 360°, thus making a circle about the intrusive core. The cleavage is therefore at each point nearly at right angles to the greatest pressure. Such zonal cleavage about batholites has been described in this country at various localities. The cleavage in the mica-schist adjacent to the granite core of the Black Hills is everywhere parallel to the igneous mass. Lawson has described like phenomena at many places in the mica-schists of Ontario. The secondary structure is everywhere parallel to the adjacent igneous masses. Emerson finds that the same relations obtain between the secondary structure and the intrusive granites in Massachusetts. Similar phenomena have been described in other countries at localities too numerous to mention. In all of these cases there can be no doubt that the magmas were under hydrostatic conditions and transmitted their pressures at every point normal to the rocks with which they were in con-

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[1] Text book of the Principles of Physics, by Alfred Daniell, 3d edition, 1894, p 78 Macmillan & Co , London and New York Elementary Text-book of Physics, Anthony and Brackett, 4th ed , 1888, pp 113-114. Treatise on Natural Philosophy, Thompson and Tait, new ed , 1890, Part I, pp 123, 124 Flow and Fracture of Rocks as Related to Structures, L M. Hoskins, part on Strain, Appendix to this paper

[2] Finite Homogeneous Strain, Flow, and Rupture of Rocks, by G F Becker, Bull Geol Soc. Am , Vol IV , 1891, pp 22-25

tact. There would therefore seem to be no escape from the conclusion that in such cases the secondary structure developed in planes normal to the pressure.

In homogeneous slates having cleavage it is not usually possible to follow the particles through their movements to their final positions. However, in rocks which are not so nearly homogeneous there are numerous minor plications. Where these plications are arranged in a symmetrical fashion, that is, do not have one set of limbs longer than the others, they give strong evidence that the thrusts were in opposite directions and normal to the secondary structure. (Pl. CXVII.) If the rock were homogeneous the crumplings would disappear and the movement of the particles would more nearly follow the law of plastic flow. Such deformation of the particles may be without differential movement normal to the pressure, and is illustrated by figs. 124 and 125 in an ideal case and by Pl. CXV in a natural case. It is not necessary that the particles be of the same size or of the same strength. As is known by macroscopical study of the schist-conglomerates and by microscopical study of ordinary slates and schists, if the movement continues far enough the old mineral particles are flattened, or flattened and rotated into parallel positions. New minerals develop with similar orientation. Therefore, as a consequence of the flowage of the stratum, the induced arrangement of the particles necessarily produces a capacity to cleave in the plane of the two longer axes of the mineral particles, as in this direction the rock may part between them.

In the case of forces resulting in rotatory movement, as shown by Professor Hoskins's discussion on cleavage (see Appendix and figs. 167–168), the structure may be explained as developing in the normal planes as in the case of pure shortening. The direction of shortening of any small area varies in its relation to the component particles at each successive moment. This variation may be due to the work of stress-couples producing simple shearing, to a change in the direction of pressure, or to a rotation of the area concerned, or two or all combined. The final result is to deform a given homogeneous area as though it were shortened in but a single direction, and after this was rotated. The cleavage is at right angles to the direction of greatest shortening of the area in its final position, this structure being due to the capacity to part parallel to the greater dimensions of the mineral particles. This resultant position is not normal to the final direction of greatest pressure, but at any given moment the deformation occurring is itself normal to the pressure. Newly developing minerals also tend to form at any moment with their shortest axes in the direction of pressure, and are rotated by the simple shearing exactly the same as the original minerals. Therefore the shortest axes of both new and old minerals are in the same direction. Thus the cleavage develops strictly in the normal planes, but its position by the rotation of simple shearing is inclined to the final direction of pressure.

I therefore conclude from analysis, from experiments upon viscous and plastic bodies, from observations in the field, and from studies with the microscope, that I am justified in the statement that *the secondary structure of a rock which is deformed by plastic flow develops in the plane normal to the greatest pressure, and that this structure is true cleavage.*

We thus see that in both the case of pure shortening and the case of shortening combined with rotation the secondary structure is parallel to the greatest dimensions of the mineral particles. This parallelism may be macroscopically observed at very numerous localities in which schist-conglomerates occur. Some of the more important of these are the Hastings district of Ontario, Green Mountains of Vermont, Felch Mountain district of Michigan, many localities in the basal conglomerates of both the Upper Huronian and Lower Huronian in the Marquette district of Michigan, the Black Hills of Dakota, and the Front Range of Colorado.

In different localities the degree of flattening of the pebbles varies from a small amount to that in which the pebbles are transformed into leaf-like areas. Everywhere and in all grades of change the secondary structure accords with the longer diameters of the flattened pebbles. (Pl. CXV and fig. 156.) The same phenomena have been observed by me in microscopical studies upon fragmental particles in hundreds of sections of the semicrystalline formations from many parts of America.

According to Becker's explanation of slaty cleavage, there is an important discrepancy between the direction of the structure and the greater diameters of the flattened mineral particles.[1]

If the above observations are correct, it would seem that there is no escape from the conclusion that the secondary structure which I here describe as cleavage is not developed in the manner described by Becker and can not be explained by his theory. I therefore return to the old explanation of the English geologists—which perfectly accords with the facts—that this secondary structure develops in planes normal to the pressure.

In further confirmation of this explanation are certain phenomena described to me by Diller and Keith.

Diller makes the following statement:

> At Crystal Lake, on Hough's Peak, Plumas County, Cal., is a conglomerate that is immediately associated with slate. Slaty cleavage is well developed in the latter, and also in the conglomerate. The greater diameters of the flattened pebbles are always in the cleavage planes. The harder pebbles are less elongated than the softer ones, and are frequently fractured, the fractures being diagonal to the cleavage.

The probable explanation of the phenomena is that the cleavage develops in the normal planes and the fractures develop in the shearing plane, as explained by Becker. At the same depth and pressure the softer parts of the rock were under conditions of flow and the hard pebbles under conditions of fracture.

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[1] Finite Homogeneous Strain, Flow and Rupture of Rocks, George F. Becker, Bull. Geol. Soc. Am., Vol. IV, pp. 55–66.

Keith makes the following statement:

> Near Blowing Rock, N C , is a mashed porphyritic granite in which porphyritic crystals of feldspar are flattened in various degrees, and their greater diameters are upon the average parallel with the secondary structure. In many cases the feldspar crystals are fractured in a direction diagonal to the cleavage, and in some cases in a single feldspar crystal there are two sets of diagonal fractures approximately at right angles to each other and each inclined about 45° to the cleavage.

The phenomena therefore correspond precisely to the idea of a pressure normal to the cleavage, which at the same time produced fractures in the more rigid feldspar crystals along the maximum shearing planes. As in the slate described by Diller, the weaker matrix was under conditions of flowage at the same depth that the more rigid feldspar crystals were under conditions of fracture.

It is a very common phenomenon in slates and schists, both macroscopically and microscopically, for the direction of the secondary structure to wrap around the harder particles. As a hard grain or pebble is approached the cleavage structure in the matrix opens out on each side of the grain, envelops it, and closes in again beyond it. The structure nowhere intersects, although upon opposite sides of a particle, near the end, the structures converge and come together as the end of the grain is reached. They would intersect if continued in their original direction. While the cleavage of the matrix, where there are many harder particles, constantly varies in direction, it nowhere intersects. Its average direction is the same as that of other parts of the rock in which resistant particles are absent. Because the structure of the cleavage, where hard particles are present, simulates a mesh structure, loose observation might lead to the conclusion that there are present two intersecting structures. The prime characteristic of a true mesh structure is that two diagonal structures shall intersect. As shown subsequently (p. 654), intersecting diagonal fissility may develop in the shearing planes.

The deviation of cleavage about hard particles is explained by the fact that the more resistant grains act as a transmitter of forces. At any given point at the exterior of a hard particle the direction of greatest pressure is normal to the grain, and hence the peripheral arrangement of the cleavage about the grain. The principle is precisely the same as that explaining the development of zonal cleavage about intrusive batholites. (See p. 637.)

The crucial point in deciding whether there is a structure which develops in the normal plane is the simple matter of fact as to whether or not the flattening of the original particles corresponds with this structure. In testing this point it is best to take examples in which the flattening of the particles is not too great (see Pl. CXV), else the lessening discrepancy between a possible structure called cleavage by Becker,[1] developing in the planes of "maximum tangential strain," and

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[1] Finite Homogeneous Strain, Flow and Rupture of Rocks, George F Becker, Bull Geol Soc Am, Vol IV, pp 55-66

that regarded as cleavage by me, developing in the normal planes, may be overlooked. As already explained, I hold that the facts of the field accord with my position. Upon this crucial point of fact I ask the observation of geologists, for by the facts of occurrence must be judged the adequacy of the explanation offered as to the manner of action of the forces which produce cleavage. It is believed by me, as will be seen, that the theory that cleavage is developing at any given moment normal to the pressure fully explains all the diverse facts of true cleavage in both homogeneous and heterogeneous rocks.

The amount of shortening of the area of a rock mass necessary to produce the property of cleavage may not be great in a slate, as shown by the amount of distortion of the bedding. In proportion as the shortening becomes greater the rock is apt to change from a slate to a schist. If the process of shortening continues until a schist is produced, it is often difficult or impossible to estimate the amount of horizontal shortening of the strata, but it is certain from observation that it is usually considerable, perhaps to one-half or one-third of the original. This is shown by the plications of layers of a slightly different color which are cut by the schistosity. (Pl. CX.) If plicated layers such as often occur in schists were straightened out, they would require a distance across the schistosity two or three times as great as at present.

It is very rare indeed that any rock is so homogeneous that the unmodified law of normal flow perfectly applies as above given. Among the sediments argillaceous rocks most nearly approach homogeneity. The massive rocks, however, still more nearly approach homogeneity. But even these are not strictly homogeneous, being composed of mineral particles of different sizes and characters. However, these particles in many instances are uniformly flattened and readjusted, so that the mass in a large way almost perfectly obeys the law. A mashed massive rock having cleavage but not fissility is a solid, strong schist, and it is in this class of rocks that cleavage in a uniform direction as the result of normal plastic flow is best exemplified.

Rarely rocks show an almost equal capacity to part in any direction parallel to fibers. In these cases the microscope shows that the mineral particles are very long in the fibrous direction, and have about the same average magnitude in all directions at right angles to their greatest diameters, instead of having two definite directions of mean and minimum diameters at right angles to each other, as is ordinarily the case in slaty cleavage. As pointed out by Professor Hoskins under Cleavage (see Appendix), this structure is explained by the deforming or maximum pressure being equal or nearly equal throughout a circle of revolution in all directions perpendicular to the fibrous structure, and by less pressure in the direction parallel to the fibers. This results in shortening in all radial directions and elongation at right angles to this, and thus the fibrous structure is formed normal to the plane composed of the radial directions of greater pressure.

It has been seen on a previous page that unmodified igneous rocks may have the capacity to cleave, and that the structure is similar to a secondary structure in sedimentary rocks. There is not so great a difference between the two in this respect as might at first be supposed. The arrangement of the mineral particles in the igneous rocks is caused by the similar original crystalline orientation of the mineral particles produced by unequal stresses in three dimensions and by the rotation of flowage. In the sedimentary rock the same is true, but the flatness of the particles is due to another cause. The chief difference is, however, that the lava is a viscous liquid and the crystallized rock a plastic solid. The manner in which the parallel minute mineral particles which produce cleavage in igneous rocks change their direction in passing around a large porphyritic crystal is as similar as possible to the way in which laminar mica scales in a slate or schist change in direction in passing around a large refractory grain. In both cases the material wraps about the rigid particles which were sufficiently strong to partially or wholly resist deformation.

The above explanation of cleavage makes this structure also analogous to the capacity to part along bedding planes in sedimentary rocks. As each erosion particle has unequal diameters, it comes to rest in most cases with its longer diameters in the plane of bedding, thus giving at the outset a laminated structure. This structure may be emphasized by the pressure of gravity. It therefore follows that the unaltered sedimentary rock ruptures more readily along its bedding plane than elsewhere. That the capacity to part parallel to bedding is less marked than parallel to the cleavage of slates and schists is due to the fact that the ratio of the minor to the mean and major diameters of the mineral particles is not so large and the regularity of the parallel arrangement not so nearly perfect in the original sediment as in a slaty or schistose rock. If a maximum deforming force be normal to the bedding, as it may be in some cases, the original imperfectly parallel arrangement of the mineral particles, with their longer axes in the direction of bedding, would be so much done toward producing a cleavage, and the result would be to give a more highly developed secondary structure parallel to the bedding with a given amount of movement than would result from the same deformation in a different direction.

In some instances, as has been seen, observations show that the conjoint action of tangential thrust and friction throughout considerable masses of rocks was apparently such as to give approximately uniform shortening of the strata in one direction. The material is confined on all sides, and its deformation is that of a plastic solid. The direction of least resistance is toward the surface of the earth. The direction of mean resistance is at right angles to the minor thrust and parallel to the surface. Consequent upon the flow, the mineral particles, new and old, at any particular point arrange themselves with their longer axes in the plane of these directions. This plane is vertical, or nearly so, and almost at right angles to the major thrust. Therefore, in approximately homogeneous rocks cleavage is frequently vertical or highly inclined, and hence intersects the bedding. This may be called *cross cleavage.*

But supposing the lateral thrust to vary greatly in depth, and considering that friction increases with depth, the movement may vary, as explained above, from upward plastic flow to differential movement in a horizontal direction. In this change we have passed from a pure shortening to a simple shearing. The cleavage would be nearly parallel to the bedding, and it may be called *parallel cleavage.* In the case of parallel shear the cleavage would accord in its principle of development with that of parallel cleavage in heterogeneous rocks, subsequently described.

These extreme cases rarely occur. Almost invariably there is a combination of pure shortening with shearing motion. The combination is ordinarily such as to give steeply inclined cleavage cutting the bedding, and therefore a cross cleavage. There are, however, undoubted gradations between cross cleavage and parallel cleavage. In all cases in nature the final resultant or direction of movement depends upon a union of all the forces concerned.

DEVELOPMENT OF FISSILITY IN HOMOGENEOUS ROCKS

If a rock be in such a position and under such conditions that it is deformed by regular fractures, it is probable that the secondary structures form in the shearing planes. Just as in the case of cleavage, at any place in a rock mass the three principal stresses are usually unequal. In the zone of fracture if the differential stress surpasses the ultimate strength of the rock, fracture occurs along the two sets of shearing planes which incline toward the greatest stress and are parallel to the minimum stress. The maximum shearing stresses in the case of normal pressure are 45° from the greatest pressure and are at right angles to each other, but Hoskins shows (see Appendix) that the fractures may incline at a smaller angle than this to the direction of greatest pressure, the latter bisecting the acute angle made by the intersecting ruptures. It is only in case the two lesser stresses are equal, or nearly so, that concoidal fractures are produced, such as occur in ordinary building-stone tests of cubes (fig. 126). In this experiment there is one direction of great stress and two directions at right angles to this of very subordinate equal stress.

Hence, in the zone of fracture, where the differential stress surpasses the ultimate strength of the rock, there may be produced a fissility in two sets of intersecting planes equally inclined to the greatest pressure. It is well known that a fissility in two directions occurs in many homogeneous rocks, and such structures have doubtless developed along the shearing planes under this law.

In case the direction of greatest normal pressure is nearly horizontal, the planes of fissility would be at angles of about 45° with the horizon. However, as no rocks are strictly homogeneous, and as the direction of greatest normal force is always compounded of thrust and gravity, the directions of the shearing may vary considerably.

In case the parting is very close, the rock is foliated. Each lamina moves slightly over the adjacent laminæ. The rubbing of the laminæ over one another, due to the differential movement, gives the slickensided surfaces which are so common on both sides of the parted laminæ. The more intense the movement, the thinner and more brilliant do the folia become. Since the partings are usually inclined to the bedding, this structure may be called *cross fissility.*

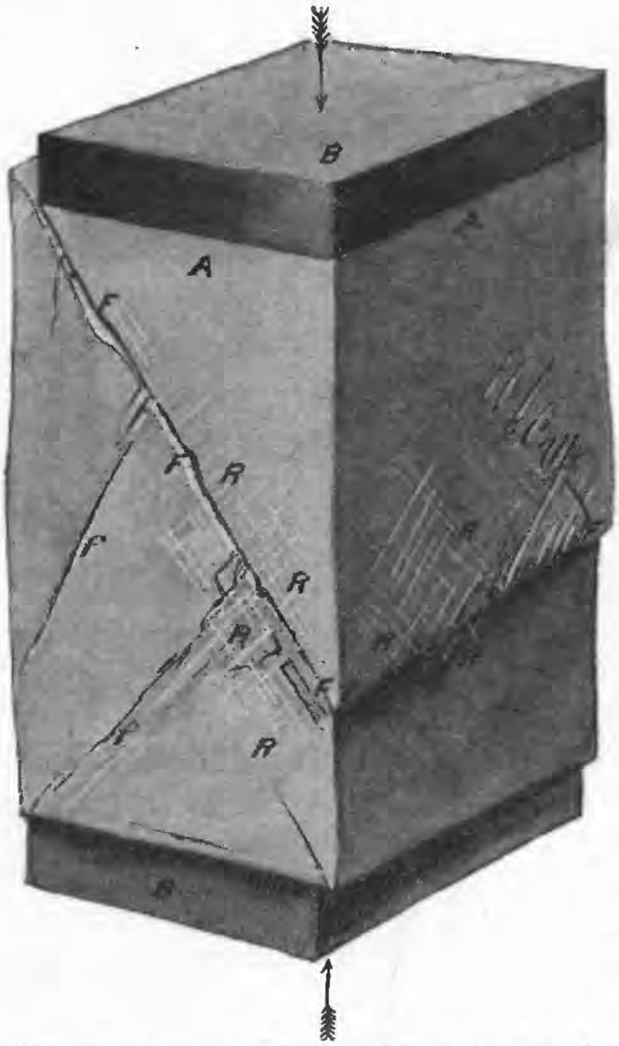


FIG. 126.—Experimental production of fractures along the shearing planes. After Daubrée.

In passing from the zone of fracture to the zone of flow it is to be expected that all gradations would be found between the development of cleavage in the normal planes and the development of fissility in the shearing planes. This point is discussed later. (See p. 654.)

Frequently fissility forms in lithologically homogeneous rocks in which the property of cleavage had already been developed, and which by subsequent denudation are brought so near the surface that the superincumbent weight is less than the strength of the rocks. When subjected to stress under these circumstances numerous fractures develop along the cleavage planes. This occurs because fractures take place so readily along these planes, and because the chances are always that there are shearing planes, although they may not be those of maximum stress.

This may be the case although the direction and force of thrust may not have varied. The direction of greatest normal pressure, combined of gravity and thrust, would be in a different direction when the rocks are in the deep-seated zone of flowage and when they are in the superficial zone of fracture. Thus, cleavage in the normal planes would pass into the shearing planes as denudation progressed.

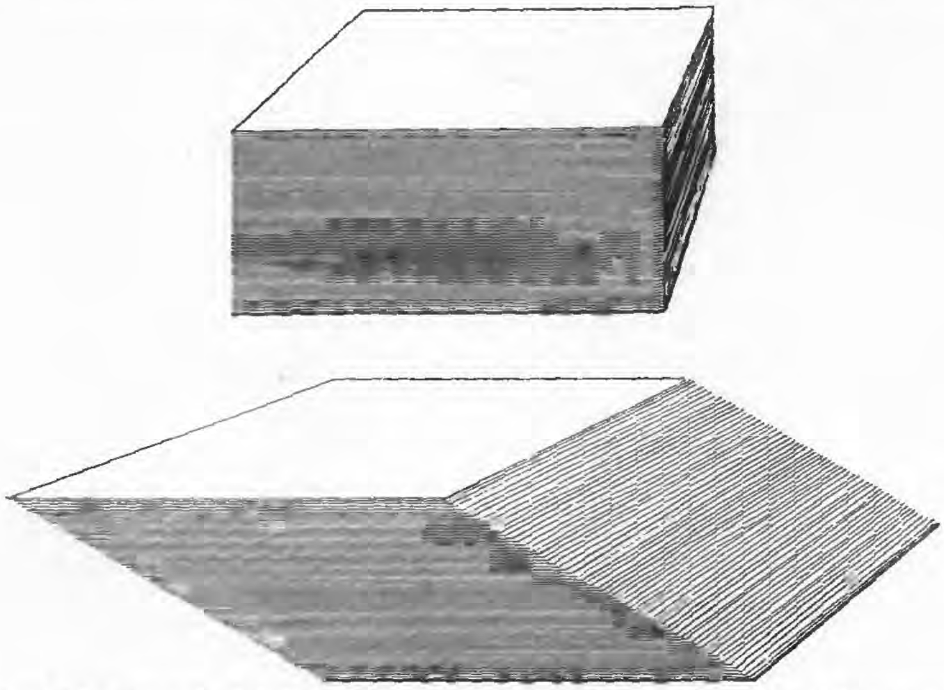
In cases in which the fissility develops along a prior cleavage, the fissility parallel to these planes would be marked. The fracturing along the other set of diagonal shearing planes, not having the advantage of a previous cleavage, would be much less marked, the deformation perhaps largely occurring by considerable movements along a few planes of shearing. In this case the infrequent cracks may properly be called joints. In the planes of fissility secondary to cleavage the folia slip over one another just as in the case of originally developed fissility independent of cleavage, producing slickensided surfaces, and the rock develops a "fault slip" cleavage or "ausweichungs" cleavage (see figs. 90 and 91, Dale, in previous paper, pp. 563, 564). In the majority of cases in which the fissile laminæ are close together and have a uniform direction for a considerable area, it is probable that the structure first developed as true cleavage in the normal planes, and that a later movement, when the rock was nearer the surface, developed the fractures along the shearing planes. The structure is thus a product of the forces producing cleavage and those producing fissility working successively under different conditions.

As will be seen below, fissility may form in a manner similar to its development parallel to cleavage or parallel to planes of weakness of any other kind, as, for instance, bedding.

The directions of the fissility are therefore dependent upon the direction of the forces, upon whether they are equal or unequal, upon the superincumbent load and the consequent friction, upon the cleavage and other previous structures, and upon previous folding.

If fissility develop along cleavage, as this structure is usually steeply inclined, the fissility will be in the same direction. That great thrust faults sometimes develop with nearly horizontal hades, or even parallel to bedding, is well known. Multiple minor thrust faults or fault slips producing fissility may similarly develop with flat hades, upon the same principles as cleavage in a like direction, and thus produce a fissility nearly or quite horizontal, or parallel to bedding. It is therefore clear that the structure may vary from a vertical to a horizontal attitude. There are therefore all gradations between cross fissility and parallel fissility, subsequently described (pp. 651–654; fig. 133), just as between cross cleavage and parallel cleavage. In the case of parallel fissility the movement may be compared to the differential movements of a ream of paper which under load is pushed unequally forward from one end, the differential movement between any two successive sheets being the same. While the bottom sheet may be shoved one-tenth of an inch, the top sheets may be shoved 10 inches (figs. 127 and 128). Between the bottom and the top the amount of forward movement would vary regularly from one-tenth of an inch to 10 inches. While the differential movement between any two sheets is the same, each sheet gains all the forward movement of all the sheets below.

Where fissility develops, either as an original or secondary structure, rubbing usually occurs between the mineral particles along the sides of the laminæ. As a result, the minerals receive an elongation in the direction of greatest movement, a less elongation in the direction at right angles to this and in the plane of movement, but are contracted at right angles to the plane of movement. Also new minerals which develop are controlled in the same manner. If the fissility be second-



FIGS. 127 and 128.—Theoretical deformation of laminated rock by uniform differential movements parallel to a previous structure.

ary to cleavage, the minerals were previously oriented with their two longer axes in the plane of differential movement, and the slipping of fissility but emphasizes an arrangement of the mineral particles which already existed.

DEVELOPMENT OF CLEAVAGE AND FISSILITY IN HETEROGENEOUS ROCKS.

When a set of layers, either sedimentary or not, of different lithological character are folded, and cleavage or fissility develops in them, the process is not simple.

As the case of alternating sediments is the most important one, and somewhat different from any other, this will be first considered.

The original series, instead of being homogeneous, is composed of beds of different characters; that is, it consists of alternations of mud, grit, sandstone, limestone, etc. Before these rocks are folded the forces of consolidation, cementation, and metasomatism may have been at work. As a result of these prior alterations, combined with original deposition, the strata may have greatly varying strength. The sandstones may have been transformed to quartzites; the grits may have been changed to graywackes; the muds may have been compacted into shales; and the limestones may have become crystalline.

When such a series is folded the accommodations occur mainly along the beds (figs. 118 and 119). The greatest readjustments and greatest compression are along the limbs of the folds (see pp. 598–600, and fig. 103*b*). Each layer shears over the one next below under enormous stress. The necessary movement at first is largely concentrated in the weak layers between the beds of stronger material (fig. 133). The shearing extends from these into the harder ones, for when motion has once begun along a certain set of planes, that very movement weakens the rocks along these planes and makes it easy for the forces applied in any direction to be decomposed into forces producing further movement along the same planes.

The maximum force producing shear is composed of horizontal thrust and gravity, and its direction will therefore usually be inclined to any layer in a horizontal position, although if gravity is unimportant as compared with thrust this inclination may be slight. When the layers become tilted this inclination is marked, although the problem becomes more complicated on account of the strength of the individual beds. These tend to decompose the forces which they receive at one point into components parallel and normal to themselves, and transmit the longitudinal thrust to another point. Upon the limbs of the folds the beds are, however, never free from superincumbent weight, and the rigidity of the overlying beds must also be often overcome. Therefore, in nearly all cases of heterogeneous rocks the direction of greatest normal stress is inclined to each layer. There are two classes of cases—those in which the rock bed is in the zone of flowage, and those in which the rock bed is in the zone of fracture. The first afford conditions for the development of cleavage; the second, those for the development of fissility. Between the two there may be gradations.

DEVELOPMENT OF CLEAVAGE IN HETEROGENEOUS ROCKS.

For a given very small area in a stratum the cleavage may vary from parallel to perpendicular to the bedding. If at any moment the direction of greatest normal pressure is in the direction of bedding, the secondary structure will tend to develop at right angles to the bedding. If, on the other hand, the direction of greatest pressure is at right angles to bedding, the cleavage will tend to develop nearly parallel to the bedding. Between these two there will be all gradations. For different beds and for different areas in the same bed the direction of greatest pressure will, at successive times, vary both relatively and absolutely, and therefore the cleavage developing in the normal planes at any given moment will gradually vary in direction. For a small, practically homogeneous area the final resultant will be the same as in homogeneous rocks (p. 638)—that is, the cleavage will be perpendicular to the direction of greatest final shortening.

Having made this general statement, let us inquire more particularly how the forces producing cleavage act in heterogeneous rocks.

As a result of the folding, combined with denudation, the relative amounts of thrust and gravity vary at different times, so that the average direction of greatest normal pressure for a given area also varies. On account of the differing strength of the beds the forces received by them are decomposed to a greater or lesser degree into directions parallel and normal to themselves, and thus the direction of greatest pressure is varied at each particular point. During the folding process the inclination of the beds is constantly changing, and as a consequence any given small area is being rotated with reference to the direction of greatest pressure. The problem is further complicated by the readjustment between the beds, which constantly changes the relative position of the material with reference to the pressure. Lastly, the readjustment usually takes place mainly within the weaker layers, and this changes by a varying amount the relative positions of different parts of the beds with reference to the greatest pressure. At any given point there will be a plane in which are the major and mean axes of the mineral particles, and this will be the plane of cleavage. It is evident that this plane will vary in position from place to place. These conclusions follow from Professor Hoskins's discussion on strain and stress (see Appendix), for all of the different compressions, acting in different directions at different times, are equivalent to some single compression acting continuously in one direction, and the shearing motion of differential movement is equivalent to a compression combined with a rotation.

Very frequently the position of the cleavage with reference to the bedding for a given small area will be controlled by the readjustment between the beds. As shown by Professor Hoskins's discussion on cleavage (see Appendix), the structure will tend at any moment to develop in the normal planes, but as a consequence of the shearing the material is rotated so that the final direction of cleavage is inclined to the direction of greatest pressure (figs. 167, 168). Since the readjustment is mainly concentrated within the weaker layers, the structure may be so rotated in them as to approach parallelism with the beds, while in the adjacent beds, in which there is less differential movement, the structure may be nearly at right angles to the beds; and at various positions between the cleavage will have intermediate directions. There will thus be developed a cross cleavage in the more resistant beds, which varies by a gentle curve into parallel cleavage in the weaker beds. On opposite sides of the layer the curves are in opposite directions (fig. 131). By these curves it is easy to determine the relative directions of the movements of the layers.

Directly following from the above we have the explanation of the step cleavage[1] of the older authors and of Becker,[2] and of the differ-

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[1] On Slaty Cleavage and Allied Rock Structures, with Special Reference to the Mechanical Theories of their Origin, Alfred Harker, Brit Assoc Adv Sci, 55th meeting, 1885, Proceedings, pp 829-830

[2] Finite Homogeneous Strain, Flow, and Rupture of Rocks, George F Becker, Bull Geol Soc Am., Vol IV, pp 84-87

ential cleavage of Dale. In this case the change in the direction of cleavage, instead of being gradual, as it is in rocks of gradually varying plasticity, is somewhat sudden in passing from one bed to another differing in rigidity. As a result of the shearing motion the cleavage is rotated more in the more plastic layers and less in the less plastic layers. Hence, *in heterogeneous rocks having cleavage, in a soft layer the cleavage more nearly accords with bedding than it does in a hard layer.* (See fig. 87 in previous paper, by Dale, p. 561.)

To summarize: We have the absolute direction of greatest pressure varying; as a consequence of the difference in the strength of the beds we have the direction of greatest pressure varying from place to place; we have the material of any given area on the limbs of folds rotated with reference to the direction of greatest pressure; and, finally, we have variable differential motion between the beds, which would momentarily change the direction of the area with reference to the pressure. However, as shown by Professor Hoskins's discussion, these all combine to produce at any given point a shortening of the particles in one direction and an elongation in one or both directions at right angles to this. Newly developed mineral particles have similar orientations. At any point perpendicular to the final position of the shortest axes of the mineral particles there will be the property of cleavage. As the differential movement at any given place is parallel to the dip, the longest axes of the mineral particles will be in the plane of cleavage and in the direction of dip. The mean axes of the mineral particles will be in the same plane but in the direction of the strike of the cleavage.

If before the folding a cleavage had already developed parallel to the bedding by deep-seated metasomatic change or by flattening parallel to the bedding below the level of no lateral stress, as subsequently suggested (pp. 661–662), this would modify the direction of the secondary structure, making it more nearly parallel to the bedding than it would otherwise be.

In areas of symmetrical or gently inclined folds and in homogeneous rocks the shortening is approximately in the line of the horizon and the cleavage therefore steeply inclined. In heterogeneous rocks the differential movement between the layers, as has been pointed out (p. 598), is ordinarily upward for a higher stratum as compared with the one next below it. In the case of abnormal folds (see p. 617) this differential movement is emphasized. Consequent upon the differential movement upon the limbs of the fold in weak beds where the shearing motion is largely concentrated, the cleavage is locally flatter than in homogeneous rocks. Whether the rocks are homogeneous or heterogeneous the rotation will be in opposite directions on opposite sides of anticlinal arches or synclinal troughs, being outward for an anticline and inward for a syncline; therefore *on opposite limbs of a fold the cleavage usually dips in opposite directions. Upon opposite sides of an anticline the cleavage* *usually diverges downward, and on opposite sides of a syncline it usually converges downward.*

Ordinarily the rotation of shearing will not go far enough to bring the cleavage into correspondence with bedding, and therefore its dip will be steeper than the dip of the strata; hence, *on opposite sides of a fold the variation in the dip of cleavage is less than the variation in the dip of bedding.* However, in the case of much-compressed normal composite folds (figs. 111 and 114) the force of gravity and unequal thrust control the direction of the moving force, and consequently the form of the secondary folds. In this case the cleavage may be rotated from its ordinary position, and upon opposite sides of the anticlinorium the cleavage may converge downward and upon opposite sides of the synclinorium may diverge downward. This applies as well to the central fan folds as to the minor folds on the flanks (fig. 112).

It has been pointed out (p. 624) in the case of much-inclined or overturned folds, that the resultant differential movement or shearing between the strata on the steeply inclined or overturned limb may be down for a geologically superior stratum as compared with an inferior stratum. It follows that the shearing on both limbs of the fold is in the same direction, and therefore that *in regions of overturned monoclinal folds the cleavage may be rotated in the same direction throughout, and will hence be monoclinal* (fig. 134). Since on monoclinal folds the differential movement is great on the longer and flatter limb of the fold, the cleavage may be rotated so as to be almost parallel to bedding, but usually is somewhat steeper. As the resultant differential movement is comparatively slight on the steeper, shorter limb, the cleavage usually cuts across the bedding at a considerable angle and is steeper in reference to the horizon. On the opposite limbs of monoclinal fan-shaped anticlines the cleavage may be nearly parallel, or may even converge downward, and on the opposite limbs of monoclinal fan-shaped synclines the cleavage may be nearly parallel, or even diverge downward.

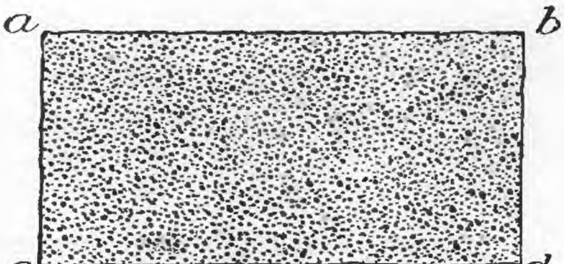
This contrast with symmetrical folds is due to the continuous rotation in the same direction of the cleavage along the arch limb of the fold combined with the rotation in the reversed limb, first opposite to and afterward in the same direction as that on the arch limb. As in the case of symmetrical folds, the variation in dip of cleavage is less than the variation in the dip of bedding. In districts in which cleavage and bedding have the relations above described, on the longer arch limbs it is often difficult to discriminate between the two, but it is believed that the cleavage is usually slightly steeper than the bedding, as already explained. On the steep or reversed limbs the minor crenulations of the strata are usually easily detected intersecting the cleavage.

When rocks are openly folded the discrepancy between cleavage and bedding is usually great. As the folding becomes closer the average discrepancy becomes less. If the compression goes so far as to form isoclinal folds the bedding and cleavage may nearly correspond upon the limbs of the folds, but the two will be at right angles to each other upon the crests of anticlines and in the troughs of synclines (fig. 133). When the compression is so great as to form plicated folds, the changes in the direction of bedding being very sharp, the discrepancy between bedding and cleavage will be slight. However, the discrepancy is real and important. The cleavage in this case may be about parallel to the axial planes of the folds, and will cut the beds at a very acute angle. In many districts where cleavage has been described as everywhere according with bedding, and the two do approximate but not exactly accord in direction upon the limbs of the folds, a close examination shows that on the crests of the anticlines and in the troughs of the synclines the two structures intersect each other.

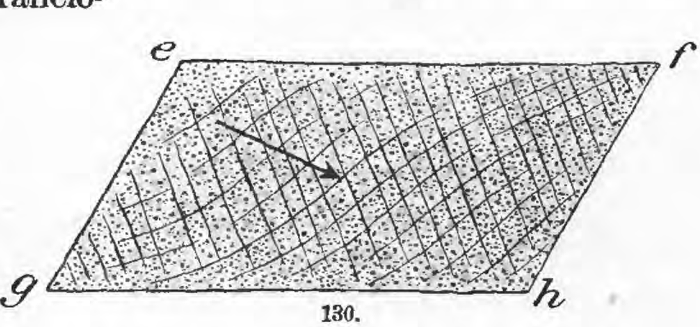
At the beginning of the process it may be noted that the shortening is at right angles to the bedding. At the end of the process the shortening is parallel to the bedding. Thus the work first done is partly undone. The resultant position of the shorter axes of the mineral particles in reference to the bed is intermediate between the two extremes.

DEVELOPMENT OF FISSILITY IN HETEROGENEOUS ROCKS.

The development of fissility in heterogeneous rock beds is still more complicated. The directions of the forces are exactly the same as with cleavage, but as fissility develops along the shearing planes, in the simplest case this structure forms in two general directions. In simple folding, as there is differential movement between the layers, the deformation of a portion of a given layer is that of a rectangle (fig. 129, *abcd*) into a parallelogram (fig. 130, *efgh*). If the layer were exactly homogeneous and the pressure normal, the secondary structures would be nearly at right angles to each other and at an angle of about 45° to the greatest pressure. According to Becker, in the case of inclined pressure the structures would have different positions, but they still would be planes. These conditions are most nearly approached in the center of a bed which at this place is massive. However, in pass-



129.



130.

FIGS. 129 and 130.—Diagram showing development of fissility along the longer and shorter diagonals of a deformed portion of a rock stratum.

In the center of stratum the fractures are in the planes of greatest shearing, but on the outside of the layer the fractures are in lesser shearing planes, the direction of fracture being controlled to some extent by bedding.

ing from the center to the weaker, outer part, the original bedding may largely control the direction of parting, the partings occurring near the planes of bedding rather than in those of greatest tangential stress (fig. 131). The result is that the planes of fissility may change from their diagonal position in the center of the layer, where it is most rigid, to nearly parallel to the bedding on the outer parts, where it is least rigid.

The diagonal *ad* (fig. 129) is shortened to *eh* (fig. 130); therefore the fissility along the diagonal *gf* is formed under conditions of compression. This results in producing many approximately parallel planes of fissility. No sooner does a parting form than the laminæ are sheared over one another, thus producing slickensided surfaces. Across this structure along the longer diagonal, in the plane of the shorter diagonal, there is actual stretching of the layers. The length of the original diagonal *cb* is increased to *gf*. Parallel cracks are therefore produced in this direction. As a crack once formed easily widens, the result is the production of a few cracks of considerable size. The broken parts do not rub over one another, and hence do not produce slickensided surfaces. These peculiarities frequently lead to oversight of the shearing along the planes of the shorter diagonal. The development of the cracks along the shorter diagonal are strictly analogous to the upward-pointing crevasses of a glacier.

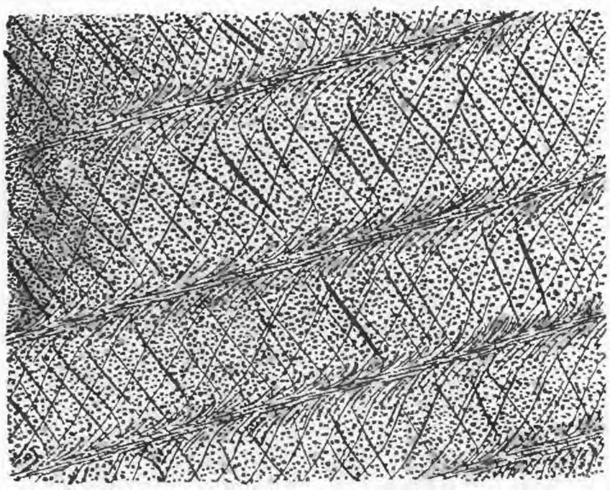


FIG. 131.—Parallel fissility and cross fissility in heterogeneous rock strata.

The planes of fissility near the border of the beds, where the rigidity is less, perhaps originally developed diagonally, may be rotated to a nearly parallel position. This rotation may change the direction of the planes of fissility either in the compressed or the stretched diagonal. The cross fissility will grade into parallel fissility by a gentle curve. On opposite sides of a layer the curves are in opposite directions, just as in the case of cleavage, and by these curves it is easy to determine the relative direction of movement of the layers (fig. 131).

This rotation is explained by fig. 132, which is supposed to represent a bed of rock made up of thirteen layers differing in rigidity. In passing from the outside of the bed to the center the coefficient of rigidity of each layer is supposed to be twice as great as that of the one next adjacent. The greatest stress is supposed to be the same throughout the bed, and in an inclined direction, and, as shown (pp. 647–648), these conditions may be approximately complied with upon the limbs of folds. When the differential stress exceeds the ultimate strength of the rock, parallel fractures along shearing planes will be formed. The fracturing will continue until the stress falls below the ultimate strength of the rock. The differential stress may still surpass the elastic limit of the rock, or if not, it may again accumulate until the elastic limit is exceeded. Flowage will then begin. On account of the varying rigidity the two layers adjacent to the center will have a certain amount of differential movement, which may be called 1. The layers next to them toward the outside will have a movement which would be represented by 2; those next to them, 4; those next to them, 8; and the outside layers a movement of 16. Now, connecting similar points in the different layers, a curve is produced which corresponds very nearly in form to those which have been observed in nature. The structure produced in the diagonal direction, in the centers of the layers, has been rotated to the position indicated. In different rocks the variation of the coefficient of rigidity would be different from that supposed, and it would undoubtedly vary irregularly instead of regularly. A more accurate discussion wonld consider each of the layers as indefinitely thin, and the coefficient of rigidity in passing toward the center of the bed as increasing by a minute increment. If different numerical suppositions be made, curves would be produced differing from those represented by the fignre, but the same in essential character.[1]

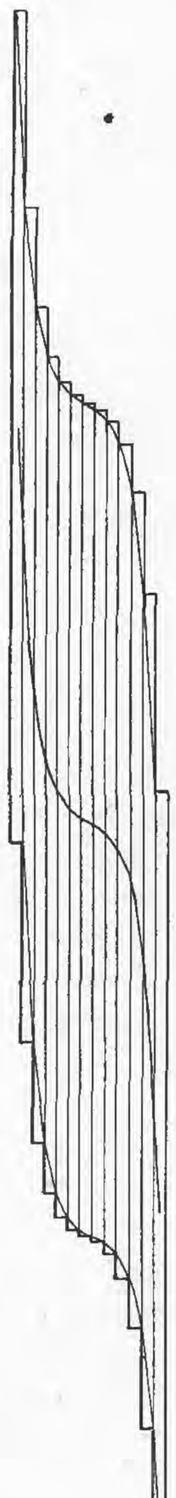


FIG. 132.—Diagram showing rotation of cleavage which originally developed in the normal planes to a position nearly parallel to the bedding.

A third way in which the curved fissility above described may be produced is as a structure secondary to cleavage. That cleavage can be produced having the same curves and relations to bedding as just described for fissility has already been shown (pp. 647–649). Such previously developed cleavage would give parallel curved surfaces of weakness. When the rock passed into the zone of fracture fissility would develop along these shearing planes whether they were those of maximum tangential stress or not.

The above phenomena (probably secondary to cleavage) are finely illustrated in the quartzites of the North Range of Baraboo, Wisconsin (figs. 150–152), and in the massive graywackes of the Ocoee series on the Hiwassee River, Tennessee, combined with cross and parallel secondary structures, as shown by fig. 131. It is possible that in the cases of both

[1] Compare Geology of the Comstock Lode and the Washoe District, by Geo. F. Becker, Mon. U.S. Geol. Surv., Vol. III, pp. 156–178, 1882.

cleavage and fissility as the folding becomes closer and closer the zones of much shearing may extend farther and farther into the rigid beds, producing secondary structures nearly parallel to bedding throughout the limbs of the folds. If the thrust be so powerful as to give the layers isoclinal dips, the secondary structures and bedding will be developed or rotated so as to be nearly parallel throughout the rock mass, except at the sharp turns on the crests of the anticlines and in the troughs of the synclines, just as in the case of normal plastic flow in homogeneous rocks. (See p. 643.)

RELATIONS OF CLEAVAGE AND FISSILITY TO EACH OTHER.

GRADATION BETWEEN CLEAVAGE AND FISSILITY.

In passing downward from the zone of fracture to the zone of flowage, one would naturally expect to find all gradations between fissility in two directions developed in the maximum shearing planes and cleavage in a single direction developed in the normal planes. To this natural expectation the phenomena seem to correspond. Rocks are found having two planes of fissility intersecting nearly at 90°; others which intersect each other somewhat more acutely, so that the rock breaks up into forms having rhombic or rhomboidal sections; others in which the rhombs or rhomboids have their axes very long in one direction as compared with those in the other; and others in which the two directions are so nearly parallel that they are not separated, except by close observation.

According to Becker[1] and Hoskins,[2] somewhat inclined intersecting structures may be explained as original developments, but the former places the direction of greatest pressure in the obtuse angle, while the latter, basing his conclusion on experiments, places it in the acute angle made by the two structures. The phenomena may be partly explained by supposing that after the two diagonal structures developed in the shearing planes, the pressure continuing to be applied with a force between the elastic limit and ultimate strength of the rock, there was a rotation of the two sets into approximate parallelism, just as there is when a net with rectangular meshes is pulled out until the intersecting lines are almost parallel. Professor Hoskins offers another explanation of this transition, as follows (see Fissility in Appendix): In an early stage of the development there may have been flowage of the rock sufficient to produce a more or less perfect cleavage. The rock, as a result of more rapid deformation or of erosion, may then pass to the zone of fracture. If the stresses remain in the same direction the fractures would not take place along planes of greatest shearing stress, but tend to approach the planes of flattening. In proportion as a previous

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[1] Finite Homogeneous Strain, Flow, and Rupture of Rocks, by George F Becker, Bull Geol. Soc Am , Vol IV, 1893, p 50

[2] Flow and Fracture of Rocks as related to Structure, L M Hoskins, part on Fissility, in Appendix to this report.

cleavage was prominent, a secondary intersecting fissility in two directions might very nearly approximate in position with the cleavage. Doubtless in many cases the different causes above given combined to produce acutely intersecting fissility.

FISSILITY SECONDARY TO CLEAVAGE.

For any given layer in a horizontal position in the zone in which fissility is developed, it is probable that horizontal thrust is great in proportion to gravity. If gravity were wholly neglected the greatest shearing stress would be at 45° to the bedding. In the zone in which cleavage is developed it is probable that gravity is very important as compared with tangential thrust. If these are supposed to be equal, the direction of greatest normal pressure would be inclined at 45° to the bedding, and the cleavage planes at right angles to this would also be equally inclined to the bedding, but in an opposite direction It therefore follows that fissility developing in heterogeneous rocks in the shearing planes and cleavage developing in rocks of the same character in normal planes may have like directions with reference to the bedding. If cleavage be developed in the normal planes inclined to the bedding, and by denudation this stratum passes to the zone of fracture, as a consequence of the lessening power of gravity, these normal planes are now shearing planes, and fissility is controlled in direction by the previous cleavage structure. It thus becomes evident that it may be exceedingly difficult, if not impossible, to discriminate between original fissility in the shearing planes and a secondary fissility which has been controlled by cleavage. In other cases, as well as these special ones, it is to be expected that a rock in which cleavage has developed under deep-seated conditions would be ruptured before reaching the surface during the long time it is in the zone of fracture. To this expectation the facts correspond. In all regions with which I am acquainted having well-developed cleavage, fissility is also found to a greater or lesser degree. Usually the fissility is more marked here and less marked there, for where a fracture or set of fractures has been formed, there it is easier for further movement to occur. Hence belts of strongly fissile rock are separated by others in which there is but slight fissility (see Dale's fig. 90, in previous paper, p. 563). In general, however, fractures along shearing planes occur near together or wide apart within all rock masses showing cleavage. To this the confusion of the two structures is doubtless largely due. It may be that the use of the term "fissility" should be restricted to a structure developing secondary to cleavage or to bedding, and that original fractures, developing along shearing planes, independent of any previous structure, should be called joints. However this may be, it appears probable that where a rock is broken into very thin laminæ in a uniform direction for a considerable area, the secondary structure originally developed as true cleavage in the normal planes. I therefore conclude that *fissility* *developing in the shearing planes is usually secondary to cleavage which developed in the normal planes.*

CLEAVAGE AND FISSILITY MAY DEVELOP AT THE SAME DEPTH.

It is clear that in heterogeneous rocks cleavage and fissility may develop in beds of different character at the same depth, for weak beds may be in the zone of flowage at the same depth at which strong beds are in the zone of fracture. For instance, the fine-grained argillaceous beds within a formation may develop cleavage, while the coarser-grained siliceous beds may develop fissility. Thus may be explained some of the cases of change in direction of the secondary structures in passing from one to the other. Also, a bed under a certain weight may be in the zone of fracture if rapidly deformed, and in the zone of flowage if slowly deformed. As has been seen under the subject of deformation (p. 602), the middle zone of combined flowage and fracture is probably 5,000 meters thick, and it may be thicker, and throughout this zone either cleavage or fissility may be formed. It is only in the zone of fracture that fissility alone can form, and only in the deep-seated zone of flowage that cleavage alone can form.

RELATIONS OF CLEAVAGE AND FISSILITY TO OTHER STRUCTURES.

RELATIONS OF CLEAVAGE AND FISSILITY TO BEDDING.

Where a rock series is composed of layers of different lithological character, and is in the zone of combined fracture and flowage, the deformation includes the development both of cleavage by normal plastic flow and of fissility in the planes of shearing, in both homogeneous and heterogeneous rocks, and perhaps of all gradations between the two. The beds in the heterogeneous rock may be each approximately homogeneons. There is necessary rearrangement within the beds as well as readjustment between them. Therefore the rearrangement within the beds, in so far as it is not affected by the readjustment between the beds, will tend to produce cross cleavage and cross fissility, while the readjustment between the beds will mainly be by parallel slipping, and will tend to produce parallel cleavage and parallel fissility (fig. 131).

In passing from the limbs of the folds toward the crests or troughs, parallel readjustment becomes less and less important, and normal plastic flow or fracture along the shearing planes becomes more and more important. At the arches and troughs the thrusts for a given bed are approximately equal, in opposite directions, and when deeply enough buried its entire thickness is under compression. The direction of least resistance is vertical. Therefore the conditions which here prevail are those of the formation of cross cleavage and cross fissility. It follows that in heterogeneous rock strata, parallel structures may prevail on the limbs of the fold, and cross structures on the crests and in the troughs. At intervening places may be found all the complex effects of the interaction of the two (fig. 133). In many cases where there is almost perfect accordance of primary and secondary structures on the limbs, and the rocks are so crystalline that the two can not readily be discriminated, at the crests and troughs both structures may readily be seen intersecting each other.

Formations are but divisions of rock masses greater than beds which are roughly homogeneous. In each formation, considered as a whole, cross secondary structures will usually be produced, while at the contacts between the formations, where major readjustment is sure to occur, nearly parallel structures may be found. In the discussion of each separately it has been seen that in the cases of extreme folding the relations between the different secondary structures and bedding are nearly the same, and therefore that cleavage and fissility developed under each of the laws will merge together, and both be approximately parallel to the reduplicated beds. They are all brought into nearly parallel positions, just as are pebbles in the folding process. In order that this should be done, it is plain that there must be such extreme rearrangement of the rock material that it could not inaptly be compared with kneading.

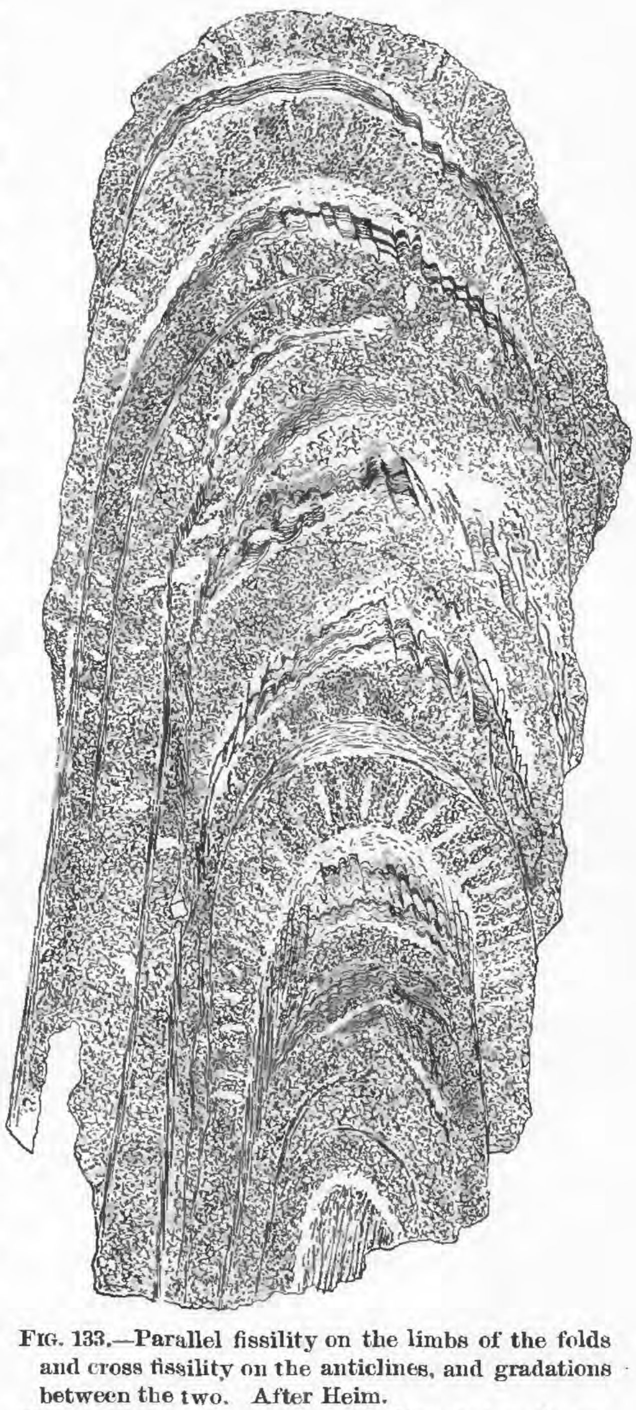


FIG. 133.—Parallel fissility on the limbs of the folds and cross fissility on the anticlines, and gradations between the two. After Heim.
The deformation is mainly by folding, but on the anticlines, where the material is partly relieved from stress, the deformation is partly by the multiple minor slips of fissility.

In rock masses in which the alternating layers of different strength are not beds, the principles of the development of cleavage and fissility are the same as in the heterogeneous bedded rocks. The different layers may be due to secondary structures. They may be due to the flowage of igneous material along primary or secondary planes of weakness, or to secondary water-deposited impregnations along such planes. They may be due to heterogeneous injections. In all of these cases, as in any other, the stronger beds will to a certain extent control the movements. The accommodations will occur along the layers when folded, and there will be a tendency for cleavage and fissility to develop parallel to them (Pl. CX.)

The more unequal the layers in thickness and strength, the more likely is the major accommodation to take place parallel to them, and thus produce cleavage and fissility which nearly accord with them. In proportion as the rocks approach massive ones, the law of cross structures prevails, but in a minor way readjustments along the laminæ may occur, and these laminæ still retain their integrity. In rocks as they occur in the field both tendencies are always present in all the parts, from the minute laminæ to the largest masses. Sometimes the first is predominant, sometimes the second. If the lamination is not strongly marked the first tendency will control, although the lesser layers or laminæ of unequal strength may in a minor way control the movements (Pl. CX).

Ordinary shale is a representative of rocks having minute layers of slightly different strength. Usually the average of the cleavage or fissility distinctly cuts the beds. The material yields to thrust by flowage or fault slips combined with minute puckerings (fig. 162). If the process be continued far enough the individual layers are folded upon themselves in a large number of parallel folds, nearly at right angles to or inclined to their original positions. Therefore, while cleavage does nearly correspond with the original beds, the particles have been so much deformed and rearranged and the layers have been so far readjusted as to make the term bedding scarcely applicable.

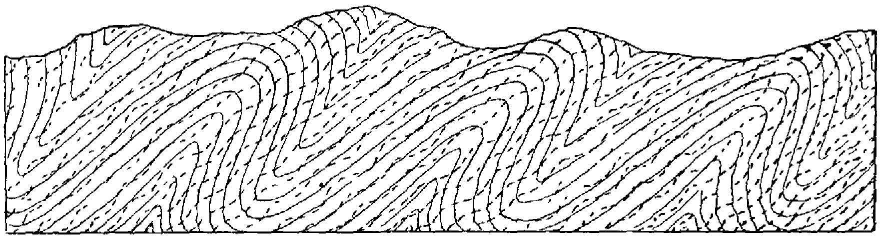
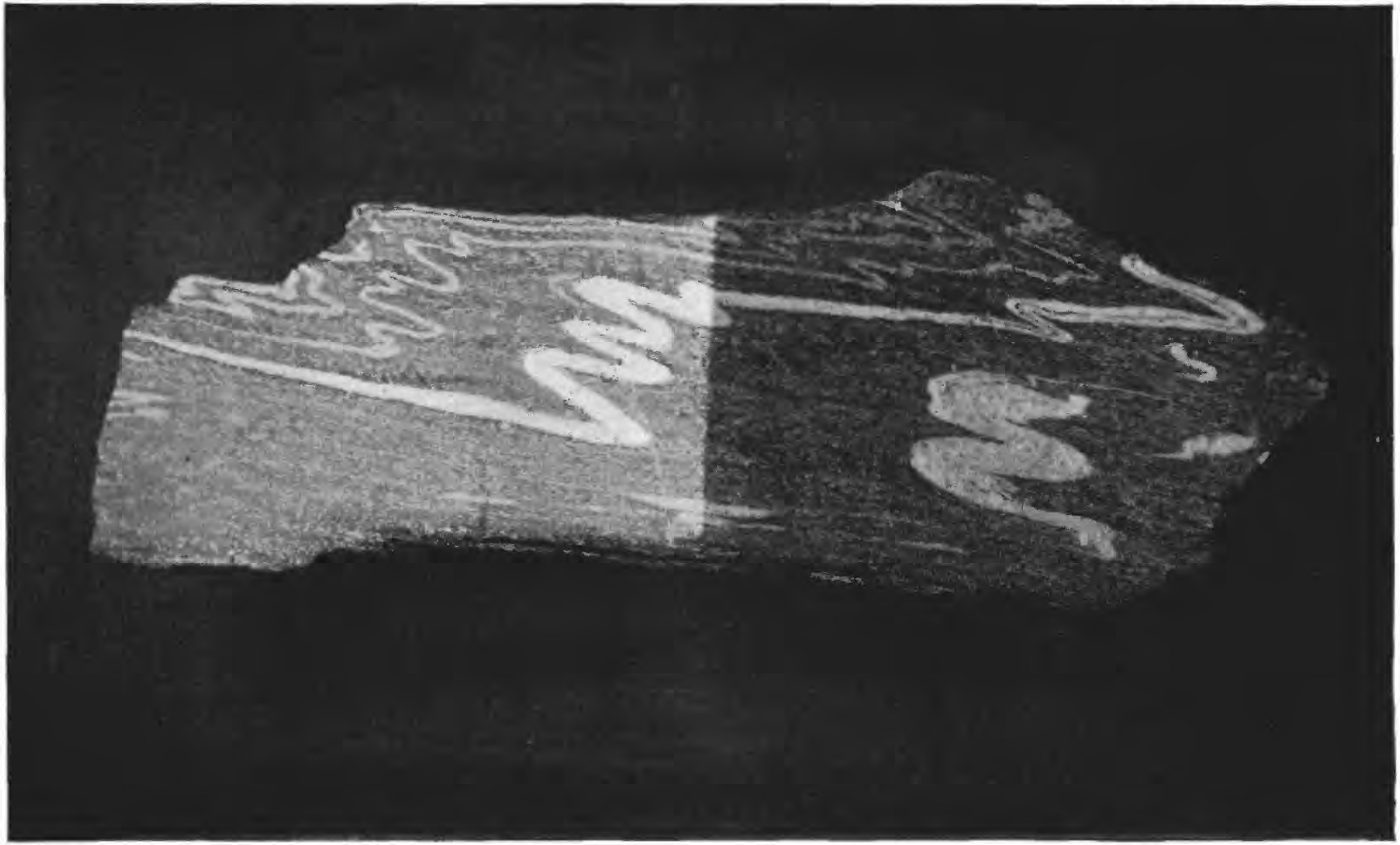


FIG 134 —Relations of cleavage to bedding in monoclinal folds

As has been seen (p. 650), beds are particularly likely to largely control the direction of cleavage or fissility if the folds are monoclinal and overturned (fig. 134). In such folds the major differential movements are along the longer limbs. Therefore the cleavage develops in a corresponding direction, being nearly parallel to the bedding on one limb of each fold and cutting across the bedding on the other, steeply inclined or overturned limb. As the area of outcrop of the steeper limbs is much less than that of the more gently inclined ones, the fact that the cleavage cuts the bedding on one side of each fold is very likely to be overlooked. As a result of the greater mashing thus developing cleavage or fissility the longer limbs of the folds are thinned more than the shorter limbs.



GNEISS, WITH STRONGLY DEVELOPED CLEAVAGE, SHOWING MINOR PLICATIONS OF QUARTZ LAMINÆ, THE DIFFERENTIAL SHEARING MOVEMENTS WHICH THE ROCK HAS UNDERGONE, COMBINED, HOWEVER, WITH VISCOUS FLOW UNDER COMPRESSION.

The quartz laminæ show thinning on the limbs of the folds and thickening at the anticlines and synclines.

If for any cause cleavage be parallel to the bedding planes, as these are apt to be shearing planes in the zone of fracture, the predominant fissility would be likely to be parallel to the bedding. The other direction of fissility would be transverse to the bedding, and might have a wider spacing. The first might be called fissility and the second joints.

In another case, after a cross cleavage has developed and the rocks have passed into the zone of fracture, the stresses may result in the development of fissility along two sets of shearing planes, one of them being controlled in direction by the cleavage, the other by the bedding. The more regular parting, parallel to the cleavage, might be called fissility, and the less regular parting, parallel to the bedding, might be called either fissility or joints, depending upon its closeness. Whether the intersecting planes of fissility are at right angles to each other would depend upon the inclination of the cleavage and the bedding.

In regions of complex folding it is difficult to make accurate general statements of the relations of cleavage and fissility to bedding. However, as a result of the action of the various forces, a bed has a definite strike and dip, and the cleavage and fissility have definite relations to these. As there are rapid variations in strike and dip in regions of complex folding, it is to be expected that there will be variations in the directions and character of cleavage and fissility. Certain of the specific relations of bedding and secondary structures in regions of complex folding have already been considered (pp. 629-630).

RELATIONS OF CLEAVAGE AND FISSILITY TO THRUST FAULTS

Between cleavage and fissility developed along the longer limbs of folds and thrust faults, which accord in dip with the beds on the longer limbs, there is only a difference in the magnitude and frequency of the movements.

When fissility or cleavage develops there are many slightly or infinitesimally separated movements of small degree. When a thrust fault develops there is a single major movement. (See Dale's fig. 95 in previous paper, p. 566.) It is believed that the relief is more likely to be by faulting at little depth, and at greater depth is more likely to be by the development of cleavage, and often, secondary to it, fissility, or more rarely by the development of fissility directly. The passage of cleavage by gradation into minute overthrust faults is beautifully illustrated a short distance northwest of Blowing Rock, N. C. Where fissility is not developed throughout the rock mass it may occur adjacent to thrust faults, due to the shearing adjacent to the thrust planes. Rock masses deformed by thrust faults and showing fissility adjacent to the faults will have zones of fissility which alternate with others in which this structure is absent. Where fissility varies in perfection of development in alternating zones, but is present throughout the rock mass (see fig. 90, Dale, in previous paper, p 563), it implies that the relative movements were concentrated to a certain extent along definite zones, but that movement everywhere occurred. It is plain that *shearing developing cleavage and fault slips along planes of fissility accomplish the same mass deformation as do thrust faults*, only it is averaged throughout the rocks instead of being largely concentrated at certain planes.

Differential movements similar to those described in the above paragraph may occur along a lamellar structure in any kind of a rock, sedimentary or igneous.

By differential movements, such as are above described, enormous masses of material may move forward long distances. The top of the mass, having the advantage of all the differential movements below, will travel the farthest (figs. 127 and 128). The base will move the least. From this mass at some later time mountains may be carved. As each stratum grinds over the one below it the former presses against the latter with all the weight of the superincumbent material. Under such circumstances it is no wonder that a coarse-grained, massive granite may be transformed into an evenly laminated schist. In the zone of fracture the schist, developed in the zone of flow, may become fissile, and the slickensided, wavy folia may be thinner than paper. It is by folding combined with differential movement that the abnormal folds described on a previous page are produced.

The cleavage or fissility so frequently present upon the flanks of anticlinal core rocks in great mountain ranges may be explained by similar movements. In the section on the analysis of folds it has been shown that much readjustment must occur upon the limbs of folds. The flanks of an anticlinal mountain core are such limbs, and hence the development of cleavage or fissility parallel to the central massif. In passing toward the center of the core we approach nearer the crown of the anticline, and penetrate to a greater depth; hence less readjustment is necessary, and therefore the secondary structures are less prominent.

RELATIONS OF CLEAVAGE AND FISSILITY TO THICKNESS OF STRATA.

Without reference to the origin of secondary structures, or any evidence upon this point, bedding and secondary structures are often spoken of as corresponding. Even reputable text-books make such statements. This confusion is most unfortunate for two reasons: (1) It often leads to great overestimates of the thickness of strata, the real thickness of the beds being supposed to be the apparent thickness as observed across the secondary structure, where, as shown by the foregoing analysis, the same bed may be repeated many times. (2) The mistake is likely to give erroneous ideas of structure. If the primary and secondary structures are thought to correspond, the whole breadth of a slate or schist may be regarded as a bed of enormous thickness, and this will lead to the preparation of sections in which the mass is represented as extending to a great depth, where it may be comparatively superficial. (Fig. 135.)

The assumption that bedding and secondary structures correspond is still less justifiable when no remaining evidence of bedding is found. If only cleavage or fissility be found, and the relations of the beds with other beds are not such as to give the direction of stratification, no inference in reference to this point should be drawn.

It is apparent that attempts to estimate the real thickness of cleaved or fissile beds must take into account two difficulties: (1) The same bed may be folded on itself many times, and these folds must be followed, or at least some estimate must be made of the thickness of the beds which would be present if the minute plications could be straightened. (2) In the complex folding of the beds there is readjustment, mashing, and consequent lengthening of the layers upon the limbs, and they are, therefore, on the average, thinner than originally. So far as such thinning occurs, it compensates for the reduplication of the beds, but it is believed that this compensation is far short of full correction. To fully overcome the difficulties is often impossible, and estimates of the thickness of the closely folded, cleaved, and fissile beds, even when all the difficulties are wholly understood and allowances made, are usually only approximate.

FIG. 135.—Closely plicated shale underlain by bed of limestone.

DEVELOPMENT OF CLEAVAGE BY OTHER CAUSES THAN THRUST.

Thus far I have considered cleavage developed in connection with and dependent upon orogenic movements. It is probable that this structure develops in other ways. It may be that deeply buried beds may become cleavable with the structure parallel to bedding, where superincumbent pressure, cementation, and metasomatic changes are the predominant forces. Such deep-seated rocks, if below the level of no lateral stress, are in the zone of great vertical compressive stress and circumferential tension. They would, therefore, be shortened vertically. If under the stress of gravity movement goes far enough, this would develop a cleavage parallel to the surface. Such cleavage in sedimentary rocks would be parallel cleavage and would emphasize the bedded structure originally formed. Just below the level of no lateral stress it is probable that the circumferential dilation would be slight, but would increase with depth. Whatever its amount, it is a real cause so far as it goes.

It is not asserted that rocks in which cleavage may thus develop reach the surface by subsequent denudation, but perfectly crystalline schistose rocks in which the cleavage corresponds exactly with the bedding, and which are but gently folded, suggest that such may have been the conditions under which the structure formed, and if the estimates given for the depth of the level of no lateral stress, from 2 to 8 miles,[1] are correct, it is certain that rocks which have been below this level in some regions have subsequently reached the surface by denudation. It is generally believed that the Laurentian and Adirondack areas are regions of profound erosion, and here are found excellent illustrations of gently folded cleavable schists, the structures of which apparently correspond with original bedding. The above explanation may be applicable to these regions. This method of the development of cleavage parallel to the surface of the earth below the level of no lateral stress is also applicable to igneous rocks.

Laccolitic or batholitic intrusives might promote this process by giving great pressure parallel to the bedding and by heating percolating waters, thus rendering them more active. In the Adirondacks the cleavage of the schists and the periphery of the batholite of gabbro have in some places a parallel arrangement, and the intrusion of the igneous rock has probably been one of the causes of the metamorphism and the parallel relations obtaining between schistosity and bedding. Readjustment between the beds, as explained on a previous page, may also have assisted in the process.

In a third case, a great boss of intrusive igneous rock may cause the secondary structure to be everywhere parallel to it, without reference to the direction of previous structures. This case probably differs but little from that of direct thrust, but the direction of thrust gradually varies through 360° in circumscribing the mass, being at all times radial. The material pushed aside obeys at each point the law of normal plastic flow, just as in ordinary orographic movements. The new minerals develop with their shortest diameters in the direction of thrust Old minerals are mashed into similar forms in parallel positions. The heat of the igneous rocks furnishes hot solutions which help to transform the old minerals. As the direction of the thrust varies gradually around the intrusive, the secondary structures follow, and therefore form a zone around the intrusive, the layers of which may be compared to those of an onion (see p. 637).

The process may be complete, and old structures, such as bedding, previous cleavage, or previous fissility, may be wholly destroyed. In other cases traces of these structures may still be found. Where the earlier structures are wholly obliterated near the intrusive, they may appear gradually in passing away from it. Thus in the same rock mass several structures may occur. The mica-schists about the intrusive granite core of the Black Hills are an excellent illustration of this case.

MODIFICATIONS OF SECONDARY STRUCTURES.

The partings of fissility may be concentrated here and sparse there. (See Dale's fig. 90 in previous paper, p. 563.) In the cracks between the

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[1] Origin of Mountain Ranges, by Joseph Le Conte, Jour of Geol, Vol 1, 1893, pp 566–568 James D Dana, Manual of Geology, 4th ed , 1895, p. 384–5.

laminæ a new mineral or minerals may be deposited from water solutions, and the secondary zones of greatest fissility would then have a composition different from that of those which are less fissile. Moreover, the parted laminæ and the minute layers of infiltrated material may be of different composition. This would give a minute alternation of layers of different characters. Such a major and minor alternation of different materials may simulate the appearance of bedding to a remarkable degree. (Pl. CXVII.) If such structures are taken for bedding, mistakes in structural work will follow.

Where fissility is developed in an igneous rock secondary impregnations may occur between the laminæ, just as above described. Thus there would be formed a rock with alternating layers of different mineral character, no part of which is sedimentary, and yet which closely simulates a sedimentary structure. If either the sedimentary or the igneous rock which has become fissile be intruded by igneous materials, these might follow the cracks in a minute way, and thus again produce a structure which is very similar to bedding.

In the above cases both the process of water impregnations and that of igneous injections tend to cement the rock. If the process be complete the crevices of the rock may be entirely healed. The once fissile rock will then have lost its fissility. It may, however, have the property of cleavage parallel to the banding. Such a cleavable rock may give no evidence that it was once fissile. From the foregoing I conclude that *banded rocks may owe their structure to fissility and secondary impregnations or injections, or both, and the bands may or may not accord with an original structure.*

After a first secondary structure has developed, later movements may produce a new cleavage or fissility, which cuts this earlier structure at right or oblique angles, or the new force may be so intense as to produce a structure which wholly destroys the earlier structure. Usually, in order that a new structure may be produced, it is necessary that the new force shall vary considerably in direction from the first, so that it can not be decomposed into two components, one parallel to the old structure and one at right angles to it. To this fact is doubtless due the comparative infrequency of cleavage and fissility in several directions in the same rock mass; but while the secondary structure is ordinarily in a single direction, an exposure or even a hand specimen may show the original bedded structure and secondary structures in two or more different directions. In fact, as has been shown, a single simple orogenic movement may produce both cross and parallel secondary structures, and the cross fissility may be in two directions.

While it is rare to find more than two or three structures in a rock, theoretically there is no limit to the numbers which might be produced; but practically, as has been seen, new movements usually emphasize old structures, or else produce new structures, which tend to obliterate the old structures. *However, in a thoroughly crystalline rock, if there be two or three structures, it is not safe to assume that the oldest and most* *intensely plicated one is bedding.* (See Dale's figs. 92–94 in previous paper, pp. 565, 566.) This has been done frequently in the case of the crystalline schists and gneisses by those who would not regard cleavage or foliation, if but a single structure existed, as evidence of bedding. The older the structure the greater is the probability that it is really bedding, but the fact that it is the earliest structure which now exists in the rock can not be regarded as conclusive, for it may have been produced by an early orogenic movement which simultaneously obliterated bedding.

After a secondary structure has developed in a formation it may be folded into anticlines and synclines. In order to be thus folded it is usually necessary that the secondary structures be not steeply inclined. As indicated on a previous page, where such a structure develops in a horizontal position it may correspond with bedding, but also it has been seen that cleavage or fissility may form with slightly inclined planes of movement which cut diagonally across the bedding. Such a cleavage or fissility may be emphasized by secondary impregnations, and injections, in which case it simulates bedding to a remarkable degree. In either of the above cases a careless observer would be almost certain to regard the structures as bedding.

The number and severity of orogenic movements may in many places have been so great along old ranges that it is not strange that it is impossible to differentiate or separate the various formations upon a structural basis. The beds have been kneaded again and again by the orogenic forces; cleavage, fissility, and banding may have developed in different directions; earlier structures may have been destroyed by later transformations; until it is no longer possible to determine the position of original bedding.

APPLICATION TO CERTAIN REGIONS.

In many mountainous regions in which there has been profound erosion, illustrations of nearly all of the foregoing principles may be found. Attention may be directed to one or two of the more important.

It has already been pointed out (pp. 621–622) that in the Appalachian and New England crystalline areas the main direction of active stress was probably from the southeast toward the northwest. At any rate, the couple composed of force and resistance was such as to make the higher strata move toward the northwest as compared with the lower strata, or to make the lower strata move to the southeast as compared with the upper strata. As a consequence of this, the folds of that area have axial planes which have a very general tendency to dip to the southeast. If the force be supposed to have been directed toward the northwest, and to have been equal for different depths throughout the thickness of the rocks now exposed at the surface, the cleavage which developed in the normal planes would dip to the southeast. This would have been due to two causes. First, the direction of normal pressure, compounded of thrust and of gravity, would have been northwest and downward, which would, therefore, have given a southeasterly dip to the cleavage. Also, because of increasing resistance and probably lessening thrust with increasing depth, the force would have caused the higher strata to have moved differentially over the lower ones. There would, therefore, have been a shearing motion, the higher strata moving upward and northwestward as compared with the lower. As a result of this shearing and of shortening, the old and new mineral particles would lie with their longer diameters in southeasterly-dipping planes and give a cleavage in that direction. The conjunction of these two forces would have given a flatter dip than would follow from either one of them alone.

While the above statement is true on the average, the case is complicated because of the differential movements in individual folds. The cleavage for a given section is in a single direction to the southeast only when the folds have a decided monoclinal attitude, and this is especially marked where the folds are all overturned. Even here, however, the cleavage tends to be flatter upon the limbs in normal positions than on the overturned limbs. In the areas in which the folds approach a symmetrical character, cleavage with northwest dips is found on the northwest limbs of the folds. The explanation of these phenomena is given on pages 649-650.

While there is a general tendency in this region for a southeasterly dipping cleavage, there are great variations in the steepness of the dip in different beds in the same locality, and variation in the average steepness in different localities. The variation in steepness in the same area is explained by the fact that the differential movement between the strata was largely concentrated in the weaker beds, so that the cleavage in them is flatter than in the more resistant beds. The general variation in the dip of cleavage in passing from area to area may be explained by a difference in the character of the rocks, by a difference in the intensity of the forces at varying depths, or by a difference in the depth of burying. The particular average inclination for a given area depends upon a combination of all of these variables.

With given forces, if the rocks are more resistant in one area than in another, there is less shearing motion, and therefore steeper cleavage in the former than in the latter. Other things being equal, if the forces are more intense near the surface than at a greater depth, the shearing motion is greater at higher horizons, and hence the cleavage is flatter in passing toward the surface. A given force would produce less and less shearing motion with increasing depth, because of the increased friction, and hence the cleavage may be flatter in passing toward the surface, just as in the foregoing case.

For any given area after cleavage developed, as denudation progressed the zone of flowage passed upward into the zone of fracture. It is clear that the cleavage planes already developed were then probably shearing planes, and this was true even if the horizontal thrust was the same and in the same direction in the zone of fracture that it was in the zone of flowage, for the direction of greatest normal pressure is composed of thrust and gravity, and therefore at a great depth is steeply inclined to the horizon, whereas in the zone of fracture, gravity being less important, the direction of greatest normal pressure is less steeply inclined, and therefore normal planes in the zone of cleavage become shearing planes in the zone of fracture. In the development of fissility along the cleavage planes there were slight differential movements between the laminæ, and hence was formed the very extensive fault-slip cleavage so well known in the Appalachians. It is believed that the more regular and widespread fissility is thus secondary to cleavage but it is recognized that fissility or joints formed in other directions, and that in the outer zone, which was never in the zone of flowage, original fissility or joints only was developed.

As pointed out by Willis, in the western area of little altered rocks in the southern Appalachians the deformation was mainly by faulting; in the corresponding area in the northern Appalachians the deformation was mainly by folding. At intermediate areas the deformation was by faulting and folding. Parallel to the fault planes fissility developed to some extent in the area of fracture, and dipping in the same direction as the monoclinal folds cleavage developed in the area of folding. In an intermediate area the deformation was by major faulting, by minor fault slips along fissility, by the pure shortening and shearing motion producing cleavage, and by monoclinal folds, all combined. The interactions of these are more fully described in other places (see pp. 659–660, 676).

Returning to the crystalline area, in the cracks and crevices between the fissile laminæ mineral impregnation from water solution occurred at many places, and thus gave the rocks a parallel banding, as described by Hobbs in the Searls quarry (Pl. CXVII). In other districts parallel injections of igneous rocks occurred, and here the metamorphosed schists are welded together along the fissile planes by igneous material. Such are the conditions in southeastern New York, and especially on northern Manhattan Island and in the vicinity of New Rochelle.

As shown in other places (pp. 662–663, 686–688), there may be all gradations between aqueous impregnations, through aqueo-igneous deposits, to true igneous injections. Usually the original rock differs in chemical and mineral composition from the impregnations or injections. The process gives a distinctly banded structure, which has often been mistaken for metamorphosed original sedimentary layers. Also the chemical composition may be so changed, if the amount of secondary material is large, as to make it impossible to tell from its chemical analysis whether the original rock is aqueous or igneous.

If the parallel mineral impregnation, or the parallel igneous injection, or the two together, had been general throughout the Appalachian semicrystalline and crystalline areas, we should have a vast series of crystalline schists with parallel banding, the bands generally dipping to the southeast, and these layers might be mistaken for beds, and thus lead to estimates of enormous thickness for the series, when in reality the original sedimentary beds were of no unusual thickness. This error has not been made for much of the Appalachian region because in most areas the metamorphism has not been so extreme but that the cleavage is detected intersecting the bedding at the sharp turns of the layers on the crests of anticlines and in the troughs of synclines. Had the metamorphism gone as far throughout the region as it has in certain places, the bedding could not be discovered, and there would be now no means of tracing out the different steps of the process of modification. But in the Appalachian and New England regions the steps of the process of the development of cleavage and fissility, the stages of the parallel impregnation and injection, and all degrees of metamorphism, may be observed, so that in some of the regions of most extreme change the genesis of the rocks and their structures are determined with reasonable certainty.

In the eastern region the areas in which the sedimentary rocks have gone through the process above described are more extensive than those of igneous rocks, but all steps of the process have also affected extensive areas of igneous rocks. Examples of the latter are the pre-Cambrian granitoid gneiss of the Green Mountains, and, more extensive than this, the great areas of ancient plutonic and volcanic rocks of the Blue Ridge and Piedmont Plateau.

A further beautiful illustration of secondary banding in comparatively recent rocks was discovered by Mr. Bailey Willis, who makes the following statement:

> In the vicinity of Snoqualmie Pass, in the Cascade Range of Washington, there occur dense, ringing slates with marked jointing in several directions, probably of Miocene age. These strata lie adjacent to an extensive area of granite which has suffered much dynamo-metamorphism. The relative ages of granite and strata are as yet undetermined. A considerable portion of the carbonaceous sediments presents the appearance of a distinctly, thinly banded gneiss, in consequence of the addition of quartz, biotite, and feldspar. The added material occurs between the layers of slate and traversing them at acute angles. Under the microscope it shows the characteristics of vein deposition, rather than the aggregates of crystals from an intruded magma. The carbonaceous slate is recognizable under the microscope, and the transition from the original slate to a gneissoid rock which can not be distinguished as having any connection with the sediments occurs within 2 or 3 feet. It is apparent that this gneiss is the result of a spreading of the slate layers, forming irregular cavities parallel to the planes of bedding, and the filling of the cavities thus produced by the minerals now found therein.

It is believed that the regularly banded and laminated Laurentian gneisses which for many miles have an isoclinal dip, over great areas in Canada, along the Madison Canyon in southwestern Montana (fig. 154), and in other regions, may be explained by the same processes completely carried out as are applicable to the Appalachians. It is not asserted whether the original rocks in these regions were igneous or aqueous. The general drift of opinion in recent years is in favor of the former origin.

RELATIONS OF CLEAVAGE AND FISSILITY TO STRATIGRAPHY

Cleavage or fissility may be developed in one set of formations and not in another set of beds in the same set of formations. Secondary structures develop readily in a shale, less readily in a fine grit, still less readily in a limestone, and perhaps with the least readiness in a quartzose sandstone, quartzite, or conglomerate. As a consequence of this, a shale between beds of limestone may take on a thoroughly cleaved or fissile character, the cleavage stopping abruptly at the beds of the limestone (fig. 149). The same is true of layers of shale between beds of grit, or sandstone, or quartzite, or conglomerate (see Dale's fig. 86 in previous paper, p. 560). In general, *in the strata constituting a formation, cleavage may develop in the less rigid beds and be absent or imperfect in the more rigid beds.* In such cases it has sometimes been assumed that the lower bed was deposited and cleavage or fissility developed in it before the superior bed was formed, the fact that a secondary structure was not so ready to develop in the upper bed being ignored.

In determining unconformities the use of cleavage and fissility follows the same principles as given on pages 632–633 in reference to folding. To safely infer that there is a structural break between series it is necessary to show that cleavage and fissility would be as likely to develop in the superior formations as in the inferior ones. It is further necessary that the two series be in actual superposition, not in adjacent lateral positions.

It has been seen that in proportion as cleavage and fissility develop, the original structures of the rock are obliterated. Where there is apparently complete destruction of the bedding for parts of folds, at areas of less movement, as, for instance, the crests of anticlines and the troughs of synclines, the beds may still be recognized, and thus the relations between the primary and secondary structures be determined.

SECTION IV.

JOINTS.

ORIGIN OF JOINTS

Various causes have been assigned for joints, of which the more important are tension, torsion, earthquake shocks, and shearing. It is believed that joints may be classified into *tension joints* and *compression joints*. The first are ordinarily in the normal planes, the second are in the shearing planes.

Tension joints.—Tension is often due to the contraction caused by cooling or by desiccation. It is well known that the peculiar columnar jointing of igneous rocks is due to the contraction and consequent tension caused by cooling, and the mud cracks of sedimentary rocks are due to the contraction and consequent tension caused by desiccation. However, it is probable that neither cooling nor desiccation is important in the production of systematic sets of joints in the sedimentary rocks.

It has already been seen that when rocks are simply folded and not too deeply buried the convex halves of the anticlines and synclines are subjected to simple tension (pp. 597-598, fig. 102). If the tension goes beyond the limit of elasticity, radial cracks will be formed which strike parallel with the rocks. Joints of this class are at right angles to the tensile force. This class of joints is beautifully illustrated in the sharp folds of the graywackes of the Hiwassee River, in the Ocoee series (fig. 136). If the folded rock has planes of weakness of any kind, due either to a primary or a secondary structure, the fracture due to the tensile stress may be controlled by these, and thus deviate from the normal planes.

Joints produced by tensile stress may have smooth or rough surfaces, depending upon the character and strength of the rock. If it is a weakly cemented sandstone, the fracture, as pointed out by Becker, is around the grains. If, however, it is a strong, tolerably homogeneous graywacke, quartzite, or limestone, or similar rock, the fractures may be clear-cut and sharp. After joints due to tensile stress have formed, subsequent movements may press the surfaces together, or may fault the strata in a minor or major way, and thus produce slickensided surfaces.

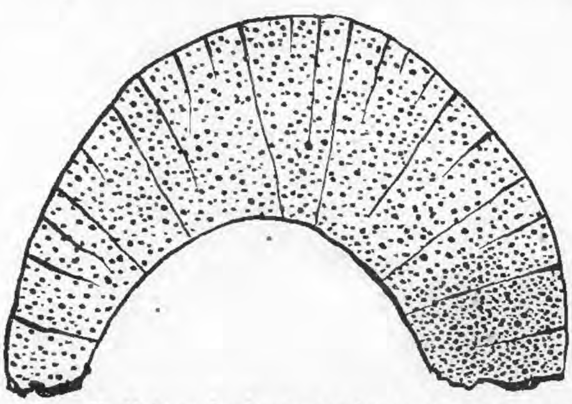

FIG. 136.—Radial cracks due to tension in sharply flexed stratum.

It has been seen in the discussion of folds that, instead of being simple, and, therefore, in a horizontal attitude, they usually have a pitch; or, in other words, the rocks are folded in a complex manner. In such regions there may be tensile stresses in two directions at right angles to each other, thus producing two intersecting sets of joints. One of these sets, that roughly parallel to the more conspicuous folds.would be called strike joints, while the other set of joints, parallel to the transverse folding, would be called dip joints. Both sets would intersect the bedding nearly at right angles. The fact that two sets of joints in these positions so frequently accord in direction with the strike and dip is strong evidence that many joints are produced by the tensile stress of folding on the stretched half of the mass folded. If the folds are nearly horizontal—that is, if the force was mainly in a single direction—the strike joints may be strongly developed and few dip joints produced. If, on the other hand, the folds are important in both directions, the strike and dip joints will both be important.

Daubrée has shown that if a brittle plate fractures when it is subjected to torsion beyond the limit of elasticity, a double set of parallel fractures nearly at right angles to each other are produced.[1] The forces which produce complex folding deform the strata, where not too deeply buried, in two rectangular directions by tensile stress; or, in other words, they are subject to torsion. It therefore appears that Daubrée's explanation of joints by torsion is but another statement of the production of joints by complex folding normal to the two principal directions of tensile stress.

A question for investigation is the extent of the area over which joints and faults run in rectangular directions. In the case of a large and strongly pitching fold, the force of torsion may produce rupture in different directions upon different parts of the folds. Upon the flank of the pitching fold, at a proper point, strike joints and dip joints may be formed, striking halfway between the ordinary strike joints and faults, and dip joints and faults at the crests and troughs, and between the two there would be all gradations.

Crosby has recently suggested[2] that when torsion has nearly, but not quite, reached the limit of elasticity in rocks, an earthquake shock may act as the trigger which sets the process in motion, and he thus combines this cause with torsion in explaining joints. Crosby also emphasized the fact that a plate when subjected to torsion does not crack along a single plane of fracture, the weakest plane, but that many parallel fractures are produced. He applies this fact to rock beds, and suggests that the fracture must first occur at some one plane, that of the greatest stress or least strength in the distorted belt. The shock of the fracture, added to the force of torsion, goes beyond the ultimate strength of the beds at the next weakest plane, thus fracturing them and producing another joint, and so on, until the complicated fracturing actually obtained in the glass plate is paralleled by the rocks. He thus makes the rupture of the first joint itself serve the purpose of a secondary shock, and this rupture a third shock, and so on, producing a set of joints in rapid succession over an extended area. Finally a place is reached where the rock has not been sufficiently distorted for the shock of the last fracture to carry the stress beyond the breaking strength. This theory is as applicable to simple tension as to torsion. In the above it appears that Crosby has overlooked the fact that he has not explained the first earthquake shock. The statement might be amended as follows: The first fracture occurs because the steadily acting orogenic forces finally go beyond the ultimate strength of the deformed beds. When rupture takes place, this gives the first shock. This initial shock carries the stress beyond the ultimate strength of the next weakest planes, and so on.

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[1] Geologie expérimentale, par A Daubrée, pp 306–314, Paris, 1879

[2] The origin of parallel and intersecting joints W O Crosby, Am Geol, Vol XII, 1893, pp 368–375.

Compression joints.—Daubrée[1] and Becker[2] show that joints may be produced by compression. In this case there will be jointing in two planes when the rocks are simply folded, and, according to Becker, there may be jointing in three or four planes when they are complexly folded, one of these being normal to tensile stress and the others in shearing planes. However, where there are more than two sets of joints at right angles to each other, it is probable that in many cases these have been caused by successive orogenic movements, the second being in a different direction from the first. Becker has explained that minor faulting is a common phenomenon of compression joints.

When the folding is simple, both sets of joints developing in the shearing planes, although dipping in different directions, would accord in their outcrop with strike, and might therefore be regarded as strike joints. When the folding is complex it may be that different sets of shearing planes would correspond to strike joints and dip joints, but upon this point further observation is needed.

In the Knox dolomite of east Tennessee the formation of joints along both tensile and shearing planes is beautifully illustrated at numerous localities. Commonly the joints produced by tensile forces are nearly perpendicular to the bedding. Two sets of joints, equally inclined to the bedding and making obtuse angles with each other, are clearly in the shearing planes.

The attitudes of joints produced by shearing and their relations to bedding would be identical with fissility, as described on pages 656–659. Whether the structure be called fissility or joints would depend upon their number. If numerous and close together the structure would be called fissility; if fewer and farther apart, jointing The same compression might produce fissility along one set of shearing planes, and joints along another. If the above be true, it is clear that there are all gradations between joints and fissility. It has been suggested that the term "fissility" might perhaps be wisely restricted to the cases where the structure is secondary to a previous one, such as cleavage or bedding, and that the term "joint" should be used to cover fractures along independent shearing planes.

In thus explaining many joints as the result of the same forces which produce folds, it is not meant to imply that there are not joints of other origins, but merely that the master joints, which run in different directions approximately parallel to the strike and dip, may be thus explained, and these are the joints which are the most useful in determining the structural relations of different series.

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[1] Géologie expérimentale, par A Daubrée, pp 315-322, Paris 1879

[2] George F Becker Finite homogeneous strain, flow, and rupture of rocks Bull Geol Soc Am, Vol IV, pp 41-75, 1893 The torsional theory of joints. Trans Am Inst Min Engineers, Vol XXIV, pp 130-138, 1894

ZONE AFFECTED BY JOINTS

Joints, implying as they do openings in the rocks, are necessarily confined to the outer zone of fracture and the middle zone of fracture and flowage. In the first zone they are of more importance and probably more regular than in the second. In the deeper zone of rock welding no joints can develop. In rocks once buried to this depth, which subsequently reached the surface by erosion, joints may be formed; for in approaching the surface they passed from the zone of flowage, through the zone of fracture and flowage, into the zone of fracture.

RELATIONS OF JOINTS TO STRATIGRAPHY

If there is a greater number of sets of joints in an inferior formation or formations than in a superior formation or formations, the two divisions being of such lithological character as to be equally likely to take on jointing, this argues that there may be discordance between the two sets, for it is probable that the lower set of formations, which has the more complicated jointing, was subjected to orogenic movements which produced a part of these fractures before the upper series was deposited. Comstock has applied this as the determining criterion in separating three supposed series of rocks in the Llano district of Texas. The lower series of formations is said to have three sets of pronounced joints running in definite directions, while the middle series has only two sets of joints running in definite directions, these two being common with two of the three in the lower series, and the upper series has a single set of joints running in a definite direction, this system being common to both the inferior series. Comstock's inference is that the system of joints in the lowest series not found in the upper two series was produced before the upper two series were deposited, and that the two sets of joints found in the lower series, one of them also affecting the middle series and both absent in the upper series, were present before the latter series was deposited. That is, the lower series was subjected to three orogenic movements, the middle series to two, and the upper series to one. Considering that two or more sets of joints may be developed by a single orogenic movement, it would seem that such a conclusion should be supported by other criteria.

SECTION V.

FAULTS.

ORIGIN OF FAULTS.

Faults differ from other rock fractures, in that there is important dislocation along the fractures, and often also they are far more extensivs. Like joints, faults may be classified into *tension faults* and *compression faults*, the first forming in the normal planes and the second in the shearing planes. Faults are, however, usually defined as normal and reverse. A *normal fault* is one in which the overhanging side descends in reference to the other, while in the reverse fault the overhanging side ascends in reference to the other. Another term applied to reverse faults is *thrust faults*, implying that tangential thrust is the controlling factor. As equivalent to normal fault may be placed the *gravity fault*, implying that gravity is the predominant force.

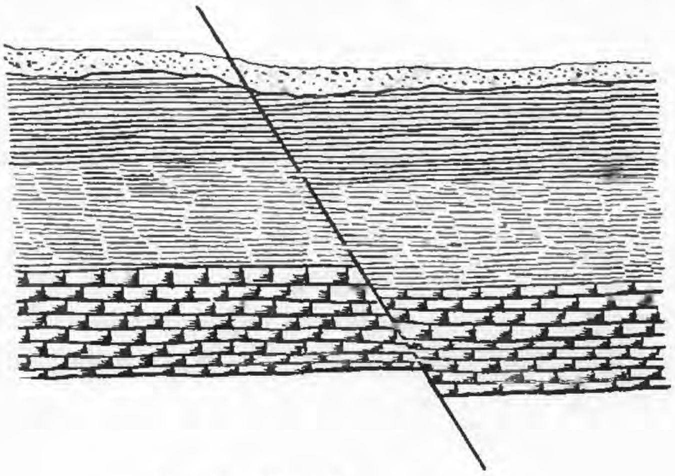

FIG. 137.—Normal or gravity fault.

In the case of the normal fault the overhanging side has a smaller base than the other. Consequently, by force of gravity it descends, as compared with the other side. In all cases, both of normal and reverse faults, gravity is a never-ceasing force. As first explained by Le Conte,[1] the principle of the inclined plane thus applies to these two forces, the hade of the fault giving the inclination of the plane. Where the hade is greater than 45°, if the forces of gravity and tangential thrust are equal the fault is normal, because gravity controls the movement (fig. 137). If, on the other hand, the hade is less than 45°, tangential thrust

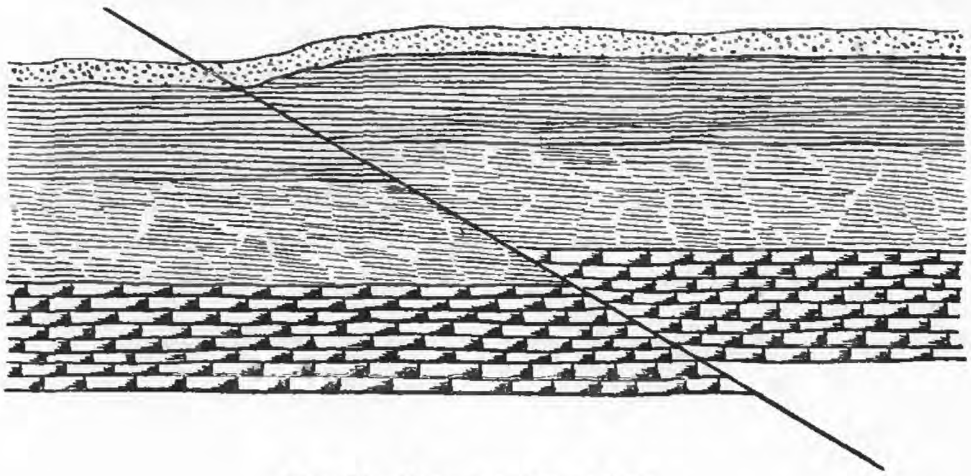

FIG. 138.—Reverse or thrust fault.

is the predominant force, and the fault is a reverse one (fig. 138). As the hade becomes steep, gravity has greater and greater relative power, and if the hade is very steep, gravity may be able to overcome the tangential thrust, even if the latter is several times as great as the former. So, also, if the hade is flat, tangential thrust even much weaker than gravity may overcome it and produce a reverse fault. This is one

[1] On the origin of normal faults, and of the structure of the Basin region. Joseph Le Conte. Am. Jour. Sci. (3), Vol. XXXVIII, pp. 257-263.

reason why, as a rule, normal or gravity faults have steep hades, while reverse or tangential faults have flat hades.

There is, however, another reason. Since tension faults form in the normal planes, they are usually steeply inclined or nearly vertical. But the very idea of tension faults implies that there is no thrust. Hence, gravity has its full effect, and the overhanging side goes down with reference to the other side. It does not follow, therefore, that all gravity faults are tension faults, although this may be the case. Compression faults form in the shearing planes, and they are therefore likely to be much inclined to the vertical. In order that rupture shall occur the thrust must be great, and hence compression faults are usually, and perhaps always, thrust faults.

Perhaps it would be well to classify faults as gravity faults and thrust faults, rather than normal and reverse faults, and thus give them names which refer them to the predominant causes. For the present this classification is preferable to the classification tension faults and compression faults; for it is possible, though hardly probable, that an inclined fracture may result from compression, and after a time thrust lessen in amount, so that gravity controls the final differential movement.

RELATIONS OF FAULTS TO EXPANSION AND CONTRACTION.

Gravity faults result in the dilation of the part of the crust affected by them (fig. 137). Thrust faults result in the contraction of the part of the crust affected by them (fig. 138). In a region in which many parallel faults occur, all of the same character, the dilation or contraction may be a considerable percentage of the breadth of the area disturbed. Since the amount of dilation or contraction with a given vertical movement increases as the hades become flat, and since thrust faults have flatter hades on the average than gravity faults, the shortening of the crust in a region of thrust faults is usually greater than the elongation in another region in which gravity faults are about equally abundant and in which the vertical displacements are the same.

RELATIONS OF FAULTS TO STRIKE AND DIP.

While there is great variability in the direction of faults, due to exceptional causes, faults are more frequently parallel to the strikes and to the dips, other things being equal, than in other directions, so that faults are sometimes spoken of as strike faults and dip faults. Since a fault may be no more than a displaced joint, this relation is easily explained in the same manner as in the case of joints. (See pp. 669–670.)

RELATIONS OF FOLDS TO THRUST FAULTS

It has been long recognized that thrust faults are often related to overfolds. If the strata are in the zone of combined fracture and flowage, the overfolds may be broken along the reversed limbs and the arch limbs be thrust over the trough limbs. In a region of overfolds and thrust faults, if it could be determined whether the differential movements are such as to carry the material moved toward the surface or away from the surface, it could be decided whether such folds and faults should be called overthrusts or underthrusts. But the differential movements, the forms of inclined and overturned folds, and the character of the thrusts are identical, whether a given bed above be considered as moving forward and upward as compared with the layer below, or be considered as moving forward and downward as compared with the layer above. In fig. 139, if the force be considered as applied at A, it would be called an overthrust fault; if the force be considered as applied at B, it would be called an underthrust fault; and yet the phenomena are identical. The movements must be such that the material goes in the direction of relief, and it is probable that this is more often toward the surface of the earth (see p. 622) rather than deeper within the earth. It is probable that in certain cases thrust has been transmitted by a strong formation or series and pushed under other strata. This is particularly likely to occur where the lower strata are weaker or where the material in advance of the active strata transmitting the force has been already raised into folds, and thus partly escapes the pressure. (See pp. 606–607, and fig. 109.)

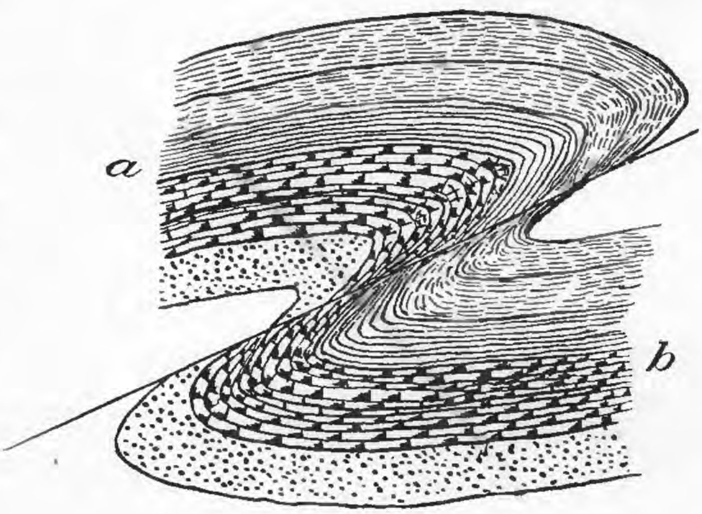

FIG. 139.—Fold passing into fault.

As explained by Willis, in regions which are but lightly loaded the forces producing thrust faults may result in clean-cut fractures, with scarcely any bowing of the layers of the rocks along the shear planes (see figs. 127 and 128, and pp. 659–660). In passing to greater depths the load is greater, and the layers, instead of all having the full movements of the clean-cut thrust faults, adjacent to the fault planes may be found to be in sharp overfolds in opposite directions upon opposite sides of the faults (fig. 139). Where the load is still greater these folds are of increased importance. Under still greater load the rocks may be first bent into an overfold, with little faulting, and finally at a greater depth the deformation may occur altogether by overfolding. It is therefore clear that in the same mountain mass there may be all gradations between clean-cut thrust faults and overfolds without faults. The transition may be longitudinal, as in the case of the Appalachians, where thrust faults which occur in the extreme southeast are gradually replaced by overfolds to the northwest. Also the transition may be transverse. In the latter case, if erosion cuts the strata to different depths after such a region was deformed, the overfolds may be found in the central parts of the mountain mass, the transition phases upon the intermediate areas, and the thrust faults without overfolds upon the outer flanks of the mountains.

Rocks at a certain depth, and therefore under a definite load, may be deformed first by folding and afterwards by faulting. Suppose a rock is deeply buried, but not so deeply as to cause the superincumbent load to equal its ultimate strength. Suppose the differential stress for a given stratum under these conditions to surpass the elastic limit, but not to reach the ultimate strength of the bed. It will then be deformed by folding, but during the process shearing occurs on the limbs, and as a result the bed is thinned, and finally the stress may surpass the ultimate strength of the rock, which will then be fractured and perhaps faulted. The same result may be reached if before a stratum or formation is thinned the differential stress increases so as to go beyond the ultimate strength of the rock. It follows from this that deformation by folding followed by faulting is normal for a considerable zone, for when the mountain-making forces for a given region first begin their work, it is to be supposed that the differential stress is moderate. As the stress increases in amount so as to exceed the elastic limit the layers would begin to be folded, and fracture would occur as soon as the differential stress reached the ultimate strength of a given layer, provided the rock was not in the deep-seated zone of flowage.

It has been seen (p. 659) that accompanying thrust-faulting fissility may develop parallel to the faults, and accompanying overfolding cleavage may develop which dips in the same direction as the axial planes of the folds. In an area intermediate between the zone of fracture and the zone of flowage, this being at successive times under the conditions of flowage and of fracture, there may be overfolding and cleavage combined with thrust faults and fissility. In passing from a faulted to a folded area, as has been noted, first there may be fissility along the thrust faults, then the strata may be slightly overfolded and tucked under along the faults, this undertucking becoming more and more prominent and fissility at the same time being replaced by cleavage, and finally we may have overfolds with cleavage, with or without faulting. Each of the different phases of the steps of change may occur on a large or small scale. In some places in an intermediate area a dozen little overfolds with fault slips may be seen upon a single hand specimen. Hence I conclude that *the average deformation of a region may be the same whether it be by a few great faults with little or no fissility, by more frequent lesser faults with or without fissility, by faults and overfolds with or without both cleavage and fissility, or by folding with or without faults and cleavage;* also that *there is every gradation between faulting and fissility, and probably every gradation between faulting and cleavage.*

ZONE AFFECTED BY FAULTS

A fault may vary in magnitude from a fraction of an inch to many thousands of feet. A fault, like a joint, is limited in horizontal as well as vertical extent. It can not be assumed to extend very far beyond where observed. A fault of an inch may die out within a few inches, both laterally and vertically; a fault of a hundred feet, within a few hundred feet; a fault of five thousand feet, within a few miles. In following a fault longitudinally the throw may be found to become less and less until it is zero, just as a bunch of paper may be torn for a part of its length and the different parts of the torn ends be differently displaced. But while faults may thus die out within short distances, they may have remarkable persistence, both in direction and in length. This does not necessarily imply that they have great persistence in depth, for just as a fold has a tendency to die out, as explained (pp. 599–600), a fault may also die out below, and sometimes also above. In the latter case the fault usually occurs in a stratum or a formation which is brittle as compared with the overlying rocks. Because of the more plastic character of the higher strata the deformation there occurs by folding. *Probably most faults at sufficient depth pass into flexures, and deeper down these flexures may die out.* (See figs. 96 and 97 in preceding paper by Dale, p. 567.) As already explained, when a bed is deformed under little weight the strain necessarily causes fracture, and the readjustment is largely by faulting along the fractures. When all the conditions are the same, except that there is such load that as a whole the rocks are in the zone of flowage, the necessary deformation is accomplished by folding. In regions of close folds it is probable that before the superincumbent beds were removed by erosion many of the latter were faulted instead of folded, for they were in the zone of fracture and flowage, and in the zone of fracture rather than the zone of flowage.

Possibly the depth at which important faults disappear is in many cases not more than 5,000 meters, although the discussion of the depth of earthquake shocks due to faults leads to the conclusion that some faults extend to the depth of a number of miles.

If there are inclined planes of weakness in the deep-seated zone of flowage, the deformation may largely occur by faulting along these planes.[1] Such inclined planes of weakness may be in sedimentary rocks or in igneous rocks. Since masses of intrusive rocks, either in the form of dikes or of bosses, usually have vertical or steeply inclined exteriors, faulting is particularly likely to occur at the contacts of igneous rocks with one another, or at the contacts of igneous with sedimentary rocks. It has already been explained that such deep-seated faults would differ in no way from the differential movements

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[1] The Mechanics of Appalachian Structure, by Bailey Willis Thirteenth Ann Rept, U. S Geol. Surv, pp 217–274 1893 Especially Pls XCV and XCVI

resulting in cleavage or fissility, except that the movements are mainly confined to narrow zones. This results in great displacement at the fault zones and little displacement in the areas between the faults. In such supposed deep-seated faulting it is to be remembered that the displacement takes place without crevice or joint. At any given movement the rock is to be regarded as welded together. The different parts simply shear over one another along the plane of greatest weakness.

RELATIONS OF FAULTS TO STRATIGRAPHY

Faults may be used to discriminate between series in precisely the same way as joints, and the criterion has far greater weight. If an inferior set of formations has a more complicated faulting than an upper series which lithologically is equally likely to be faulted, this is strong evidence that the lower set of formations was faulted before the upper set of formations was deposited. Faults are frequently not easy to demonstrate or to trace out. Hence this criterion for discriminating between series is not so valuable upon the whole as are the more conspicuous and readily discovered phenomena of folds, cleavage, fissility, and joints, but if the conditions are favorable for tracing out the faults of a region, the information thus furnished may give positive evidence as to structural breaks between series.

GENERAL.

In the foregoing pages folds, cleavage, fissility, joints, and faults are regarded as the conjoint products of thrust and gravity. Similar forces acting upon heterogeneous rocks under various conditions produce diverse phenomena. Thus several classes of phenomena which are often treated as independent and unconnected are genetically connected. A fault may accord in inclination with any of these structures. Between faults and joints, fissility, or cleavage there are all gradations. When there is a marked displacement along a break it is called a fault. Whether a given minor displacement is thus named often depends upon the point of view. Wherever there is fissility there is slipping or faulting, using this term in its exact sense. Usually minor displacements are not called faults unless they occur across the beds or other structures. A displacement across a prior structure of such magnitude as to be called a fault might be ignored if it occurred along the structure. Folding and cleavage belong normally to the zone of flowage; fissility, joints, and faults belong normally in the zone of fracture. In the zone of combined flowage and fracture all the structures occur together in a complex manner, the particular combination of phenomena depending upon the relative thickness, strength, and brittleness of the rock beds concerned.

SECTION VI.

AUTOCLASTIC ROCKS.

ORIGIN OF AUTOCLASTIC ROCKS

When rocks are folded by strong orogenic forces, and they are not so heavily loaded as to render them plastic, they are frequently broken into fragments, and "*autoclastic*"[1] rocks are produced. The autoclastic rocks which readily show their origin may be called *dynamic breccias*, and those which resemble ordinary conglomerates may be called *pseudo-conglomerates*. Brittle rocks are the most likely to become autoclastic; hence it is that cherts, quartzites, cherty limestones, graywackes, and rather siliceous slates are some of the kinds which most frequently present the phenomena described. The movements of the broken fragments over one another in many cases so thoroughly round them that they have the appearance of being waterworn, and the matrix between the larger fragments may consist almost wholly of well-rounded fragments of a similar character. For instance, in a semi-indurated quartzite the larger complex fragments may be well rounded by their mutual friction while the matrix may consist of the simple original waterworn grains which are rent apart. In another case the original rock may have consisted of beds of mud interlaminated with thin beds of grit. By consolidation and cementation these beds may have been transformed to alternating shale and graywacke. The shale is plastic under slight load; under the same load the graywacke is brittle. When such a set of beds is deformed the shale yields largely by flow and the graywacke by fracture. The beds of graywacke are broken into fragments of varying sizes, which are ground over one another, and thus are rounded. At the same time the shale flows and fills the spaces between the fragments. Also slaty cleavage may be developed. As a result, a pseudo-slate-conglomerate is produced, having a slate matrix and pebbles of graywacke, which, so far as its own characters are concerned, could not be discriminated by anyone from a true conglomerate. Fortunately, in most cases it is possible to find transition phases between such a rock and one in which the process has not gone so far, and thus one is enabled to determine that the rock is autoclastic. One method of the formation of pseudo-conglomerates is described by Dale in the previous paper. (See fig. 100, p. 569.)

ZONE OF AUTOCLASTIC ROCKS

The zone in which autoclastic rocks may be produced is confined to the outer 10,000 meters of the earth's crust, and the formation of widespread autoclastic rock is probably limited to the outer 5,000 meters. At a depth greater than the larger number the pressure in all direc-

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[1] Structural geology of Steep Rock Lake, Ontario, H L Smyth, Am Jour Sci , 3d ser , Vol XLII, p 331

tions exceeds the crushing strength of any rock, and therefore if it were possible for crevices to form such as are necessary to produce brecciation they would be almost immediately closed by flowage. Consequently, at great depths it is to be supposed that no crevices form in the rocks as the result of dynamic movements, and therefore that no breccias are produced.

From the foregoing it follows that autoclastic rocks may develop whether the formations concerned are homogeneous or heterogeneous. Also that they may develop whether the beds are all within the zone of fracture for them or whether they are in the zone of fracture for a part of them and in the zone of flowage for the other part. In the first case dynamic breccias are likely to form. In the second case only the stronger rocks are broken, the fragments being buried in the members which flowed, and pseudo-conglomerates are frequently formed.

RELATIONS OF AUTOCLASTIC ROCKS TO BASAL CONGLOMERATES.

Since it is possible that pseudo-conglomerates may be mistaken for true basal conglomerates, the criteria which discriminate the two are of great importance.

(1) An autoclastic rock must derive its material mainly from the adjacent formations. If, for instance, it is produced from interstratified. layers of limestone and quartzite, it will contain only limestone and quartzite detritus, and the fragments will be mainly from the more brittle formation. Further, an autoclastic rock may have a part of its material from the superior formation as well as from the inferior. However, in some cases the brecciated layer may itself have been conglomeratic, although not a basal conglomerate, and thus some material will be found from extraneous sources. But in most instances the material is of local origin. In true basal conglomerates, on the other hand, while the material is very frequently derived in large measure from the immediately subjacent formations, they also usually contain a small proportion of material from various foreign sources, and do not contain any material from the overlying formations, as may the autoclastic rocks.

(2) In an autoclastic rock, if the pebbles are closely examined they will in many cases be found to be less rounded than in a true basal conglomerate. If the belts of brecciation be followed for some distance a considerable variation will frequently be found in this respect, fragments being here well rounded and there very imperfectly rounded. The well-rounded fragments are concentrated, as are also the angular fragments. A basal conglomerate, on the other hand, has a considerable uniformity in the degree of the rounding of its pebbles in passing along the same horizon, but at the same place the large fragments may be angular and the small ones well rounded. In a basal conglomerate very near to the underlying formation many of the contained fragments may be angular, but in an extreme case the fragments of a basal con-

glomerate are upon the average usually not so angular as those of an autoclastic rock.

(3) In many cases the interstices of an autoclastic rock are filled with material of a vein-like character, whereas in a basal conglomerate the filling material is largely finer detritus. But sometimes, as in the case mentioned of a semi-indurated quartzite, the filling material of an autoclastic rock may be waterworn grains of sand, which have been separated by dynamic action, and are therefore indistinguishable from the ordinary matrix of a true conglomerate.

(4) In most instances a bed of autoclastic rock, if followed, may be traced into an ordinary brecciated or partly brecciated form. A basal conglomerate, on the other hand, if followed along the strike and dip, may change its character, but it will be a gradual change into the ordinary mechanical sediments, whereas an autoclastic rock is likely to have very sudden variations in character.

Using all of the above criteria, it is difficult in some cases to discriminate between an autoclastic rock and a true conglomerate. Usually, however, if an area be studied sufficiently long, and if the relations be examined closely, a true judgment may be reached.

Autoclastic rocks are not likely to develop from shales and limestones, but if near enough to the surface even these rocks may become brecciated. As a consequence of orogenic movements, in the zone of combined fracture and flowage, where the alternate layers are thick, the shales and limestones may flow and the cherts and quarzites become brecciated. The brecciated and nonbrecciated layers, under these circumstances, may not become mingled to any considerable degree. Thus we may have a set of autoclastic rocks interstratified with layers which show no sign of brecciation. It may be that the plastic layers, as a result of the stress, may be minutely corrugated. The movement of the broken particles in the rigid layers against the crests and troughs of the folds may have truncated them. We might then have pseudo-conglomerates resting upon folded truncated layers (fig. 153), and it might be concluded that there is a structural break between the two, the inference being that one formation was folded and truncated before the overlying clastic formation was deposited upon it. This occurs in the Marquette district of Michigan.

Another case is as follows: A lower shale or grit may be overlain conformably by a sandstone. By cementation these formations may become indurated; the grit into graywacke, and the sandstone into quartzite. After this an orogenic movement may develop cross cleavage or cross fissility in the softer, lower formation, the secondary structure abutting against and sharply terminating at the overlying quartzite. The same movement may develop a pseudo-conglomerate in the overlying formation. In the later stages of the process the differential movement may tear off fragments of the lower slate or schist and include them with the broken, harder formation. Such a pseudo-conglomerate simulates to a remarkable degree a basal conglomerate resting unconformably upon an earlier series, in which it might be supposed that the secondary structure was produced before the overlying formation was deposited. Exactly these relations obtain within the Ajibic quartzite formation of the Lower Marquette series, northeast of Palmer. At first it was supposed that the pseudo-conglomerate was basal and marked an unconformity, and it was only after the locality was repeatedly visited and studied in the utmost detail that the true relations between the two formations were discovered.

Similar phenomena may occur between formations different from those above described, in which the inferior formation is weaker than the superior formation.

As another illustration of the great difficulty in sometimes distinguishing between the two, a case in the Adirondacks may be cited in which a thick formation of gneiss is overlain by a bed of crystalline limestone containing interlaminated smaller beds of gneiss. The whole series has been closely folded. The gneiss, as a result of the folding, is closely corrugated, and to a certain extent its upper folds are truncated by the shearing action. The limestone has acted like a fluidal substance, accommodating itself easily to its new position, and by recrystallization has taken on a massive character. The thin belts of gneiss within the limestone have been broken to fragments. The fragments in the limestone matrix have ground against one another until they became well rounded. They are disseminated through the limestone (Pl. CXIII). As the layers of gneiss are thicker and more numerous near the base of the limestone, this part of the formation appears as a limestone containing numerous bowlders and smaller fragments of gneiss resting upon a gneiss formation. Thus an unconformable contact was inferred when the area was first examined, but an extended and close examination of the region showed all stages of transition, from the phase of the rock which appeared to be a true conglomerate to that in which the thin layers of gneiss are interstratified with limestone. Similar phenomena have been observed in the Original Laurentian area and in the Marquette district of Michigan. (See p. 804.)

ABUNDANCE OF AUTOCLASTIC ROCKS IN THE PRE-CAMBRIAN.

As the number of orogenic movements has been so much greater upon the average in pre-Cambrian rocks than in post-Cambrian rocks, it follows that the autoclastic rocks in these ancient formations are far more important than in the later deposits. As a matter of fact they are found to cover extensive areas in Algonkian regions.

SECTION VII.

METAMORPHISM OF THE SEDIMENTARY ROCKS.[1]

Metamorphism is here used in its broad sense to cover the alterations of all classes of rocks by all processes. In what follows no attempt will be made to give a full treatment of the subject. The purpose is rather to briefly sketch a few of the more important processes of metamorphism which have affected large areas of the pre-Cambrian rocks in North America, and to point out the original conditions and the forms which have resulted from the modification of the various rock masses. The metamorphism of the sedimentary rocks will be considered more fully than the metamorphism of the igneous rocks, as in stratigraphical work the former is of more importance, although it is recognized that it is necessary to understand the manner of metamorphism of the igneous rocks in order to discriminate between the altered forms of the two classes.

The prominent forces producing metamorphism are pressure, heat, and chemical affinity. Pressure may be resisted by rigidity, or may pass into mass motion. In the former case the conditions are those of *static metamorphism*, and the motions are molecular. In the latter case the conditions are those of *dynamic metamorphism*, and the motions are both molecular and mass. The heat may result from dynamic action, be obtained from liquid rock intruded from below, or from the interior of the earth by the normal increase of temperature due to depth. In the chemical changes water is the menstruum through which most of the transformations are made. It carries the materials from one place to another, and thus the composition of great masses of rocks may be changed.

PROCESSES OF METAMORPHISM.

The chief processes considered in the transformation of the sedimentary rocks are consolidation, welding, cementation, injection, metasomatism, and mashing.

Usually in the formation of a metamorphic rock two or more of these processes act together, but in some cases one is predominant, in others another, and in still others two or three or more may be equally important. Nevertheless, it is advisable to consider each of the above processes by itself, the nature of the work it performs, and the results which may be produced by the particular process without others, so far as this can be done. This is not possible in some cases, since with certain processes others always occur. The metamorphosing processes mentioned are taken up below in the order of complexity, the least complex being considered first. In general, however, the rocks treated under each individual process are the joint products of that particular metamorphosing process, and those processes which have gone before. It is

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[1] At a future time I hope to treat metamorphism and the metamorphic rocks in a general and more satisfactory manner

customary to speak of certain of the processes of metamorphism as static and of others as dynamic, but in a strict sense all changes which take place within rocks are dynamic. All involve the movement of material. However, in some cases the movements are largely molecular, and for such cases the term static will be retained (with the understanding that it is not accurate) as a convenient term to separate them from those cases in which extensive movements of the rocks in large masses is the dominating fact in alteration. To the latter the term dynamic metamorphism is here restricted.

CONSOLIDATION.

One of the processes which change sedimentary rocks from their original condition to an altered condition is that of consolidation. Consolidation is produced by the mere pressure of superincumbent strata or by the stress of thrust, so that the mineral particles are brought closer together. As a consequence the rock becomes coherent. The cause of this coherency, resulting from the readjustment and nearing of the particles, is a question for the physicist rather than for the geologist. This coherent power is particularly efficient in the case of clayey rocks and other rocks composed of fine particles.

WELDING.

If rocks are so deeply buried that the superincumbent weight is beyond the crushing strength, or if they are in the zone of flowage, it is possible that the particles may become welded together and thus form a crystalline rock. This depth would of course vary for different minerals and rocks, and consequently there would be a thick middle zone of combined consolidation and welding between an outer zone of consolidation and an inner zone of welding. It may, perhaps, be unusual for strong sedimentary rocks to reach the zone of welding and afterward arrive at the surface by erosion, but that welding assists consolidation at very moderate depths for the softer materials—such as coal, clay, and limestone—can hardly be doubted.

CEMENTATION.

By cementation is meant the binding together of the rock particles by the infiltration of mineral material in solutions and its deposition as minerals in the interstices of the rocks. Of these minerals the most important are quartz, opal, calcite, ferrite, mica, chlorotoid, chlorite, feldspar, augite, zoisite, epidote, and serpentine. Many other rock-forming minerals act as cements, but their importance is small. Of all of the foregoing minerals quartz is the most important, calcite the next in importance, and ferrite third. Under the term ferrite is included hematite, limonite, magnetite, and the other oxides of iron. Hematite and limonite are, however, the more abundant ferriferous cements.

The crevices may have been the minute spaces between the grains, the laminar cracks between the fissile leaves, or larger crevices parallel to or cutting the lamination (fig. 145). Between the three cases there are all gradations. In all cases the secondary minerals interlock, and in the larger spaces they may have a coarsely crystalline structure. The quantity of entering material varies in different cases from a relatively unimportant amount to predominance. The minerals from extraneous sources may permeate the rock through and through, and fill all the interspaces, microscopic and macroscopic. The result is in many instances to give a most extraordinarily complex structure, the places between the original minerals being filled, the folia being emphasized by the parallel impregnation, and the whole being intersected by larger masses of holocrystalline interlocking mineral materials, some of which are parallel to the original structure, some of which are diagonal to it, and some of which are parallel for a certain distance and then cut across it. The material filling the larger crevices often has distinct vein-like forms (fig. 145). When examined carefully, the impregnating material parallel to the lamination may be found to follow the folia very closely, or it may be found to follow along them for some distance, then break across one or more, and then follow them again. In proportion as there is a tendency for the material to break across the folia the veins usually are of unequal size, and the original laminæ sometimes appear to be farther apart than would be true under ordinary conditions. This suggests that the entering material may have acted as a wedge, forcing asunder the laminæ. The process of cementation may be said in general to apply to all porous rocks, and in many cases it is the chief cause of induration.

In the cementation of rocks the new mineral material may be added in different ways. It may attach itself to the old grains of like mineral character, or it may be deposited as independent interstitial material; if mineral particles be fractured, it may heal them with the same or some other mineral. When the interstitial mineral attaches itself to an old mineral of a like character, the two being in optical continuity, the mineral is said to have been enlarged. This enlargement process is far more important in the case of quartz than in the case of any other mineral, although enlargements of feldspar, hornblende, calcite, garnet, and tourmaline have been observed, and some of them frequently. This process of enlargement means that the component grains of a clastic rock are minerals still, and have the structure and potency of minerals. These minerals, originally produced in igneous or metamorphic rocks, are taken from their original positions and deposited in a secondary rock. The beds are buried by overlying formations. Mineral-bearing solutions pass through the new rock, and each mineral fragment chooses from the solutions material like itself. This it attaches to itself in optical continuity, even though the time intervals between the first and second growths be indefinitely long. By this renewed growth crystal faces are often rebuilt. If the growth continues, the enlargement of a particle meets similar enlargements from other grains. By further growth these interlock, and finally fill up all the interspaces and perfectly indurate the rock.

The process of cementation is largely confined to the two higher of the three zones of which we have knowledge—the zone of fracture and the zone of combined fracture and flowage. When fully within the lower zone, it is not to be supposed that the particles are physically separate; therefore there is no opportunity for cementation.

INJECTION.

By injection is meant the penetration of a rock by a molten magma. The injected material may fill the larger crevices, such as those produced by fissility, jointing, faulting, or brecciation, and to some extent it may penetrate the interspaces between the individual grains of ordinary sedimentary rocks. But it is probable that pure igneous injection between the mineral particles does not usually penetrate a great distance from a continuous mass of the magma.

It is believed, as will be seen below, that the process of injection passes by gradation into cementation. The forms which injection veins take are in all respects similar to those produced by cementation, and veins produced by either process may have the same relations to the previous structure of the rock. (See pp. 684–685.)

Magmas of any kind may be an injecting material, but intermediate and acid rocks more frequently inject rocks in a complicated fashion. If the injected material penetrates between the grains, it may add a large amount of some new mineral. For instance, if in a mica-schist a feldspar is plentifully added, it may be transformed into a gneiss. If the injections are parallel to regular planes of fissility, the rock will not only be foliated but will be banded, the old layers having all of the original minerals, and possibly added new ones, while the spaces between the folia are composed almost wholly of the entering material. Such a banded rock may have an added complexity due to dikes of the same minerals which do not follow the lamination. In the more complex regions, after a first injection, it has happened that there was complicated fracturing of the rocks, thus making new crevices. These have made the conditions favorable for a second injection, and this has followed. It is not improbable that in some regions there have been several distinct periods of fracturings and injections. Observation has shown that injection is particularly likely to occur adjacent to bosses of igneous material, especially to great batholites of granite, syenite, porphyry, and other acid or intermediate rocks.

CEMENTATION AND INJECTION.

Pegmatization has been variously explained as the result of true igneous injection, of aqueo-igneous action, and of water impregnation or cementation during ordinary metamorphism. For a long time the last two theories were generally supported. Recently Brógger[1] has

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[1] Syenitpegmatitgange der sudnorwegischen Agit und Nephelinsyenite, W C Brogger, Zeitschr fur Kryst , Band XVI, 1890, pp 215-235

strongly enforced the idea that pegmatite veins are true igneous injections. In support of this idea he cites the undoubted frequent association of pegmatitic veins with intrusive masses of acid rock, and the fact that many of the pegmatitic veins behave like other eruptives, and that their structure is that of igneous rocks. That certain pegmatites are eruptives seems to have been shown beyond question. In favor of a possible different origin for some pegmatites, it is to be noted that intrusive masses of rock would give favorable conditions in the adjacent rocks for impregnation by the aqueo-igneous process or by the ordinary metamorphic process, in either case furnishing a source from which the material could be drawn by warm percolating waters, and thus enable them to take large quantities of mineral matter in solution.

It seems to me that to adequately explain all the facts of pegmatization described in various regions of the world, we must conclude that all three processes have been at work—in some cases igneous injection, in some cases aqueo-igneous action, and in other cases pure-water cementation, and in still others combinations of two or all of these processes. It is further believed, that there may be no sharp separation, but, on the contrary, all gradations between the three—that is, it is thought highly probable that *under sufficient pressure and at a high temperature there are all gradations between heated waters containing mineral material in solution and a magma containing water in solution. In other words, under proper conditions water and liquid rock are miscible in all proportions.* From the water solutions true impregnation or cementation would take place; from the rock solutions, true injection. Pegmatization may comprise these and the intermediate processes.

Indeed, is it to be expected that under great pressure and at high temperatures there will be any sharp line of demarcation between the processes of aqueous cementation and igneous injection? At the surface it is usually easy to sharply separate aqueous from igneous action, but deeper within the earth even the strongest rocks are latently plastic. At great pressure heated waters must have power to absorb a quantity of material far beyond that at the surface of the earth. Truly liquid rock is highly impregnated with water. It therefore seems not improbable that at considerable depths we may have, on the one hand, material which all would call water solution, and on the other hand, other material which all would call liquid rock, with no sharp division line between the two. If this be so there will be all stages of gradation between true igneous injection and aqueous cementation, and all the various phases of pegmatization may thus be fully explained.

This idea of continuity was first suggested to me by the phenomena observed in the schistose rocks surrounding the intrusive core of the Black Hills. Remote from the intrusives the sedimentary rocks are mica-slates; adjacent to it they are mica-schists and mica-gneisses. The core rock is a great batholite of granite, 7 miles broad and 11 miles long. Besides this central mass there are to the southwest a number of smaller masses, from 1 to 4 miles long, which may be connected below with the greater mass. From the central mass great quartz-feldspar dikes radiate. In passing away from the core the dikes become smaller and have a less typical form. At the same time the material assumes the appearance which we ordinarily denominate as pegmatitic. These veins might be considered true igneous injections. Passing still farther away, the pegmatitic masses begin to have vein-like characters—that is, there is a rough concentration of the material in different layers parallel to the walls. In going still farther away, a true banded-vein structure is found. In passing yet farther away, feldspar becomes less and less important in the veins and the quartz more abundant, until remote from the granite the impregnating material is mainly quartz. In the pegmatized area of schist, adjacent to the granite, there is also an extensive development of feldspar within the interspaces of the rock, changing it into a gneiss. If one examined only the outer zone, in which the quartz impregnations occur, he would not doubt that they were ordinary deposits from water; if he examined the masses of the inner zone, adjacent to the great granite mass, he would not doubt that they were true igneous injections; but passing back and forth from one zone to the other, he observes that there is every gradation between the two, and must reach the conclusion that true igneous injection was predominant adjacent to the mass; that in the central zone aqueous and igneous agencies were about equally important, and that in the outer zone aqueous agencies were predominant. It is impossible to believe that the larger dikes—plainly offshoots of the central batholite—are not igneous injections; it is equally impossible to believe that the ordinary granite magma has penetrated to considerable distances between the individual grains of the schist and thus impregnated it with feldspar.

In the Lake Superior region, in some places there is a great development of feldspar within the interstices of rocks, and in the crevices, of minute pegmatitic veins of quartz and feldspar where no granite mass has been discovered even by the closest detailed study, and where the rocks of lower formations are entirely free from granitic intrusions. In this case it seems clear that pegmatization has taken place during the metamorphism of the rocks, in connection with dynamic action, and without the assistance of any extraneous igneous material, and is therefore essentially aqueous. In contrast with this case is that described by Brögger in southern Norway, in which igneous injection satisfactorily explains all of the phenomena. It is to be noticed that in this region the process of pegmatization occurred at a maximum depth of 2,000 feet, while much of it occurred at a depth varying from 100 to a few hundred feet. The more complex phenomena of pegmatization which can not be explained by igneous injection alone, so far as my observation goes, are in regions in which the rocks have been buried to a very considerable depth.

METASOMATISM.

Metasomatism may be defined as the process of metamorphism by which original minerals are partly or wholly altered into other minerals, or are replaced by other minerals, or are recrystallized without chemical changes, or one or all of these together. In the alteration of a mineral into other minerals, or in its replacement by other minerals, there may be addition or subtraction of certain constituents. As a result of the changes, the new rock may gain or lose variety in the minerals composing it. Either by the substitution of constituents, or by the loss of constituents and therefore concentration of other constituents, a rock may have a predominant mineral.

Under the same conditions that metasomatism transforms a rock it may be also modified by consolidation, welding, cementation, injection, or mashing.

Metasomatism may be considered (*1*) from the point of view of the alteration of the original mineral particles, or (*2*) from the point of view of the minerals which are produced by the process of alteration, or (*3*) from the point of view of the texture of the rock produced.

(*1*) *Alterations of original mineral particles.*—To trace out all the changes in the rock-forming minerals would require a treatise, but fortunately the abundant rock-forming minerals are few in number, and the more abundant minerals which result are also not numerous. The more common changes of the more common minerals are summarized below:

Opal, *chalcedony*, and *quartz* do not alter into other minerals, although they may be replaced by other minerals, and may furnish silica, in whole or in part, for replacing other minerals, or may furnish silica which unites with other compounds and assists in the modification of adjacent minerals. Opal may take on a crystalline condition and become chalcedony or quartz. Actinolite, serpentine, and magnetite have been observed to replace quartz. In the case of the two former minerals, the manner of the replacing is such as to suggest that the serpentine and the actinolite have eaten their way into the quartz, since needles of actinolite and fibers of serpentine project into the quartz beyond the solid mass of these minerals. These relations suggest that the other constituents, with the exception of silica, were at hand or were furnished by percolating water out of which the serpentine and actinolite formed, and that the quartz itself may have furnished the necessary silica to produce these minerals.

Feldspar alters extensively in a number of different ways. From the acid feldspars, with or without the addition of other constituents, quartz separates, and with this one or more of the micas, a more basic feldspar, or kaolinite. From the intermediate and basic feldspars, with or without additional substances, develop one or more of the minerals quartz, chlorite, zoisite, epidote. Some of the more common cases of alteration are as follows: Feldspar passes (1) into quartz and muscovite, the secondary muscovite being frequently in minute flakes, which are often called sericite; or (2) into quartz, more basic feldspar, and muscovite; or (3), with loss of alkalies and alkaline earths, into quartz and kaolinite; or (4), with the addition of magnesium and iron, into quartz and biotite; or (5), with addition of iron and magnesium and loss of alkalies, into quartz and chlorite; or (6), with loss of alkalies, into quartz and zoisite or into quartz and epidote; or (7), into acid feldspar and zoisite. These alterations are not always distinct and separate in the same mineral. To illustrate, out of the same granule of feldspar, biotite, muscovite, another feldspar, and quartz may form. In a similar way other combinations may take place at the same time.

Amphibole most frequently alters into the uralitic form or into chlorite, and from this zoisite or epidote may develop. Biotite also often results from the alteration of amphibole.

Augite frequently alters to hornblende, and from this secondary and tertiary minerals, as above, may be produced; or the augite may alter directly into chlorite, and from this zoisite or epidote may develop; or it may pass at once into biotite.

The micas, biotite and muscovite, as fragmental constituents, are usually permanent, although not infrequently the biotite may be bleached. The permanence of the fragmental constituents of this character is very natural, since, as seen by the foregoing, biotite and muscovite are minerals which are extensively produced from other minerals by metasomatic processes.

In *calcite* a part of the calcium may be replaced by magnesium, and dolomite is produced. The carbon dioxide may be liberated and the calcium oxide may unite with other compounds, present or infiltrated, and form various complicated silicates, especially tremolite.

In place of *dolomite*, we may have, with loss of carbon dioxide and union of the magnesium and calcium oxide with silica, tremolite; when impure and by union with other substances, hornblende or other silicates.

Ankerite is here used to inclnde minerals intermediate between dolomite and siderite. In place of ankerite we may have (1) by loss of calcium, magnesium, and carbon dioxide, and gain of oxygen and in some cases water, magnetite, hematite, limonite, goethite, or turgite; or (2) with loss of carbon dioxide and union of the bases with silica, actinolite.

In place of *siderite* we may have (1) magnetite, by loss of carbon dioxide and with partial oxidation; (2) hematite, by loss of carbon dioxide and complete oxidation; (3) goethite, turgite, or limonite, by loss of carbon dioxide, complete oxidation, and hydration; and (4) grünerite, by loss of carbon dioxide and union of the iron protoxide with silica.

(2) *Minerals produced by alterations.*—The individual minerals produced by alterations and replacements will not be here given, as this

would be but a repetition in a different order of the matter on the previous pages. However, it not infrequently happens that in a given rock a single secondary mineral may be abundant or predominant. In this case the process may be named by this predominant mineral. Some of the more important of these processes are micatization, feldsparization, amphibolitization (which would include actinolitization, grünneritization, and uralitization), chloritization, zoisitization, epidotization, ferritization, and dolomitization.

For the most part these processes are so well understood that they will not be here separately described. For the present purposes they are sufficiently outlined in the consideration, upon subsequent pages, of the individual metamorphic rocks. A few words may, however, be said in reference to some of them.

Silicification covers both the deposition of silica within the interstices of rocks and the replacement of other minerals by silica. In reality it is a combination of the cementation and metasomatic processes, using these terms in their broadest sense. As the original minerals change from one form to another, quartz may be produced by their decomposition, or silica may take advantage of the changing combinations, entering and occupying the places once held by the original minerals. Also crevices formed by dynamic action or otherwise are taken advantage of by silica and deposited either in opaline or quartzose form. Oftentimes the larger amount of the silica comes from an extraneous source. The quantity of silica thus entering may be so great as to produce rocks bearing 90 per cent or more of silica. The secondary silica may deposit as opal, chalcedony, or quartz, or as an intimate mixture of them. The areas of rocks affected by silicification are oftentimes great, and the the process may transform the character of entire formations.

Among basic sedimentary rocks serpentine very often develops. Its manner of acting is similar to that of silica. It may occupy the crevices and cracks formed by dynamic action or in other ways, or the spaces between the constituent minerals, or, finally, the place once taken by other minerals. Exactly as in the case of silica, material for the serpentine may be furnished in part or in whole by the minerals present, or the material of the serpentine may come from an extraneous source. Also, widespread formations may be extensively serpentinized, so as to give for considerable areas almost solid masses of serpentine.

(3) *Texture of rocks produced.*—If the conditions are static and the processes of recrystallization are complete, there is a tendency to preserve the original structure of the rock, whether it be massive or banded. If the static conditions were those of unequal stress in various directions, the metasomatic minerals may have an arrangement with their shortest diameters in the direction of greatest stress, or with their readiest cleavage in one of the principal planes of stress.

Of the cleavable minerals, chlorite, biotite, and muscovite, the former is likely to form under static conditions. In proportion as dynamic action is important, biotite and muscovite often develop instead of chlorite. This relation may be studied in a formation which has been mashed in different degrees.

Usually, under static conditions the minerals interfere with one another in their development, so that crystal outlined particles are not produced, and for any given small area the structure may be as interlocking and crystalline as in the case of an ordinary igneous rock.

However, as will be shown below, when dynamic conditions are followed by static conditions there is often a distinct tendency toward the development of porphyritic minerals. As the minerals rearrange themselves by metasomatic processes large individuals of certain minerals may develop in the interspaces between the other minerals, often inclose the other surrounding minerals, or else absorb the material of which they are composed, and thus grow by their destruction. Such minerals very commonly have crystal outlines. The more important minerals of this kind are mica, chiastolite, garnet, staurolite, feldspar, tourmaline, cyanite, fibrolite, chlorotoid, and hornblende. In this class of minerals a single individual may be larger than hundreds of individuals of the background. The individuals sometimes reach a magnitude of several inches, and those of an inch in diameter are common. The minerals mentioned differ in their capacity to absorb the other minerals which before occupied the space they now occupy In proportion as they lack capacity to absorb the constituents of prior minerals, they have the capacity to grow around and inclose them, so that a single individual may be a large, reticulating, honeycombed mass which incloses a large amount of other material. In some cases the inclosed material may be several times as great in quantity as the host. As minerals conspicuous for their capacity to include other minerals may be mentioned andalusite and staurolite; occupying an intermediate position are garnet and feldspar, while tourmaline usually does not contain any considerable quantity of the prior minerals.

Often the porphyritic minerals show a distinct zonal structure, comparable in every way to the zonal structure sometimes shown by minerals in igneous rocks. The zonal structure is frequently seen in minerals having a varying composition, as, for instance, garnet, and is rare or has not been observed in minerals having a rather definite chemical composition, as, for instance, staurolite. It is believed that this zonal structure is due in most cases to the varying composition of the mineral solutions or adjacent minerals, or both. In some cases there may have been an actual cessation of growth and later a renewed growth. In this case the renewed growth is analogous to the process of enlargement of fragmental mineral particles.

The porphyritic minerals usually show no evidence of pressure or of dynamic movements unless orogenic forces have been at work since their formation. However, such minerals develop chiefly in schistose rocks which have before suffered profound dynamic action. Often accompanying the movements great masses of intrusive rock have appeared, and under these circumstances the secondary porphyritic constituents are particularly likely to be found. Considering these facts, and also that the minerals themselves show no dynamic effects, it appears highly probable that they have developed under nearly static conditions after strong movements have ceased, but while the solutions present were heated either mechanically or by the intrusives, or both. Perhaps the most conclusive evidence of this is furnished by mica, chlorite, and chlorotoid, which in some cases occur in large, well-defined crystals, with their cleavages at right angles to the schistosity of the rock. Thin sections in some cases show that the crystals have not been strained. This occurrence is finely illustrated in the Manhattan schist of New York and also in the mica-schist of the Upper Huronian in the Lake Superior region. Had the rock been subjected to important interior movement since the development of the crystals, it is not probable that they would have their present positions.

That the porphyritic minerals are statically developed is still further indicated by the frequent appearance of them in a somewhat regular but by no means invariable order as the degree of metamorphism increases. Variations in their order of appearance and the appearance of certain minerals in some cases in preference to others are largely explained by differences in the original composition or the structure of the metamorphosed rock. In the feebly metamorphosed rocks chiastolite often first appears. This mineral is frequently found in cleavable slates. As the metamorphism becomes a little more intense garnet is found. This mineral may be abundant in the mica-slates. As the metamorphism goes still further staurolite develops. This mineral with garnet is abundant in the mica-schists. At the same time chlorite may appear; feldspar may come in simultaneously or before, but is usually later than the garnet and staurolite. In a further stage of metamorphism ottrelite and cyanite appear. These may be found in the mica-schists, and particularly characterize the mica-gneisses. In the extreme stage of metamorphism hornblende and mica are abundantly found. Abundant new tourmaline usually marks a somewhat advanced stage of metamorphism, and often is present in the schists peripheral to intrusives, and especially granite. The different areas are not usually sharply defined, but grade into one another, and the most intensely metamorphosed area may contain all of the minerals developed by feebler metamorphic processes. This is to be expected, for, by the supposition that the porphyritic minerals developed at the time of unusual heat, during heating and cooling the conditions would be successively favorable for the formation of each of the minerals.

In the case of regional metamorphism, when dynamic action ceased the conditions would be favorable first for the development of minerals requiring high temperature, and would be successively favorable for the formation of minerals requiring lower and lower temperatures.

In the case of metamorphism produced by intrusion, for the zone nearest to the igneous rock there would be successively the conditions for the formation of minerals requiring least heat, more heat, and most heat, and then again, as the mass cooled, for those requiring less heat and least heat. During the heating process the porphyritic minerals first developed might later be transformed into other minerals requiring a higher degree of heat for their development, as described by Emerson.[1] In the remote areas affected by the intrusion only the minerals requiring the least heat would develop.

MASHING.

Under mashing is included the process which is usually described in geological writings under the terms dynamic metamorphism and shearing, the authors meaning by the latter differential movement along certain parallel planes. However, it is not usually recognized that shearing parallel to one plane is invariably accompanied by shearing transverse to this plane. Nor is it generally understood that pure shortening is possible only by shearing along two sets of intersecting planes, each set being inclined to the direction of shortening. In other words, in the cases ordinarily described as shearing, there is really shearing along at least two sets of intersecting planes, and shortening in another direction. (See pp. 636–640.) As the term shearing is ordinarily used, it seems to be assumed that the structure produced by the movement develops in the shearing planes, when, as shown on previous pages, this may or may not be true. In the zone of flowage mashing occurs, and the secondary structure develops in the normal rather than in the shearing planes. In the zone of fracture the secondary structure develops in the shearing planes. For the foregoing reasons the term mashing is introduced to cover the deformation of pure shortening and the more complex deformation of pure shortening accompanied by shearing motion. It is hoped that shear and shearing may be restricted to their proper usage.

In the treatment of folding, cleavage, and fissility it has been shown that layers are deformed by plastic flow, by fracture, and by accommodations between them, but each of the beds of a formation or a series of formations has a considerable thickness, and in the deformation not only must readjustment occur between the beds but rearrangement within the beds themselves. When individual minerals are pressed or pulled to a sufficient extent they are deformed by flow or fracture or bending, or two or all combined, and thus are adjusted to their new positions. (Fig. 101 and Pl. CXV.) This deformation may be partly accomplished by the rearrangement of the mineral particles with respect to one another.

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[1] Porphyritic and Gneissoid Granites in Massachusetts, by B. K. Emerson. Bull. Geol. Soc. Am., Vol. I, 1890, pp. 559-561.

The process may go so far as to much flatten the grains by flowage or to produce peripheral or entire granulation of the individual original grains. In different cases all phases of the latter may be seen, from slight undulatory extinction, through fracturing, to the well-known peripheral granulation and to the condition in which all the grains of all the minerals are wholly granulated. Not only may all the minerals and combinations of minerals thus be flattened by flowage or granulation, but the resultant layers or particles may be intermingled to some extent, and thus we may have laminated or foliated schists with a regular alternation of minerals of different kinds or combinations very similar to what has often been taken to be bedding. If the original rock was a coarse conglomerate and the metamorphism is complete, each pebble makes a lamina of a different kind from those adjacent, and thus gives the rock a banded character.

Under the same conditions in which mashing occurs, consolidation, welding, cementation, injection, and metasomatism are doing their part, and probably more actively than under ordinary conditions. That consolidation is at work is plain. The thrust causing mashing may also produce welding. The movements in the outer parts of the crust form numerous cracks, which at once give access to water, heated probably by dynamic action and therefore rich in solutions, and hence conditions are favorable for cementation and injection. That dynamic action promotes metasomatic change is well known. Under such circumstances the alteration of the old minerals to new ones permanent under the new conditions goes on with great rapidity.

While pebbles or minerals are frequently spoken of as stretched, for the most part this term can not be applied in the same manner that it is to india rubber or steel, for most minerals pass their elastic limits by comparatively slight deformation. Consequently, in closely folded rocks the deformation is mainly not by the molecular strain of elasticity, but by the processes above described. As has been seen under Cleavage and Fissility, when beds are deformed the flattening, rotation, and development of new minerals all combine to develop a parallel arrangement with longer axes or cleavage, or both, in a common direction, thus producing rock cleavage, or fracture occurs along shearing planes, thus producing fissility. The rocks therefore acquire the property of slatiness or schistosity, and the process which produces these properties is mashing. There are found, of course, all stages, from the stage in which a thin layer of slate or schist is produced across, within, or between beds, to that in which all or nearly all of the rock is changed from its ordinary character to a slaty or schistose one.

Under stress different beds, pebbles, and grains act differently, depending upon depth of burying and upon texture. There are therefore the same cases here as under cleavage and fissility. These are the interior movements of both homogeneous and heterogeneous rocks in the zone of flowage and the zone of fracture. A rock which as a whole is so deeply buried as to essentially obey the law of flow, may accomplish this result largely by the fracturing of the individual mineral grains as well as by their rearrangement and plastic deformation.

From the foregoing it is plain that slates and schists are the conjoint product of one or more of the processes of mashing, metasomatism, injection, cementation, welding, and consolidation.

Deformation in the zone of flowage.—Minerals deformed in the zone of flowage show no interspaces under the microscope, but their remarkable shapes, undulatory extinction, and granulation in polarized light give evidence of their change of form (fig. 101). If the beds are homogeneous and are composed of particles of small size they may approach a uniform viscous liquid in their character and obey the laws of plastic flow. Since in most cases the stress is unequal in three dimensions, there is a direction of greatest pressure; at right angles to this is a direction of mean pressure, and at right angles to these two a direction of least pressure. Plastic material composed of particles of small but measurable size, when placed under these forces, may be lengthened in the direction of least pressure and shortened in the direction of greatest pressure, and one or the other in the direction of mean pressure, depending upon its power. As a consequence, the particles will be arranged with their greater, mean, and minor diameters corresponding to least, mean, and greatest pressures. Also if new minerals develop they will form, according to the same law, with their major axes in the direction of least pressure, their mean axes in the direction of mean pressure, and their minor axes in the direction of greatest pressure. In proportion as the flow is differential, parallel to a certain plane, the mineral particles will be rotated by the shearing motion from a position at right angles to the direction of greatest normal pressure, although at any given time the mineral particles will tend to develop with their longer axes at right angles to the maximum pressure.

Under the subject of Cleavage and Fissility it has been seen that under different circumstances the direction of the cleavage dependent upon mashing may be at right angles or parallel to bedding, and that in heterogeneous rocks it may vary from one to the other within comparatively short distances or within a single bed.

It is believed, for the same reasons applicable to cleavage (see pp. 636–641), that in most cases of widespread uniform slates and schists the structure originally develops, as above described, in the normal planes rather than in the shearing planes. If this be true, it is objectionable to describe slaty and schistose rocks as sheared, with the implication that the structure is in the shearing planes.

Deformation in the zone of fracture.—In the zone of fracture it has been shown that fissility is produced. The relations which this structure has to bedding have been fully given (pp. 656–659). By the rubbing of the laminæ over one another the mineral particles tend to become arranged with their longer axes parallel to the planes of greatest fissility, whether these are across the bedding or parallel to it. The individual grains take these positions as a result both of fracture and of rotation. If the movement continues long enough each grain will have its greatest diameter nearly in the plane of fissility and in the direction of greatest movement, its mean diameter in the same plane and at right angles to the greatest diameter, and its least diameter perpendicular to the plane of fissility. If the fissility developed along a previous cleavage the mineral particles were previously arranged with their longer axes in the planes of fissility. If so, this arrangement may be emphasized by the differential movement between the laminæ.

In the elongation of the grains in the major plane of shearing or fissility they may be stretched in a direction cutting this (figs. 129 and 130), and thus a set of tensile fractures may be produced. In the case of these parallel tensile fractures cutting the fissility, the latter structure may form, and probably very often has formed, secondary to a previous cleavage. The phenomena of tensile parallel fractures are particularly well shown in certain of the Black Hills quartz-schists and in some of the Adirondack mica-gneisses. In the gneisses the parallel cracks traverse both the quartz and the feldspar fragments.

In more numerous cases there are two sets of compressive fractures across the mineral particles, cutting each other, and in some instances these intersect the slatiness or schistosity. These cases are explained by fractures along the two sets of shearing planes. When they intersect a cleavage it is probable that the rock was first in the zone of flowage. Under these conditions cleavage developed in the normal planes. Afterward the rock passed into the zone of fracture, and two sets of intersecting planes of fracture were formed across the cleavage. If the direction of stress be inclined to the cleavage, as is usually the case, one of the sets of shearing planes is controlled by the previous cleavage, as described above, and a fissility develops along the cleavage planes.

The tendency to produce fractures across the mineral particles along parallel planes may be modified by the texture of the rock. The forces are nowhere received by any individual grain exactly in the average direction. The combination of forces which affect each grain or fragment is a function not only of the direction of the larger movement but of the particular way in which the part of the forces which acts upon the particle is transmitted to it. Hence, one could not expect in any case that there would be perfect regularity in fracturing, but merely that there might be a general parallelism.

The tendency for the particles to break in parallel directions would be further modified by the cleavage of the minerals. Instead of responding to the forces like a homogeneous substance, the much greater ease of breaking along certain planes of cleavage, rather than along other planes, would often be the controlling factor, the forces being resolved into those parallel and perpendicular to the cleavage. Therefore, unless the mineral particles have similar axial orientations, it is not to be expected that in rocks composed of readily cleavable minerals the verification of the law of parallel fractures will be found. On the other hand, in the case of difficultly cleavable minerals like quartz it should more frequently be found to apply, and such is the fact. Quartz rocks which have been subjected to crushing pressure often show a marked tendency to fracture in one set or two sets of right-angled planes. That this is not mineral cleavage is shown by the fact that the planes of fracture sometimes run across entire sections without reference to the orientation of the individual grains.

While the parallel fractures above described are rather frequently noted where the movements along the shearing planes are comparatively slight, upon the whole they must be considered the exception rather than the rule. Ordinarily, where there is a decided fissility, for the reasons just given the fracturing of the mineral particles is irregular, producing granulation.

The cracks formed along the planes of fissility by the slipping of the laminæ over one another, and the more minute cracks formed by the complex fracturing of the individual minerals, may be healed by welding or cementation. The cracks within and between the grains may be cemented by substances the same as or different from the minerals cemented. If the cementation be imperfect, secondary gas or liquid-filled cavities may be formed. Usually the broken fragments are somewhat displaced, but occasionally, in the case of parallel fractures, the particles are broken apart and left very nearly in their original relative positions, in which case the healing may be so perfect that the fact that the rock has been fractured may be shown only by the gas or liquid-filled cavities and by the secondary inclusions. Thus are explained many of the inclusions in cavities which are so frequently noticed to occur along regular parallel planes.

In many cases the cementation of the fissile laminæ fills the cracks with secondary materials, and the cementing mineral or minerals in a given case are usually different, or in different proportions, from the minerals of the adjacent laminæ, and hence there is a tendency to preserve and emphasize the laminated arrangement (Pl. CXVII). Igneous injections would perform the same healing function and also give the rock a banded character. In either way, or by a combination of the processes, a rock may be formed having a regular alternation of layers of differing characters, the structure having no relation to original bedding.

METAMORPHIC SEDIMENTARY ROCKS

It is not the intention to consider all the metamorphic forms of sedimentary rocks, but merely those which constitute important pre-Cambrian rock masses.

ROCKS MODIFIED MAINLY BY CONSOLIDATION AND WELDING.

The effects of consolidation upon the various forms of conglomerates, sandstone, grits, and shales are so well known that nothing need be said. Deeper within the earth it is probable that the grains are not only brought into close contact, but are actually welded.

ROCKS MODIFIED MAINLY BY CEMENTATION, ASSISTED BY CONSOLIDATION.

Usually cementation works in conjunction with consolidation. The latter is important in the finer sediments, and assists in the coarser sediments. In the finer sediments cementation may be as important or more important than consolidation, and is far more important in the coarser sediments. The ordinary sandstones are mainly indurated by consolidation and cementation. The more common cementing materials are iron oxide, calcium carbonate, and silica. Any one of these may be the chief cementing agent, or two or three may be combined. Iron oxide is a weak cement. Calcium carbonate is of medium strength, and silica is a strong cement. Each of these cementing substances may attach itself to old grains of like composition, or it may separate as an independent mineral in the interstices.

Quartzite.—One of the most important rocks produced by the cementation process is quartzite. The term quartzite is here restricted to quartzose sandstones which have been so firmly indurated by the cementing process that when broken the fractures pass through the original grains and not around them. Less firmly cemented rocks may still be called sandstones. In the production of indurated sandstone and quartzite the quartz may be deposited either as enlargements of old grains or as independent interstitial material. In either case the induration may be so perfect that a vitreous quartzite is produced. In many parts of the continent the process of cementation has transformed from sandstone to quartzite extensive areas, each covering hundreds or thousands of square miles, and of widely differing geological ages. These quartzite formations vary in thickness in different places from a few feet to as much as 12,000 feet. If we suppose a sandstone to be composed of spherical grains of quartz of equal size, the particles being packed as closely as is possible, the amount of new quartz required to completely fill the interspaces is, as calculated by R. S. Woodward, more than one-third of that occupied by the original grains. In no sandstones are these conditions fully realized, for the grains of sand are of different sizes, and there is also in the interstices more or less extraneous material. On the other hand, it is not likely that the grains are packed by natural processes in the most compact manner possible. If we suppose the space to be reduced by one-half, the amount of quartz added is still one-sixth of the amount of that originally existing in the rock. It is therefore certain that the amount of secondary silica required to indurate such great quartzite formations as occur in the Paleozoic and pre-Paleozoic of the continent is enormous. That required for vein filling is inconsiderable as compared with this. Many of the cemented quartzites show little or no evidence of strain, which proves that dynamic action has not been potent in the induration. Neither is there any evidence that a high degree of heat is requisite to dissolve the silica, or to deposit it as quartz upon or between the old grains.

Arkose.—In an arkose the infiltrated material may enlarge both the feldspar and the quartz, or crystallize independently. Graywackes may also owe their induration almost wholly to this process of cementation. One of the chief infiltrated minerals which indurate this class of rocks is quartz, but feldspar, chlorite, calcite, and ferrite all play an important part.

ROCKS MODIFIED LARGELY BY INJECTION, BUT ASSISTED BY CONSOLIDATION, CEMENTATION, METASOMATISM, AND MASHING.

All of the classes of rocks described as metamorphic on the previous and following pages may be subjected to the process of injection. Usually that form of injection or cementation known as pegmatization has occurred only among rocks which are profoundly metamorphosed, and especially by the process of mashing. If pegmatization occurs without extraneous igneous injection it can be expected only in the cases of extreme metamorphism. Therefore, sandstones, graywackes, slates, quartzites, and similar little-metamorphosed rocks are rarely pegmatized, while on the other hand quartz-schists, mica-schists, mica-gneisses, and impure marble are often pegmatized. The processes of alteration are those described under the other headings, with the addition of the injected or infiltrated pegmatitic material. As the material of the pegmatite is more often quartz and feldspar than any other minerals, the schists are often transformed to gneisses, which may be merely laminated or may be banded, this depending upon the degree to which the pegmatizing process goes.

ROCKS MODIFIED MAINLY BY METASOMATISM, CEMENTATION, AND CONSOLIDATION, BUT ASSISTED BY MASHING.

Graywacke and graywacke slate.—Graywackes and graywacke-slates are produced from grits and mudstones. The grit may be composed almost wholly of quartz and feldspar, when it may be called an arkose, or with the quartz and feldspar there may be a great variety of other fragmental minerals, among which mica, pyroxene, and amphibole are important. These may be either simple fragments or complex fragments derived from fragmental rocks, from the crystalline schists, or from the igneous rocks. The process of induration, so far as the quartz is concerned, is the same as in the modification of sandstones to quartzites. The old quartz grains are enlarged and in the interstices new quartz is deposited, thus firmly cementing the rock. Other cements, such as calcite and ferrite, may be present. In the arkoses the induration may be wholly by the infiltration of the quartz, as already indicated, combined with the enlargement of the feldspar grains. More commonly the feldspar partly or wholly decomposes. Its most frequent alteration is into chlorite and quartz, or mica and quartz, although from it any of the minerals or combinations of minerals given as produced by the decomposition of feldspars (pp. 689-690) may be produced. Where there was little mashing chlorite is apt to be abundant. As mashing becomes important mica appears instead of chlorite. The fragmental pyroxene and hornblende may be decomposed, producing various secondary minerals (see p. 690). The complex fragments may alter in many ways. To describe them would be to give a treatment of the alteration of minerals. The final result of the alteration is to produce a consolidated rock which may have a very great variety of mineral constituents. One of the most characteristic features is, however, as indicated by its name, its gray color. If the original rock be fine-grained, the rock may have a structure somewhat similar to a slaty structure parallel to the bedding, and it may be called a graywacke-slate. While the new minerals may have something of a tendency to similar orientation, they usually do not become regular parallel. The slight tendency toward a parallel arrangement usually accords with bedding, but in some cases it may not do so. The banded character of the original rock is ordinarily preserved, even if all of the decomposable detrital minerals are altered into new ones.

Ferruginous chert and jaspilite.—By ferruginous chert is meant all that class of rocks composed of the various iron oxides and chert. Chert is used to cover silica in its opaline, semicrystalline, or completely crystalline, quartzose form. Chert differs from quartzite, however, in being nonfragmental. Some common names applied to different phases of the ferruginous cherts are ferruginous slate, hematitic slate, and limonitic slate. These rocks are often produced from siliceous siderite or ankerite by the decomposition of the iron carbonate and the partial or complete oxidation and hydration of the protoxide of iron, combined with the rearrangement of the particles, and frequently the introduction of silica. Where the constituents of the rock are not extensively rearranged the original regular stratiform arrangement of the siderite is preserved, and the rock is called a ferruginous slate. As the rearrangement goes further, oxide of iron is apt to become concentrated in bands, alternating with bands which are predominantly chert. Also in this stage a concretionary nodular or geodal character is apt to be developed, and then the material may be called banded ore and jasper, or chert with bands and shots of ore. In the earlier stages frequently the silica, as in the original rock, is partly opaline, and as the rearrangement becomes more nearly complete the silica takes the form of finely crystalline, interlocking quartz. Each individual grain may become coated with a film of hematite, thus giving it a red color. In this case banded iron oxide and jasper are produced, called by Wadsworth jaspilite. These processes are best illustrated by the iron-bearing formations of the Lake Superior region.

Grunerite-schist.—Grunerite-schist is a rock consisting of interlocking grünerite and quartz, with or without magnetite, other iron oxides, and accessories of various kinds. It is often produced from siliceous siderite. By the decomposition of the iron carbonate the iron oxide is set free. In part it takes on more oxygen and becomes magnetite, and in some cases hematite. In part it unites with silica present or with that introduced to form iron silicate or grunerite. At the same time a part of the original silica usually recrystallizes as quartz, and often silica is introduced from an extraneous source. The process is then one of metasomatism. Very frequently there is a greater or less concentration of the quartz, so that the rock consists of alternate bands. In one set of these bands grunerite is abundant or predominant, in the other it is sparse. The grunerite needles are not parallel, although their longer axes may have a tendency to lie in similar directions. More often than not this arrangement accords with bedding. While the rock is spoken of as a schist, there is very imperfect cleavage, if any, although the rock parts more readily parallel to alternating bands of grunerite and quartz than in other directions. Grünerite-schists very often are apparently assisted in their development by igneous intrusives. It may be suggested that these igneous rocks have at once prevented the access of oxygen sufficient to completely peroxidize the iron, and have produced hot solutions bearing an abundance of silica, which, favored by the heat, have largely united with the iron present, and therefore developed the grünerite. The chief known areas of grünerite-schist are within the iron-bearing formation of the Lake Superior region.

Actinolite-schist.—Actinolite-schist is a rock consisting of interlocking actinolite and quartz, with or without magnetite, other iron oxides, and accessories of various compositions. Actinolite-schist develops from siliceous ankerite in a way precisely similar to the development of grünerite-schist from siliceous siderite. The only difference is that a part of the silica unites with the calcium, magnesium, and iron to make actinolite. As the conditions for the production of actinolite are incomplete oxidation of the iron and abundance of silica, it naturally follows that the residual iron oxide usually develops into magnetite, as in the case of the grünerite-schists. A part of the silica originally present or that brought in by solution separates as completely crystalline quartz, and as a result of the processes we have an interlocking crystalline mass of actinolite and quartz, or of actinolite, magnetite, and quartz—that is, actinolite-schist, or magnetite-actinolite-schist.

The quartz is usually concentrated to a considerable extent in bands, as a result of which the rock consists of interlaminated layers of quartz containing little actinolite and magnetite and layers composed largely or predominantly of actinolite and magnetite, with some quartz.

These rocks have been most extensively observed in the iron-bearing formations of the Lake Superior region, and further, they have developed most abundantly in the areas where there are numerous cutting and interstratified intrusive rocks, the cause being the same as in the case of grünerite. The mineral particles, in their orientation and arrangement in reference to bedding, are very similar to those in grünerite-schist.

Hornblende-schist.—Hornblende-schist may be produced from an impure dolomite or ankerite, the process being essentially the same as in the production of actinolite-schist or actinolite-magnetite-schist; only, on account of the greater multiplicity of bases present, hornblende is produced rather than actinolite.

Marble.—That limestone is often changed to marble is well known. The change may occur as a metasomatic one, as a consequence of the intrusion of igneous rocks, or as a result of dynamic metamorphism. When the transformation of a limestone to a coarsely crystalline marble occurs the impurities present develop at the same time into various silicates, among which garnet, the micas, pyroxene, amphibole, and serpentine are important. In some cases, at least, as shown by Merrill, the serpentine is secondary to the pyroxene.

Where the beds of marble occur interlaminated with other rocks, which are modified only by consolidation, cementation, and metasomatism, it appears clear that the process may have taken place without mashing. In some cases the depth at which the change took place was not great, and in all probability the temperature was comparatively low. The recrystallization doubtless occurred through the assistance of water. That such a transformation should occur is not surprising, as it is known that limestone forming in warm localities at the present time, by the assistance of water, quickly assumes a granular crystalline condition.

When marble is intruded by igneous rocks it is plain that the necessary conditions for its recrystallization exist—heat and warm solutions. That recrystallization does occur under these conditions is known, not only from observation at numerous localities, but by experiment. In proportion as the limestone is deeply buried and the intrusive mass is large the area of limestone changed to marble increases in size, and in the case of great intrusive bosses the area transformed may be large. In both of the above cases the recrystallization is conceived to have occurred under essentially static conditions.

However, the coarser and more extensive beds of marble are generally in regions in which there has been strong dynamic action. Usually the marble beds between layers of crystalline schists do not show cleavage or fissility, although such a structure is more likely to appear as the marble becomes impure. While the folding was taking place it must be believed that the particles of the limestone moved over one another, although perhaps this relatively soft substance acted more like a viscous body than did ordinary clastic rocks. However this may be, after dynamic action had ceased there was probably sufficient residual heat to recrystallize the calcium carbonate under static conditions into a completely granular rock. Doubtless the process was promoted by hot solutions. The fact that the altered limestone takes a massive crystalline character similar to that which it assumes in contact with an igneous rock is confirmatory evidence of the supposition of static conditions at a higher temperature than normal. The supposed static recrystallization of marble has its parallel in the fragmental rocks in the development of large crystals of garnet, staurolite, and other porphyritic minerals.

From the above it is not to be inferred that marble never shows evidence of cleavage or fissility. If before or after recrystallization it be deformed, and afterwards does not again recrystallize, the rock may show a brecciated, laminated, or schistose structure, and the individual crystals of calcite or dolomite may be thoroughly granulated.

ROCKS MODIFIED LARGELY BY MASHING, BUT ASSISTED BY METASOMATISM, INJECTION, CEMENTATION, WELDING, AND CONSOLIDATION.

Schistose quartzite and quartz-schist.—Schistose quartzites and quartz-schists are produced from quartzose sandstones or quartzites. The processes of mashing and cementation may go on together in the little altered sandstone, or the sandstone may first be cemented to a quartzite and a later movement, combined with cementation and metasomatism, may develop from it a schistose quartzite or quartz-schist. At many places all stages of gradation may be seen. These stages may be best observed in a region not too strongly folded, for here, on the crests and in the troughs of the folds, there will have been but little readjustment, while on the limbs of the folds, and especially between the beds, the movements may have been considerable, and thus on the crests and in the troughs of the folds and in the center of the beds the least changed rocks will be found, while at the outer parts of the beds and on the limbs of the folds a completely crystalline schist may be formed. In the least mashed phase the quartz grains may be but slightly flattened or rotated from their original positions. In passing to a more altered phase regular lines of fracture may occasionally appear at right angles to each other. As the pressure becomes stronger granulation begins, which first affects the exterior of the grains, but finally entirely destroys them. At the same time in the interstices new quartz and perhaps secondary mica may have developed from the impurities, and thus there will be formed from an ordinary sandstone or quartzite a completely crystalline quartz-schist or micaceous quartz-schist, showing no sign of fragmental origin. Occasionally the entire rock may recrystallize later under static conditions and produce a quartz rock showing little or no strain effects.

The mineral particles have a decided tendency to a parallel arrangement. In proportion as this tendency appears the rock passes from a quartzite to schistose quartzite, and finally into quartz-schist.

Slate and mica-slate.—Slate and mica-slate develop from fine-grained argillaceous rocks, the chief constituents of which are usually quartz and feldspar. The feldspar alters into quartz and mica. From a single fragmental grain of feldspar are produced many individuals of interlocking quartz and feldspar. At the same time these minerals form in the interstices, and interlock with each other and with those produced from the fragmental grains, so that a completely crystalline interlocking ground-mass of mica and quartz is produced from an arkose. If large fragmental grains of quartz are not present to indicate the clastic character of the rock, the secondary interlocking quartz and mica do not betray this. The mineral particles, and especially mica, have a well-developed parallel orientation, with their longer axes and cleavage in a common direction, and to this is largely due the capacity of the rock to cleave. As mashing continues the rock may become schistose, and as metamorphism progresses it finally passes into a mica-schist.

Mica-schist.—Mica-schists ordinarily develop from a shale, arkose, grit, or conglomerate. Just as in the case of a mica-slate or quartz-schist, all stages of the change may be seen. We have here, besides the decomposition of the quartz-schist into quartz and mica, the granulation of the quartz and feldspar. The process is essentially the same as the development of a mica-slate by metasomatism, except that the fragmental quartz grains are destroyed by mashing, and the fracturing of the feldspar by dynamic action greatly promotes decomposition. The process takes place in its perfection the more easily and with less dynamic action in proportion as the rock is fine grained. Thus, a shale may completely change to mica schist, while an interbedded coarse-grained grit may still reveal evidence of its fragmental origin. In the same way a conglomerate may have its matrix completely changed to a mica-schist, and the resistant pebbles be merely deformed; but in the case of extreme alteration the most resistant and largest pebbles and bowlders are entirely destroyed. Large bowlders may be observed in different stages, from oval forms (Pl. CXV), through greatly elongated and widened fragments, to forms in which the greatest diameters are several times the normal (figs. 155 and 156). In this case the rock, when broken parallel to the direction of greatest movement, appears to be a perfectly crystalline gneiss or schist, but at right angles to this direction still plainly shows its conglomeratic character. As the process goes on the pebbles and bowlders are flattened more and more, until they become thin lenticular masses, perhaps scarcely thicker than cardboard. When the process has gone as far as this the material becomes so mingled with that of the matrix that it is difficult to exactly define the outlines of the fragments, and, finally, as the process continues, no evidence of the pebbles and bowlders is left. In their places are thin strata of material of a mineralogical character different from that of the adjacent laminæ. At the same time that this extreme mashing is going on, the rock takes on more and more a finely laminated character.

At various steps of the process the matrix may be in turn mica-slate, mica-schist, and foliated mica-schist. In proportion as the process continues the mineral particles more nearly approach a parallel orientation, instead of a part of them winding in and out about the more refractory particles (see p. 640).

Mica-gneiss.—Mica gneisses develop from shales, arkoses, grits, and conglomerates in the same manner as do the mica-schists, except that out of the old feldspar a good deal of new and usually acid feldspar is produced, especially albite. The development of new feldspar is particularly likely to take place when adjacent igneous intrusions have occurred, and especially granitic intrusions. Doubtless the hot mass of granite promotes the formation of solutions which carry abundant feldspathic material, and out of this, in part at least, the new feldspar develops.

Chlorite-schist.—In case of the graywackes, the alteration of the feldspar may produce quartz and chlorite, instead of quartz and mica, in which case a chlorite-schist is produced. Also from volcanic fragmentals, which are especially likely to contain a good deal of pyroxene, amphibole, and basic feldspar, chlorite-schists are abundantly developed.

Hornblende-schist and hornblende-gneiss.—If a fragmental rock has such a composition that hornblende may develop as a secondary product, a hornblende-schist may be produced, and if at the same time feldspar is also abundantly formed, a hornblende-gneiss may result. It is to be said, however, that the perfectly crystalline hornblende-schists and hornblende gneisses which have been demonstrated to have been derived from fragmentals are few in number, and they do not closely resemble the hornblende-gneisses derived from eruptives by dynamic and other metamorphic processes.

Ferruginous chert, jaspilite, grünerite-schist, and actinolite schist.—These rocks have been described as developed mainly by metasomatism, cementation, and consolidation, assisted by mashing. When the latter is subordinate, as in the rocks described, while they have a well-developed laminated structure, they are not strongly schistose. In proportion as mashing becomes important the rocks become strongly schistose. The processes of alteration are the same as already described (pp. 701-703), except that the minerals present before the dynamic action and those that developed during the processes are brought into a parallel arrangement, as explained under mashing. The jaspilites show particularly well the slickensided surfaces due to differential movement between the laminæ. Along and between these laminæ the hematite is flattened into brilliant micaceous flakes, which give a lustrous surface parallel to the planes of fissility.

GENERAL.

In general, when completely crystalline rocks result from the metamorphism of sediments they have a laminated or schistose structure.

Quartzite has in the past been regarded as an exception to this, but it has been seen that this rock also reveals its fragmental character under the microscope, and therefore it is not a crystalline schist in the sense here used. Quartz-schist would come under this definition. Marble, however, is an important case of a completely granular rock produced from a sediment. As explained above, it is thought that the difference in schistosity between ordinary metamorphosed beds and marble is due to the fact that calcium carbonate readily recrystallizes after a dynamic movement has ceased, while this is not the case with other minerals. This is shown by the Adirondack marbles, which contain fragments of the associated gneisses. The crystals of calcite often show little or no strain effects, but the mineral particles of the gneiss show strongly the effects of dynamic action.

Whether mineral particles can be deformed in the zone of flowage without showing strain effects and without recrystallizing is an undecided question. In some cases there may be differential movement along gliding planes in a crystal, as a result of which the relative positions of the different parts of the crystal would remain the same, and therefore in polarized light undulatory extinction would not occur.

The regaining of an unstrained condition by mineral particles in rocks which have been greatly deformed may be parallel to that of the recovery of stretched Canada balsam and the partial recovery of strained steel. When viscous Canada balsam is stretched it takes on a fibrous structure, as shown by polarized light. If not further deformed, after a time under the same conditions of temperature, it loses its polarizing power—that is, the molecules by rearrangement have released themselves from their strained condition. Barus[1] has shown that to some extent strained steel has this same power of restoration at ordinary temperatures. Still more analogous to rocks is the case of strained glass, which in the chemical laboratory has been noted to begin crystallization at ordinary temperatures, whereas carefully annealed, and therefore unstrained, glass retains its clearness indefinitely. Recovery from a state of strain must mean a molecular rearrangement within the solid. Probably the recovery of mineral particles from a state of strain beyond the limit of elasticity can be accomplished only by partial or complete recrystallization. From present information I am inclined to believe that in most if not all cases of crystalline schists in which the mineral particles show no evidence of strain there has been an almost complete recrystallization, partly or wholly under static conditions.

RELATIONS OF METAMORPHIC SEDIMENTARY ROCKS TO STRATIGRAPHY

The amount and character of the metamorphism of a series of formations may be an important guide in structural work. It may serve to separate one series from another and assist in determining the structure

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[1] Fourteenth Ann Rept U S Geol Surv, Part I, p 147

within a series. The criterion has limitations, however, which are readily deducible from the manner in which metamorphic action occurs.

Since metamorphism is produced by consolidation, welding, cementation, injection, metasomatism, and mashing, any one process acting separately or combined with others, it follows that a series of rocks may be profoundly metamorphosed locally and the metamorphism be less or of a minor character in an adjacent area. Not only is this so, but different parts of the same fold are in most cases metamorphosed to a different degree, depending upon the position within the fold. Still further, one set of beds may be more readily metamorphosed than another, so that one formation may become completely crystalline while the adjacent formation may still be plainly fragmental; as, for instance, a shale may change to a mica slate or mica schist and an interbedded quartzite be but little affected by any process except cementation. As pegmatization is so frequently dependent upon the presence of an intrusive rock, it follows that an extreme phase of metamorphism engendered by this, combined with other processes, may have a very local character.

Notwithstanding all of these limitations, if a set of formations be superimposed upon another set of formations, and one has become crystalline throughout, while the other shows little or no change, it is probable that the first series underwent a period of metamorphism before the new series was deposited. But in order to make this conclusion at all certain the superior formations should be of kinds which are equally likely to be metamorphosed; and further, it must be certain that it is a case of superposition, for laterally the metamorphosing forces may die out rapidly and the altered rocks pass quickly into those but little changed. Still further, if the metamorphism be due to pegmatization as a consequence of the intrusion of great batholites of granite the process may die out rapidly in a vertical direction, so that the extremely metamorphosed lower formations would gradually pass into the unmetamorphosed beds higher up, with no structural break. To a certain degree, also, metamorphism occurs directly as a consequence of deep burying, for the deeper the rocks are buried the greater is the pressure to which they are subjected and the warmer the solutions which percolate through them. But probably the change in metamorphism as a result of varying depth of burial is so slow that it would involve no practical difficulty in separating series. It is further clear that metamorphism is much more dependent upon environment, dynamic action, and igneous intrusion than upon age. Age affects metamorphism largely in that old rocks are more apt to be deeply buried, folded, and intruded by igneous masses than are younger rocks.

If the foregoing conclusions are true, the giving of structural names to pre-Cambrian series upon lithological grounds, as was done by Hunt, has no justification whatever.

SECTION VIII.

METAMORPHISM OF IGNEOUS ROCKS.

The definition of metamorphism given in reference to the sedimentary rocks (p. 683) is equally applicable to the igneous rocks. Also the forces producing metamorphism and their manner of working are the same in both classes of rocks.

DEFORMATION.

In the study of folding it has already been pointed out that the structure of igneous masses greatly affects the forms assumed when deformed. If of uniform composition in a large way, as for instance in massifs, the igneous rocks may act as homogeneous bodies; if composed of masses or layers of different character and strength, the readjustments under deformation will comply, at least in part, to the law of heterogeneous rocks.

PROCESSES OF METAMORPHISM.

The igneous rocks include both intrusives and extrusives, and the extrusive rocks comprise both lavas and tuffs. The igneous rocks are modified by the same processes as the sedimentary rocks, namely, by consolidation, welding, cementation, injection, metasomatism, and mashing. On account of the great variety of minerals present in the igneous rocks the processes of alteration are more complicated than in the sedimentary rocks. In this paper no attempt will be made to separately analyze the effects of each of the processes mentioned upon the various types of igneous rocks. It will be sufficient for the present purpose to summarize the results which have been reached by various workers as to the kinds of schists which have been produced from the igneous rocks, and their conclusions as to the forces which have brought about these results. No note will be taken of those modified igneous rocks which still, by their structure and their characteristics, are plainly of igneous origin. These are recognized in the field at once as of igneous origin, and therefore are likely to produce no trouble in working out the stratigraphy. However, at many places there are extensive areas of igneous rocks which are so profoundly metamorphosed as to approach closely in their characters to those of the metamorphosed sedimentary rocks.

For the modification of the igneous rocks to the various crystalline schists and gneisses which form extensively, mashing of the mass of the rock is usually necessary. As a consequence the conditions become, as has been seen in the sedimentary rocks, highly favorable for the action of metasomatism, cementation, etc. Also a fissility is frequently developed, which readily permits of water impregnations or igneous injections. By water impregnation the spaces may be filled, and thus give the rock a banding as well as a foliation, or the same result may be produced by the igneous injections. In many cases where the injected rock bands consist of materials of very different characters, it is probable that successive injections of different character occurred. Following the suggestion of Geikie and Teall, and applying it to a different case, it is not impossible that a heterogeneous magma could be injected along planes of fissility. While the foliated structure of most of the schists and gneisses of igneous origin is thus explained by mashing combined with metamorphic changes after solidification, and often conjoined with impregnation or injection, the banded structure of some gneisses has been explained by other processes. Certain of them have been supposed by Adams to have taken on a flowage structure while a part of the magma was still liquid or very hot and under great pressure. It has been supposed that the banded structure of gneisses could be produced by the differentiation of an igneous mass in situ and by successive intrusions of different material within this mass. Geikie and Teall have suggested that the banded structure of a gneiss may be produced at once by the intrusion of a heterogeneous magma. We therefore conclude that purely igneous gneisses have very diverse histories.

METAMORPHIC IGNEOUS ROCKS.

The more important kinds of metamorphic igneous rocks are classified under schists and gneisses. Included in the schists are pyroxene-schists, amphibole-schists, chlorite-schists, epidote-schists, zoisite-schists, and mica-schists, especially sericite-schist. The gneisses comprise mica-gneiss, augite-gneiss, hornblende-gneiss, and other kinds. There are, of course, all gradations between the different schists and between the different gneisses, as well as between the varieties of schists and gneisses. Hence we have chloritic hornblende-schists, chloritic mica-schists, and many other combinations. It has been conclusively shown that extensive areas of the pyroxene-schists, amphibole-schists, chlorite-schists, epidote-schists, and zoisite-schists have developed from basic igneous rocks, while mica-schist, and especially sericite-schist, when of igneous origin, have generally developed from the more acid igneous rocks. The more basic gneisses have usually developed from basic or intermediate rocks, while acid gneisses of igneous origin, and especially mica-gneisses, have usually formed from acidic rocks.

COMPARISON OF METAMORPHIC SEDIMENTARY AND METAMORPHIC IGNEOUS ROCKS

It has been seen on previous pages that a large number of kinds of schists and gneisses may be produced by the metamorphism of sedimentary rocks; also it has been shown that similar crystalline schists may be derived from igneous rocks. It is further certain that a schist or gneiss may be derived partly from sedimentary and partly from igneous rocks. For instance, a metamorphosed fissile sedimentary rock, such as mica-schist or mica-gneiss, may be injected in a complicated way parallel to the planes of schistosity, and thus produce a banded gneiss, part of which is igneous and part of which is sedimentary. The rock may be predominantly of either one of these materials. If the injected sedimentary rock be subsequently folded, this will produce differential movements parallel to the banding, and the igneous and aqueous bands may be merged into one another and have structures so similar that it is impossible to determine what part of the rock is igneous and what part aqueous. The Manhattan schists of southeastern New York, and especially near Long Island Sound, are a perfect illustration of a gneiss produced by the extreme metamorphism of a sedimentary schist and the subsequent parallel and cross injection of granitic material.

From the foregoing it is clear that an inseparable schist or gneiss formation may be produced from altered intrusive rocks, from altered lavas, from altered tuffs, from altered sediments, and from any possible combination of two or more of these.

Doubtless in regions in which the gneisses are of a very complex character, a number of the processes mentioned in the previous pages, and possibly others unknown, must be united in order to explain all of the phenomena.

While similar crystalline schists may be derived from sedimentary rocks or from igneous rocks, or partly from each, one who has had much experience in the field is apt to have a bias toward the one or the other origin in the case of each particular variety of crystalline schist. But if a given schist formation can at no place be traced into a form characteristic either of a sedimentary rock or an igneous rock, it is extremely hazardous to make positive assertions.

Indeed, in some cases igneous rocks assume aspects which may mislead the most skillful observer. If a rock be intruded in a complicated fashion, the intrusive may inclose and partially absorb many fragments of the intruded rock. These will then have a rounded character, which suggests a conglomerate, and may lead to the belief that the whole is a metamorphic sedimentary rock. This mistake has been made in reference to the Cottonwood granite of the Wasatch, which contains rounded fragments, or else segregations in situ, which have distinctly the aspects of bowlders. Similar phenomena have led to like conclusions in the Lake Superior region. In some instances it may be that the intruded rock is a schist, in which case parallel injections often follow the schistosity. Thus we would have a pseudo-conglomerate, below which are alternating layers of different kinds. These phenomena in the Lake Superior region have led certain geologists to the conclusion that this is a case of downward progressive metamorphism. Lawson has, however, shown that in the

Rainy Lake[1] and Lake of the Woods[2] districts the phenomena are due to *intrusion*. *These difficulties are greatly increased where the rocks* have been mashed subsequent to the intrusions.

Another case in which a crystalline schist derived from an igneous rock may present a deceptive appearance is that of metamorphosed porphyritic rocks, either igneous or sedimentary. By the mashing of a porphyritic igneous rock the matrix may become schistose and the phenocrysts may become rounded and closely resemble residual fragmental material. The resemblance between crystalline schists of this kind and metamorphosed sedimentary rocks in which porphyritic constituents have developed under static conditions is often very close. This is especially so if such metamorphosed sedimentary rocks have been mashed since the development of the crystals. In either case the apparent fragmental constituents are not fragments at all, although in one the rock is an altered clastic.

In another instance secondary lentils or veins of some mineral or combination of minerals may be formed by replacement or in the cracks of the rock. Subsequent mashing may break the veins into fragments and give to them and the separate lentils rounded forms which very closely simulate pebbles. This happens in more instances with quartz than with other minerals.

While the schistose igneous rocks may have foliations, bandings, and lithological characters which very closely simulate those of metamorphosed sedimentary rocks, it is still true of the rocks belonging to the Algonkian and later periods that in many districts the majority of the metamorphosed igneous rocks can be discriminated from the metamorphosed sedimentary rocks.

The much-mashed igneous rocks are apt to have a very regular, fine foliation and great uniformity of character. If an igneous mass gradually varies in composition in its different parts, as is so often the case with differentiated magmas, the mashed varieties grade into one another. The complete absence of minor plications, indicating the absence of a parallel structure before the schistosity was produced, is most striking. It should perhaps be remarked that this is a reversal of the interpretation frequently made at the present time, and which was almost universally made a few years ago. The conclusion is that *the finely, regularly laminated, homogeneous crystalline schists are usually of igneous origin.*

The converse proposition, that the banded and heterogeneous schists and gneisses are of sedimentary origin, can not be made, for the igneous rocks, intrusive and extrusive, in a given area may have had an original banded character, or may have had great complexity in their parts, as a result of which their mashed equivalents show a banding. This is particularly likely to be true of lavas and tuffs. Further, it has been

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[1] Report on the geology of the Lake of the Woods region, with special reference to the Keewatin (Huronian ?) belt of Archean rocks A. C. Lawson, Ann Rept Geol and Nat Hist Survey Canada, 1885, new series, Vol I, pp 5-151 CC

[2] Report on the geology of the Rainy Lake region A C Lawson, Ann Rept Geol and Nat Hist. Survey Canada 1887-88, new series, Vol III, pp 1-196 F.

seen that the mashed, originally homogeneous, igneous rocks may have become cleaved or fissile, and that along the secondary structure impregnations or injections may occur and the rock thus become banded. If a new mashing now takes place which develops tertiary structure cutting the secondary one, the minor plications of the secondary structure may simulate similar plications of sedimentary strata.

The metamorphosed sedimentary rocks are not usually so changed as to obliterate all evidence of their original condition. This is true even of the metamophosed shales. Minute variations in the coarseness of the laminæ are usually sufficient to produce the minor plications which somewhere will be found to intersect the secondary structure. Moreover, in a larger way, thick formations of shale are apt to contain some beds of grit, sandstone, or limestone. These give different crystalline schists, and each of these is different from the metamorphosed shale. Variations in original lithological character are still more prominent when great formations are considered. It has been seen that a sandstone formation may be transformed into a quartz-schist, or micaceous quartz-schist. Limestone may be transformed into marble, bearing greater or lesser quantities of silicates, depending largely upon its original purity. The arkoses and shales may be transformed into schists and gneisses. If they were calcareous, this property is likely to persist. There is no evidence that any transformations through which sedimentary rocks go are sufficient to obliterate the original differences in thick formations of greatly varying lithological character. In the case of schistic or gneissic series, widely disseminated graphite and the presence of ferruginous beds have been regarded as indicating a sedimentary origin.

This principal is well illustrated by the Paleozoic, metamorphosed, sedimentary rocks of the Green Mountains of New England. In this area the Paleozoic rocks have almost completely lost all interior evidence of clastic characters. It is only very rarely, where the rocks were conglomeratic, that any particles can be recognized as fragmental. However, the shales and grits are transformed to mica schists and mica-gneisses, the sandstones to quartz-schists, and the limestones to marbles. The schists are not evenly homogeneous and regularly schistose with a secondary structure in a single direction, as is so characteristic of metamorphosed igneous rocks. Each formation is composed of minor beds, these beds of minor laminæ. Notwithstanding the metamorphism, these retain to a greater or lesser degree their integrity. At many places the bedded structures intersect the secondary schistose structure. In a larger way the relations of the formations to one another are those of sedimentary rather than igneous rocks. No one skilled in work in the crystalline rocks would fail to recognize this Paleozoic series as of sedimentary origin. On the other hand, any one of these formations is easily discriminated from the pre-Paleozoic, gneissoid granites.

In regions of extreme metamorphism, where both igneous and aqueous rocks have had long and complex histories, including the development of secondary and perhaps tertiary structures, and sometimes impregnations and injections, no criterion as to texture or minor plication or regular banding is sufficient to discriminate the two. Even in regions in which the great formations may indicate with a high degree of probability that a considerable portion of the material is of sedimentary origin, it may be true that another considerable portion is igneous and can not be discriminated from the aqueous part of the series.

This difficulty is well illustrated in the Grenville series of the Original Laurentian area, in the Adirondacks of New York, in the pre-Paleozoic areas of western Massachusetts and Connecticut, in the eastern gneissic area of Maryland, and in the crystalline area of the southern Appalachians. At various places in these districts formations are found which are without doubt sedimentary. Such formations are marbles, quartz-schists, and certain mica-schists and mica-gneisses. However, associated with these rocks, clearly of sedimentary origin, are other gneisses or schists with perfectly conformable structures which may be of sedimentary or of igneous origin. Some of the gneisses have a distinctly granitoid aspect. Whether part of these problematical rocks were igneous and part sedimentary is as yet undetermined, as are also the relations which obtain between them. These rocks of doubtful origin may be an early series, upon which the recognizable sedimentary rocks were deposited. If so, the original unconformity has been obliterated by orogenic movements. They may be intrusive within the sedimentary series, the subsequent orogenic movements having produced, in both, secondary structures in common directions. Or, finally, many of the rocks of doubtful character may be metamorphosed sedimentary rocks, belonging with the other sedimentary rocks, but so altered that their detrital origin can not be asserted.

RELATIONS OF METAMORPHIC IGNEOUS ROCKS TO STRATIGRAPHY

Before considering the relations of igneous rocks to stratigraphy it is necessary to recall the forms which they usually take and the manner in which they may be expected to die out. The intrusives are ordinarily known as batholites, bosses, laccolites, sills, and dikes. The extrusives are either lavas or tuffs. Frequently dikes radiate from a batholitic or laccolitic mass, become less and less abundant in passing away from the igneous mass, and finally disappear. Not infrequently the intrusives and extrusives are closely associated, intrusives being in one part of a region or district and equivalent extrusives in another part. But whether the rocks are intrusive or extrusive, if the quantity of igneous material is large and it is in various forms the igneous rocks usually do not die out at once, but gradually. Ordinarily the distance required for their disappearance is considerable, but in certain cases there are exceptions to this.

For the most part the ordinary masses of volcanic rocks do not profoundly affect the beds with which they are associated. On the other hand, large intrusive masses may metamorphose surrounding sediments for distances to be measured in miles.

As a consequence of the gradual disappearance of eruptives under ordinary circumstances, the abundance of eruptives in one horizon and their absence in an adjacent horizon indicate that a structural break probably exists between the two, or that a fault has displaced the strata. If no phenomena are present which indicate faulting, this renders the first alternative probable. The sudden disappearance of eruptives is a particularly valuable criterion in separating adjacent series in cases in which parallel secondary structures have been induced in both. These secondary structures may have obliterated or nearly obliterated the original bedding, so that there may be none of the ordinary evidences of structural breaks, but if a set of dikes passes to a certain horizon and is suddenly cut off, this is very suggestive of an erosion interval between the two series. In cases of this kind the eruptives themselves are likely to have been extensively altered by the forces which produced the secondary structures in the sedimentary rocks, and they may have been changed from their original condition to schists, and can be shown to be dikes or intrusives only by their structural behavior or by microscopical examination.

When a series is cut by intrusives it sometimes happens that there is a difference in the resistant power of the dike and the containing rock. In case the dike be more resistant, and the two were subjected to eroding agencies, it protrudes somewhat from the underlying formation, while in the opposite case there is a hollow. This latter is the condition of affairs described by Pumpelly at Hoosac Mountain, where an ancient dike cuts through the gneissoid granite. After a hollow of differential erosion was formed a new series was deposited. In approaching the dike the members of the new series thicken somewhat and pass into the sag. The greater thickness of the lower beds at the hollow finally compensates for it, and the thickened beds gradually pass up into ordinary regularly stratiform beds. In this case later orogenic movements produced consonant secondary structures both in the gneiss and in the overlying formations, and this relation of the dike to the two series was the first evidence found of a structural break between them. They had hitherto been considered as conformable, although a very close study had been made of them. Later, other evidence confirmed this inferred unconformity.

In a different case the contacts between the two unconformable series may not be found, but one series may be cut through and through by dikes and contain bosses of igneous material and interstratified intrusives or extrusives, with perhaps also volcanic fragmentals, while the adjacent set of formations may be wholly free from igneous rocks. Relations of this kind have force in proportion to the extensiveness of the phenomena. If one series is rich in volcanics for many miles, while another series is entirely free from them, and the irregular distribution of the two is such as not to be explained by a fault, the evidence of a structural break between the series is very strong.

In any of the above cases the time break between the two series must have been long enough for the taking place of a full cycle of igneous activity.

In proportion as the igneous rocks are metamorphosed it is difficult to apply the above criteria. Where they are no longer distinguishable from the sedimentary rocks the criteria given for determining structural relations are not available.

SECTION IX.

STRATIGRAPHY.[1]

Having considered the phenomena of disturbed sedimentary and igneous rocks, we are now ready to take up the broader questions of pre-Cambrian North American stratigraphy. These are treated under the heads of bedding, ripple-marks, basal conglomerates, unconformity, and structural work in nonfossiliferous rocks.

BEDDING.

In the little-altered rocks it is usually easy to recognize bedding. The characteristics of beds and the criteria for recognizing them in little-altered rocks are so well known that they need not be repeated, except in so far as is necessary to contrast them with those of modified rocks.

From the previous chapters it is evident that the recognition of bedding is not so easy in rocks which have undergone a considerable degree of alteration, and in which secondary structures have been developed, for very frequently the secondary structures which may or may not be parallel to bedding have been regarded as bedding. Further evidence of the same fact are the mistakes which have frequently been made in reference to igneous rocks. The unmodified flowage structures of lavas have at many places been supposed to be bedding, and the lavas therefore sedimentary. Still more frequently in igneous rocks such secondary structures as cleavage or fissility have been taken for bedding, and the rocks therefore regarded as sedimentary. Hence it is necessary in stratigraphical work to consider what phenomena may be taken as evidence of bedding in semicrystalline and holocrystalline rocks.

In the coarse-grained sedimentary rocks there are usually alternating bands of different character or size, and in the fine-grained rocks alternating laminæ. The naked eye discriminates these laminæ by a slight difference in color. When the microscope is applied to them the

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[1] In the preparation of parts of this section I am much indebted to the paper by the late Prof R D Irving, *On the Classification of the Early Cambrian and pre Cambrian Formations*, Seventh Ann Rept U S Geol Surv, pp. 365-454

chief causes of the lamination are found to be the same as in the coarser layers—differences in coarseness and character of the rock particles composing the laminæ. The size of these particles in the fragmental rocks apparently corresponds to the transporting power of the water at the particular moment of deposition.

A larger or smaller number of minor laminæ make up a stratum or bed. The strata differ among themselves in the same manner as do the laminæ, each stratum being upon the whole composed of finer or coarser material than the adjacent strata. There may be gradations from one stratum to another, exactly as there are gradations from one lamina to another. A greater or lesser number of beds or strata of the same general character, and of considerable thickness and persistence, constitute a formation. Formations may grade into one another, exactly as may beds and laminæ. A formation of conglomerate may be followed by a formation of sandstone; this by one of shale or of calcareous sandstone, and either of these by a limestone. The formation is usually the smallest unit separated in mapping. When an area is mapped on a large scale by minute study, a large number of rather thin formations are usually discriminated. If the work is more rapid and general, several of the minor formations of allied character are thrown together and the whole is regarded as a single formation. The more minute the subdivision the less extended areally is a formation upon the average; the larger the formation the more likely is it to have a wide areal extent.

On the one hand, as a consequence of secondary changes, the original differences in beds may be emphasized by secondary impregnation along the beds or in openings between them made by the folding. On the other hand, the secondary changes may lessen or even obliterate bedding. Very often where the eye does not recognize the laminæ, strata, or beds upon the fresh fracture, they may be plain upon the weathered surface. Because of the difference in resistant power, the forces of erosion at work at any given locality cut away the less resistant layers with relative rapidity, leaving the more resistant layers protruding. The layers which are more resistant under one set of circumstances might be less resistant under others. For instance, for a given formation the most resistant layers might be different in a tropical desert from those which are most resistant in a cold, humid region.

In the fragmental rocks the alternating laminæ may be used to determine whether the structure is bedding, until the metamorphic processes have gone so far as to obliterate the original clastic particles. If a rock has been subjected merely to the processes of consolidation and metasomatism, the alternating layers are recognized by the rounded grains of the various minerals, and especially quartz. In the finer-grained rock the microscope may be necessary to make the determination. If the layers are thus shown to be original the bedding is determined with certainty. This criterion may be applied even when the rock has been considerably mashed, and has become a mica slate. But if the mashing was so intense as to make the rock holocrystalline, positive evidence of the direction of the minor laminæ may have disappeared. The geologists working in the Green Mountains have found that where the rocks are holocrystalline the bedding may be indicated by secondary quartz laminæ. (See Dale's fig. 81 in previous paper, p. 556.) These can be relied on, however, only where they cut the cleavage and fissility, and even then it must be certain, in order to demonstrate the structure to be bedding, that there is no prior cleavage or fissility along which the impregnations might have occurred (see Dale's fig. 92 in previous paper, p. 565), for a rock may show cleavage or fissility in one or more directions. Parallel to either of these structures there may be alternating bands of different mineral character or of different color due to secondary impregnation or injection. There may be alternating groups of layers of different character taken as wholes, which suggest beds in a remarkable degree. However, none of these structures or any other can be always relied on as evidence of the direction of bedding in a completely crystalline rock, for it has been seen that such structures are produced by secondary processes, and that two or three different secondary structures may exist in the same rock, none of which are bedding, but all of which are produced by metamorphic processes.

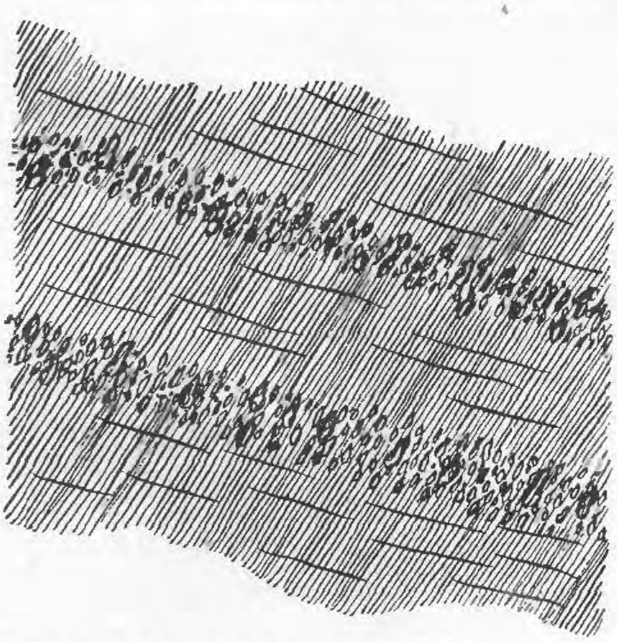

FIG. 140.—Deformation of conglomeratic layers in rock in which a cross foliation is developed.

In sedimentary rocks in which the metamorphism was so intense as to wholly obliterate the clastic characters of the matrix, or of the entire mass where originally a shale, grit, or sandstone, if the rock contained bands of conglomerate, the rows of pebbles may still indicate the direction of bedding (fig. 140). That is, a more intense dynamic action is required to destroy pebbles than to completely granulate the smaller particles (Pl. CXV). Generally, in this case the pebbles are crushed, and they may be rotated. As a consequence the greater dimensions of the pebbles correspond to the secondary structures (Pl. CXV), but the belts of conglomerate occupy their original relative positions (fig. 140). In an advanced stage of change the pebbles are crushed until each becomes a lamina scarcely distinguishable from a bedded layer. Such a rock, when looked at on a surface parallel to the schistosity, may appear completely crystalline. This may even be the case in one plane perpendicular to the schistosity, but the pebbled character may be still discernible in the plane at right angles to both of these (fig. 156).

When the processes of transformation have reached the extreme the pebbles themselves are destroyed, and there is then no way to determine bedding except by the major alternation of sediments; that is, as beds of shale, graywacke, sandstone, and limestone are originally different chemically and mechanically, and as material does not readily migrate in a large way in alteration, when the beds become metamorphosed they do not change into similar rocks. As has been seen, from a bed of shale or grit is produced a mica-schist or mica-gneiss; usually

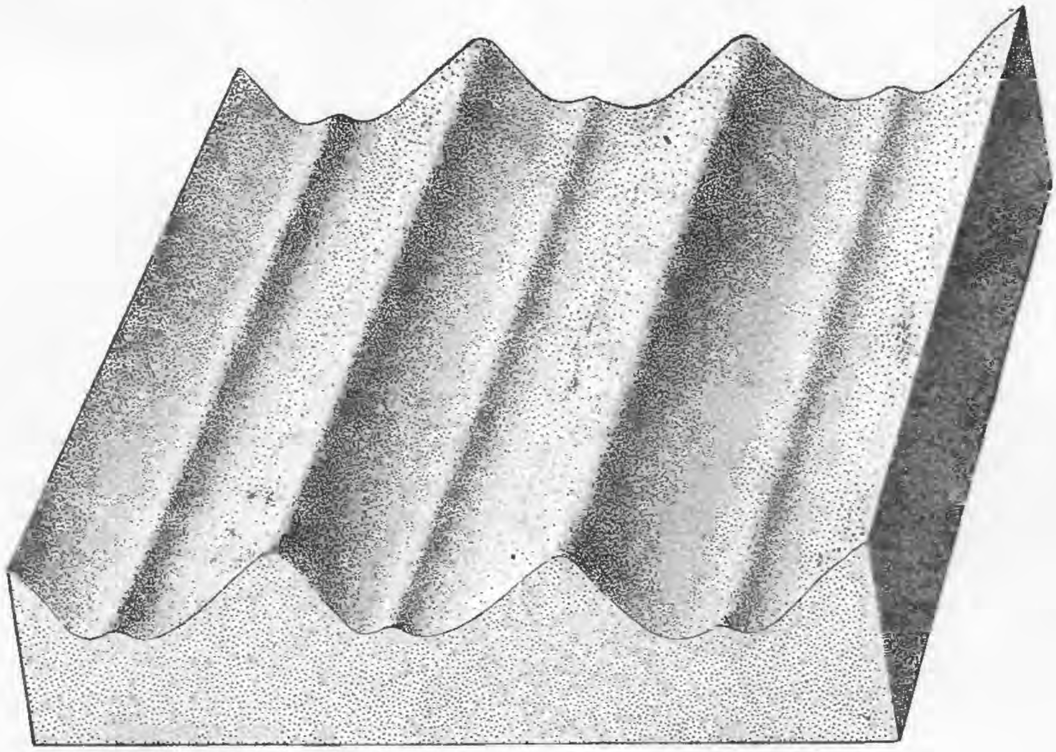

FIG. 141.—Normal ripple-marks.

from a bed of quartzose sandstone is produced a quartzose schist; from a bed of limestone is produced a marble. We conclude that in the case of extreme metamorphism the only safe guide as to the direction of bedding is the contact between formations which are thus dissimilar.

Certain of the completely crystalline gneisses are in layers which simulate beds to a remarkable degree. Viewed from a distance the layers have the exact appearance of beds of sandstone. It is only when the rocks are closely examined that their crystalline character is discovered. It has been seen under Cleavage and Fissility that there is a tendency for secondary structures to be produced parallel to bedding, both in the deep-seated zone of flow and the middle zone of fracture and flow. In many cases it is probable also that deep-seated metamorphic processes, under the pressure of the superincumbent beds, preserve the original structures. In some places it is therefore probable that the layers of crystalline schists are really fossil beds, but until this is shown by the criteria above given it can not safely be assumed in structural work.

RIPPLE-MARKS.

The forms of ripple-marks may sometimes be of assistance in deciphering stratigraphy. Normal ripple-marks consist of a series of sharp ridges separated by rounded hollows, each of which, however, often has a slight, sharp ridge in its center. The appearance is shown by fig. 141. The obverses or casts of such ripple-marks have an entirely different appearance. They consist of broad rounded ridges, each of which has a slight depression in its center, and the ridges are separated by steep depressions. This appearance is shown by fig. 142. The

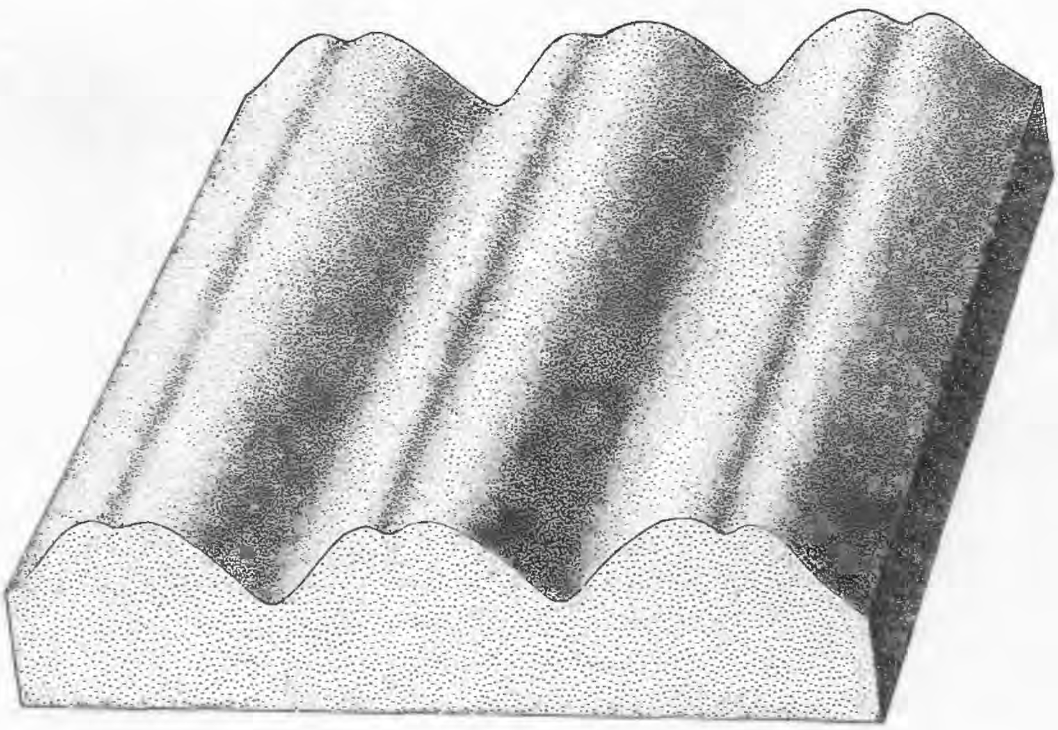

FIG. 142.—Casts of normal ripple-marks.

profile of either of these figures is shown by fig. 143, which is placed in a vertical position. One side represents the ripple-marks as normally formed, the other their cast or obverse. In case the beds of a steeply inclined formation bear ripple-marks, these determine at once which way the formation was uplifted. The profile (fig. 143) should be turned to the right in order to bring it back to its original position. The decision may be as easily made even when the minor elevations in the hollows are absent. In this case in normal position the depressions are gently rounded, while the elevations are of the same form as in the previous case.

This criterion may be of assistance in working out the structure of a difficult area. It often happens that in regions of closely folded rocks, if the manner of upturning of a formation can be determined at a certain locality, the structure of a considerable area at once appears. Conversely, if the structure is believed to be determined the discovery of ripple-marks on the steeply inclined layers gives a test as to the correctness of the conclusions reached. This principle was explained by Jukes and Geikie[1] many years ago, but is neglected in modern text-books.

FIG. 143.—Profile of normal ripple-marks.

BASAL CONGLOMERATES.

By a basal conglomerate is meant a conglomerate deposited upon an eroded, previously consolidated, or modified rock by the encroachment of the water upon the land. The material for the conglomerate is largely derived from the subjacent formation, although shore currents usually bring some material from other and distant sources. Immediately adjacent to the underlying formations the blocks composing the conglomerate are mainly from the inferior formations, and they are often angular, but this phase usually passes quickly upward into a phase containing well-waterworn bowlders, and from this to phases containing bowlderets and pebbles, and from these into sandstone or shale. A basal conglomerate may vary in thickness from a few inches to many feet, depending upon the character of the shore and upon the rapidity of the transgression of the sea. In case cliffs have to be worn away, the basal conglomerate has a very considerable thickness. If, on the other hand, the sea transgresses over a region which has been baseleveled, or nearly so, the advance is marked only by a thin bed of conglomerate, and it is possible that under these conditions no basal conglomerate may form. As a marked instance of a thin conglomerate may be mentioned the occurrence on the Potato River, in the Penokee series of Wisconsin. Resting upon the upturned edges of the Archean schists is a conglomerate containing bowlders as large as 3 or 4 feet in major diameter. This bowlder bed varies from 2 to 4 feet in thickness, and passes quickly into the ordinary slate of the quartz-slate formation. So sudden is the transition that if a belt 4 feet wide were covered the schists of the basement complex would be seen upon one side and the slate upon the other, the fibers of the schist being nearly at right angles to the strike of the fine-grained slate (fig. 144).

[1] Student's Manual of Geology, Jukes and Geikie, 3d edition, 1871, p. 63.

A true basal conglomerate, where it exists, implies that between the two series there has been an erosion interval or an unconformity. The significance of this phenomenon will be considered later.

There are certain phenomena which may be mistaken for genuine basal conglomerates:

(1) Coarse volcanic fragmental material may be deposited upon a bed of ash, lava, or sedimentary rock, or dropped upon the water over ordinary sediments. If the formations are later buried and then somewhat altered by the metamorphosing processes the conclusion may be drawn that such a conglomerate is a true basal conglomerate. This is

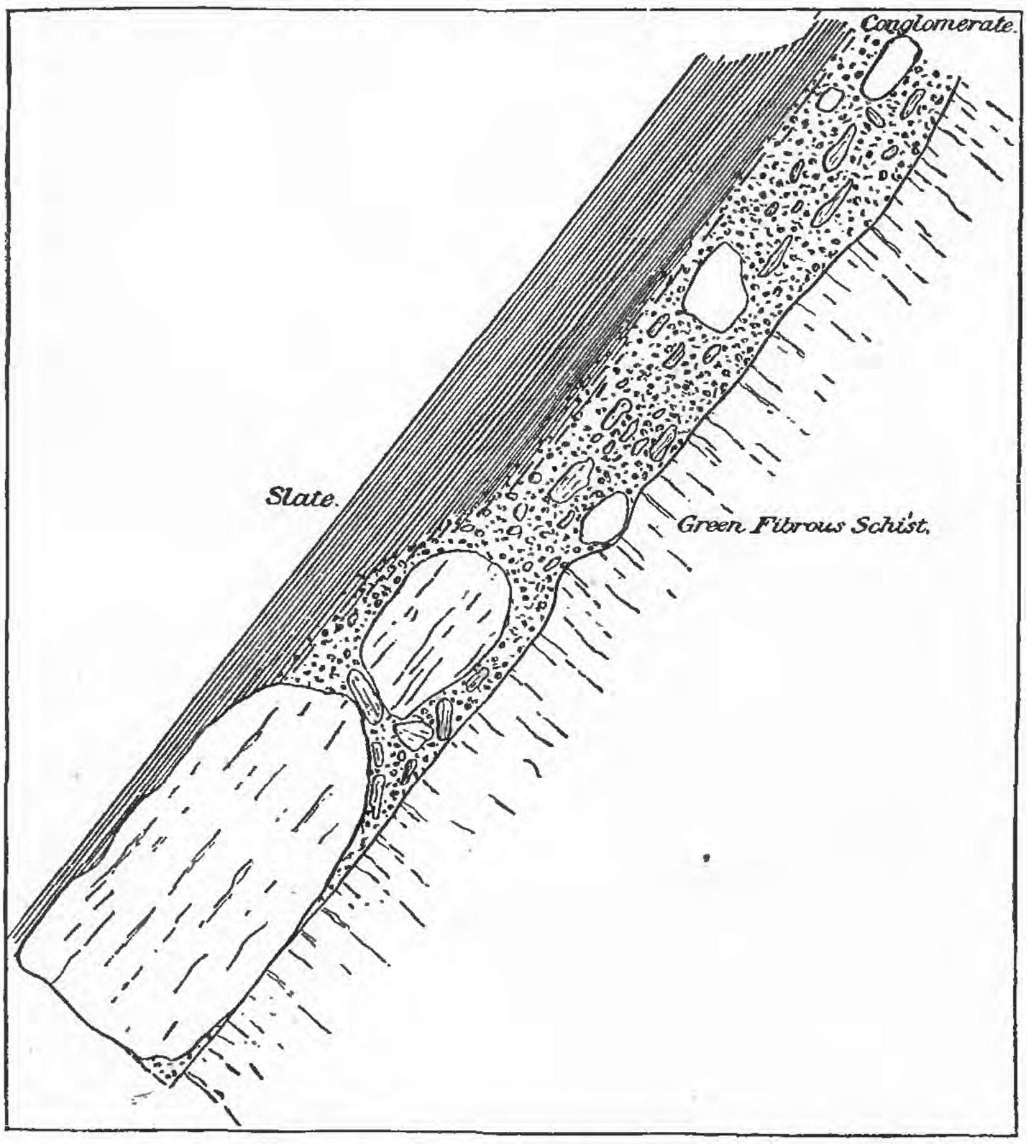

FIG. 144.—Basal conglomerate of Upper Huronian resting on green schist of Archean.

especially likely if the phenomena are not closely examined. Such a conglomerate, however, differs from a true basal conglomerate in that the blocks which compose it are not of the same character as the subjacent formation; and if they have not been too profoundly metamorphosed they will be recognized as having the characters of volcanic bombs rather than of waterworn pebbles. Further, if the contacts are closely examined it will frequently be found that there are really gradations from the ash or sedimentary formations to the conglomerates. If, however, the sedimentary formations were previously consolidated there would be no tendency for the two to blend.

(2) Erosion conglomerates derived from contemporaneous lavas have frequently been mistaken for basal conglomerates. If lavas are poured out near the level of the sea or adjacent to a shore-line, or are subaqueous, the water at once attacks them and builds up a conglomerate. Other lavas may overflow this conglomerate, or volcanic clastic material may be dropped upon it. These may again be attacked by the water and another conglomerate be formed. Thus in a single series there may be many interlaminations of lavas and true conglomerates. In the Keweenawan series of Lake Superior there are scores, if not hundreds, of such interstratifications.

(3) Conglomerates may be formed in shallow seas by storms of exceptional violence. Coarse material may be carried to a considerable distance from the shore-line and deposited conformably upon a great thickness of beds which have been built up on a subsiding bottom. Such a conglomerate is discriminated from a true basal conglomerate by the following phenomena: There is no sharp contact between the inferior formation and the conglomerate, but generally a gradation. The bedding of the conglomerate accords with that of the underlying formation. The pebbles and bowlders of the conglomerate are not derived from the inferior stratum or formation, but from extraneous sources. It is possible that by means of icebergs bowlders may be carried far from the shore-line, so that large masses may be deposited in ordinary beds. The sparseness of this material would usually be such as to cause no difficulty.

(4) Intraformational conglomerates, described by Walcott,[1] may be mistaken for basal conglomerates. In this case, during the deposition of a series as the result of a slight movement, a part of the area of deposition may be raised for a time above the sea. If the material be sufficiently indurated the waves may form pebbles and bowlders from the formation and deposit them in the deeper waters upon the eroded or uneroded areas. Later the whole may be covered with similar or dissimilar formations. Pebbles thus derived may be rounded or angular. The phenomenon is particularly likely to be found in a limestone formation, for this kind of rock may become crystalline or thoroughly cemented during or immediately after its formation. The same phenomenon has been observed to occur in argillaceous beds. As is well known, mud, if exposed to the atmosphere, may become compacted by simple drying. Such material may furnish pebbles of sufficient durability to hold together, if not too long subjected to wear. Sandstones and coarse grits are far less likely to become indurated under the circumstances attending the deposition of intraformational conglomerates,

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[1] Bull U S Geol Surv. No. 134, pp 34–40, 1896

but it is possible that even these materials may be found as pebbles of such conglomerates.

Intraformational conglomerates usually may be easily discriminated from true basal conglomerates by the following criteria: The pebbles are most often limestone, shale, or slate. In some cases the pebbles when formed were so soft as to be distorted or indented by their pressure against one another. In some cases they may be welded together. In other cases the pebbles merge into the matrix as a result of welding and of similar composition. The pebbles are often of the same composition as the matrix in which they are contained. Ordinarily, few or no large pebbles of indurated or crystalline formations from an extraneous source are found, although if the ridge of temporarily exposed rock join the main shore such material may be brought in by the deflected shore currents.

(5) Autoclastic rocks may be mistaken for basal conglomerates. The manner in which a breccia may be developed in a brittle stratum between plastic strata has been described. It should be remembered that the lower bed may be folded, its folds truncated, and above this there may be an autoclastic rock (fig. 153). In another case the lower formation may have a secondary structure which abuts against a pseudo-conglomerate formed at the base of a more brittle overlying stratum or formation, and in this pseudo-conglomerate may be fragments from the underlying schist. Also an autoclastic rock may develop along a fault zone, and is here particularly likely to be mistaken for a basal conglomerate. Criteria have already been given (pp. 680–682) for discriminating between autoclastic rocks and ordinary conglomerates. All of these apply to this case.

(6) Pseudo conglomerates produced by igneous intrusion may be taken for basal conglomerates. In such cases the intruding rock is apt to be a deep-seated batholite which has metamorphosed the intruded rock. Numerous fragments are caught in the intrusive near the contact; their borders are absorbed, and thus the rock assumes a conglomeratic aspect. The igneous relations obtaining between the intruded and the intrusive rocks usually show the true character of such a pseudo-conglomerate. However, if later dynamic action has transformed the igneous rock into a crystalline schist indistinguishable from schists of sedimentary origin, it may be difficult to determine the true character of the pseudo-conglomerate. This difficulty is increased if adjacent to the pseudo-conglomerate the igneous rock was intruded in bands parallel to the structure of the intruded rock.

If two or more of the methods which produced the different types of conglomerates simulating true basal conglomerates unite, additional difficulties arise, and still more precaution must be taken to discriminate the resultant conglomerate from a true basal conglomerate.

UNCONFORMITY.

An unconformity between series implies a difference in number of orogenic movements with intervening erosion. This difference in number may be one or more than one. Even if the difference is but one the time gap between the two must have been very considerable, and it may have been of vast duration. Discordant series may differ in folding, in metamorphism, in their secondary structures, in their relations to eruptives, etc. Each of these phenomena has been discussed in reference to structural work, and the bearing of each upon unconformity has been pointed out. Nevertheless it seems advisable to bring together at this place the phenomena upon which an unconformity may be established, even at the risk of repetition.

PHENOMENA INDICATING UNCONFORMITY.

As guiding phenomena in the discovery of unconformities we then have (1) ordinary discordance of bedding; (2) difference in the number of orogenic movements to which the series have been subjected; (3) discordance of bedding of upper series and foliation of lower; (4) relations with eruptives; (5) difference in degree of crystallization; (6) basal conglomerates; (7) general field relations.

(1) In cases of ordinary discordance of bedding nothing need be said, except to state that unconformities should not be inferred from a single small contact where the apparent discordance may be due to false bedding or to local currents or very local minor disturbances. Also the discordances caused by faulting may be mistaken for an unconformity if care is not taken. The amount of evidence for the unconformity should be sufficient to show a real discrepancy of bedding for a considerable area. Within a short distance the amount of discordance of bedding between two series may vary greatly. Frequently an orogenic movement relieves itself mainly along a comparatively narrow zone. Such a zone is usually one of differential uplift and consequently of great denudation. The adjacent plain may be little folded and not deeply eroded. When a new series is deposited upon this older series the former lies approximately parallel to the bedding of the older upon the plain, but along the zone of disturbance the first may be directly athwart the bedding of the second.

(2) Difference in the number of orogenic movements to which the series have been subjected is often an important means of determining uncomformities. In order that an unconformity shall occur the older series must have been subjected to at least one more orogenic movement than the newer. In the most favorable case the older series has undergone two or more orogenic movements, while the newer series has undergone but a single one. When the lines of these movements are in the same direction and result in folding, the only difference between the two series consists in steepness of inclination; but in case the earlier movements were in a different direction from the last the older series will show a set of folds, due to the resultant effect of the two or more movements, while the newer series will be simply folded. As a matter of course, in this discrimination, bedding must be used

rather than foliation. Oftentimes it will happen that the latest movement has produced a prominent cleavage or foliation which is common to both older and newer series; and under these circumstances the real discordance which may exist between the two series is particularly apt to be overlooked, and a district will be described as having a simple monoclinal structure, or one in which the series is reproduced by faulting, when evidence is at hand for two or more discordant series.

The orogenic movements, instead of producing folding, may cause jointing or faulting, these results, as suggested by Willis, being, perhaps, due to insufficient load. These phenomena are, however, serviceable in discovering an unconformity, for the sets of faults or joints produced in the older series before the newer series was formed are not found in the latter. Where there have been later orogenic movements which have produced faults or joints in both series, the unconformity may be shown by the presence in the older series of two sets of joints or faults in different directions, provided the directions of thrust were different, while the newer series is affected by joints or faults in only a single direction. If the joints or faults made by both the newer and the older movements are in the same direction, they will not be of much service in detecting an unconformity, the only difference being their greater number in the older series.

When one of the orogenic movements has resulted in folding and the other in faulting or jointing, the combination of phenomena is as easily used to detect an unconformity as when effects of the same kind are produced by both movements.

(3) Discordance of the bedding of an unfoliated series with the cleavage or fissility of an adjacent series may be taken as evidence of unconformity if the former is such that it would take on a secondary structure as readily as the latter; for, whatever the origin of the altered series, the development of cleavage or fissility, which must have formed before the new series was deposited, required much time. An unconformity could not be inferred from the fact that a heavy formation of quartzite or of limestone cuts across the cleavage or fissility of an argillite or mica-schist, for clayey rocks take on secondary structures very readily. In the same series it often happens that more massive beds escape foliation which may be prominently developed in less massive members. But if a formation with slaty or schistose structure is overlain by another formation without secondary structure, which from its composition is as likely to take on one as the underlying formation, a discordance, while not demonstrated, is a probability for which other evidence should be sought.

(4) Eruptive rocks are often an important guide in determining structural discordances. These are valuable when the older series has passed through an epoch of eruptive activity before the newer series was deposited. In such cases, bosses, contemporaneous or intrusive beds, volcanic fragmental material, or dikes may occur in the older

series, which nowhere are associated with the newer. It is possible, of course, that eruptives may penetrate the inferior members of a series and never reach the higher formations; but if it be found that the supposed inferior series is associated with abundant material of igneous origin which never passes beyond a certain plane, it is almost demonstrative evidence of the later age of the newer series. A notable instance of this is found in the Doe River section of eastern Tennessee, where the granitic rocks, supposed to be older than the associated clastics, are cut by very numerous schistose dikes which never intrude the latter. If it were not for these dikes it might be reasonably inferred that the granitic rock is an eruptive later than the clastics (although the absence of contact phenomena would be against this), but as the basic dikes are unquestionably intrusives of later age than the granites, and yet never cut the sedimentary rocks, this explanation can not possibly apply. Evidence of this kind is particularly decisive if the dikes are traced up to the plane of contact and are found to be eroded or disintegrated, as is the case in the Stamford dike at Clarksburg Mountain, Massachusetts, described by Pumpelly, which enabled that author to determine positively that the granitoid gneiss is unconformably under the Cambrian quartzite.

(5) Closely connected with (3) and (4) is degree of crystallization as a guide to unconformities. It has been seen that crystalline character is often taken on in proportion as dynamic action occurs. Where the folding, which affected only the older series, was severe, it as a whole is more crystalline in character than the newer. Igneous material is also often a potent factor in the production of crystalline character. As, however, recrystallization is often produced by cementation, metasomatic change, etc., this criterion must be used with caution, and regarded as a cause to search for other evidences of an unconformity rather than to be used alone as a basis upon which to infer an unconformity. But even a difference in the amount of static metamorphism, if the rocks are equally likely to be affected, may be evidence of difference in age. In determining degree of crystallization, the modern petrographical methods serve one of their most useful purposes, since many rocks which in exposure or in hand specimen appear to be about equally crystalline are shown in thin section to be of a fundamentally different character. A completely crystalline rock in some cases can not be discriminated microscopically from one which is merely indurated by cementation. For instance, a thoroughly crystalline granite and a recomposed rock built up of the débris of this granite, especially when the particles are in the form of individual minerals rather than pebbles, present much the same appearance in mass, but a glance at sections of the two under the microscope shows the thoroughly crystalline interlocking character of the one and the clastic character of the other. Another case quite as marked is the discrimination between much foliated eruptive rocks and ordinary argillaceous rocks showing

secondary structures. In the latter class the particles of quartz and feldspar may often be seen with their oval forms nearly as regular as on the day in which they were deposited, while in the other case an entirely different appearance is presented.

(6) Basal conglomerates are one of the most important means of determining a plane of unconformity, but it must be clearly shown that the conglomerate is really a basal one. Conglomerates may occur at other positions than at basal horizons, and it will not do to assume that an unusually conglomeratic layer is basal. A conglomerate is likely to be basal when the major portion of the débris is derived from the immediately subjacent member; but even here the exception must be made that in case this subjacent member is a surface igneous rock the presence of the conglomerate is no evidence of a time break. If, however, the igneous formation is of such a character as does not pertain to any but a deep-seated rock, the fact that it is at the surface and yields fragments to the overlying formation is evidence of a time gap. Also, evidence of a break is just as decisive when the underlying rock has a secondary structure which was produced prior to the deposition of the conglomerate. This may be determined from the fact that fragments broken from a slaty or schistose rock are apt to be longer in the direction of the lamination, and when deposited in the overlying series they naturally lie with their secondary structure at an angle to that of the underlying series. It matters not whether the inferior series be of sedimentary or of igneous origin. In either case a long time was required to develop the secondary structure and to bring it to the surface by erosion. While basal conglomerates are often found, they are also often absent where other evidence shows that there are discordant relations between two series. This absence is explained in some cases by Pumpelly's disintegration theory, the encroaching shore-line finding a set of disintegrated rocks which are ready to yield particles of the constituent minerals rather than pebbles. Such conditions are likely to occur if the land area is baseleveled.

(7) General field relations are often sufficient to establish discordant relations between series where all other lines of evidence are lacking. Where, in a region, immense stretches of rock of one series are always found in an undisturbed condition, while an adjacent series is always disturbed, discordant relations may be inferred. This is particularly evident when the horizontal series fills bays in the older rocks, or is found as inliers surrounded by the older rocks. Again, the general field relations may establish an unconformity, even if both series are disturbed. One case of this is the occurrence of a uniform belt of stratified rocks which, perhaps with a monoclinal structure and a somewhat uniform strike and dip, runs for great distances, the rocks of the adjacent unconformable series being here of one kind and there of another kind. The evidence for the unconformity in this case is still further emphasized if the lower series, instead of having a simple structure, is folded in a complex manner.

General field relations may betray unconformity even where the newer series was folded in a more complex manner; as, for instance, where it was subjected to two orogenic movements, the first of which placed it in a monoclinal attitude, and the second of which, acting at right angles to the strike, gave it a fluted structure. The lower series, instead of having this regular structure, having been subjected to still earlier orogenic movements, is more irregular in its distribution, and the difference in simplicity of areal relations, of the two series increases in proportion to the number and intensity of the earlier movements. However, as the movements which affected the newer series increase in number, the difficulties of discovering discordances by general field relations increase. These and other cases of general field relations which show unconformity may not appear to the observer while doing detailed work, since no contacts or other ordinary indications of unconformity are found, but appear strongly when the work is platted. To my mind, general field relations of the kinds above cited are in some instances more decisive evidence of unconformity than almost any kind of local relations. Where the local proofs above considered, combined with general field relations, unite as evidences of unconformity, as is often the case if the worker takes advantage of all the facts available, the accumulated evidence for discordant relations, even in difficult regions, is often decisive.

ERRONEOUSLY INFERRED UNCONFORMITY.

Unconformities have been frequently inferred on insufficient grounds. False bedding on a large scale may be mistaken for unconformity. Inclined false beds may be truncated by water action, and over the edges of the truncated layers new beds may be deposited. This phenomenon may occur along a single horizon for a distance of miles. In this case the truncated lower beds are not sufficiently indurated to yield coherent fragments to the overlying beds. However, as noted under intraformational conglomerates, the lower beds may, under favorable conditions, yield fragments to the higher. The fact that a lower bed or formation has cleavage or fissility while an overlying one has not may be taken as an evidence of unconformity. However, since cleavage or fissility may be developed in certain rocks more easily than in others, it may affect a lower bed and stop abruptly at a higher and more massive bed, and this in a continuous conformable series. In this case there are usually no fragments derived from the cleaved or foliated formation to be found in the overlying formation, but in some cases such fragments of dynamic origin may be found (see pp. 681–682). Frequently the misinterpreted evidence of unconformity is a discordance in the strike and dip of the foliation of two formations at some distance apart. The strikes and dips of banded and contorted schists and gneisses often vary so greatly, even within short intervals, that a difference of this kind can not be taken as an indication of discordance. This error has sometimes occurred because it has been assumed that foliation accords with bedding. When it is recognized that this structure is secondary, that it may be produced in either sedimentary or igneous rocks, and that it does not generally correspond over large areas with bedding, it becomes plain that such evidence ought not to be used as an indication of a structural break. An apparent discordance may occur as the result of faulting. Such a contact is particularly likely to be mistaken for unconformity when an autoclastic rock develops along the contact zone and the beds below the fault chance to be more crystalline than the overlying beds. In this case the distinctions made on pp. 680–681 between the character of an autoclastic rock and that of a basal conglomerate enable one to detect the true nature of the phenomenon. When alternating beds of a rigid and plastic character are folded, as for instance limestone and cherty quartzite, or shale and cherty quartzite, the plastic bed—limestone or shale—may take on minor plications, while the rigid beds are broken into a breccia. At the same time the plications of the plastic layer may be truncated by the grinding of the broken fragments of the harder layer (fig. 153). Such phenomena are particularly likely to be mistaken for unconformity. The true character of the phenomena is indicated by the fact that the broken material is a breccia, which differs from a true conglomerate in that the fragments are all local, being wholly derived from the rigid members folded. The phenomena are still more deceptive if a secondary structure is developed in the lower formations which abuts against but does not pass into the higher formation. Finally, volcanic conglomerates or tuffs, erosion conglomerates derived from contemporaneous lavas, conglomerates formed in shallow seas by storms of exceptional violence far from the shore, intraformational conglomerates, and autoclastic rocks, as shown on pp. 721–724, may be mistaken for true basal conglomerates, and thus unconformities may be inferred erroneously.

OBLITERATION OF THE EVIDENCE OF UNCONFORMITY.

In cases of unconformable series, when the newer series has not been greatly deformed, it is usually easy by some of the criteria given to detect an unconformity. In proportion as orogenic movements and consequent metamorphism affect the new series, it is increasingly difficult to do so, and when these processes go to the extreme all evidence of the most profound unconformity may be entirely obliterated.

(1) When two discordant series are closely folded the readjustment of the material in the folding tends to bring the beds of the two series into a parallel position, and if the folding goes so far as to produce an isoclinal structure, they may become almost parallel. That this is true is shown by the fact that in isoclinal folds, whatever the position of the original beds, they have a uniform dip. Moreover, it sometimes happens that the folding process goes so far as to nearly or entirely obliterate the original bedding of series, in which case little or no

evidence of discordance can be expected to be detected by the bedding. Obliteration of bedding is more likely to occur in case the discordant series or formations were composed of a shale or mud, and less likely to occur in case they were composed of heterogeneous beds of different resisting character, as shale, sandstone, or limestone.

(2) The difference in number of orogenic movements to which discordant series have been subjected is difficult to detect if the movements which have affected the later series are severe. These later movements may have modified the previous structures so as to dominate and obliterate the evidence of them.

(3) If movements affecting the newer series are severe, it may not be possible to get discordance of the bedding of a newer series with the secondary structure of an earlier series, for the later severe orogenic movements may develop common secondary structures in both newer and older series. This obliteration of the bedding of the upper series and the production of a common foliation is much more likely to occur upon the legs of the folds than at the crest of the anticlines or the troughs of the synclines. Hence these places, and particularly those where there are cross-sections of the crest and trough, should be examined. It is here very often easy to detect the original bedding cutting the schistosity, while upon the limbs of the folds the two are apparently in perfect accordance.

(4) Where the lower series is permeated with eruptives which entered before the overlying series was deposited, this is one of the most permanent evidences of unconformity. But if the orogenic movements are profound, it has been seen that even igneous rocks may be transformed into schists which can not certainly be discriminated from sedimentary rocks, and therefore if the later movements are intense, even this evidence of unconformity may not be available.

(5) In case the orogenic movements or other metamorphic forces are sufficiently powerful to produce a holocrystalline structure in the newer series, difference in degree of crystallization is no longer an available guide to an unconformity.

(6) Even the thickest basal conglomerates containing pebbles and bowlders of the most resistant character may be transformed into crystalline schists which show no evidence whatever that they were originally pebbled rocks. This has been shown in numerous cases by undoubted transitions from comparatively little mashed conglomerates to completely crystalline schists. But even where the orogenic movements are strong enough to obliterate the conglomerates along the zones of maximum mashing, such as the limbs of folds, they may often still be found with distinctly recognizable characters at the crests of anticlines and in the troughs of synclines. Just as in case (3), places favorable for the preservation of conglomerates should be sought. Discordant series are known in which the metamorphism was so intense that the lower and upper series, with a common foliation, at some local-

ities apparently grade into each other, whereas at other localities, where the conditions were less favorable for the destruction of the conglomerates, great basal conglomerates with all their typical characteristics are found. Certain geologists writing of these areas, and finding the localities where there are transitions between the two series, and not discovering those in which the conglomerates occur, have concluded that the higher series was progressively metamorphosed into the lower. Others, with the same facts available, in cases where the lower series is igneous have concluded that it is intrusive in the higher.

(7) Where the orogenic movements were at all extensive it is not ordinarily possible to use general field relations as evidence to establish unconformities, for old and new series are likely to be infolded in such an intricate manner as to give no evidence by their relations of an unconformity. But if two sets of formations, each with definite characters, occur in broad areas in the same district, this may suggest that the two sets are unconformable, even if they have a common type of folding and like secondary structures in similar attitudes.

EXTENT OF UNCONFORMITY.

It is well known that at many periods, if not during all periods, of geological history the land has, in reference to the sea, slowly risen here and slowly fallen there, but slight advances and retreats of the ocean do not produce unconformities, although conglomerate beds may be produced. An unconformity implies at the least an epeirogenic movement which places the land above the sea, a time of erosion, and another movement which depresses the land below the sea, and therefore the phenomenon can scarcely be less than regional in extent. Often, also, affecting a part or a whole of the region are orogenic movements, which may be either gentle or so severe as to closely plicate the strata. In the past, while the regional extent of unconformities has not generally been explicitly asserted, it has been tacitly recognized; for several of the major divisions of the geological column were first made upon widespread unconformities. In these cases the lapse of time represented by the unconformities was sufficient to cause a change in the life, either by evolution or by new physical conditions, so that in the rocks upon the opposite sides of the unconformities are different faunas. While unconformities are in some cases limited by a geological province, in other cases they may affect an entire continent.

One or two instances may be given. The unconformity at the base of the Cambrian of North America is universal throughout the entire eastern and northern part of the continent. The Appalachian revolution at the close of the Paleozoic not only made a profound unconformity which extends over the whole of the eastern part of the continent, but changed the physical conditions for a much larger area. Again, the unconformity between the Miocene and the Pliocene is at least coextensive with the distribution of the two series of rocks in the eastern and western parts of the United States. The conditions requisite to produce an unconformity are, then, such that, if pronounced, it can scarcely be less than regional in extent, while an occasional unconformity may affect a large part of a continent.

It is by no means certain that some of the larger unconformities may not be intercontinental in extent. If Suess's theory is true, that the emergences of entire or nearly entire continents from the sea are really due to differential subsidence—and from it I see no escape—it follows that the emergence of one land area by the sinking of the sea bottom would be accompanied by the emergence of all other land areas which were not under a greater depth of water, unless they too subsided with the sea bottom. After such land areas were eroded the subsidence of one of them might follow until it was submerged. This would not necessarily result in subsidence of the other land areas which emerged at the same time. Later, however, these other land areas might subside and be submerged. It would then follow that the unconformities thus produced in different continents would begin at the same time but not be of the same duration. It is to be noted that this possible partial intercontinental equivalence of unconformity is producible by the initial subsidence of the sea bottom. Intercontinental unconformities are not asserted, but I believe that they are possible, and that the determination of whether or not they exist is a hopeful question for investigation.

THE TIME REPRESENTED BY UNCONFORMITY.

The time represented by an unconformity may vary from a fraction of a period to one or more eras. Where the rocks of an inferior series are but little folded and consolidated or cemented, so as to yield fragments to the superior series, it may be that the unconformity took for its accomplishment but a minor part of a period. Orogenic movements and erosion, while slow from the point of view of years, are recognized to be so rapid that several such movements may occur within a single period. For instance, within the Cretaceous an unconformity is recognized by White. In the Carboniferous of Great Britain two unconformities are recognized by Geikie. Even where the rocks were somewhat closely folded, with consequent development of cleavage or fissility and metamorphism of the rocks, the unconformity may occupy only a part of a period. This is shown by the Green Mountain area. Here the Lower Silurian or Ordovician rocks were folded and metamorphosed before the Upper Silurian rocks were deposited upon them unconformably. Where, however, repeated orogenic movements have occurred, or where the folding of the strata is of the most intricate character, or where there have been repeated outbursts of igneous material and the igneous rocks thus intruded are of a character which could be produced only far below the surface, it may be questioned whether such profound changes can occur within less than a period of geologic time. If, for instance, coarse-grained granitic rocks or coarsely foliated completely crystalline rocks are found at the surface, their secondary structure being truncated, this indicates profound erosion, for coarsely granulated rocks and thoroughly developed crystalline structures could have been produced only at great depth.

On the other hand, an apparently very slight unconformity may mark an era or more than an era of time, and such an unconformity may be a continuation of the same unconformity which shows the most violent contrast of the two series in folding, relations to eruptives, and degree of crystallization. This may be illustrated by supposing a transgression of the ocean to pass over the eastern half of the United States. West of the Appalachians post-Pleistocene rocks would be deposited upon the nearly horizontal, gently eroded, and feebly indurated Paleozoic rocks of Ohio, Indiana, and Illinois. So far as the structural phenomena are concerned the discordance would be so slight that it might have occurred within a comparatively short interval of time, geologically speaking. In the New England area, on the other hand, the new rocks would be deposited upon the intricately folded, profoundly metamorphosed, and deeply denuded Paleozoics of the Green Mountains. Here the phenomena would show a major unconformity, and yet this would be a continuation of the same unconformity in the little disturbed area to the west.

As actual instances of a great time gap, either with slight or no discordance, may be mentioned the following: In the southeastern United States the Upper Devonian rests directly upon the Silurian, no discordance being thus far discovered. In Texas, White[1] reports the Lower Cretaceous rocks as resting directly upon the Carboniferous with apparently perfect conformity, the whole of the Triassic and Jurassic being missing.

I therefore conclude that *a slight unconformity may mark no more than a minor part of a period;* that *a great unconformity probably always marks at least a major part of a period;* and, finally, that *a slight or great unconformity may mark eras of time.*

STRUCTURAL WORK IN NONFOSSILIFEROUS ROCKS

Unconformity.—Since a discordance can not be assumed to be less than regional in extent, unconformities give the best datum horizons from which to build in working out the pre-Cambrian stratigraphy of a geological province. This may not be true among the Cambrian and post-Cambrian rocks, even in the same region, because fossils have often furnished the main datum horizons. However, as has been said, in the regions in which the period names were first applied, the rocks were usually delimited by physical breaks, and even after these periods were given a definite meaning upon a biological basis there was a strong tendency to separate the periods in each individual region upon a physical rather than a biological basis. As examples of this may be cited the Newark system[2] (Jurassic or Triassic, or both), which is separated

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[1] Correlation Papers—Cretaceous, by Charles A White. Bull U S Geol Surv No 82, 1891

[2] Correlation Papers—The Newark System, by I C Russell Bull U. S Geol Surv. No 85, 1892

by an unconformity below from the Paleozoic and by an unconformity above from the Cretaceous. In the same province the Eocene is delimited by Clark[1] by unconformities from the Cretaceous and the Neocene, although great faunal changes are naturally connected with these structural breaks. Williams[2] (H. S.), primarily a paleontologist, says that physical revolutions "constitute the most satisfactory marks for the primary classification of geological history," and he bases nearly all the larger divisions of the geological column of North America upon physical breaks. Even in the post-Algonkian, then, we find that physical unconformity is of the greatest importance in major stratigraphy. In the pre-Cambrian, fossils for structural work are yet lacking, and hence unconformity is here of even greater importance.

Since pre-Cambrian time was so long, there may be in the same region several unconformities, and hence it is necessary, in mapping any individual region, that the number of existing unconformities be determined. This may usually be accomplished by considering carefully the fullest sections obtainable in many different areas. Having once established the number of unconformities, it is generally possible to place a given series in its correct position in reference to the unconformities discovered. Failure to recognize an unconformity may, however, result in throwing two series together, as in the case of the Upper Huronian and the Lower Huronian in the Lake Superior region.

It can not be assumed that because strata are between two unconformities they are of equivalent age, for an unconformity in one part of a region may cover the time represented by two or more unconformities and intervening series in another part of the same region, this being due in some cases to the entire removal in parts of the region of the intervening series during the erosion interval represented by the upper unconformity. For instance, in parts of the Lake Superior region the Upper Cambrian sandstone rests directly upon the Archean, while in adjacent districts between the sandstone and the Archean there are three unconformities and three intervening series, each of great thickness. Moreover, if above a horizon of unconformity it has been shown in different districts that the same series occurs, it does not follow that the lower members of this series are of the same age. The transgression of the ocean may have occurred slowly, and thick formations may have been deposited in one part of a region which are not found in another part, because the sea had not yet reached this part of the area. Hence a series above an unconformity may consist in one part of the area of a certain set of formations, and in another part of the area of another set of formations, a downward continuation of the first, these being absent in the first area because this district was above the water when the sediments of the adjacent district were deposited. Also in different districts of the same region formations of a different lithological character may be deposited at the same time.

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[1] Correlation Papers—Eocene, by Wm B Clark Bull U S Geol Surv No 88, p 379, 1891

[2] The Elements of the Geological Time Scale, by H S Williams Journ of Geol, Vol I, pp 283-290, 1893 Geological Biology, by H S Williams, 1895, pp 39-47

Sequence of formations.—Subordinate to unconformity, but accessory to it, and helping to identify horizons of unconformity, is sequence of formations. If a set of beds of a peculiar lithological character occurs in a certain order in one part of the region, and are bounded above and below by unconformities, and a similar set of beds with like relations to unconformities is found in another district, the inference is that the two sets of formations and the two unconformities are the same, although the possibility that either one of these unconformities may split up into two or more unconformities with intervening series must be recognized.

As an instance illustrating this principle may be cited the Penokee and Animikie series. On the south shore of Lake Superior is the Penokee series, consisting of a quartz-slate formation, an iron-bearing formation, and an upper slate formation. The series is separated by an unconformity from the Keweenawan above and by an unconformity from the Lower Huronian and Archean below. On the north shore of Lake Superior, dipping southward, is the Animikie series, composed of three similar formations in like order, and having like relations to the Lower Huronian, Archean, and Keweenawan. The rocks of the two districts are therefore believed to be parts of a once-continuous series. Sequence of formations must, however, be used with caution, and in connection with other phenomena, for, according to the ternary law of strata, alternating formations of limestone, shale, and sandstone may be deposited again and again.

With proper checks and good judgment, however, sequence of formations, combined with unconformity, may be used with a considerable degree of certainty in correlating from district to district within a given geological province.

Lithological character of formations.—Next in value in structural work to sequence of formations is a single formation of a definite lithological character. This criterion has, however, decided limitations. A formation of a certain character may die out or may change its character; contemporaneous beds upon opposite sides of a separating ridge may have entirely different characters.

A formation is more likely to change in lithological character if nearer a shore-line; hence littoral formations need to be closely inspected. On the other hand, formations in mediterranean seas may have a like character and little variation in thickness for vast distances. Similarity of lithological character is likely to be of wider extent than equal thickness. These statements are particularly well illustrated by the great Silurian limestones of the Mississippi Valley. A similar wide extent is, however, possible for shales, as is illustrated by the Devonian of the southern Mississippi Valley. Also, there is no reason why sandstones deposited in shallow seas should not have a very wide extent.

The number of different kinds of original sediments is so small that the conditions which cause their deposition may occur again and again;

also similar formations in different series may have similar metamorphism, produced at the same time by folding, and consequently may contain similar metamorphic rocks of different ages. As a remarkable instance of this may be cited the iron-bearing formations of the Upper Huronian and Lower Huronian, which were originally cherty siderite or ankerite, but which, since Upper Huronian time, have been transformed into the numerous varieties of peculiar rocks constituting the iron-bearing members. The lithological likeness was such as to lead to the conclusion that they belonged together, and this mistake deferred a proper understanding of Lake Superior stratigraphy for many years. Lithological character, however, considered in connection with the original condition of the rock, its relations to eruptives, and its degree of metamorphism, is an important assistance in correlation, especially when taken in connection with sequence of beds and unconformity. But to infer, as has been done, that quartzites, not only in the same geological province, but in different geological provinces, are of the same age because lithologically alike, or that a period is characterized by eruptive rocks of a definite kind, as, for instance, the anorthosites, or that the rocks of a certain period are white gneisses, is wholly unwarranted. The first of these suppositions would involve the conclusion that a thick sandstone formation which has been subsequently cemented to a quartzite had been deposited but once in pre-Cambrian time, the second that extensive areas of igneous rocks of the same kind are necessarily of the same age, and the third that the white gneisses are all of the same origin and age.

Correlation.—Thus, while we have the means to work out the stratigraphy within a region, and to subdivide the rocks into series and formations with a greater or less degree of certainty, we as yet are helpless in passing from region to region in pre Cambrian correlation. When several series occur in like order separated by unconformities, and having certain lithological analogies, there has been a tendency to place them as equivalent; as, for instance, in the Grand Canyon region of Colorado and in the Lake Superior region. In each case we have at the bottom crystalline gneisses, granites, and schists; above this complex in one region a Vishnu series, in the other a Lower Huronian series; in the one an Unkar series, in the other an Upper Huronian; and in the one a Chuar series, in the other a Keweenawan. These series in each district are separated by unconformities, and in the Grand Canyon region are unconformably below the Tonto sandstone, and in the Lake Superior region unconformably below the Potsdam. Pre-Cambrian time was, however, so long that it is possible that all of the three sedimentary series of the Grand Canyon region are wholly above the three sedimentary series of the Lake Superior region. Any one of the unconformities in either region may represent the time in which all of the sedimentary series and the separating unconformities, with concomitant metamorphism, were being formed in the other region.

While all of these extreme suppositions are clearly possible, it can hardly be said that any one is probable. However, it can not be said to be improbable that sedimentation was taking place in one of the regions when erosion was occurring in the other, and thus that one or more series in one region is equivalent to one or more of the unconformities in the other district. Finally, it is not impossible that the Lake Superior and Grand Canyon regions belonged to the same geological province during the whole or a part of pre-Cambrian time, in which case some of the periods of erosion and sedimentation were in a general way contemporaneous. The two regions were in the same province in early Cambrian time. At the beginning of that period both regions were above the water. The Cambrian transgression, beginning at the southeast, reached the Lake Superior region and the Grand Canyon region at approximately the same time, and thus the Upper Cambrian deposits are roughly equivalent; but it can not be shown as yet that this unconformity does not extend to a more remote time in one region than in the other region, i. e., that one region arose from the sea before the other. If this were the case, a part of the erosion interval in one region would be equivalent to a part of the deposits of the other. If, as has been suggested (pp. 732–733), great unconformities are caused by differential subsidence, it may be possible to extend some unconformities throughout a continent, or even from continent to continent.

The only ways known in which the questions of correlation between geological provinces in pre-Cambrian rocks can be certainly solved are to find fossils in the series concerned or to work out the physical history of the continents. That fossils will be found in the immediate future in these ancient formations in such abundance as to solve the major questions of correlation is hardly to be hoped, but it is probable that assistance in some regions may be rendered by paleontology; for already pre-Cambrian fossils have been discovered in some areas. However, the more hopeful direction of attack is along the line of the physical history of the continent. Much work has been done in recent years in this direction, and such great progress is being made that we may hope to carry the history of the continents, at least in outline, for some distance back into the pre-Cambrian.

Reasons are subsequently given for favoring the view that the crystalline complex underlying all of the sedimentary series was probably formed under exceptional conditions, and that these may be placed together as belonging to one great division of geological time. For this division the term Archean is advocated. For the great fraction of the world's history represented by the deposits between the Archean and the Olenellus fauna, the term Proterozoic for the era and Algonkian for its equivalent period are used. It is recognized that the Proterozoic era should be divided into several periods, and that this will be done in the future is possible. Since at present we have not sufficient knowledge to do this, the term Algonkian was introduced by the United States Geological Survey to cover the rocks deposited during the whole era, with the understanding, however, that when rocks are referred to as Algonkian in different geological provinces, it does not necessarily imply that they are of equivalent age. It implies only that they occupy some part of the great time space between the Archean and the Cambrian.

In each individual geological province the only safe method of work, then, is to build up a system of stratigraphy independent of the stratigraphy of other geological provinces. If unconformities occur, these give a basis for separating the formations into series. The series may be divided into formations. The series and formations should be given local names, and thus avoid implied correlation of them with the series and formations of other provinces. If in the future paleontological or other evidence becomes available, so that it shall be possible to equate the formations and series of the different provinces, the local names will not be the less valuable, and in the meantime progress will not be checked by the implication that we have knowledge where knowledge does not exist.

PRACTICAL METHODS OF FIELD WORK

A completely satisfactory monographic report upon an area of much folded pre-Cambrian rocks should be accompanied by a map which shows in detail the position and character of all important exposures and a sufficient number of sections in various directions to make the structure clear. Such a map should show the observations, as well as the inferences which are drawn from them. This might well be accompanied by a second map, on a smaller scale, giving the generalized conclusions without the observations upon which they were based.

This statement applies to certain post-Cambrian areas as well as to pre-Cambrian areas, but the work which is necessary to a determination of the structure is in the one case usually very different from the other. In a simply folded area of Cambrian or post-Cambrian rocks one can often construct a map by making traverses across the strike of the rock at intervals wide apart, examining on the way the more prominent exposures and quarries. Oftentimes only a very small amount of material other than fossils needs to be collected. This, however, is not the case where the fossiliferous rocks are closely folded, and especially where metamorphism has gone so far as to obliterate fossils or to render their discovery difficult.

In the most complexly folded districts, in order to attain the above results it may be advisable to do the following: (1) All of the exposures are visited, studied, specimened, and located; (2) the rocks are provisionally named in the field, and specimens are taken in all cases in which there is any doubt as to their present or original character; (3) strikes and dips are taken at numerous places; (4) the characters of the folds, simple, composite, and complex, are determined, and each fold is represented upon the map by suitable conventions; (5) in the notes and on maps are given data as to all secondary structures; (6) a magnetic survey may be made, for magnetic formations may be traced from outcrop to outcrop in this way when not continuously exposed; (7) formation boundaries are followed in detail, for in intricately folded areas the boundary line between formations is of so complicated a character that it can not be inferred to run for any distance in the direction which is observed at a particular point; (8) as fast as the work progresses it is mapped in the field, in order that the geologist may get a proper idea of the structure of the area already covered, and thus continue the work intelligently; (9) after the field work is finished, thin sections are made of all rocks the characters of which are doubtful or which are likely to give any clue to the history of the district. The provisional field determinations of the rocks are thus verified or corrected, and the genesis of the rocks is worked out. After this is done it may be necessary to further revise the work in the field, and particularly to rectify the formation boundaries.

The particular method of mapping will depend largely upon the character of the country and the excellence of the base maps which are available. If large-scale, accurate topographic maps are at hand the location of an exposure is at once determined, in both its horizontal and its vertical elements. If the district is one of numerous roads and trails these greatly simplify the work, as a network of determined lines are furnished both for easy and rapid movement and for starting-points in locations. Having a base map of the highest grade, with simple instruments one may quickly determine where he is, and place upon the plat at once all his observations. As an example of such exceptionally favored regions may be mentioned the Highlands of Scotland, where the 6-inch ordnance maps are available. Yet even here, with all the advantage thus furnished by this map, the detailed mapping of this region has been an exceedingly slow process.

In many of the mountainous regions of the United States topographic maps on a scale of 1, 2, or 4 miles to the inch are available. With these maps the more prominent points may be easily located, but it is sometimes difficult to identify the smaller features. Here a simple light traverse plane-table, like the United States Geological Survey model, may be used to locate one's self. After a point is determined the geology may be worked in for some distance about by the odometer, by pacing, or by some other rapid method of measuring distances. From a determined point other points may be quickly located, and the work thus extended.

For critical areas it may be found that the topographic base is not adequate, in which case it will be necessary to supplement it by an especially large-scale topographic map. Methods of making such a topographic map will not be here discussed in detail. It may be said, however, that if two men work together, one as an assistant at the instrument and the other as geologist, the work will progress at a comparatively high degree of speed, and the topographic and the geologic mapping be done at the same time. The assistant may be provided with a Johnson plane-table and a simple telescope alidade. The geologist, in addition to his ordinary equipment, has a light stadia rod. As he traces the boundary between the formations, or finds any other points which need location, he elevates his rod and is located by the assistant. The latter, when not occupied by this duty, is working in the topography. Observations of the geologist and assistant have like numbers, so that the field observations of the geologist may be placed upon the topographic map at the end of the day's work or in the office.

In still other areas no topographic maps are available. Here geological work must be based on the township surveys, if these have been made. In important economic areas these township-plat surveys may serve as a primary basis, and the plane-table be used to make a base map where the relations between topography and structure are close. In some districts of closely folded rocks in which the relation between structure and topography is not close, satisfactory work may be done without a tographic map, but at a much slower rate than with a good map. Locations may be made by a regular system of traverses from the section corners and quarter posts and intermediate points across the section lines. In general, the direction of traversing will be across the strike of the rocks. Whether the traverses be made at intervals of 2, 1, one-half, one-fourth, or one-eighth miles will depend upon the intricacy of the geology. In mapping forest-covered districts, the time of the geologist, and therefore the expense upon the whole, is saved by having an experienced compassman as an assistant, who does the pacing and therefore the locating, while the geologist is free to go in any direction in search of ledges and to make his observations. He can then be located wherever he wishes by the compassman.

Since there are extensive areas where the rocks are covered by drift, disintegrated material, or alluvium, it may often be found necessary to supplement the above work by magnetic surveys. If certain formations are magnetic and others nonmagnetic, and but occasional outcrops are found, by making a magnetic survey it is often possible to trace the magnetic stratum across the intervening nonexposed areas, and thus to determine the structure with a high degree of probability, when it would not have been possible to make the determination had the magnetism of a part of the formations been absent. The formation having this magnetic quality may be an iron-ore-bearing formation, an amygdaloid, or in fact any rock which bears any considerable quantity of magnetite.

The instruments necessary for making these magnetic surveys are not complex magnetometers, but the simple dial compass and dip needle. The dial compass is provided with an upper revolving circle graduated to degrees, enabling the geologist to take the strike, while the needle is free, and thus determines the variation at each observation. The lower graduated circle may be movable, so that the average variation can be set off, in a district where there is no local magnetic disturbance. Thus the instrument makes all corrections, and there is less opportunity for mistakes to creep into the observations. Such an instrument may also be furnished with clinometer, rule, and protractor, so that the only instruments necessary for the geologist are the dial compass, dip needle, a hammer, and a lens.

In using the dial compass in districts of magnetic disturbance, it is necessary that proper corrections be made for longitude and for the equation of time. The meridian is then determined by the dial, and the magnetic variation read at regular intervals. After the magnetic meridian is determined at each observation, the dip needle is used and the magnetic dip is ascertained. If the belt is one of great magnetic power, the vibrations of the dip needle may also be observed. In many cases either one of these instruments will serve to follow a formation from outcrop to outcrop over covered areas, but when different magnetic formations are closely associated, and thus the magnetic influence of one overlaps the other, it is frequently necessary to make very close observations with both instruments over the same area.

In wholly unsurveyed areas cruder and less perfect methods must be adopted. For a first reconnaissance over a large area where no topographic maps or township plats are to be had, the distances may be measured by the micrometer compass and the directions with the needle, the course being followed from the time one starts from camp until his return, or until some other check point is available. By this method, combined with observations for latitude and longitude, a reconnaissance geological map may be constructed. Of this character are many of the surveys of the Northwest and of the vast interior of Canada.

A few words may be said as to good morals or good methods of work. The notes concerning any given exposure should be taken before the exposure is left. The very fact of writing what is seen sharpens the intellect and directs observation to undetermined points, and thus makes the notes more accurate and fuller than they would otherwise be. Notes written after an exposure is left always have an uncertain element, dependent upon the faithfulness of the memory. In taking the strikes and dips of rocks a certain invariable order should be followed. The strikes should always read from the north. All specimens should be distinctly marked in some way at the moment of collection. The notes bearing upon the ledges from which specimens come should also have these numbers at their proper places, so that the specimens may be connected with the notes. A uniform style of graphical methods of representing strikes, dips, axes of folds, synclines, and anticlines should be adopted. In short, an invariable habit of work should be followed, and thus much energy saved. At the end of the day ideas which may occur touching the relations between the facts observed should be recorded. The attempt thus to give a generalization from the day's work sharpens the wits and makes the geologist think of relations which were not before observed, and better fits him for the next day's work. He has an hypothesis or hypotheses which he is either to verify or to disprove, and consequently the following day he will work with greater keenness and insight.

PART II.

HISTORICAL GEOLOGY.

In the following résumé of the present state of knowledge of the various regions of North America the order is not consistently geographical or geological, but rather that of the development of exact knowledge of the pre-Cambrian rocks. The great Canadian pre-Cambrian area is a geological unit, yet detailed study has been confined to particular localities, and of necessity the districts which have been units of work have been followed in this paper. The Original Laurentian area is treated first. Following this the Adirondack district, the Hastings district, the Original Huronian district, and the Lake Superior region are taken up in order. These are considered next because exact knowledge of the pre-Cambrian rocks therein is greater than of those rocks in other areas. Following the Lake Superior region the Great Northern region, Eastern Canada, and Newfoundland are considered; then the isolated areas of the Mississippi Valley, the Cordilleras, and, finally, the Eastern United States. The latter region, although the earliest to be studied, is taken up last, for it is an area in which the conditions for obtaining exact knowledge are the least favorable and in which comparatively little structural knowledge of the pre-Cambrian has been acquired. The summaries of the present state of knowledge concerning the individual districts are not accompanied by references to literature. To give such references would very greatly extend this paper; and they are hardly necessary, since the pre-Cambrian literature has already been summarized in Bulletin 86 of the United States Geological Survey, and since that volume appeared, in successive numbers of the Journal of Geology. The statements made, except where they are specifically referred to some one else, must be regarded as my own opinion of the most probable conclusions obtainable concerning the various regions, considering the present state of knowledge. As a matter of course, the opinions expressed concerning many regions are based upon the work of others. Undoubtedly in various regions future work will show that I am wrong to a greater or lesser degree. The necessary brevity of this paper has made unavoidable the omission of modifying and qualifying facts and the opinions of others. The purpose is to give a brief exposition of the present state of knowledge of the pre-Cambrian, rather than an exhaustive discussion of the facts.

The terms group, system, series, are used with the stratigraphical significance given them by the International Geological Congress. The chronological terms, era and period, corresponding to the first two, are used. Formation is used as one of the members of a series, as quartzite formation or limestone formation of the Huronian series. The term crystalline schist is rigidly confined to rocks which have a completely crystalline interlocking texture and a schistose structure due to a parallel or foliated arrangement of the mineral ingredients or of aggregations of these ingredients. The finely banded gneisses are typical examples. All rock masses which show within themselves indubitable evidence of clastic origin are excluded from the crystalline schists. An unaltered clastic or a semicrystalline formation may grade into a crystalline schist.

As indicated in the general discussion on the previous pages, the terms Cambrian, Algonkian, and Archean may be delimited as follows: The term Cambrian includes rocks below the Ordovician down to those containing the Olenellus fauna. Algonkian is a systemic term covering all recognizable pre-Cambrian clastic rocks and all semicrystalline and crystalline rocks of equivalent age; it therefore includes completely crystalline rocks, but does not include all rocks of this kind, as holocrystalline rocks of sedimentary origin occur in post-Algonkian time. The Archean includes all pre-Algonkian rocks.

The term region is applied to a large area composing what is believed to be a geological province. A district is a subdivision of a geological province. Where knowledge permits, the rock succession, correlations with other districts or regions, and the principles illustrated are considered in order for each region or district. In most cases were the whole truth known nearly all of the principles would doubtless be illustrated, but in this summary only those principles which are illustrated with exceptional clearness are mentioned.

SECTION I.

THE ARCHEAN.

CHARACTER OF THE ARCHEAN

The Archean may be considered to comprise the oldest group of rocks of which we have any knowledge. The group is often called the Basement Complex. In certain areas these rocks are separated from the Cambrian by one or more series of sedimentary rocks of great thickness. In some regions these intervening series may be separated from one another by unconformities, and they may be separated from the Cambrian and from the Archean by unconformities. Thus in certain areas we know that the basement rocks are vastly older than the Cambrian. The character of the Archean will first be considered in those regions in which we have evidence of vast antiquity. In the Original Huronian district, between the Cambrian and the Archean, or Basement Complex, there are probably two series of sedimentary rocks. These are separated by an unconformity from the Cambrian above and in like manner from the Archean below. In the Lake Superior region, separated from the Cambrian and from one another by unconformities, are three great series of sedimentary rocks. The lowest of these series derived its detritus from and rests upon the foliated edges of the Archean. In the Grand Canyon region of the Colorado the conditions are similar, certainly two and perhaps three unconformable series of pre Cambrian rocks, inferior in thickness only to those of the Lake Superior region, being separated by a great hiatus from the Archean below. In southwestern Montana, below the fossiliferous Cambrian, is a downward extension of slates and quartzites of great thickness, and unconformably below this series is the Archean. Similar relations obtain in the Wasatch Mountains. In the region about Hudson Bay are certainly two and perhaps three series of unconformable rocks between the Cambrian and the Archean, and separated from these by unconformities. In certain other regions it is highly probable that the Archean and the Cambrian are unconformably separated from one or more intervening series of sedimentary rocks. Consequently, in many regions the Archean, in essentially its present condition, as shown by definite structural evidence, is vastly older than the Cambrian.

In all of these regions in which the Basement Complex is so much older than the Cambrian, it consists of a most intricate mixture of nearly massive rocks, among which granite and gneissoid granite are predominant, and of gneissic and schistose rocks, all of which are completely crystalline. Between the various masses there are such intricate structural relations that nowhere has any certain structure been made out over considerable areas. The granites and basic eruptives may occupy considerable areas; the gneisses may be regularly laminated and grade into the granites; the crystalline schists may occupy the outer zones of an area; they may all be confusedly intermingled, schists, gneisses, and granites alternately predominating; sometimes the schistose rocks appear in dike-like forms in the granites; at other times the acid rocks are in dike-like forms in the schists; at still other times the granite, gneiss, and schist are rather uniform and persistent for considerable areas. The granites usually show a rough lamination, which may not appear in hand specimens, but which is evident in large masses.

The minerals in the rocks usually show evidence of dynamic action; they do not have the clear-cut definite relations characteristic of the later plutonic rocks. In the chief mineral constituents of the rocks there is essential uniformity in all of the areas, although certain less common minerals may be found in one area which have not been discovered in another. Orthoclase and acid plagioclase feldspar, quartz, hornblende, muscovite, and biotite are the standard minerals. To describe accurately the appearance of the rocks of the Basal Complex is exceedingly difficult, but anyone who examines a set of specimens from the various areas will perceive the truth of the statement made as to the essential likeness of the rocks from different regions. A suite from any one of the regions which has been personally examined by me, if unlabeled, could by no possibility be asserted not to come from any other.

The unparalleled intricacy of the structure of this complex, the general laminated arrangement of its parts, and the broken and distorted forms of the constituent minerals are evidence of repeated orogenic movements of the most powerful character. Further, the Basement Complex is recognized not only by its positive but also by its negative characters. Nowhere in it is there a persistent thick formation of quartz-schist (although vein quartz is abundant), of limestone or marble, of a graphitic schist, or of a conglomerate. If sandstones and limestones or other sedimentary materials have been a part of this system, the profound and varied mutations through vast lapses of time have wholly obliterated all evidence of their presence.

Besides the areas mentioned in which these most ancient rocks occur there are many other areas in which there are between the Cambrian and the Basement Complex or Archean great series of clastic rocks, although here the evidence at hand in favor of vast age for the Basement Complex is less than in cases before cited. Herein are included the Front range of Colorado, which has between the Basement Complex and the fossiliferous rocks on its eastern slope the clastic series of Boulder, Coal, and Thompson creeks; and the Quartzite Mountains of Colorado, where between the Basement Complex and the Carboniferous there is a great series of quartzites. There is definite structural evidence for placing the basement rocks of these and other areas with those first considered. In a third class of areas no definite evidence in the nature of intervening series shows that between the Cambrian and the Basement Complex has intervened an era or even a period.

Because of the unique lithological character of the Basement Complex in all these regions, and because of the essential likeness in structure, we have ground for grouping these rocks together, whether exactly of the same age or not. Arguments for correlation founded on lithological grounds may well be distrusted, but the exceedingly strange, varied, and complex lithological and structural characters of this group, of which we have no evidence of duplication anywhere in later times, are an argument of great weight. In the complexity of its parts and the implications of its structure it gives evidence of vast antiquity.

In Algonkian, Cambrian, Silurian, Devonian, and even later times, completely crystalline schists have been produced over large areas; but, while often in these systems no evidence now remains of clastic characters, they rarely if ever closely resemble this fundamental complex. In the beginning of its history a clastic series was of necessity a shale, a sandstone, a limestone, a chert, or some other form of sediment, and often contained carbonaceous material. Cementation, metasomatism, mashing, and other processes of metamorphism may have profoundly changed any of these deposits. A limestone may have been transformed into crystalline marble, or if impure into a hornblende-schist containing scarcely a remnant of original carbonate. A cherty iron-bearing carbonate may have become an actinolite-magnetite-schist. Carbonaceous shaly material may have become a graphite-schist; but if such a rock was represented in the Basement Complex, what has become of the carbon? A sandstone may have become a granular quartzite or a foliated micaceous quartz-schist. But that great quartzite formations like those of the Huronian of Lake Superior or the pre-Olenellus of the Wasatch can have become wholly obliterated by any process short of fusion is almost inconceivable. As has been said, none of these rocks are found in the Archean throughout its whole vast area. In its positive as well as its negative qualities it is a unit. While it can not be considered demonstrated that all of the Archean areas are of the same age, it may, then, be accepted that in North America there is a system of granites, gneisses, and crystalline schists which are the oldest known rocks, and which have representatives in many areas throughout the United States, although most widespread and abundant in Canada. That such a basal system exists is not a new idea; but it has not generally been recognized that between it and the Cambrian there elapsed an era in which were alternating cycles of the deposition of rock systems and of vast erosion intervals.

As here used, the term Archean is restricted to this Basement Complex. It is no longer possible to regard as a unit or treat together all the pre Cambrian rocks. The rocks included in the Basement Complex are everywhere called Azoic or Archean. The crystallines and semicrystallines above this complex, often called Archean, must be distributed from the Devonian or earlier to the pre-Cambrian. It is clear that if Archean is to remain a serviceable term it must be restricted to some unit. Such a unit is the Basement Complex, and to it the term Archean is most appropriate.

ORIGIN OF THE ARCHEAN

As to the origin of the Archean, four different views are prominent: (1) The Archean consists of metamorphosed sedimentary rocks; (2) the Archean is igneous, but of later age than certain of the pre-Cambrian clastics with which it is in contact; (3) the Archean is igneous and represents a part of the original crust of the earth, and is therefore older than any sedimentary rocks; (4) the Archean is igneous and represents a part of the original crust of the earth or its downward crystallization.

(1) The Archean consists of metamorphosed sedimentary rocks. Those who believe in the clastic origin of the Archean, as above defined, will not question the conclusion reached as to the age of the Basement Complex; for to produce a group of rocks so different from any known

metamorphic clastics must imply not only great age but probably sediments which were originally deposited under conditions different from those of later times. This school, while believing in the detrital origin of the Archean as a whole, is aware that it has been cut again and again by eruptives of all kinds, and that the supposed clastics have been profoundly metamorphosed by contact and dynamic action, and in many places have been so changed that the place where the intrusives end and the clastics begin can not be pointed out.

If this sedimentary view of the origin of the Archean be correct, as no universal break in geological continuity can be asserted it should be found that between the Archean and the clastics there are gradations. Hitchcock, Marvine, Stevenson, King, Winchell, and others, accepting such a sedimentary origin, believe that gradations have been found between the Basement Complex and the recognizable clastics in the Rocky Mountain system, in the Lake Superior region, and in the Appalachians. These authors have regarded the fact that as a whole the basement rocks show lamination as evidence that they were originally sedimentary. A few years ago it was assumed as a matter of course that distinct lamination in a rock, however faint, is evidence of sedimentation. The existence of lamination in the gneissoid granites, gneisses, and schists, and the fact that these rocks were believed to grade into the clastics, were taken as conclusive evidence of the original sedimentary origin of the whole. These gradations, and also the fundamental differences between the Archean and the indisputably sedimentary rocks, have been explained by supposing that the first sedimentary deposits of the earliest ocean were different in character from any subsequent rock; that from these unique deposits the more typical rocks of the Basement Complex have developed; and that the apparent transition between these rocks and the ordinary sediments marks the time when the conditions were changed from the exceptional ones of the early ocean to those in which ordinary sediments were formed, and in which life perhaps may have entered.

It is now everywhere recognized, as early shown by E. Emmons and Lieber, that schistose structures are present in many eruptive rocks; it is also recognized that like structures which have no relation to the original lamination are produced in sedimentary rocks, as early noted by Tyson, E. Emmons, Lieber, Blake, Adams, E. Hitchcock, Jackson, Jukes, and Rogers. E. Hitchcock, E. Emmons, and Lieber traced the actual gradations between schist-conglomerates and crystalline schists, while Mather traced the blue fossiliferous limestones into completely crystalline, granular marbles. Laminated or schistose structure in crystalline schists then bears neither for nor against a clastic origin.

The gradation of the finely laminated schists and gneisses into the coarsely granitoid phases has been admirably described by Jukes, for the rocks of Newfoundland; by Lieber and E. Emmons, for the rocks of the southern Appalachians; by Hitchcock, for the rocks of

Massachusetts and Vermont; by Marvine and Stevenson, for the rocks of Colorado; by King, Hague, and S. F. Emmons, for the rocks of the West in the region of the fortieth parallel; and by Lawson, for the rocks about Lake Superior. Most of these writers and many others, including Selwyn, approaching the problem from the side of the clastic rocks, have regarded the coarsely crystallized rocks as produced by metamorphism, although they have considered the more granular rocks as produced by the extreme process of metamorphism—aqueo igneous fusion. Those who have maintained this origin for these rocks have recognized the fact that they have locally acted as eruptives, although in general the material is thought not to have moved far. Marvine so clearly saw that the facts could be explained in two ways that he says that, while he regards the whole as metamorphosed sedimentary rocks, another observer approaching the field from a different direction, where the evidences of intrusive nature are most manifest, would reach the conclusion that the whole is eruptive. Hitchcock and Stevenson and most of the others are in practically the same position.

The school of geologists that regards massive rocks as metamorphic without any intervening time of fluidity, that regards granitic and gneissic layers interlaminated with the schists or slates as selectively metamorphosed, and that regards fragments of slate, schist, and gneiss within massive rocks as residual unmetamorphosed material, while nearly gone, still has representatives. That the matrix of a fragmental rock could become slowly heated to such a temperature or be subject to such other conditions as are necessary in order that it should crystallize as a coarsely granular granite, and not at the same time equally metamorphose the other layers and destroy the bowlders and pebbles which it contains, seems incredible. The explanation implies. not only that the fragments and the bands of slate and schist have been able to resist the forces of change during the slow processes which have been sufficient to produce coarsely crystalline material adjacent, but that in situ they have continued to resist these forces during all the time required by the matrices to pass once more into ordinary conditions. The processes embodied in such "selective metamorphism" certainly need explanation.

(2) The Archean is igneous, but of later age than the pre-Cambrian clastics with which it is in contact. The facts presented by those who have described downward gradations from unmistakable clastics into a crystalline complex have not been interpreted as above by this school. It has declined to apply the term "metamorphism" to a product which has become fluent, and has insisted upon its essentially igneous character. Lawson is conspicuous as having recently put this side of the case strongly; but it is noteworthy that Winchell, belonging to the first school, and Lawson, to the second, have had essentially the same facts before them, both having done their work in the same region. Lawson further holds that the intrusive rocks have been produced by the

subcrustal fusion of the overlying sedimentary rocks. The difference is largely one of definition and emphasis rather than of ideas. Both regard the granite-gneiss as material which has resulted from a change in the condition of original sediments and which has not moved far.

The theory that the Archean or a part of it is a liquefied floor of sedimentary rocks is open to the objection that it is an unverified hypothesis. When once a sedimentary rock has become fluent, and is wholly free to crystallize anew, how shall the material be identified? To state that such material has not moved far is pure assumption. If the fusion theory is true, the average composition of the unfused part of the clastic series and the subjacent material should agree. To obtain average analyses of rocks which vary widely in mineral character within short distances is not easy, but is a thing which must apparently be attempted if this theory is to be maintained, for I see no other way in which an attempt can be made to verify the hypothesis. This method has been applied for the first time by Adams. In the Original Laurentian district he has compared the composition of the gneisses of the Grenville series with that of the Ottawa basal gneissoid granite. He finds the first to have the composition of a shale or grit, and the second that of a granite, and therefore concludes that the Ottawa gneiss can not have been produced by the metamorphism or fusion of the Grenville rocks.

Another class of geologists of the second school, noting the contact relations between the granitic rocks and the clastics, hold that the former, called by others Lower Laurentian or Archean, are eruptives of later age than the clastics with which they are in contact, without attempting to give any theory as to the source of the material. Herein are included Hawes, Hall, Mather, Foster, Whitney, Wadsworth, Rominger, Herrick, and others. Rominger distinctly recognized the granites and granite-gneisses of this kind on the south shore of Lake Superior as the subjacent rocks upon which the schists rest. Herrick saw the same relations with reference to his granitic and schistose groups on the north shore. In the last two cases the facts before the writers are precisely the same as those of the geologists who advocate the subcrustal fusion theory; but, by giving no explanation of the source of the material for the granite-gneisses, they have escaped the difficulty of the unverified assumption that these eruptives represent fused sediments. However, they fail to explain what has become of the floor upon which the clastics were deposited. Some floor they must have had. Where these eruptive contacts are found the floor has disappeared, and if so the eruptives, if extraneous, must be considered to have absorbed or cut across it.

The three positions—that the granite-gneiss is selectively metamorphosed material, is due to subcrustal fusion, or is an extraneous intrusive—may be considered to grade into one another. Those who insist on the first have selective metamorphism and contact phenomena to explain. Those who insist on subcrustal fusion may be called upon to identify their material. They can show the former fused condition only by contact phenomena, and contact phenomena are not evidence of progressive fusion, but only of intrusion. Those who regard the granite-gneiss as intrusive may be asked what has become of the floor upon which the clastics were deposited.

(3) The Archean is igneous, and represents part of the original crust of the earth, and is therefore older than any sedimentary series. This is apparently the conclusion of E. Emmons and Lieber. These careful observers not only maintained the igneous origin of the granite-gneiss of the southern Appalachians, but traced the gradations between basic schistose rocks and massive eruptives, including hornblende-schist and unmistakable dikes, and drew the correct conclusion, lately regarded as a discovery, that such rocks are sometimes metamorphosed eruptives. While the major portion of the granite-gneiss and associated rocks was considered older than the oldest clastics, later intrusives of a similar character were recognized. This theory that the Basement Complex is igneous is held by Geikie as to the major part of the Archean of Great Britain. Geikie says of the true Archean of Great Britain that with certain possible exceptions it not only contains no material which gives any evidence of ever having been sedimentary material of any kind, but it further contains no material which can be considered a surface volcanic, while in it there are many rocks which are certainly plutonic eruptives. Many German geologists hold the Archean of Germany to be igneous. Among these Lehmann and Roth have been conspicuous. Indeed, these last two have maintained the igneous origin of all the pre-Cambrian rocks.

The geologists of this third school, with the second school, recognize the igneous character of the granite-gneisses having irruptive contacts with the clastic series, but they decline to recognize these rocks as Archean. Such rocks are eruptives. Their age is to be designated precisely as are eruptive rocks which cut Cambrian, Silurian, or Devonian strata.

As bearing in favor of the really igneous character of the Archean is the fact that no case has been demonstrated, except possibly that of the marbles and some quartz rocks, of the production of a perfectly massive crystalline rock from a clastic without intervening fluidity. Metamorphism, whether the original rock is a massive eruptive or a stratified sedimentary, produces a laminated or schistose rock. If a granitic structure can be taken as evidence of an eruptive origin—and we know many eruptive rocks do have such a texture—a very strong case can be made for the eruptive origin of the larger part of the fundamental complex. The line of argument is precisely analogous to that by which the whole has been held to be sedimentary. There are complete gradations from the most thoroughly schistose and laminated phases to the most massive phase. Also bearing in favor of a truly igneous character for the Basement Complex is the fact that the rocks referred in the first part of this section to the Archean are more closely simulated by igneous rocks which have irruptive contacts with ancient clastics than by any recognizable metamorphosed sedimentaries. In this connection may be mentioned the occurrences in the Appalachians and in British Columbia of relations between granitic rocks and strata as late as the Carboniferous or Triassic analogous to those which often prevail between the granite and granite-gneiss and the pre-Cambrian crystalline schists. Here the one class of rock is known to be sedimentary, the other intrusive.

It may be said that the actual gradations between the Algonkian and Archean in certain places are evidence that the latter are not igneous rocks earlier than the former; that gradations can be explained between subsequent intrusives and clastics, but not between igneous rocks and sedimentaries of later age. It has, however, been shown that as a consequence of profound dynamic action two unconformable series, the one of which is composed of material from the other, and therefore resembles it in composition, may have had developed within them conformable secondary structures and gradations, the original structures of the clastic series being simultaneously obliterated. Also, Pumpelly has recently ascertained that subaerial disintegration of the earlier series is an important adjunct in the production of such gradations. It has been demonstrated that in certain areas perfect conformity and complete gradation exist between series separated originally by wide unconformities, the earlier of which was probably of igneous origin, while the later was certainly sedimentary.

(4) The Archean is igneous, and represents a part of the original crust of the earth or its downward crystallization. However, the Archean having been subjected to repeated dynamic movements, and consequently to profound metamorphism, and having been intruded by vast and in many places predominant quantities of intrusive material, is now far more complex in character and structure than originally. This fourth view is offered as a more probable approximation to the truth than any of the preceding. It may be possible that everywhere erosion has cut off the outer part of the first solidified crust of the earth, but if so it seems certain that the downward crystallization of this first crust has taken its place, for we can not suppose that erosion has anywhere caught up with inward crystallization. Lava flows are not an exception, for these always come up through crystallized material.

If the theory be true, it follows that the rocks formed by downward crystallization may really be later in age than many sediments, for rocks now at the surface may have crystallized in post-Archean time, when sedimentary rocks were being deposited in the early seas. However, these rocks, by the hypothesis of their origin, can never be assigned to any definite period of sedimentation, and they may well be considered as Archean. These rocks are certainly a class by themselves, which, if not placed here, can not be referred to any of the geological periods. Further, sedimentation must have begun in the earliest seas while upon parts of possible continental areas volcanic materials alone were still accumulating. These latter, in accordance with the definition, would belong to the Archean. There would be in this case no positive equating of one with the other. When, later, upon these Archean rocks, contemporaneous with the earlier sedimentary rocks, clastics began to form, this would be for this region the opening of the Algonkian. However, it is not impossible that all such supposed contemporaneous Archean and Algonkian formations may have been destroyed by erosion. Certainly this would have been the case with a large portion of them, and it follows that this difficulty may be theoretical rather than practical.

Accepting for the moment the above hypothesis, how far does it explain the phenomena of the Basement Complex?

a. The gneissoid granite of the Archean is very similar to gneissoid granites which are certainly eruptives of later ages, and is therefore precisely similar to well-known metamorphosed igneous rocks.

b. The dark-colored hornblende gneisses, mica-gneisses, and chlorite-schists are lithologically like those which are known to have been produced in many places from altered eruptives.

c. In many areas it is possible to trace the gneissoid granites into massive granites, and the hornblende-schists, mica-schists, chlorite-schists, hornblende-gneisses, mica-gneisses, chlorite-gneisses, and other schists and gneisses into massive rocks with typical igneous structures. If these structures are evidence of igneous origin, it is plain that the schistose rocks which can thus be traced into massive forms are igneous. However, a far larger body of the schistose rocks can not be thus traced back to a massive condition, and they can only be inferred to be of igneous origin because of their likeness to similar rocks which are igneous.

d. That a great hiatus so frequently, if not always, separates the sedimentary rocks from the Archean strongly supports the hypothesis, for if the first outer crust has been removed by erosion, and the background of the Archean represents the downward crystallization of the crust of the earth, the structural relations which obtain between these rocks and the lowest sedimentary rocks would be those of unconformity. This coincidence of the requirements of the theory with the facts in the field is very significant. The explanation of the apparent gradation between the Archean and the overlying sedimentary rocks is the same as in the third theory. (See p. 752.)

e. The complete absence of sedimentary rocks or of any of the typical kinds of rocks which are produced only by the metamorphism of sedimentary rocks is fully explained by the theory.

If the theory be accepted, it is recognized, as in the case of the third theory, that the amounts and kinds of later igneous rocks are vast in quantity and great in variety; also that many of the earlier igneous rocks have been so profoundly metamorphosed that it is exceedingly difficult, if not impossible, to determine what part of the

Archean represents the inward crystallization and what part later intrusives. If a conjecture may be hazarded upon this point, it is thought to be probable that the banded gneisses, which are the predominant rocks over such vast areas of the Archean, and which have been known in general as the fundamental gneiss, represent this supposed inward crystallization. In making this statement it is recognized that the fundamental gneiss is not so homogeneous as might be understood from the earlier descriptions, and that in almost every area of it there are many varieties of rocks; and yet so striking and uniform is the character of the predominant rock, that it has been almost universally denominated the fundamental gneiss. These gneisses are certainly the oldest rocks now present in the Archean, so far as we have any evidence, for they are cut through by the later eruptives. In certain areas it has been ascertained that several varieties of eruptives exist, each succeeding eruptive cutting the fundamental gneiss and the preceding eruptives. Thus, in the Marquette district of the Lake Superior region Wadsworth reports that dikes of hornblende-gneiss or hornblende-schist cut the country gneiss of the region. These dikes are cut by another porphyritic dike, while both are cut by gray granite, and this in turn is cut by red granite. In some districts the intrusives are all of Archean age; in others they are partly Archean and partly post-Archean.

The question arises whether there are any surface volcanics belonging with the true Archean. It is certain that in some regions, as yet unseparated from the Basement Complex, are large areas of volcanics, including lavas, curious brecciated lavas, volcanic fragmentals, and probably intermingled lavas and volcanic fragmentals. Whether these volcanic rocks belong to the Basement Complex or can be separated from it on a structural basis is yet undetermined. In the Lake Superior region, where they are most extensively known, they are unconformably below the oldest sedimentaries, but there may still be a vast lapse of time between them and the time of the fundamental gneiss. Provisionally, however, we consider them as a part of the Basement Complex or Archean. In some districts the volcanic rocks are found to grade into dark-colored schists which no longer show evidence of their surface origin. Similar dark-colored schists constitute one of the divisions of the Archean. If these are derived from surface volcanics this might explain the difference between the prevalent light-colored, uniform, fundamental gneiss and the dark-colored, schistose division of the Archean. It is certain that in many regions the dark-colored schists are very old, since they have been cut by many succeeding eruptions, and bear evidence of repeated dynamic actions.

From the foregoing it is plain that, whatever the origin of the Basement Complex, the parts of any given area of it may not be of the same age. Of necessity, all subsequent eruptives have passed through the earlier rocks. The dikes which everywhere cut them are pipes through which later eruptives have passed. Large lakes of liquid material have formed within the Archean, which crystallized as bosses, causing it to contain considerable masses of characteristic igneous rocks. Where these rocks are predominant the materials must be mapped as eruptives later than the gneisses cut, but they may be Archean or post-Archean. Where the intrusives are subordinate to the Archean material they are often difficult to separate from it. Between the areas which rank as eruptives of post-Archean age and the genuine Archean there are doubtless gradations. Along the zone of contact, if the mass of later eruptive be great, there may be an area which can be placed equally well with the Basement Complex or with the later eruptives. Further, perhaps at various times and places parts of the Archean have become practically fluid, and from this condition the material has again crystallized in the forms characteristic of eruptives. The crystallized parts would then show intrusive or transition relations with the unfused portions. In the cases both of extraneous intrusives and fused Archean material there might therefore be gradations, as there are between the Archean and undoubted sedimentary rocks.

Therefore the problem of the relations of the Archean, as a whole, to the overlying clastics is somewhat the same as that between parts of the Archean, since the finely laminated Archean crystalline schists and gneisses and the later intrusive granite-gneisses and granites with which they are associated have contacts in every respect analogous to those occasionally found between the Archean complex and the clastic series. For example, it will be seen that rocks heretofore called Archean on the north shore of Lake Huron comprise two parts. One part is older and lies unconformably below, yielding fragments to the Original Huronian. The other part has intrusive relations with the clastics and the Archean, with transition phenomena in both places. If this material is an extraneous intrusive, it is a post Archean eruptive; if in situ it represents a portion of the pre-Huronian floor completely metamorphosed by selective metamorphism or by aqueo-igneous fusion, it can fairly, according to the first and second schools, be called a part of the Archean.

From the great diversity of opinion as to the origin of the Archean rocks, and from the fact that many of the opinions are beliefs rather than verified conclusions, it is plain that we have no definite knowledge upon parts of the subject. That there are comparatively few or no wholly massive rocks in the Basement Complex is precisely what would be expected under any theory. Its history is too long. Whether originally igneous or aqueous, it could not be hoped that there would be found the characteristic lithological forms of igneous or aqueous agencies. Many or all of these rocks were subjected not only to the movements which have taken place since Paleozoic time, but to the movements which occurred in the far greater length of previous time, if not too deeply buried to be beyond the influence of the outer foldings, in which case they were buried beyond the crushing strength of rock, were latently plastic, and were probably at a high temperature. If originally massive and igneous in the ordinary sense, dynamic action has obliterated the regularity of the arrangement of the constituent particles and has given them a more or less laminated or schistose structure. If sedimentary, all trace of that original sedimentary structure has been obliterated by the repeated foldings, contortions, and perhaps high degree of heat to which they have at various times been subjected.

DELIMITATIONS OF THE ARCHEAN.

It is generally accepted that the Archean has no limit downward. It is the oldest system, and surely includes, if such rocks exist, all of the original crust of the earth. But as denudation progresses material far within the earth approaches the surface, not by intrusion, but by gradually rising as a whole. Before reaching the surface the material has become crystallized. This original crystallization may have taken place in or even later than Algonkian time. Hence, if these rocks are to be considered as belonging to the age in which they were crystallized, the Archean grades below into the Algonkian, even as it is believed in places to grade above into the Algonkian. The truth of this position is not lessened by the fact, if fact it be, that the earth as a whole when subjected to sudden stress acts as a rigid body Even if true, it is equally certain that the crust of the earth under continued stress of considerable amount adapts itself to it, thus showing real plasticity. But it can not be assumed that the rock material deep within the earth, under pressure far beyond the crushing strength of any known material, and at a high temperature, exists as crystallized minerals, although this may be the case. We only know that it has these forms when the material, rising by erosion, nears the surface.

The upper limit of the Archean is not easy to define, and the task is rendered more difficult because geologists are not agreed upon the origin of the Archean. As has been seen, if either the sedimentary or the subcrustal fusion theory of its origin be accepted, gradations would be found between the Archean and clastics of Algonkian or post-Algonkian ages. Upon either of these theories, if sedimentary rocks are only buried deep enough, or folded severely enough, they will pass into crystallines by progressive metamorphism or by subcrustal fusion, just as do rocks of Cambrian and post-Cambrian ages. This the elder Hitchcock so clearly saw that he distinctly said that the so-called Laurentian granites and gneisses of Vermont are probably, in part at least, not older than the fossiliferous series.

If the Archean be made to cover all the crystallines below the pre-Cambrian clastics, it includes rocks the age of which varies from Algonkian to pre-Algonkian. This anomaly is perhaps best met by making a more or less arbitrary division between Archean and post-

Archean crystallines. The natural theoretical plane to choose is that marking the beginning of life; that is, to include in the Archean all truly Azoic rocks. While this suggestion has a plausible sound, we must believe that the dawn of life was very gradual and that its traces in its early stages are exceedingly sparse, so that there would be great if not insuperable difficulties in its practical application.

If the theory that the Archean includes only presedimentary rocks be accepted, its upward limit is easy to define; the Algonkian begins for each region at the time of the deposition of the first sedimentaries. But there are those who deny the existence at the present time of any such ancient rocks, although they concede their existence at one time, and they believe that the Archean as thus defined represents a vast lapse of time in the history of the earth. This denial of the present existence of any rocks of greater age than the oldest sedimentaries is of course a pure unverified assumption, defended on the ground of probability. If the original crust of the earth be defined as including more than the first outer skin, it is a question whether the converse proposition is not equally probable. Even if the position be true, the school that believes in the igneous origin of the Archean would still have a large mass of rocks for the Archean by including in it all the material which in the slow process of inward crystallization has now reached the surface of the earth, not by intrusion in the rocks above, but by erosion. This position would, however, be controverted by those who regard such rocks as plutonic and belonging to the age of their equivalent sedimentaries. But, as already shown, in the nature of the case it is not possible to designate the particular age to which these rocks belong. That there exists upon the surface of the earth a part of the original crust, or its downward continuation by later cooling, can hardly be doubted; and since these rocks can never be assigned to any definite period of sedimentation nor separated from other Archean rocks, they must be deemed Archean. They are a class by themselves which, if not placed here, can not be referred to any of the geological periods. Further, this class of rocks where in contact with detritals, of whatever age, by the very hypothesis of their origin must rest unconformably below them.

But the difficulties in the theoretical delimitation of the top of the Archean are so great that I confine myself to a statement of some possible solutions rather than commit myself to any theory, although I now incline toward the one last given. Although the obstacles are not nearly so great in delimiting the later periods, the difficulties of making an exact definition for the Silurian, Devonian, or Carboniferous periods are so considerable that almost any of those given in text-books have been found to disagree with the facts of some localities. If this be true of the later periods, of which so much more is known, it should not be surprising that the obstacles to an accurate delimitation of the Archean are at present apparently insuperable.

But while it is impossible to make a wholly satisfactory theoretical definition of the Archean, it is frequently easy in the field to say with a great degree of probability what rocks are Archean and what are post-Archean. For instance, in the Arizona region, as has been seen, above the typical Archean complex there is the most profound unconformity, above which the rocks are readily recognized clastics. From my point of view the same thing is true for a large part of the Lake Superior region. In the Uinta and Wasatch mountains, again, below the quartzites of probable Algonkian age is a great unconformity, and then appears the implicated Archean. In certain other regions the separation of the Algonkian and Archean is a matter of exceeding difficulty. As representative of this class of cases may be taken the Front range of Colorado, along the east side of which are unmistakable clastics, with an apparent gradation between them and the crystalline complex. In the Appalachians again, where in large part the oldest clastic rocks recognizable are Cambrian, it can not be said what part of the complex below is Algonkian and what part is Archean. In this region the separation of the Cambrian from the pre-Cambrian can be accomplished only by minute and laborious study. In places the two appear to be in conformity and to grade into each other. It is only recently that this gradation in the Green Mountains has been shown by Pumpelly to be consistent with a great unconformity between the two. The causes producing this gradation between the Cambrian and pre-Cambrian in Massachusetts (post-Cambrian dynamic action and pre-Cambrian disintegration) may also be found to explain the conformities and gradations between the Algonkian and Archean.

While, then, it is not easy to define the Archean, it is plain that the discrimination in the field between the Archean and the Algonkian is a practicable one, and should continue to be applied even if its exact theoretical meaning can not be said to be certainly known. It has been the custom in the past to refer to the Archean practically all crystalline rocks, with many semicrystalline rocks which seem to be very old, or the age of which is not determined. Under this practice vast areas in the Appalachians have been referred to the Archean which are now being placed in the Paleozoic. Doubtless in the same way many other areas which have been classified as Archean will, upon closer study, be removed from it and the rocks be distributed from the Algonkian upward. At this point a reform in geology is needed. If, for instance, the oldest rocks of clearly recognizable age are Triassic, and these Triassic rocks rest upon a complex the structural relations of which are not studied in detail, this complex should be denominated pre-Triassic rather than Archean. A large part of the difficulty in understanding from the literature the actual facts as to the occurrences and relations of the crystalline schists has arisen from this practice of using the Archean as the dumping-ground for everything of unknown age.

STRATIGRAPHY OF THE ARCHEAN

After characterizing the Archean the methods applicable to its subdivision are easily deduced. If no part of it is demonstrably sedimentary, structural methods can not apply; its subdivisions must be made upon purely lithological grounds. If a part of it is demonstrably eruptive the relative ages of these parts may often be ascertained, and all are necessarily newer than the part not recognized as eruptive, else these could not be shown to have this origin. Many attempts to apply stratigraphical methods to parts of the Archean have been made, but they have not thus far been successful. Such attempts have been based upon the belief that foliation represents sedimentation, but even where mapping has been done upon this erroneous basis it has been stated that the structures are so complicated that little progress has been made.

So complex is the character of the Archean and so rapidly does it change its character, that the lithological mapping of it is a labor of great difficulty, and it can be accomplished only with exceeding slowness even where the exposures are numerous and excellent large-scale topographic maps are available. Without almost continuous exposure and good base maps the representation of the areal distribution of the different rocks of the Archean is a hopeless task.

SECTION II.

THE ALGONKIAN.

NECESSITY FOR A GROUP BETWEEN THE ARCHEAN AND THE CAMBRIAN

It is widely agreed that the rocks containing the Olenellus fauna shall be taken as the base of the Cambrian. This fauna is abundant and varied. It includes all the stems of the animal kingdom except the vertebrates. Some biologists say that nine-tenths of the differentiation had taken place at the beginning of Cambrian time. This implies a prior life of vast duration.

The progress of paleontological knowledge has of late been formationally downward. Before there was a recognized Cambrian there was a well-known Silurian, and it is probable that when all parts of the world become geologically known other faunas will be discovered below the Cambrian as distinctive in character as the Cambrian is from the Silurian. If this be done, definite information will be available to correlate rock series of different parts of the world in the time-place between the Cambrian and the Archean.

If the conditions of the globe were such that life existed in pre-Cambrian time, they also were such that stratified rocks could be deposited not unlike those of later times, so that the only question which arises in this connection is whether any of these stratified rocks now remain in such a condition as to be recognizable. The study of recent years shows that such intervening clastic series do exist below the Olenellus fauna in many regions of North America, and in some cases the volumes of rock and great intervening erosions represent a lapse of time which may possibly be compared with all subsequent time. If geological history were to be divided into three approximately equal divisions, these divisions would not improbably be the time of the Archean, the time of the clastic series between the Archean and the Cambrian, and the time of Cambrian and post-Cambrian. In this connection it is well to recall that many years ago Logan suggested that the thickness of the Laurentian and Huronian may surpass that of all succeeding formations, and that the appearance of the so-called Primordial fauna may be considered as a comparatively modern event.

It is imperative that some term shall be available to cover the great mass of rocks between the Cambrian and the Archean. Irving was the first to realize and urge the necessity for such a term, and proposed for it Agnotozoic.[1] This term implies the existence of life in this system, and the evidence upon this point is conclusive. Life is indicated by the presence of thick beds of graphitic limestones, beds of iron carbonate, and great thicknesses of carbonaceous shales, which are represented by graphitic schists in the more metamorphosed phases of the rocks. It has been urged by Whitney, Wadsworth, and others that the limestone and graphitic schists may have had an origin other than organic. Whitney and Wadsworth have gone so far as to say that there is no valid evidence of life in any pre-Potsdam rocks. This was, however, before it was generally recognized that the Potsdam is Upper Cambrian and that an abundant Cambrian life extends far below. If it be true that these limestones and iron-ore beds are no evidence of life (and it may be admitted that another origin is possible without implying that it is probable), it would hardly be maintained that the hydrocarbons which occur so abundantly in the little metamorphosed shales of the Huronian about Lake Superior are other than of organic origin, and if so, the graphitic schists which stand in the same great system in the geological column were originally in all probability hydrocarbonaceous shales. However, we are not obliged to depend upon the the presence of these varieties of rocks as the only evidence of life. Whether the *Eozoon canadense* found in the original Laurentian of Canada is of organic origin will not be discussed here. It may be true that many of the specimens which have been called Eozoon are results of the forces of crystallization; but, admitting this, it does not follow that all of the material called Eozoon is of this character. Passing by this question, the pre-Cambrian fossils described by Walcott[2] from the

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[1] Classification of Early Cambrian and pre Cambrian formations R D Irving, Seventh Ann Rept U S Geol Surv, for 1885-6, pp 453-454

[2] Algonkian Rocks of the Grand Canyon of the Colorado, C D Walcott, Journ of Geol, Vol III, 1895, p 327

Grand Canyon of the Colorado include: "A minute discinoid or patelloid shell, a small Lingula-like shell (which may be a species of Hyolithes), and a fragment of what appears to be the pleural lobe of a segment of a trilobite belonging to a genus allied to the genus Olenellus, Olenoides, or Paradoxides. There is also a Stromatopora-like form that is probably organic."

A lingula-like shell has been found by Winchell in the pipestones of Minnesota. Selwyn has described tracks of organic origin in the Animikie (Upper Huronian) series of Lake Superior. Murray, Howley, and Walcott found several low types of fossils in the pre-Olenellus clastics of Newfoundland.

That these fossils are of organic origin can not be doubted. But while many will admit the clastic character of the great groups of rocks considered, and the organic origin of the forms mentioned, as well as the carbon of the carbonaceous shales and schists, they will say that these are merely evidences that the rocks in which they lie are Cambrian. The reply to this is, that it is a question of nomenclature. If it be premised that all clastic and fossiliferous rocks more ancient than the Olenellus horizon are Cambrian, it is useless to try to prove that there are pre-Cambrian clastic rocks which bear life. It is, however, necessary to recognize that the carrying downward of the term Cambrian to cover not only the great thicknesses of rocks which are now included in it, but all pre-Cambrian clastics, will probably make the Cambrian as great as or greater than all the subsequent periods put together. That this is inadvisable is plain, and the clastic rock masses below the Olenellus fauna are so enormous that the proposal to introduce a general term like Agnotozoic as the equivalent of Paleozoic, Mesozoic, and Cenozoic, to cover this great group, is a conservative one. Irving foresaw that the term would be objected to, because sooner or later the life will become to a greater or less degree known, and he suggested as an alternative for Agnotozoic, Eparchean, in contradistinction to Archean, which was reserved by him to cover the Basement Complex. As the character of the life of this group is already beginning to be known, it seems to me that the term Proterozoic, considered for the place by Irving,[1] but rejected, is preferable to either Agnotozoic or Eparchean.

In a conference of the members of the United States Geological Survey, called by the Director at Washington,[2] these terms were discussed with reference to atlas-sheet mapping, although there was no question on the part of anyone as to the necessity for some such term. Recognizing the impracticability of the certain correlation with one another of the one or more pre-Cambrian clastic series which occur in the various regions, and recognizing the fact that for use in mapping a uniform plan must be adopted, some one suggested that a term of the

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[1] Classification of early Cambrian and pre-Cambrian formations, R. D. Irving, Seventh Ann. Rept U. S. Geol. Surv., for 1885—86, p. 454.

[2] Tenth Ann. Rept. U. S. Geol. Surv., for 1888-89, Report of the Director, p. 66.

same class as Cambrian, Silurian, and Devonian should be selected for rocks here included, and to occupy this place the term Algonkian was proposed and accepted. The proposed general scheme of classification for the lower part of the geological column is as follows

Paleozoic	Carboniferous Devonian Silurian Cambrian
Proterozoic	Algonkian
Archean	Archean

The introduction of the term Algonkian has been objected to on the ground that it will supersede the older term Huronian. In answer to this it may be said that Huronian has not been generally used as Algonkian is defined, and the latter therefore does not supersede the former term. Huronian will be retained for certain of the clastic series of Lake Superior and Canada, as well as for rocks in an equivalent position in other parts of North America and Europe, if such equivalence can be determined, just as before Algonkian was introduced. The Huronian will stand as one of the great series of rocks which together make up the Algonkian.

DELIMITATIONS OF THE ALGONKIAN

The further back we go in the history of the world for any given region the more frequent have been the changes through which a rock stratum has passed, and therefore there is increasing difficulty in determining bounding planes with sharpness, although in different regions rocks of the same degree of metamorphism may differ vastly in age. The truth of this is well illustrated by comparing the eastern and western regions of the United States. In the former powerful movements have occurred until late in Paleozoic time, as a result of which the Cambrian, Silurian, and Devonian rocks over large areas have not been separated from the pre-Cambrian. In certain areas this separation has been accomplished, but only by the most accurate and painstaking application of modern methods. In parts of Massachusetts and Vermont the areas covered and the results reached have involved an enormous amount of labor, although of late paleontology has been an important help in unraveling the problem. Under these circumstances how much more difficult should one expect it to be to separate the pre Cambrian clastic series from the Archean.

In parts of the West, where no close folding has occurred since Cambrian time, it is easy to separate the Cambrian from the pre-Cambrian, and in regions in which metamorphosing influences have not been at work for a still longer time it is easy to separate the pre-Cambrian clastics from the Archean. But in other regions this separation is made with the greatest difficulty, and doubtless over large areas it will never be satisfactorily done. Just as in parts of the Appalachians it may be impracticable to separate the Cambrian rocks from the pre-Cambrian clastic series, so it will be for a long time impossible to decide in some regions upon sharp boundary lines between the pre-Cambrian clastics and the Archean. Giving full force to this position, it is no reason why the discrimination should not be made where it can be.

Recent work in petrography has demonstrated that dynamic action and environment, not time, are the important elements in the obliteration of clastic characteristics. Rock movements also destroy the evidences of discordances between series where there have been real unconformities. This destruction of the evidence of structural breaks comes about largely as the result of an approaching parallelism of bedding caused by the close folding, but far more important than this is the production of common secondary structures, with the simultaneous development of crystalline schists from the newer series. As a consequence, basal conglomerates are in some places almost the only means of discriminating between the newer and older series, and if the metamorphosing influences were strong enough to destroy the pebbled character of such beds, changing them into schists or gneisses, as has occurred in many places in the Cambrian of the Appalachians, this means of detecting a break between series is also lost. The problem is rendered still more difficult because of the fact that in many districts where there are real unconformities there was originally no basal conglomerate. At many localities in the far West the basement fossiliferous series are built up of the constituent minerals of the underlying rocks rather than of large fragments of them, and even where not folded have in some places so closely simulated the original rocks that geologists have been at a loss to determine at what plane the clastics begin. If it has proved difficult to separate the unfolded clastics from underlying crystallines, how much more difficult must it of necessity be to separate series that have together been subjected to intense and perhaps repeated dynamic action.

The Algonkian has been defined as including all recognizable pre-Cambrian clastics and their equivalent crystallines. In the consideration of the character, origin, and delimitation of the Archean the lower limit of the Algonkian has been given. Its basal plane is the lowest of the recognizable clastic rocks. It has been seen that there are great differences in ease of recognition of the basal Algonkian plane in different regions. In the Uintah Mountains, in the Grand Canyon of Arizona, in portions of the Lake Superior region, in the Original Huronian region, and elsewhere between the Algonkian and the Archean there are great unconformities, above which are the readily recognizable clastic rocks, and below which are the thoroughly crystalline basal complexes. Even in many regions in which there has been repeated folding since Archean time, and in regions obscured by eruptive activity, it is perfectly clear that a large part of the rocks are clastic and belong with the Algonkian, while other parts have all the characteristics of the Basement Complex. Occupying an intermediate position, occasionally areas of rock are found which can not certainly be placed with the Algonkian or the Archean, but this difficulty is not peculiar to these periods. In folded districts the same difficulty is occasionally found in separating the Cambrian and Silurian, and in Canada great areas of unaltered flat-lying rocks have been mapped as Cambro-Silurian because of the difficulty of separating them into Cambrian and Silurian.

Many of the members of the Canadian Geological Survey have described the Huronian and the Laurentian as conformable, with gradations between the two. This apparent accordance and gradation is in many cases due to the fact that placed with the Huronian are many rocks which would under the usage of the terms here proposed be regarded as Archean. In other cases there are apparent conformities and gradations between undoubted clastics and the underlying rocks having all the characteristics of the fundamental complex. The significance of these gradations has been already discussed (see pp. 730–732). It was seen that they are not inconsistent with genuine structural breaks.

It has been stated that the base of the Cambrian is placed by many at the Olenellus fauna. The widespread uniform character of this fauna, both in Europe and in America, makes it particularly easy of identification, and therefore valuable for purposes of discrimination. Evidently all the reasons for placing this fauna at the base of the Cambrian apply as well for placing the horizon below this as uppermost Algonkian.

In the Lake Superior region and in many other localities, above the Algonkian are unconformities, the first of the Cambrian being middle or upper. In other regions, as in Newfoundland, the upper Algonkian is marked by an unconformity, and the formation immediately above bears the Olenellus fauna. This is the most favorable and clear case. In the Wasatch and several other ranges of Utah and Nevada, in British Columbia, and probably in the southern Appalachians, below the Olenellus fossiliferous Cambrian are conformable series of great thicknesses. Are these lowest Cambrian or uppermost Algonkian? May not the Olenellus fauna be found in the future to extend downward for a long way through a greater or less thickness of these apparently barren rocks? If in any region the fauna be found to extend downward for a long way, it is probable that species and genera characteristic of the Olenellus horizon as now known will drop out and others will appear which are different. The Olenellus would thus grade into a pre-Olenellus fauna. Such a gradation will doubtless somewhere be found, while in other regions the change from an Olenellus fauna to one of a pre Olenellus type may occur abruptly. In either case, there will finally appear a fauna which is not the present known Olenellus fauna, but which is as different from it as is the Cambrian from the

Silurian (Ordovician). As the term is here used, such a fauna is pre-Cambrian, and rocks containing it are Algonkian. In the following paragraphs great barren inferior series conformably below the known Cambrian are placed with the Algonkian on the ground of probability. The presence of an abundant Lower Cambrian life at a certain horizon within the conformable succession, with apparently complete absence of life in immense thicknesses of rocks conformably below, which, so far as lithological character is concerned, are equally likely to bear fossils, throws the weight of evidence in favor of the Algonkian age of these rocks. It is, however, more than probable that some part of the conformable downward extensions of the Cambrian, which are here provisionally referred to the Algonkian, will in the future be found to belong with the post-Algonkian.

The newest Proterozoic or Algonkian rocks of different regions may stand in different positions, just as the superior rocks of the Paleozoic may in any given region be Cambrian, Silurian, Devonian, or Carboniferous.

In the application of the term Algonkian to rocks in the field in difficult cases, it should be used only where there is a high degree of probability that the series concerned are really pre Cambrian and post-Archean. Rocks of sedimentary origin in a crystalline or semicrystalline condition, which chance to be devoid of fossils and which have no determinable relations with the fossiliferous series, should not be called Algonkian without some strong evidence of pre-Cambrian age. Sedimentary rocks of uncertain age below a determined fossiliferous series should be denominated only as older than this series. For instance, if the fossiliferous formation is Cretaceous, they should be called pre-Cretaceous. If the above be true of sedimentary rocks, it is still more applicable to the surface volcanic rocks, the age of which can be determined only by structural relations and which vary in age from Archean to Recent

In some regions the pre-Cambrian rocks are predominantly fine grained crystalline schists, gneisses, and gneissoid granites in certain areas, but in other areas there may be limestones, slates, quartzites, and other associated formations which are presumptively Algonkian. Unless a structural break between the two is discovered there is a great temptation in this case to apply the term Algonkian to the whole region; but when it is remembered that original unconformities between the Archean and the Algonkian may be obliterated, it becomes evident that the only safe procedure is to apply the term Algonkian to the rocks which certainly belong to this period, and to use the term pre-Cambrian for the granitic, gneissic, and schistose rocks, which may be, to be sure, metamorphosed Algonkian eruptive or sedimentary rocks, but which also may be Archean. In certain localities the term Algonkian has already been applied to such an unseparated complex. To use the term in this indiscriminate manner will be sure to render it value-less, because it will become so vague. If the tendency to give a definite position to a complex of rocks of undetermined age can not be resisted, it is far better to call it Archean than Algonkian, as the former has been for many years the receptacle for the unknown.

DIFFICULTIES IN ALGONKIAN STRATIGRAPHY

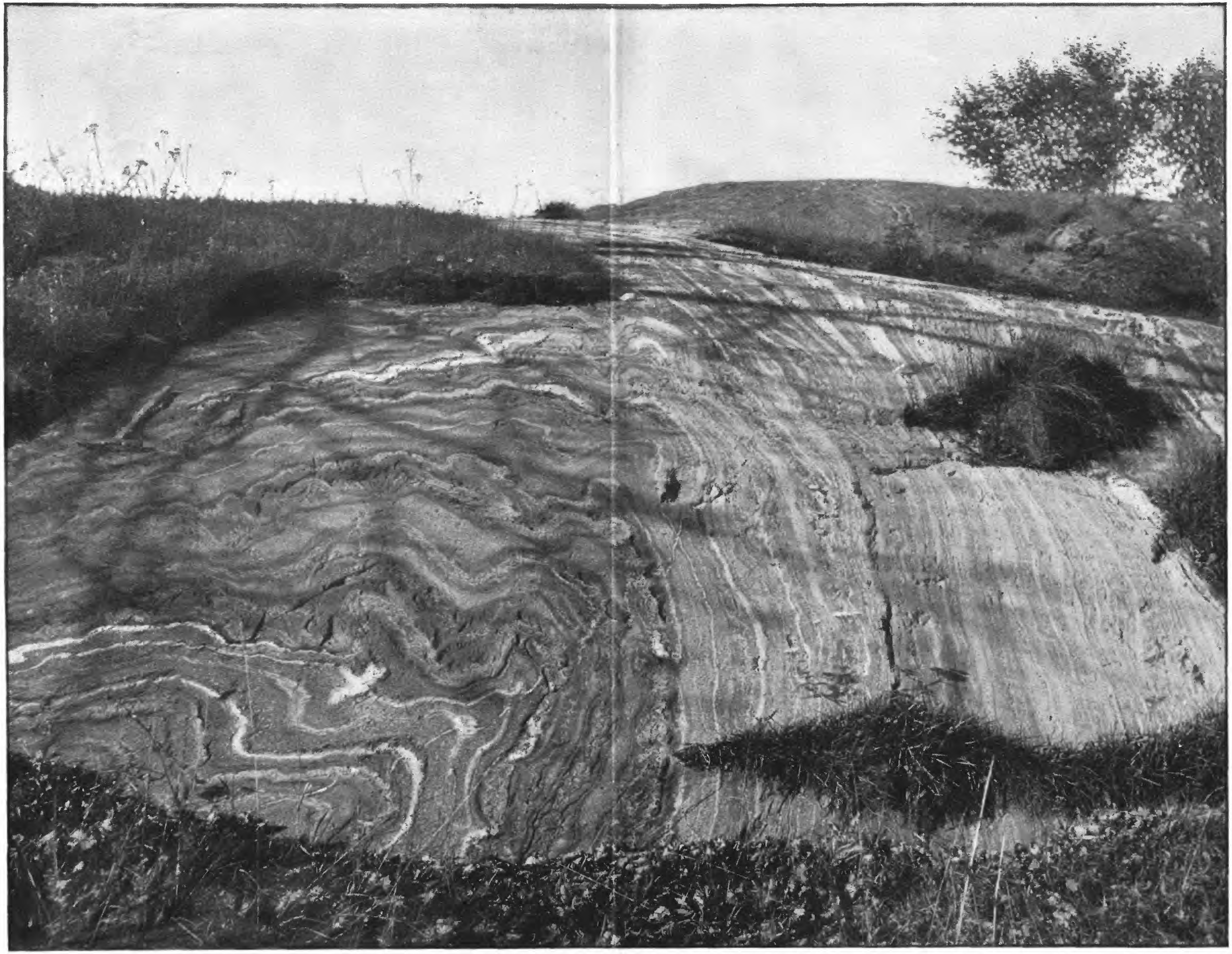
Since among the pre-Cambrian clastics paleontology is not yet available in correlation, it is exceedingly difficult to make widespread subdivisions of the Algonkian, such as are made in later time. The difficulty is further increased by the unequal metamorphism in different regions of series of the same age. The Algonkian is in just such a position as regards wide correlation of its constituent series as would be the Paleozoic or Mesozoic if their known fossil contents were so small as to be useless for the purposes of correlation. The structure of individual districts and regions could be worked out and the formations correlated, but the attempt to equate the Cambrian, Silurian, Devonian, or Carboniferous of one region with rocks of the same age in a far distant one would be an almost hopeless undertaking. In the Carboniferous the beds of coal would serve as an important guide, but if implicitly followed and no fossils were available, the Triassic of Virginia, the Carboniferous of the Central United States, and the Cretaceous of the West would be placed together. If the iron-carbonate formations of the Algonkian in the Lake Superior region, which appear to be more characteristic than any other one kind of rock, were followed as a guide, the result would be to place together two unconformable series.

We may, perhaps, go so far in some cases as to correlate series which occur in different districts of the same region when a set of characteristic formations constituting the series occurs in like order and the series are in the same relative positions to overlying and subjacent series, one or both of which are known to be identical in the different districts. If in each of a number of areas several pre-Cambrian series occur, of the same general character in each area, with like relations to one another and to the Archean and Cambrian, and not so far apart as to be outside of the same geological basin, it is probable that a provisional correlation is warranted. While, then, it is not practicable to subdivide the Algonkian into general series which shall cover the whole of North America, it is often possible to do so in a single geological basin, or in adjacent basins in which the relations of the separate formations and series can be worked out.

SECTION III.

THE ORIGINAL LAURENTIAN DISTRICT.

The Original Laurentian district and its eastern extension may be considered to cover the broad area of pre-Cambrian rocks which have been closely studied north of the Ottawa and St. Lawrence rivers



CRUMPLED GNEISS; SHORE OF OTTAWA RIVER NEAR FERRY OPPOSITE MONTEBELLO.

Photograph by R. W. Ells.

between the cities of Ottawa and Montreal. This does not include the Hastings district of Vennor. The statement below is largely based upon the work of Logan, Adams, and Ells.

SUCCESSION

The Basement Complex, or Archean, occupies the larger part of the district. This is called the Ottawa gneiss or Lower Laurentian, by the Canadian geologists. The Archean consists mainly of a granitoid gneiss, reddish or grayish in color. Different parts of it differ in coarseness, in relative proportion of constituent minerals, and in distinctness of foliation. It is poor in the iron-bearing minerals, but bands of hornblende-gneiss are not uncommon. Other schistose rocks are occasionally found. Contained in this gneiss are considerable areas of intrusive material, of which granite and syenite are two of the most important kinds. In this gneiss is, however, no material which is demonstrably of sedimentary origin, or even of surface origin, nor any material which suggests metamorphosed sedimentary or surface volcanic material. Its lithological characteristics are those of modified plutonic rocks. It shows, both in the field and under the microscope, evidence of profound orogenic movements. It has no structure but foliation. Throughout much of the area the dip is in an eastern direction at moderate angles. The vast thicknesses which have been given for the Lower Laurentian have been based upon the supposition that the gneissic structure is bedding.

Resting upon the Archean is a series of Algonkian rocks. By the Canadian geologists these are called the Grenville series, and placed as Upper Laurentian. They will be referred to here as the Grenville Algonkian. The Algonkian is of a much more intricate lithological character than the Archean. In this series gneisses are still the predominant rocks, as in the Archean, but they present a greater variety of mineral composition, are more frequently strongly foliated, and often occur as well-defined bands or layers, like strata of sedimentary formations. Analyses of these gneisses by Adams show that they have the composition of shales and slates rather than that of the Archean granites and gneisses; especially, the former contain less alkalies than the latter. Interstratified with the acid gneisses are hornblende-gneisses and hornblende-schists, beds of quartz schists, and thick beds of crystalline limestone. The gneisses are very often strongly garnetiferous. The limestones, and sometimes the gneisses, are graphitic, and in certain places are so rich in magnetite as to furnish iron ores. The folding of the series is complex, the contortions of the gneisses (Pl. CXI) and their infoldings with the marbles being remarkably intricate (Pl. CXII). At various places the orogenic forces have been so great that bands of gneiss within the marble have been disrupted and autoclastic rocks produced. These breccias frequently resemble closely a conglomerate, especially when bands of gneiss have been broken within a marble.

Even when the interstratified gneiss is brecciated the marble is often perfectly massive. Since in certain cases thick bands of gneiss have resisted pressure so as not to be fractured, while other belts of gneiss immediately above, interstratified with the marble, have been broken into autoclastic rocks, the phenomena have suggested that the breccias are basal conglomerates, and that there is a structural break between the part of the series bearing the marble and the gneiss. below. However, in all cases in which close study has been made these pseudo-conglomerates have been traced step by step into the ordinary interlaminated set of gneisses, schists, and marbles. Ells believes the marble series in the original Grenville area to be in numerous synclinal troughs, underlying and between which is the Ottawa gneiss.

This upper series, consisting as it does of regular alternations of marbles, quartz-schists, and gneisses, bearing graphite and iron ores, is believed to be a profoundly metamorphosed sedimentary series, although there has not been discovered anywhere in the region any other evidence of clastic characters. So profound have been the orogenic movements that the once-rounded grains, and even the pebbles and bowlders, if they ever existed, have been wholly destroyed.

According to Adams, the gneisses of this series, unlike those of the Archean, show little or no granulated structure, but are characterized by extensive recrystallization with the development of new minerals.

In the district gabbro covers numerous areas, some of them thousands of square miles in extent. The gabbro in many places has been profoundly modified by dynamic action, so as now to be regularly laminated over extensive areas. There are gradations at many places between the massive and laminated varieties. This gabbro was formerly regarded as a later sedimentary series, but is now known to be an intrusive of later age. Various basic and acidic rocks are intruded along or across the lamination of the sedimentary series.

Resting unconformably upon the upturned edges of the deeply eroded pre Cambrian rocks of the region are the little-disturbed Cambrian rocks.

The relations which obtain between the Basement Complex and the Algonkian, so far as yet ascertained, are those of apparent gradation. This is therefore one of the districts the phenomena of which may be explained by any of the different theories as to the origin of the Archean. The downward gradation was explained by Logan to be that of progressive metamorphism, the basement gneiss, as well as the Grenville series, being regarded as sedimentary. The relations have been explained by Lawson by the subcrustal fusion of the Grenville series, thus producing the granite-gneiss. However, Adams's determination that the gneisses of the Grenville series most nearly like those of the Archean differ from them radically in chemical composition apparently shows that the hypotheses of Logan and Lawson are untenable, for if an average analysis of the entire Grenville series were taken, it

INTRICATELY FOLDED INTERLAMINATED GNEISS AND LIMESTONE.

The limestone contains nodules of gneiss, and the gneiss nodules of limestone, both produced by dynamic action.

is highly probable that this difference would be still more marked. Consequently it is not probable that the Archean gneiss was formed by the fusion or metamorphism of the Grenville series.

There remains the final hypothesis that the basement gneiss may be of igneous origin, either earlier or later than the sedimentaries, the apparent gradation not being real, but due to the profound metamorphism which has subsequently occurred. If the schistosity in the upper series was produced by accommodations parallel to the bedding, it is to be expected that a chief zone of readjustment would be at the contact between the upper sedimentary series and the lower igneous series. This being the case, it would follow that along this plane of movement the two series might be welded together, and a crystalline schist be produced, in part from one and in part from the other. Which of these three solutions will be considered most probable in the case of a given individual will depend largely upon the personal equation and the area in which the investigator's work has been done. If he has been working in a district in which one of the three sets of relations are clearly demonstrated, he will be inclined to believe that this is the explanation which will apply to the district of the Original Laurentian. From present evidence I am inclined to believe that the Ottawa gneiss is igneous, and older than the Grenville series.

Both Logan and Ells have subdivided the Grenville Algonkian into formations, but their successions are not the same, and as yet final maps of the area have not been published. While there is no doubt that several formations exist, the separation of them is exceedingly difficult, on account of the complicated structure and profound metamorphism. It follows that no accurate estimate of the thickness of the series has as yet been made.

CORRELATION.

If the principles of correlation advocated in Part I are true, we have no basis upon which to compare the rocks of the Original Laurentian area with those of the Original Huronian or other distant districts. As yet it has not been shown that the areas of the Grenville Algonkian and the Original Huronian belong to the same geological province, and until this is done it can not be assumed that the more crystalline character of the former, and the presence of a clear unconformity between the Algonkian and the Archean in the Huronian district, give facts upon which to infer that the rocks of one area are older than those of the other. It is well known that in the eastern part of America strong dynamic action has affected the Paleozoic rocks for extensive areas, while in the Lake Superior region the Cambrian rocks are undisturbed. These later movements and the intrusions of the gabbro may have been the cause of the increased metamorphism of the Laurentian. The Hastings Algonkian (considered later) occupies an areal position between the Original Laurentian and the Original Huronian. Also it is altered to an intermediate degree.

This suggests that it may be equivalent to both or a part of both, and that the different amounts of metamorphism in the three areas may be explained by the increased dynamic action in passing east. Also the unconformity at the base of the Algonkian in the Original Huronian area may be equivalent to an unconformity which exists at the base of the Algonkian in the Original Laurentian, the apparent gradation and absence of discovered evidence of unconformity being explained by dynamic action and igneous intrusion. While the Grenville Algonkian can not be shown to be older than the Huronian of Lake Huron, on the other hand it can not be shown to be equivalent to or newer than it. As yet we can make no closer comparison than to say that both are Algonkian, and occupy some part of the time between the Cambrian and the Archean.

The Original Laurentian district and the Adirondack district are thought to belong to the same geological province. In the following pages it will be seen that the Grenville Algonkian is paralleled very closely in character and relations by the Adirondack Algonkian, and is probably equivalent to it. The gabbros of the two districts are also probably contemporaneous.

PRINCIPLES ILLUSTRATED.

If it be regarded as proved that the Algonkian rocks are sedimentary, this district furnishes good illustrations of the following principles: (1) Development of thick and extensive formations of completely crystalline schists, gneisses, and marbles from sedimentary beds; (2) formation of autoclastic rocks; (3) formation of a massive sedimentary rock, marble; and (4) monoclinal gneissic banding

(1) Among all the rocks of the district there has not been found, either macroscopically or microscopically, any evidence of clastic characters. The thick beds of limestone are changed to crystalline marble. The beds of sandstone have had each of the fragmental grains granulated and destroyed. The pebbles of the conglomerates, if such have existed, have also been mashed beyond recognition. Yet such is the regular interlamination of thick beds of marble, quartz-schists, and various gneisses, certain of the narrow bands being very graphitic, as to lead inevitably to the conclusion that the whole was once a sedimentary series.

(2) While no genuine conglomerates are found, the bands of brittle gneiss within the plastic limestone have been shattered over extensive areas, and the fragments have been rubbed against one another until rocks were produced which are very similar to genuine conglomerates. These may, however, be traced to the brecciated and finally to the unbrecciated bands of gneiss.

(3) Fragments included in the marble are evidence of profound dynamic action. This is further shown by the strain effects within the fragments and by the highly contorted gneisses which are always

found adjacent. Notwithstanding this, the including marbles are often massive, and show little or no evidence of strain. This renders it highly probable that this rock recrystallized under static conditions after movement ceased, the change being produced by the heated condition of the rocks, caused by dynamic action or igneous intrusion, or both.

(4) Adams describes the Archean gneisses of the district as having a foliation which very generally dips to the east. As shown in another place (pp 662–668), such uniform foliation over wide areas is probably explained by the formation of a cleavage, the development of fissility secondary to this cleavage, and later parallel impregnations or injections between fissile laminæ.

SECTION IV.

THE ADIRONDACK DISTRICT.

The Adirondack district is in the State of New York west of Lake Champlain, directly south of the Original Laurentian district. It includes the Adirondack Mountains and a portion of the surrounding area.

SUCCESSION

The little disturbed Cambrian sandstone rests unconformably upon the pre-Cambrian rocks of the district. The rock succession in this district and the lithological characters of the rocks are almost identical with the Original Laurentian district, except that the equivalent of the Ottawa gneiss may be absent. The relative areas occupied by the different rocks are, however, different. The great central mass of the Adirondacks is anorthosite or gabbro. The gabbro in the interior is generally massive, but on its outer border it grades at many places into a regularly laminated rock resembling very closely a laminated gneiss. It is clearly intrusive in the Algonkian, as shown by its containing fragments of the latter, by contact metamorphism, by cutting dikes, and by other field relations.

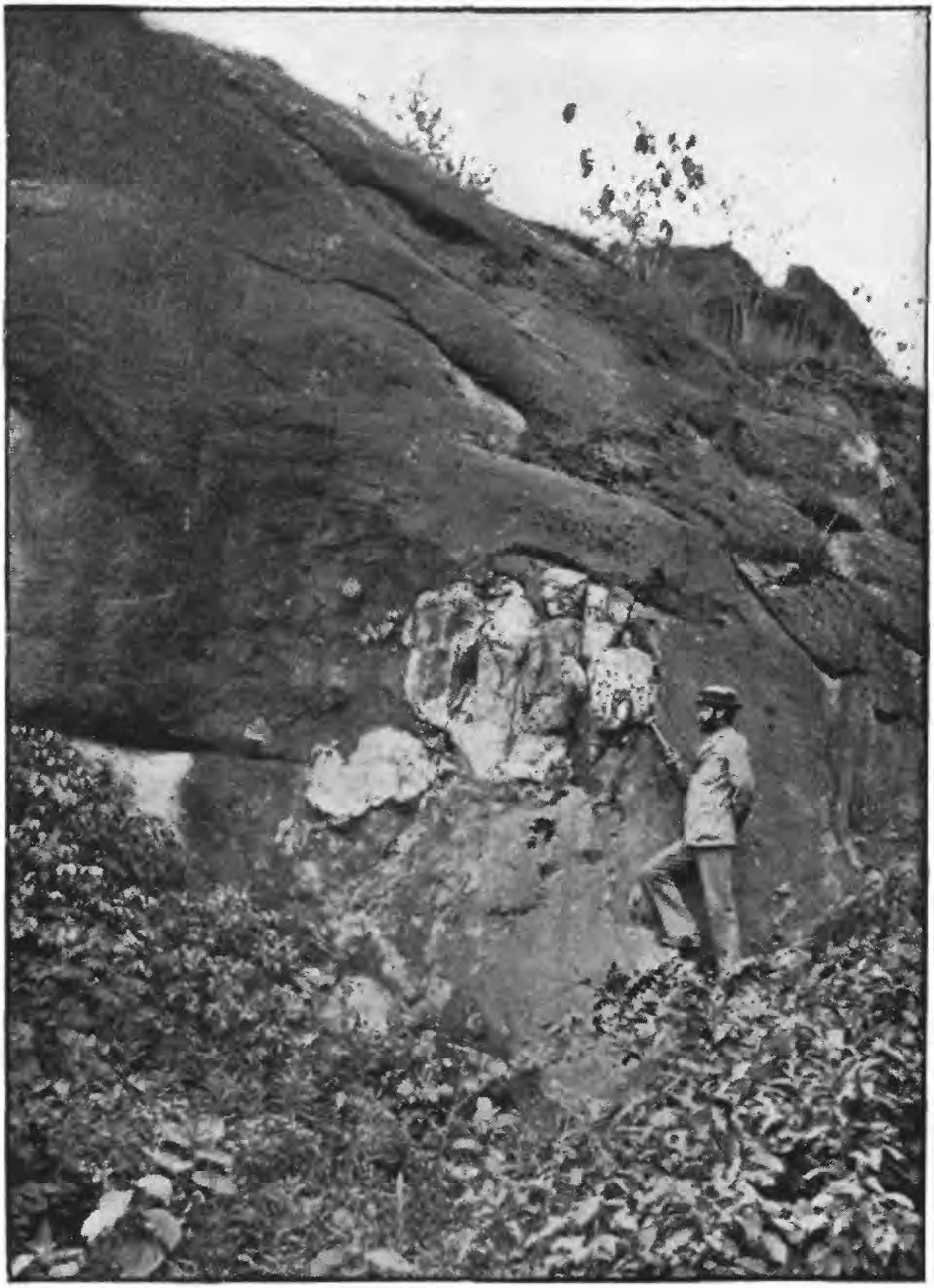
About the gabbro area is a broad zone of the metamorphosed Algonkian sediments, which Smyth (C. H.) proposes to call the Oswegatchie series. The contact between the two is not sharp, there being a belt of some width in which the sedimentary rocks and intrusives are intermingled. On the west side of the mountains, in passing toward the center from the gneissic area, the gabbro is first found in subordinate quantity, then becomes more and more abundant, then predominant, and finally is the only rock. These relations are characteristic of great batholitic intrusions. On the east side of the mountains the waters of Lake Champlain prevent one from determining whether or not a belt of sedimentary rocks free from gabbro lies east of the zone in which the two are intermingled.

The peripheral belt of Algonkian is a great series of bedded rocks having for much of the area, in a general way, a quaquaversal arrangement, the dips being rather flat. The rocks about the gabbro consist of white and red, regularly laminated, often garnetiferous gneisses; of crystalline limestones, some of the belts being of considerable extent and apparently of great thickness; of lesser quantities of garnetiferous quartz-schist; and of graphitic gneiss, and also include beds of magnetic iron ore. The gneissic beds, interlaminated with the limestone, are garnetiferous and micaceous, or pyroxenic and hornblendic. Many of the latter may be intrusive. Near Hague is a bed of strongly graphitic gneiss between beds of ordinary gneiss, which, viewed at a distance, has the appearance of a layer of coal in an ordinary bedded succession. The Adirondack Algonkian is everywhere completely crystalline. Neither macroscopically nor microscopically do any of the rocks show any clastic structure, but the original beds were not obliterated. The direction of the bedding may therefore be determined in parts of the region by the contacts of the layers of different lithological characters. So far as observed, the schistosity of the series corresponds with the bedding.

Between the marble-bearing gneisses are the intervening gneisses free from limestone, which are red or gray and orthoclastic. The broader of these areas are on the south and west sides of the Adirondacks. Smyth thinks that near Natural Bridge the gneiss grades into gabbro. On the western and southern sides of the Adirondacks the marbles are much more extensive than on the eastern side. The largest belt is 20 miles long and 6 miles broad.

At many places the contact of the marble with the gneiss is of a most extraordinary character. The plane between them is one of great irregularity. Interstratified with the limestone are gneissic or pegmatitic layers. As a result of a strong movement, at many localities the interstratified gneiss and pegmatite have been broken into fragments which are contained within the marble (Pl. CXIII), thus producing autoclastic rocks which in some places simulate remarkably erosion conglomerates. However, between the breccia and the interlaminated gneiss, pegmatite, and marble there are all gradations. The marble associated with or containing the disrupted fragments of the gneiss in some places shows no evidence whatever of movement, being massive and coarsely crystalline. The included fragments and gneiss adjacent, on the other hand, give all the evidences of strong movement.

The relations which obtain between the lower gneiss and the Algonkian are identical with those obtaining between the Archean and the Algonkian in the Original Laurentian district, and any one of the explanations offered for the latter may be thought to apply to this region. If it prove true, as suggested by Smyth, that the red gneiss is connected with and is a facies of the intrusive gabbro, the oldest series of the district may be the Algonkian sediments. Except for small areas, no maps have been published which subdivide the Algonkian into formations, and no estimate of the thickness of the series has yet been attempted.



MASSIVE LIMESTONE CONTAINING NUMEROUS FRAGMENTS.

The whole has a strongly conglomeratic appearance; the fragments are, however, dynamic. Photograph by Walcott.

CORRELATION

The Adirondack district is directly south of the Original Laurentian district. It is separated from the latter by no great distance, but it will never be possible to connect the formations of the two areas, since the intervening distance is covered by Paleozoic sediments. However, the two districts appear to belong to the same geological province, and the lithological similarities of the Algonkian series are such that there can scarcely be a reasonable doubt that they are contemporaneous. Also, in all probability, the great gabbro masses of the two areas were contemporaneous. Whether there is in the Adirondack district a lower series equivalent to the Archean gneiss of the Original Laurentian is uncertain.

PRINCIPLES ILLUSTRATED.

All the principles illustrated by the Original Laurentian district (see p. 770) are equally well shown by the Adirondack district. Further, the following additional principles are finely illustrated: (1) The quaquaversal arrangement of the Algonkian series about the gabbro points to the introduction of this great batholitic mass as a cause of this distribution; (2) the development of foliation parallel to bedding.

(1) Probably before the appearance of the gabbro the Algonkian was nearly horizontal for much of the district. During the intrusion of this great mass of rock the sediments were uplifted in a general way about it, and consequently dip away from it. To this usual rule there are many local exceptions. The direct contact action of the fluent mass of the gabbro, the wider effect of the thermal waters emanating from it perhaps to great distances, and the mechanical readjustments in the sedimentary rocks, were probably important causes of the metamorphism of the clastic series.

(2) In the formation of schistosity parallel to bedding, which occurs in parts of the district, vertical shortening and consequently horizontal elongation below the level of no lateral stress may have begun the process. When the rocks were subsequently folded the different degrees of strength of differently indurated beds evidently controlled the direction of differential movement, and the production of cleavage parallel to the bedding was thus assisted. Further, as before suggested, the great batholitic mass of gabbro may have promoted the accommodations parallel to bedding, and also, by furnishing hot solutions, which followed the structure, may have favored the development parallel to the schistosity of new minerals by metasomatic processes.

SECTION V.

THE HASTINGS DISTRICT.

The Hastings district includes an area between the Ottawa and St. Lawrence rivers southwest of the city of Ottawa, extending from Peterborough and Hastings counties on the southwest to Lanark and Renfrew counties on the northeast.

SUCCESSION

The Basement Complex or Archean of this district differs in no particular from that of the Original Laurentian area, except that intrusive syenites may, perhaps, be more abundant. The Algonkian rocks are also very similar to those of the Laurentian area. As in that district, there are interstratified mica-schists and mica-gneisses, hornblende-schists and hornblende-gneisses, quartz-schists, and marble; mica-slates are also found. There is, however, the great difference that in the Hastings area conglomeratic schists and gneisses are abundant. These may be seen in typical development about and between Madoc and Bridgewater. These conglomerates contain a great variety of pebbles, including granite, syenite, felsite, gneiss, marble, and quartz. The pebbles of the conglomerate vary from distinct, well-rounded ones to those which are flattened in a remarkable manner, in some cases being not more than a half inch broad and 5 or 10 inches long. Cut in certain directions, the rock containing these pebbles appears to be a perfect crystalline schist. Cut in another direction, it is clearly a conglomerate with a schistose matrix. The greater diameters of the flattened particles invariably accord with the direction of schistosity. The schist-conglomerates grade at various places into nonconglomeratic crystalline schists or gneisses. The demonstrably sedimentary origin of a portion of the rocks of the district and their gradation into crystalline schists give additional evidence of the sedimentary nature of the marble-bearing series. Felsite, felsite-breccia, and other volcanics are associated with the sedimentary rocks. These are extensive in area and are an important feature of the district. Also associated with the Hastings series are abundant augitic and hornblendic rocks, many of which are probably eruptive.

According to Venner, the Algonkian is in infolded troughs in the Archean, exactly as is the Algonkian in the Archean of the Original Laurentian area, according to Ells. The Archean gneiss is far the most widespread, while the gneisses bearing the marbles occupy comparatively limited areas.

As to the relations which obtain between the Archean and Algonkian, so far as descriptions go, the same interpretations may be offered as in the case of the Original Laurentian and Adirondack districts. However, Venner, who has done more work in the Hastings district than anyone else, believed that the two are unconformable, and in support of this view there is the presence of very numerous fragments of gneiss, syenite, and granite in the upper series which are exactly like the Archean and appear to have been derived from it. Since the Hastings Algonkian is less metamorphosed than the Grenville Algonkian, the former district is a more favorable one in which to study the relations of the Archean to the Algonkian, and if in the future it shall be found that the parallel schistosity of the two is really superinduced, and that between them there is a structural break, this would have considerable weight in reference to the relations which obtain in the Original Laurentian area between the Archean and the Algonkian.

CORRELATION

In geographical position the Hastings series is not very remote from the Original Laurentian. Also, as has been seen, there is a great similarity in the successions of the two districts, the main difference being in the presence of unmistakable conglomerates in the Hastings district and the presence of volcanics. It is probable that future work will connect the two districts, and positively determine the relations between them. It is thought that the Hastings Algonkian will ultimately be found to be a part of the same series as the Grenville Algonkian. This was the view of Logan, and it has been the position of most of the Canadian geologists; but certain of them, on account of the conglomerates and the volcanics, have correlated the Hastings Algonkian with the more remote Huronian rocks. If, as suggested on a previous page, the Grenville Algonkian and Original Huronian, or a part of it, may be equated, this correlation may prove to be equally justifiable. On a subsequent page evidence is given for dividing the Original Huronian into two unconformable series, the lower of which is the more crystalline. Should this subdivision stand, the lower of the two Huronian series is perhaps more probably to be correlated with the Hastings and Grenville Algonkian.

PRINCIPLES ILLUSTRATED.

This district gives fine illustrations of the extensive development of crystalline schists which are beyond all reasonable doubt of sedimentary origin. While extensive areas have lost all evidence of their fragmental characters, here and there the pebbles of the coarser-grained conglomerates have been preserved, although the matrix itself is completely crystalline. The flattening of the pebbles of the conglomerates to oval forms, to cardboard-like layers, to films indistinguishable from the other laminae, and all gradation phases are beautifully illustrated. It is evident in many places that the resultant banding of the schist or gneiss is independent of bedding. This district also furnishes one of the finest instances known of the accordance of the greater diameters of the flattened fragments with the secondary structure, and therefore shows that in this area the schistosity developed normal to the pressure. (See pp. 636–641.)

SECTION VI.

THE ORIGINAL HURONIAN DISTRICT AND ITS NORTHEAST EXTENSION.

The Original Huronian area borders the north channel of Lake Huron and extends west to Lake Superior. The continuation of this

Huronian area is mapped as a broad belt extending far to the northeast. This vast region has, however, been studied in detail only adjacent to the north channel of Lake Huron and in the Sudbury district, a short distance from Georgian Bay. What follows applies only to the area which has been mapped in detail.

SUCCESSION.

The Archean of this district, as in the previous districts discussed, consists more largely of gneissoid granite than of other kinds of rocks, and there are also present various dark-colored schistose gneisses, and the whole is cut in the most intricate fashion with later intrusives, and oftentimes by pegmatite veins. The complex as a whole was profoundly affected by dynamic actions and deeply denuded before the Lower Huronian was deposited upon it. Resting upon this Basement Complex are the probably unconformable Lower Huronian and Upper Huronian series. In the original area, mapped by Logan and Murray, the Lower Huronian consists of five formations, in ascending order as follows: (1) Gray quartzite, 500 feet; (2) chlorite slate, 2,000 feet; (3) white quartzite, 1,000 feet; (4) lower slate conglomerate, 1,280 feet; (5) limestone, 300 feet; total, 5,080 feet. Logan states that the estimates of the thickness of (1) and (2) are very doubtful. The chlorite-slate (2) is a surface volcanic. Resting upon the Lower Huronian is the Upper Huronian, consisting of eight formations. According to Logan these are as follows: (1) upper slate conglomerate, 3,000 feet; (2) red quartzite, 2,300 feet; (3) red, jasper conglomerate, 2,150 feet; (4) white quartzite, 2,970 feet; (5) yellow, cherty limestone, 400 feet; (6) white quartzite, 1,500 feet; (7) yellow, cherty limestone, 200 feet; and (8) white quartzite, 400 feet; total, 12,920 feet.

The above terms, proposed by Logan and Murray, could hardly be improved at the present time, except that the slate conglomerates would perhaps be called graywacke and graywacke-conglomerate. It is stated by Logan that included within these formations are considerable beds of extrusive and intrusive igneous rocks. These are not separated from the sedimentary rocks, and thus the total thickness above given is considerably more than the actual thickness of the sediments. That the igneous rocks are in certain cases contemporaneous overflows is shown by their amygdaloidal character. Abundant intrusives are also present. These include both greenstones and granite, which occur in the forms of bosses, dikes, and sills. The intrusion of bosses of the granite in the Huronian has caused increased metamorphism about them, and since they cut both the Archean and the Algonkian to a certain extent, they have bound together these groups. These intrusives are extensive in some areas, and this has led certain observers to overlook the structural break which exists between the Archean and the Huronian Algonkian, and to conclude that all of the gneiss of this area is really intrusive and later than the Huronian, it being supposed to be produced by the melting of the lower beds of the Huronian.

On some islands about four or five miles east of Thessalon, below the gray quartzite (1) of the Lower Huronian is a great basement conglomerate which contains waterworn fragments from all of the many different varieties of rocks of the Archean. This conglomerate passes up into the ordinary quartzite. The Archean here consists of dark-colored, fine-grained gneisses which have been intruded in the most intricate fashion by granite, and later both have been pegmatized. Numerous fragments of the gneiss are within the granite. Some are angular; others by absorption are partially rounded.

Near the wagon road from Sault Ste. Marie to Garden River the lower slate-conglomerate is in almost direct contact with the granite of the Archean, and here its basal horizon is a recomposed granite-breccia, which so nearly resembles the original granite that its fragmental character is discovered only on the weathered surface, by reason of the more rapid disintegration of the matrix, thus leaving the irregular fragments of granite as protruding masses. This granite stucco, by decrease in the size of its fragments and increase in the quantity of the matrix, passes upward by gradation into the ordinary graywacke-conglomerate (lower slate-conglomerate) of the district.

That the Lower Huronian rests unconformably upon the Archean is shown by these two contacts, at which the relations are perfectly clear. Before these contacts were discovered the existence of this unconformity was held upon the ground that in the Huronian are very numerous fragments of gneissoid granite and syenite which are exactly similar to the granite gneiss and syenite of the Basement Complex. This unconformity implies that the subjacent series had been folded, foliated, intruded by various igneous rocks, and profoundly eroded before the Lower Huronian was deposited. The unconformity is thus as profound and indicates as great a lapse of time as it is possible for an unconformity to show. The Lower Huronian and Upper Huronian have been considered separately, since there is probably an unconformity between them. This, however, rests upon less certain evidence. On the whole, the Lower Huronian seems to be more closely folded and somewhat more crystalline than the Upper Huronian. The field relations of the formations of the Upper Huronian to those of the Lower Huronian are such in certain localities as to make them difficult to explain without an unconformity. Also at a limestone quarry about two miles east of Garden River the upper slate-conglomerate in typical development bears pebbles and bowlders of the limestone of the Lower Huronian, and the contact is clearly one of erosion and between two formations wholly different in lithological character. There is no evidence, however, that the erosion was great, and this change in itself would not necessarily mark a great time gap. The probability of an unconformity between the Lower Huronian and Upper Huronian is further supported by the presence of numerous jasper fragments in the red jasper conglomerate, which are presumably derived from the jasper which is associated with certain parts of the Lower Huronian.

In the Original Huronian area we therefore have the following ascending succession: Basement Complex or Archean, unconformity, Algonkian. The Algonkian is further subdivided into Lower Huronian and Upper Huronian, these series being separated by a probable unconformity. All of the above series were folded and deeply eroded before the deposition of the unconformably overlying horizontal Cambrian.

The formations of both the Lower Huronian and the Upper Huronian are gently folded, the dips for most areas being only a few degrees. In parts of the district the folding is somewhat closer, but the rocks are nowhere closely corrugated. In this particular they contrast strongly with the Grenville Algonkian.

In the earliest work upon the area north of Lake Huron, Logan and Murray called the Huronian rocks a nonmetamorphic series, in contrast with those of the Laurentian area Their sedimentary and little-altered character is at once recognized This corresponds to what one would expect from their gentle folding. While it is true that the Huronian rocks have not been much metamorphosed, they are thoroughly indurated—so completely so that when the rocks are broken the particles of quartz in the graywackes and quartzites and the pebbles in the conglomerates are fractured instead of being pulled from their sockets. A microscopical study shows that their induration is mainly due to consolidation, cementation, and metasomatism. In the quartzites the quartz grains have been enlarged, and in many cases much independent interstitial silica has deposited. The feldspars have extensively altered to various secondary minerals, particularly to quartz and chlorite. While the microscope shows undulatory extinction in the mineral fragments, and even in some cases distinct fracturing, the movements have not been sufficient in the typical area to develop schistosity, although complex jointing is often found. Back from the coast, in the area in which batholites of granite are abundant, the metamorphism is much more advanced. There intrusives and mashing play an important part. In proportion as the dynamic forces were strong, biotite and muscovite largely replace chlorite as an alteration product of the feldspar. The altered rocks instead of being graywackes and graywacke-slates are mica-slates and mica-schists.

Within the area of the Original Huronian there is a certain amount of variation in the stratigraphical succession and a considerable variation in the degree of alteration. For instance, at Garden River the three lower formations are absent, the lower slate-conglomerate resting upon the Archean. As the Huronian is mapped to the northeastward from Georgian Bay, considerable changes take place in its character, but as yet no attempt has been made to follow the individual formations far from the lake shore.

The recent work of Bell in the Sudbury district shows that the Archean, Lower Huronian, and Upper Huronian have there the same general characters as near the coast, but as no subdivision of the series into formations is given, the latter may be different. While the Upper Huronian is in a general way similar to that of Georgian Bay, there are also present extensive areas of devitrified volcanic glasses and breccias.

In this Sudbury district Bell summarizes the character of the Huronian as follows: The Lower Huronian is "a series comprising quartzites, massive graywackes, often holding rounded and angular fragments; slaty graywackes with and without included fragments, drab and gray argillites and clay slates, dioritic, hornblendic, sericitic, felsitic, micaceous, and other schists, and occasionally dolomites, together with large included masses or areas of pyritiferous greenstones. This group constitutes the ordinary Huronian of the district." The Upper Huronian consists of "a thick band of dark-colored siliceous volcanic breccia and black slate (generally coarse), overlaid by drab and gray argillaceous and nearly black gritty sandstones and shaly bands. The breccia is underlaid in places by quartzite-conglomerate." Great bosses of intrusive granite and diorite abound, and the associated rocks are much more metamorphosed than are the Huronian at the North Channel. The contact effect, thermal waters, and mechanical action have extensively changed the shales and grits into mica-schists, and the quartzites occasionally approach quartz-schist.

CORRELATION.

As to the relations of the Huronian Algonkian and the Grenville and Hastings Algonkian, nothing more can be said than is given on a previous page. Logan thought the Huronian to be probably newer than the Grenville, because of the structural break which obtains on the north shore of Lake Huron between the Huronian and Archean, but which is apparently absent in the Original Laurentian area between the Grenville and Archean, and because the Huronian rocks are not metamorphosed, while those of the Grenville series in the Laurentian district are completely crystalline schists. However, it has been seen that crystalline character is not primarily due to age, but to dynamic action and igneous intrusion, and also that the apparent unconformity between the Laurentian Algonkian and the Archean may be really illusory. In the following section upon the Lake Superior region reasons will be given for placing the two lower series of clastic rocks there found as the equivalents of the Lower Huronian and Upper Huronian of the north shore of Lake Huron.

PRINCIPLES ILLUSTRATED.

In this district one may see the Basement Complex or Archean in its typical development, there being unusually fine examples of intrusion of the earlier gneisses by later granites, with the characteristic pseudo-conglomerates of intrusion. A basal conglomerate and erosive contact of unconformity are exhibited upon a fine scale east of Thessalon. It so happens that at one of the localities east of Thessalon, where an intrusive granite in the Archean is best observed, the basal conglomerate of the Lower Huronian is immediately adjacent, and rests here upon the granite and there upon the gneiss, so that we have side by side the contrasting phenomena of eruptive and erosive unconformity. Along the North Channel the induration of rocks by consolidation, cementation, and metasomatism, with little dynamic action, is finely illustrated. Along the railroad between Algoma Mills and Sudbury, and at other localities, the development of mica-schists by a combination of intrusion and mashing and the above processes is well illustrated. The great age of the little altered rocks affords excellent proof that age combined with considerable depth of burying is not sufficient to render rocks crystalline. The Original Huronian is the first district in which unconformity and degree of crystallization were used to separate the Archean from the Algonkian; also, it is the first district in which pre-Cambrian sedimentary series were separated into formations and mapped, and an attempt made to accurately determine their thickness.

SECTION VII.

THE LAKE SUPERIOR REGION.

The ancient formations south of Lake Superior may be grouped into five great divisions: The Basement Complex, the Lower Huronian, the Upper Huronian, the Keweenawan, and the Lake Superior sandstone, These five divisions are separated by unconformities of great magnitude, two of them, at least, being of the first order. According to the classification adopted by the United States Geological Survey, the Basement Complex is Archean; the Lower Huronian, Upper Huronian, and Keweenawan constitute the Algonkian for this region; and the Lake Superior sandstone is Cambrian.

The area comprised in the Lake Superior region includes all the pre-Cambrian rocks south and west of Lake Superior to the Paleozoic deposits, and a broad zone on the north shore, extending roughly from the Lake of the Woods to Lake Nipigon, and thence southeast to the Original Huronian area. The northern limit of this area is indefinite, but the treatment below applies only to those areas which have been studied in some detail. Included in the region south and west of Lake Superior are also various outliers, surrounded by Paleozoic sediments, some of which are of great extent. The pre-Keweenawan districts which have been studied more or less closely in the great central area are the Marquette, Menominee, Penokee, Mesabi, Vermilion, Lake of the Woods, Rainy Lake, Hunters Island, and Kaministiquia. The more important outlying districts are the Sioux quartzites of Dakota, Iowa, and Minnesota; the Wisconsin River valley slates, schists, and quartzites; the Chippewa and Baraboo quartzites of Wisconsin; and the Minnesota River valley gneisses. The Keweenawan rocks have received comprehensive study.

SUCCESSION.

THE ARCHEAN.

The characteristic rocks of the Basement Complex are: (1) granites and gneissoid granites; (2) massive and foliated intermediate and basic rocks, such as syenite, gabbro, and peridotite; and (3) finely laminated or banded gneisses and schists.

The granites and gneissoid granites are placed together, because between the two are innumerable gradations. The granitoid rocks have the greatest variety in composition, coarseness, and degree of foliation. They include hornblendic, augitic, micaceous, and chloritic varieties, and vary from a very acid granite to syenite. They also vary from coarse, massive to thoroughly foliated rocks. If one speaks accurately and includes among granites only those rocks which are completely massive, the gneissoid granites include the greater part of the granitic rocks; for in large exposures it is usually possible to find some evidence of foliation. The granitoid areas are of greatly varying sizes, running from small patches to those many miles in diameter. Where entirely surrounded by the schistose division of the Basement Complex they frequently have oval or ovoid forms. In nearing the outer border of the granitoid areas the foliation often becomes more and more prominent, and near the edge of an area the rock frequently passes into a well-laminated gneiss, similar to many rocks of the third division.

The intermediate and basic plutonic rocks, like the acid ones, show both massive and foliated varieties, with gradations. They do not cover nearly so extensive an area as the granites. In some places the basic rocks appear to grade into the granites.

The schistose rocks include fine-grained mica-schists, mica-gneisses, hornblende-gneisses, chlorite-gneisses, and various other green schists. The mica-schist and mica-gneiss or the green schists may each occur in extensive belts to the exclusion of the others, or they may occur intermingled or with gradations. All of these schists, on account of their foliation, were formerly supposed to be sedimentary, but many are now known to be greatly modified basic and acid igneous rocks. These schists have a gray, light or dark green, or black color, are usually strongly foliated, and the variations in strike and dip of this foliation within small areas are very great. Not infrequently these schistose rocks are traced by gradations into massive igneous rocks on the one hand and into surface lavas or tuffs on the other. The closest and long-continued field and laboratory study has wholly failed to show that any of the schists are of sedimentary origin.

The contacts between the schistose division and the granitoid division of the Basement Complex are often those of intrusion, the granitoid rocks being the later. In passing from a schistose to a granitoid area, one first finds small, pegmatitic-looking veins of granite. Proceeding, one finds these veins becoming more numerous, and, after a time, unmistakable dikes of granite appear, which multiply in number and size as the granite area is approached, until the granite is found in great bosses. Here we have perhaps a nearly equal quantity of schistose and granitoid rocks, and in this intermediate zone the schists may be found as a mass of blocks within the granite, sometimes at but small distances from their original positions, the whole having frequently a somewhat conglomeratic appearance. However, these pseudo-conglomerates, so well described by Lawson, grade more or less rapidly on the one hand into the schists and on the other into the solid gneissoid granite. The complete change may occur within a short distance, or it may extend over a mile or more.

The elucidation of the relations between the schistose and massive areas of the Basement Complex is far from complete. It is certain that the massive rocks, from acid to basic, grade into typical foliated schists. It is equally certain that other large schistose areas have been produced from surface volcanics of various kinds. There are other large areas of schists and gneisses which as yet have not been traced into either unmistakable plutonic or volcanic rocks. Any or all of the massive or schistose rocks have been repeatedly intruded by igneous rocks of different kinds, so that it frequently happens that intrusive granite or peridotite, or other rocks of different ages and different degrees of alteration, are in the same district. As yet it is therefore impossible to say what varieties of rocks of the Archean are the oldest. The clean-cut, massive igneous rocks which show little or no trace of orogenic movements and intrude the more or less foliated rocks are usually comparatively late. In some places these late intrusives occupy great areas. Where these intrusives occur in the broad Archean areas separated from the Algonkian and Paleozoic rocks, it is impossible to say whether such igneous rocks are of Archean or of post-Archean age.

The Basement Complex is then composed of intricately interlocking areas of massive and schistose rocks. Moreover, all of these rocks are completely crystalline. None of them show any unmistakable evidence of having been derived from sedimentaries, but many can be traced with gradations into igneous rocks, and therefore the greater proportion of them are igneous, if rock structures can furnish proof of such an origin.

Northwest and north of Lake Superior many of the mica-gneisses of the Basement Complex have been called Coutchiching, and many of its green schists and perhaps surface volcanics have been called Keewatin. However, it is possible that under each of these terms Algonkian rocks have also been included. This is almost certainly true of the Keewatin.

The Basement Complex is the most widespread of any of the Lake

Superior systems, and it doubtless runs under all later formations to a greater or less distance. That it is continuous under all such formations can not be asserted, for while it was once so, it is possible, perhaps even probable, that in places, as a consequence of sedimentation and folding, the Basement Complex has been so deeply buried that fusion has locally resulted. It is even possible that such fused material is a partial source of the later volcanic eruptions.

Before the earliest sedimentary rocks were deposited the Basement Complex was subjected to enormous orogenic forces, which folded and metamorphosed the rocks in a most intricate manner. Accompanying these movements, which undoubtedly occupied a vast period of time, were intrusions of various deep-seated igneous rocks, and also doubtless their volcanic equivalents were extruded.

The effect of these earlier orogenic movements and igneous intrusions upon the Archean rocks can not be discriminated from that of later movements and intrusions which also affected the Algonkian series. The total results only can be seen. As has already been indicated, as a result of the movements a cleavage was extensively developed, the rocks becoming metamorphosed and schistose. In the case of some of the green schists a fibrous structure was formed

Subsequent to and during the orogenic movements atmospheric forces were at work. Erosion continued long after the mountain-making movements had ceased, and for much of the Lake Superior region reduced the Basement Complex nearly to a plane or base-level. As evidence of this may be cited the fact that at the end of the erosion interval the Basement Complex, consisting of differing lithological materials, and therefore having a variable resisting power, did not vary in altitude more than a few hundred feet for long distances. At the beginning of Lower Huronian time the Basement Complex was, in the Lake Superior region, a universal system, and it now occupies all the areas not separately considered below.

THE LOWER HURONIAN.

After the forces of erosion had nearly exhausted themselves, there was the first advance of the sea over the Lake Superior region of which we have any evidence, as a result of which the Lower Huronian was deposited.

The Lower Huronian rocks are best known in the Marquette and Menominee districts, on the south shore of Lake Superior; in the Vermilion and Kaministiquia districts, along the north shore of Lake Superior; and in the Lake of the Woods, Rainy Lake, Steep Rock Lake, and Hunters Island districts, northwest of Lake Superior.

South of Lake Superior the fullest series anywhere found is in the Marquette district. The series in the Menominee district is somewhat different, but may be placed parallel to that of the Marquette district.

The following is the descending succession, that for the Menominee series being from Smyth:[1]

Lower Marquette	*Lower Menominee*
Negaunee iron formation, 1,000 to 1,500 feet	Slates bearing rich ores Michigamme jasper
Siamo slate, in places including interstratified amygdaloids, 200 to 625 feet thick Ajibik quartzite, 700 to 900 feet Wewe slate 550 to 1,050 feet	Slates and altered basic and acidic volcanics, maximum thickness, 2,000 feet
Kona dolomite, 550 to 1,375 feet Mesnard quartzite, 100 to 670 feet	Crystalline dolomite, 700 to 1,000 feet Basal quartzite, 700 to 1,000 feet

The full succession given is not everywhere found in the Marquette district. This is due to the transgression of the Lower Huronian sea from the northeast, and to the fact that before the Archean land was entirely overridden the Ajibik quartzite had begun to form. It therefore follows that the Kona dolomite, Wewe slate, and Ajibik quartzite, by overlapping, are each partly in contact with the Archean and partly in contact with the underlying formation. The only important difference between the Marquette and Menominee districts is that the slates and volcanics which occur in the Lower Menominee are not subdivided into formations, whereas in the Marquette district these are divided into two slates separated by a quartzite.

The basal transgression horizon is always a quartzite-conglomerate, a quartzite, or a feldspathic quartzite. The conglomerate is of two types, depending upon the character of the underlying formation, which is here granitic and there schistose. Where metamorphism has been severe it passes into a conglomerate-schist, quartz-schist, mica-schist, or mica-gneiss. In the Marquette district this basal horizon must be subdivided between the four formations from the Mesnard quartzite to the Ajibik quartzite. At many localities the basal conglomerate, composed of detritus of the Archean, reposes discordantly upon the foliated edges of that system. In other localities the Archean and Lower Huronian appear to grade into each other. A common foliation is the rule. The dolomite is so crystalline as to make the name marble appropriate. It frequently contains a considerable amount of chert and of detrital impurities. The iron-bearing formation contains all the ore bodies of the Lower Huronian of the two districts. It is almost wholly chemical or organic, being composed of siliceous siderite, hematitic slate, cherts, jaspers, and grünerite-magnetite-schists. These different varieties grade into one another both vertically and laterally. Intrusive in the Lower Huronian series of the south shore are very numerous dikes and bosses of diorite (altered diabase), and in the Menominee district there are occasional dikes and bosses of granite. The extrusives, which cover a large area in the Menominee district, comprise a remarkable series of greenstones, greenstone-conglomerates, agglomerates, amygdaloids, and lesser quantities of acidic lavas.

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[1] Relations of the Lower Menominee and Lower Marquette Series of Michigan (preliminary), by H L Smyth Am Jour Sci (3), Vol XLVII, 1894, pp 216-223.

At Black River Falls, Wis., is a series of ferruginous schists which is probably the equivalent of the iron-bearing formation of the Menominee and Marquette districts. In the Penokee district is a cherty limestone which is supposed to be equivalent to the dolomite of the Marquette and Menominee districts.

In the Kaministiquia and Vermilion districts, on the north shore of Lake Superior, quartzites, conglomerates, quartz-schists, graywackes, mica-slates, mica-schists, and all the varieties of the iron-bearing formation are found. Also associated with these are very abundant volcanic rocks, both basic and acid and extrusive and intrusive. As yet no general stratigraphical order for these various rocks can be given.

In the Lake of the Woods, Rainy Lake, and Hunters Island districts, the Lower Huronian rocks, called Keewatin by the Canadian geologists, consist of quartzites, graywackes, slates, green schists, sericite-schists, and various basic and acid intrusive and extrusive volcanic rocks, the latter being in the forms of both flows and tuffs. As yet no attempt has been made to place the formations in a definite stratigraphical order, although they have been separated in mapping into various lithological divisions. As described, perhaps the most characteristic feature of these districts is great batholitic masses of gneissoid granite. These were long called Laurentian, but clearly they must be regarded as post-Lower Huronian plutonic rocks. Another important feature of the districts is the great abundance of volcanics, both lavas and tuffs. These materials occupy large areas. The series are very generally affected by a strongly developed foliation, which is generally parallel to great intrusive masses of gneissoid granite. In some cases, also, the rocks have a parallel banding. These structures have been assumed to correspond with bedding, but of this no evidence has been given, and it is probable that in most cases they are secondary and produced in connection with the intrusion of the granite. At various places conglomerates at the base of the Lower Huronian contain waterworn fragments of quartz and bowlders of granite. These were regarded by Lawson as indicating a prior period of erosion, and he says that at the inauguration of the period there was an abrupt change in the conditions of deposition.

In the Kaministiquia, Vermilion, Lake of the Woods, Rainy Lake, and Hunters Island districts the Lower Huronian rocks and those of the Basement Complex have very generally a foliation in a common direction, and at many localities there are apparent gradations between the two. The relations between the Archean and the Lower Huronian in these districts have been explained in three different ways: (1) The gneissoid granites called Archean have been regarded as intrusive in the Keewatin; (2) the Archean has been regarded as conformable older sediments which are more metamorphosed than the Keewatin; (3) the occasional conglomerates at the base of the Keewatin have been regarded as evidence of unconformity between the two, the common foliation and apparent gradations for most localities being considered as secondary phenomena produced by dynamic action and consequent metamorphism. The intrusive granites are classified as Huronian or post-Huronian eruptives, as are other intrusives. Only those rocks are placed in the Archean which antedate the Huronian.

Northwest of Lake Superior the only area in which a definite order of formations has been made out is at Steep Rock Lake. Smyth gives the following ascending succession for this district: Conglomerate, maximum thickness 100 feet; limestone, from 500 to 700 feet thick; ferruginous formation, probably volcanic ash, maximum thickness 600 feet; interbedded crystalline traps, maximum thickness 1,000 feet; calcareous green schist, about 600 feet thick; upper conglomerate, maximum thickness 100 feet; greenstones and greenstone-schists, thickness about 1,400 feet; agglomerate, thickness not given; and clay slate, thickness not given. The estimated thickness for the whole series is 4,500 feet.

The Steep Rock Lake series rests with characteristic basal conglomerates upon the eroded edges of the Archean rocks. The series has been subjected to two orogenic movements. The first gave the series a monoclinal structure with steep dips. The second was at right angles to the first, and folded this monocline into two synclines and a connecting anticline, the axes of which have a pitch varying from 60° to vertical. The Basement Complex was affected by this folding, as shown by the plications of dikes. Accompanying the second folding regional cleavage was developed at right angles to the forces, and this is continuous from the Basement Complex into the Steep Rock Lake series. On account of the folding the relation of the cleavage to the contact line varies from parallel to vertical. Accompanying the folding one major fault was formed. There was also an extensive development of autoclastic rocks, both within the Steep Rock Lake series and within the Basement Complex.

From the foregoing summary it is apparent that it is yet too early to determine whether any formations of the Lower Huronian can be followed over all the districts of the Lake Superior region. It is certain that some formations extend for considerable distances, but it is doubtful whether it will ever be possible to correlate the formations of the farther separated districts.

For a long time the Lake Superior region had been an area of deposition. At the end of Lower Huronian time the region was raised above the sea, folded, and subjected to erosion. The orogenic movements of this time were very severe, in places closely crumpling the rocks of the Lower Huronian. In other localities, away from the axes of great disturbance, the Lower Huronian rocks were but gently tilted, as is shown by the small discordance in places between them and the succeeding series. In certain localities the areas of great disturbance are but a short distance from those of comparative quiet.

As soon as the Lake Superior region was raised above the sea it became an area of degradation. This period of the history of the Lake Superior region was a long one, as is shown by the great inter-Huronian erosion. We do not know what Lower Huronian formations of a higher horizon than any now found were wholly removed by the degradational forces. The depth of erosion varies greatly. The entire Lower Huronian series was removed over wide areas, and also an unknown depth of the Basement Complex itself. At other localities, as in the Penokee district, the only vestiges of the Lower Huronian series are patches of dolomite, with a maximum thickness of 300 feet, all of the remaining formations being carried away. In the Marquette and Menominee districts the erosion stopped over considerable areas within the iron-bearing formation, this being due to the resistant character of that rock. As has been stated, the Lower Huronian has an estimated thickness of about one mile, and hence the differential erosion amounts to at least 5,000 feet.

THE UPPER HURONIAN.

At the close of the long period of erosion which followed the Lower Huronian deposition the water once more advanced upon the Lake Superior region, and the Upper Huronian series was deposited.

Lithologically this series consists of conglomerates, quartzites, graywackes, graywacke-slates, shales, mica-slates, mica-schists, ferruginous slates, cherts, jaspers, ferruginous schists, and igneous rocks, including both lava flows and volcanic fragmentals, as well as basic and acid intrusives. The series, as a whole, is very much less crystalline than the Lower Huronian, although locally the shales and graywackes have been transformed into mica-schists, and even into gneisses.

The Upper Huronian immediately about Lake Superior in most districts is divisible into three formations. a lower fragmental formation composed of slate, quartzite, and conglomerate, an iron-bearing formation, and an upper slate, the basis of separation being that of mechanical and nonmechanical detritus. The central mass of the inferior formation is mainly a quartzose slate, but locally, and especially where thin and at upper horizons, it passes into a quartzite, while the basal horizon is frequently a quartzite or quartzite-conglomerate. The nature of this conglomerate varies greatly, depending upon the character of the underlying formation, which in some areas is the Basement Complex and in others the Lower Huronian. In the first case the slates may rest upon the gneissoid granite, upon the schists (fig. 144), or upon the junction of the two. The basal conglomerate corresponds in character, being a recomposed granite or granite-comglomerate, a recomposed schist or schist-conglomerate, or, finally, a combination of the two.

Where the lowest member of the Upper Huronian rests upon the Lower Huronian series the underlying formation may be any one of the formations of the Lower Huronian. As a consequence the basal conglomerate may consist mainly of the fragments of any one of these formations, or of all of them together. Not infrequently detritus derived from the Basement Complex is mingled with that of Lower Huronian origin. However, as a consequence of the resistant character of the jaspery iron-bearing formation of the Lower Huronian, and of mining operations, the discovered contacts are most frequently between the Upper Huronian and this iron-bearing formation. In the basal conglomerate or recomposed rock at these points the characteristic fragments are chert, jasper, and other ferruginous materials, and it is locally so rich in iron as to bear ore bodies. The uppermost horizon of the lower slate of the Upper Huronian in the Penokee district is a pure, persistent layer of quartzite. The central mass of the formation is a graywacke or graywacke-slate, passing in places into a shale or sandstone.

Above the lower slate is the iron-bearing member, consisting of various ferruginous rocks, including cherts, jasper, magnetite-actinolite-schists, iron ores, and ferruginous carbonates, in some places bearing glauconite. It has been shown that all these varieties have been mainly derived, directly or indirectly, by transformation, from an original lean iron bearing carbonate, which was of chemical or organic origin, or a combination of both. Mingled with these nonmechanical sediments is a greater or less quantity of mechanical detritus.

Above the iron-bearing formation is the upper slate formation. This is composed mainly of shales, frequently carbonaceous or graphitic, slates, graywackes, and mica-schists, often garnetiferous and staurolitic. The mica-schists are usually toward the upper part of the formation. The stages of the transformation between the plainly clastic and the holocrystalline rocks have been somewhat fully made out.

The lower slate formation is of variable thickness, but is usually less than 1,000 feet. The iron-bearing formation is also of very variable thickness, its maximum being about the same as that of the lower slate. From its maximum thickness the formation varies to disappearance, the horizon being usually represented, however, by carbonaceous and ferruginous shales and slates. The upper slate formation includes the great mass of the Upper Huronian series. Its maximum thickness, including possibly interlaminated igneous rocks, is about 12,000 feet.

In some districts, as for instance the Marquette, the iron-bearing formation is unimportant, and can not be traced as a continuous horizon. In such areas the Upper Huronian, viewed in a large way, is a single great fragmental formation composed mostly of argillaceous rocks and their metamorphosed equivalents. Near the base of the Upper Huronian, in parts of the Marquette district, is a magnetite-grunerite-schist, called the Bijiki schist.

In certain areas during Upper Huronian time there was great volcanic activity, as a result of which peculiar formations were piled up, wholly different from any of the ordinary members of the series. This volcanic activity greatly disturbed the regular succession, so that for each of the volcanic districts an independent succession exists, the sedimentary and volcanic formations being intimately interlaminated.

The two areas which are best known are the Marquette iron district and the east end of the Penokee district. In the Marquette iron district is an extensive area of greenstones, greenstone-conglomerates, agglomerates, and surface lava flows, many of which are amygdaloidal. Between the tuffs and ordinary water-deposited sediments there are all gradations at many places. In the Penokee district the materials are almost identical. The ordinary succession for this district extends in unbroken order for 50 miles or more, but east of Sunday Lake this is suddenly disturbed by the appearance of the volcanics. The character of the rocks and their order soon become so different that if one were not able to trace the change from one area into the other there would be a great temptation to regard the part of the series bearing volcanics as earlier or later than the Penokee series proper. But the continuity of the two can not be doubted. Thus the occurrence well illustrates that lithological character in pre-Cambrian time, as in post-Cambrian, is no certain guide as to relative age. Finally, associated with the Lake Superior Upper Huronian rocks are many later intrusive dikes and interbedded sills, chiefly diabases, gabbros, and diorites; but local granitic intrusives also occur, particularly in the Crystal Falls district, and possibly also in the Menominee district.

The type area of the Upper Huronian is the Penokee district. Here the fullest succession is found under the most favorable circumstances. It consists of a quartz slate formation, an iron-bearing formation, and an upper slate formation. The quartz-slate has an average thickness of about 500 feet. The central part of the formation is a mica-slate. At its base is a horizon of conglomerate, and at its top is a persistent layer of quartzite about 50 feet thick. The iron-bearing formation has an average thickness of 800 feet. It consists of cherty iron carbonate, ferruginous slates and cherts, and actinolitic and magnetitic slates. Within this the iron-ore bodies are found. The upper slate formation has a maximum thickness of about 12,000 feet. It varies in character from clay-slate through graywacke and graywacke-slate to mica-slate. The Penokee series is intruded by diabase, which occurs both as cutting dikes and as interbedded sheets. Therefore a considerable portion of the thickness of 13,300 feet above given may be composed of these intrusive rocks.

The other districts in which the Upper Huronian series can be best studied are the Marquette, Mesabi, and Animikie. Remote from the Lake Superior region proper the rock series which are below correlated with the Upper Huronian have not the same successions of formations as in these districts. The Upper Huronian north of Lake Huron has a set of formations which can not be separately correlated with the formations above given; the same is true of other series which are placed in the Upper Huronian. The position of these latter as a part of the Upper Huronian must not be considered as finally determined, but rather as representing the probability from the weight of evidence at the present time. It can not be expected that in a great geological basin the same subordinate succession of formations will be everywhere found.

With the Upper Huronian rocks of the Wisconsin River valley and the Baraboo district are various quartz-porphyries and porphyry-tuffs. Between these districts, surrounded by Paleozoic rocks, are areas of similar porphyries and porphyry-tuffs which are doubtless of the same age. Intimately associated with these rocks are micrograrnites and granites. The microgranite of Berlin has a well-developed cleavage in one direction, and a rift at right angles to the cleavage. The cleavage is due to the parallel arrangement of innumerable minute flakes of mica and crystals of hornblende. The phenocrysts of feldspar are greatly flattened in the plane of cleavage, and are fractured diagonally to the cleavage. In some cases there are two sets of diagonal fractures about at right angles to each other, and at 45° to the cleavage. Many of the fractures have been healed by secondary infiltrations. In the case of this microgranite, it appears that the cleavage developed normal to the pressure, and that the fractures occurred at the same time in the porphyritic feldspar crystals in the shearing planes.

So far as one can judge from present knowledge, the Upper Huronian is the most widespread of the Lake Superior pre-Cambrian sedimentary series. The great region including the various districts extends from the Sioux quartzites of Dakota on the southwest to the Huronian rocks north of Lake Huron on the east, and thence far to the north, and from Lake Huron to the Animikie series of the national boundary west of Lake Superior. Within this area are included, in addition to the districts mentioned in this paragraph, the major portion of the large area of Huronian rocks in the upper peninsula of Michigan, the eastern arms of which are the Menominee, Felch Mountain, and Marquette iron-bearing districts; the Wisconsin valley series; the greater part of the Penokee-Gogebic iron-bearing series of Michigan and Wisconsin; the Chippewa and Baraboo quartzites of Wisconsin; the St. Louis slates of Minnesota; and the newly developed Mesabi range of Minnesota. That most and perhaps all of these areas were once connected there can be no reasonable doubt.

The broad semicircular zone of Upper Huronian rocks extending from the national boundary west of Lake Superior through Ontario, Minnesota, Michigan, and Wisconsin to the north channel of Lake Huron, and thence north to the east side of James Bay, suggests that the transgression of the sea was from the south and east, and that the source of the mechanical detritus is the great expanse of so-called Laurentian rocks west of Hudson Bay and north of Lake Superior. How far the sea transgressed over this area, and whether it also advanced toward it from the north and west, is unknown. It is probable that as the sea advanced from the south the great mass of fragmental detritus making up the Baraboo and Sioux quartzites was laid down before the sea had transgressed to what is now the north shore of Lake Superior, and thus would be explained the difference in the character of the formations of the Sioux quartzites, Baraboo quartzites, etc., and those of the Upper Huronian rocks adjacent to Lake Superior.

In this case the advancing ocean was perhaps making its progress by land and sea erosion, quite as much as by subsidence. However, there is reason to believe that the whole of the area included within the west end of the Lake Superior basin, i. e., from the Animikie district to the Mesabi range, and thence to the Penokee district, was submerged practically at the same time. For here we have three great formations of like character in identical order. The lowest formation, the quartzite and quartz slate, with conglomerates derived from the Basement Complex and the Lower Huronian, is the first deposit of the advancing sea. After this came a deepening of the water, when the calcareous and ferruginous formation, now constituting the iron-bearing member, was laid down. Then, perhaps as a consequence of the upbuilding of this formation, came a shallowing of the water and the deposition of the great thickness of clayey sediments of the Upper Huronian. As the last formation must have been deposited in shallow water, and yet is of great thickness, the bed of the ocean was probably sudsiding during the remainder of Upper Huronian time.

At the end of the deposition of the Upper Huronian rocks the Lake Superior region rose above the sea, and the atmospheric forces once more set to work. The orogenic movements following the Upper Huronian, like those following the Lower Huronian, were locally intense, but in general the folding was of a gentle character. In certain areas, and some of them of considerable size, the plications were so severe as to give the Upper Huronian rocks a foliated structure and a completely crystalline, schistose, or gneissic character; but for much larger areas the changes in the Upper Huronian rocks are mainly those of cementation, metasomatism, and consolidation, although mashing played a subordinate part. As in the case of the Lower Huronian, the areas of intense plication are in places but short distances from those in which the rocks have been merely tilted.

How deep the Upper Huronian denudation went it is impossible to say. We know only that at a maximum the Upper Huronian rocks are now 13,000 feet thick, and in certain other places are entirely absent, the higher members disappearing first and the lower members last. Thus the difference of the Upper Huronian denudation is measured by 13,000 feet. To this must be added the unknown thickness of the Upper Huronian rocks which have been wholly swept away, and the thickness of the Lower Huronian and Basement Complex which were cut at this time. The thickness represented by these three elements is unknown, but it is probably great.

Of the outer limits of the Upper Huronian transgression we are as ignorant as of the preceding ones, but it is certain that it extended to the outer areas mentioned as belonging to this series. Beyond these limits no knowledge is available. The original extent of the Upper Huronian to the east, south, and west will probably never be determined, since the ancient rocks are covered by the Cambrian and post-Cambrian sediments. Whether the transgression extended over the Great Northern Area of Canada to the Paleozoic deposits will doubtless be ascertained when this vast region is studied in detail.

ALTERATION OF LOWER HURONIAN AND UPPER HURONIAN.

It is impossible to discriminate the effects of the inter-Huronian orogenic movements from the post-Huronian orogenic movements; therefore only their total effect upon the Huronian series can be given.

The processes of deformation resulted in the folding of the series, in fracturing them over extensive areas, in the production of secondary structures, and in the metamorphism of the beds. In all of the districts the folding of both the Upper and Lower Huronian is of a complex type. Great complexity is illustrated in the Marquette, Menominee, Vermilion, Kaministiquia, Steep Rock Lake, and probably other districts. The character of the folding in the more complex areas has not been worked out in detail except in the Marquette and Steep Rock Lake districts. Major faults are not conspicuous, although faulting in a minute way within the beds may be everywhere found.

The Lower and Upper Marquette series may be taken as illustrative of deformation by combined flowage and fracture. While the beds as a whole are folded without major displacement, all of the brittle formations, such as the alteration phases of the sandstone, limestone, and iron-bearing formation, are shattered through and through, so that a hand specimen can hardly be obtained which does not show complex fracturing. When the microscope is applied to the material it is further found that movement has occurred throughout the rock, not a single section among hundreds being found which does not show rearrangement. The argillaceous beds, on the other hand, were extensively deformed without fracturing. Accompanying the deformation, cleavage and fissility were widely developed. A schistose structure was also developed in the Archean. As a consequence at many places the Upper Huronian, Lower Huronian, and Archean have a common foliation. In the closely folded districts the same forces which produced secondary structures also partly or wholly destroyed the original bedding. Where evidence of original bedding is still found this may or may not accord with the secondary structures.

The deformation further resulted in extensive metamorphism of the Huronian rocks. The argillaceous beds were transformed into slates, mica-schists, often garnetiferous and staurolitic, or mica-gneisses; the sandstones into quartzites and quartz-schists; the limestones into cherty dolomites or marbles; the cherty iron carbonates into the various rocks of the iron-bearing formation; and the volcanics into chloritic, biotitic, and hornblendic schists. In the alteration of the iron-bearing carbonates, largely by metasomatic processes, the original bedding is in most places emphasized. The processes concerned in this metamorphism were ordinarily consolidation, cementation, metasomatism, and mashing.

In certain districts the process was greatly promoted by the intrusive igneous rocks, many of which are doubtless of Keweenawan age. In connection with granitic intrusion at certain places there is extensive pegmatization of the beds. In the Michigamme slate of the Upper Huronian in the Marquette district this pegmatization has, however, occurred as a result of extreme dynamic metamorphism independently of any igneous intrusion.

The contact horizon between the Archean and the Lower Huronian and that between the Lower Huronian and the Upper Huronian were naturally planes of accommodation, and at these planes particularly schistosity in the unconformable series developed At the contact horizon between the Lower Huronian and the Archean, where basal conglomerates existed, they have been largely transformed to schist-conglomerates or crystalline schists showing no trace of a conglomeratic character. These modifications of original relations make it difficult at many localities, or even in entire districts, to detect the structural break between the Archean and Lower Huronian. While this is the case, it oftens happens in favorable places, and in almost every district at some locality, that the dynamic metamorphism was not so great, and therefore basal conglomerates may there be found resting upon the truncated edges of the Archean. The Upper Huronian has been so slightly folded over large areas, or for entire districts, that the unconformity between it and the Archean or the Lower Huronian is most glaring. However, in the districts of greatest plication, like the Marquette, Menominee, Felch Mountain, and Kaministiquia, the folding was so intense as to bring the bedding of the two series into approximate harmony, to develop conformable secondary structures, and partly to obliterate conglomerates. Consequently this unconformity was not discovered for many years. A close study in recent years, however, has shown that basal conglomerates may be found at hundreds of localities between the Upper Huronian and the Lower Huronian. These are particularly abundant when the contact is above the iron-bearing formation of the Lower Huronian.

In general the Lower Huronian is more crystalline than the Upper Huronian, because subjected to one or more periods of deformation and of igneous intrusion more than the newer series. While this is true as a general statement, for certain areas the inter-Huronian orogenic movements were so slight as to render it probable that the lower series was not strongly metamorphosed, although it was doubtless consolidated and cemented, and metasomatic alterations probably occurred. In districts in which the post-Upper Huronian deformation was severe this series is scarcely less crystalline than the Lower Huronian. However, for the great areas of Upper Huronian the folding is gentle, and consequently the rocks show mainly the effects of the processes of consolidation, metasomatism, and cementation, rather than those of mashing and pegmatization. The Lower Huronian in general may be said to consist mainly of crystalline schists and semicrystalline schists, and the

Upper Huronian consists mainly of semicrystalline schists and rocks which are merely consolidated and cemented, but in some cases crystalline schists occur.

THE KEWEENAWAN.

Again a change of conditions occurred, and enormous masses of igneous rocks appeared. After a time a part at least of the region sank below the sea, since sandstones and conglomerates are interstratified with the lavas. In some places the basement lavas are thus interbedded with these clastics, but by the time the lavas reached such parts of the region, in other parts great thicknesses of igneous rocks may have been piled up.

The Keweenawan rocks border nearly the entire area of the Lake Superior basin. They appear on the east shore of Lake Superior, cover a large area on Keweenaw Point, in northern Wisconsin, and in eastern and northeastern Minnesota, and a great area about Lake Nipigon.

The Keweenaw series is composed lithologically of gabbros, diabases, porphyrites, amygdaloids, felsites, quartz-porphyries, etc., and of sandstones and conglomerates. Many of the basic and acid rocks constituting much of the series are surface flows. The diabase flows frequently pass in their upper parts into porphyrites and amygdaloids. Many flows are porphyritic or amygdaloidal throughout. The beds of quartz-porphyry and felsite are abundant in certain districts, but usually have no great lateral extent While a single basic or acid flow may be traced but a little way, frequently a set of flows of the same general character may have a great extent and thickness. But even the sets of flows can not be regarded as general formations for the whole of the Lake Superior basin. No tuffs have as yet been found.

Since the number and thickness of the volcanic beds as well as the detritals vary greatly, the Keweenaw series as a whole is widely variable in character and thickness in different districts. From the base up the Keweenawan may be separated into three great divisions: (1) Basal gabbro, (2) interstratified lavas and clastic rocks, and (3) clastics.

(1) The great basal gabbro occupies a broad belt in northeastern Minnesota, running from Duluth to the boundary between the United States and Canada, and having a width for much of the way of from 20 to 25 miles. This basal gabbro also covers a broad area in northern Wisconsin. The rock has everywhere a typical granitic structure. It includes lithologically very magnetitic gabbro, olivine-gabbro, normal gabbro, and masses of basic feldspar or anorthosite. The relations of these varieties to one another have not yet been determined. Much of the gabbro has a laminated arrangement of the mineral particles, and corresponding with this arrangement the rock has a bedded or sheeted appearance, but whether these structures were produced by the flowing out of great beds at the surface or by the cooling of a deep-seated igneous mass has not yet been determined.

(2) The second division of the Keweenawan consists of all of the varieties of lava of the series, and interstratified sandstones and conglomer-

ates, the material of which was almost wholly derived from the neighboring lava flows. In the lower part of the division numerous volcanic flows are usually found, with few or no detrital beds. In passing toward the middle of the division, the sandstones and conglomerates become more and more numerous and of greater thickness. A given detrital bed may vary from a mere seam of narrow local extent to thick beds of sandstone and conglomerate, one of which has been traced by Marvine for more than 100 miles. Still higher the sandstones and conglomerates become predominant, and finally the volcanic products disappear.

(3) The third division is composed wholly of sandstone and conglomerates, derived very largely from the erosion of the lower divisions.

Where the lavas of the middle division approach the basal gabbro they terminate against it diagonally, giving the appearance of an unconformity. From present knowledge the phenomena might be explained by regarding the great basal mass of gabbro as an intrusive which entered between the middle division of the Keweenawan and the Upper Huronian, or it might be regarded as a post-Huronian extrusive of such vast thickness as to have a gabbro structure. In the latter case the outer part was removed by erosion before the formation of the middle division of the series.

The Keweenawan is the thickest of the series about Lake Superior, its maximum being estimated by Irving at the Montreal River to be 50,000 feet. From this thickness it varies to nothing. This vast quantity of material does not, however, of necessity marks a period longer than, or perhaps even one as long as, the Lower Huronian or Upper Huronian, for the greater part of it is of igneous origin. The lava flows in their extent and thickness are to be compared with the great volcanic plateaus of the far West rather than with local volcanoes, such as Vesuvius, or the local volcanoes of the Upper Huronian and Lower Huronian. No volcanic fragmental material associated with the lavas has as yet been discovered.

The fact that erosion was contemporaneous with eruption for much of Keweenawan time is to be noted. Certainly when the period was well inaugurated much of the Lake Superior basin was frequently, if not normally, below the sea or near tide-water. Many of the eruptions may have been subaqueous. Here and there volcanic masses of such magnitude were built up as to rise above the water, and upon such areas the sea at the base and the air and rain above immediately began their course of destruction. The acid and more viscous lavas may have formed the more prominent elevations, and thus the attack was here more vigorous. This may partly explain the predominance of the acid pebbles in the conglomerates.

This great volcanic period was doubtless one of unstable equilibrium, the lithosphere falling here and rising there. The final resultant of all the movements was the production of the Lake Superior syncline. This synclinal movement affects not only the Keweenawan rocks but the lower series, and in areas in which the unconformity between the

Upper Huronian and the Keweenawan is not great there is such a likeness in strike and dip of the two series as to suggest at first that the two are conformable. It is only as the contacts between them are followed for some distance, and the Keweenawan is seen to be now in contact with one member of the Upper Huronian and now with another, that it is perceived that between the two there is an unconformity.

What proportion of the Keweenawan had accumulated before the Lake Superior syncline began to form it is impossible to say. Possibly the larger foci from which the great extrusions of lava occurred were in the area now covered by water. Probably sinking went on at the same time as volcanic action, such as is common as a result of the upbuilding of mountainous masses of volcanic material. This suggestion, if true, would partly explain the apparent absence of volcanic fragmental material, which naturally would accumulate near the foci.

Nowhere are the Keweenawan rocks so closely folded as to give them a secondary structure or a much altered character. Their induration is almost wholly a process of cementation. The diabases, gabbros, and diorites so extensively intruded within the Lower Huronian and Upper Huronian rocks are, in part at least, in all probability, of Keweenawan age, but this is difficult to prove.

THE CAMBRIAN.

At the close of the Keweenawan deposition the Lake Superior region was again raised above the sea, and the pre-Cambrian erosion continued until the enormous thickness of Keweenawan and Huronian deposits was wholly truncated. What must have been mighty mountains were reduced to mere stumps. Following this denudation the sea once more transgressed upon the land, and the horizontal Lake Superior sandstone was deposited. It now occupies many of the bays about Lake Superior. It once was much thicker, and perhaps covered the highest points of land. Certainly it or an overlying formation once was at least 1,000 feet higher than the level of Lake Superior, but these higher deposits have since been almost completely removed, so that they occur only in patches within the depressions of the older rocks.

Since Cambrian time no important orogenic movements or outbursts of volcanic material have occurred in the Lake Superior region; consequently the rocks have received little subsequent alteration. To these facts is due the possibility of outlining the pre-Cambrian history of this area with greater fullness than has been done in areas in which later disturbances have obscured the early history.

CORRELATION

In the foregoing discussion the two lower clastic series above the Archean have been called the Lower Huronian and Upper Huronian. In both the Lake Superior region and the Original Huronian district we have a Basement Complex of identical character, and unconformably above this Basement Complex and unconformably below the Keweenawan we have two unconformable clastic series. The corre-

PLATE CXIV.

PLATE CXIV. Jaspilite.

FIG 1. Folded jaspilite, from Jasper Bluff, Ishpeming The illustration beautifully shows the secondary infiltration of iron oxide and deformation by combined fracture and flow By close observation iron oxide of three different ages may be seen The oldest is the dark-gray hematite Intersecting this is a more brilliant, steel-gray hematite and magnetite, and cutting both of the former are other veins of brilliant hematite and magnetite The history of the rock seems to be, briefly, as follows Banded hematite and jasper were bent by folding, probably while the rock was deep seated. During this folding the hematite was mashed and foliated. In a later stage, when the rock was more rapidly deformed near the surface, fracturing occurred This gave the conditions for the first infiltration of iron oxide, and later, when the rock was perhaps still nearer the surface, further deformation resulted in new fractures. Finally the crevices thus formed were filled with the latest iron oxide.

FIG. 2 Brecciated jaspilite, from Jasper Bluff, Ishpeming The illustration gives evidence of the same history as shown by fig 1 However, during the final process the layers of jasper, which were bent at the earlier stage, were broken through and through, producing a breccia The same evidences are seen of three stages of iron oxide as in fig 1 The less brilliant gray is the earliest mashed hematite; the intermediate gray represents a first infiltration After this there was shattering, and finally the breccia was cemented by brilliant, steel-gray hematite and magnetite

Fig. 1.

Fig. 2.

A.Hoen & Co. Lith. Baltimore.

JASPILITE FROM NEGAUNEE FORMATION OF LOWER MARQUETTE SERIES.

sponding formations of each of these series are not the same in all districts; but this could not be expected in a geological province so great as the one here considered. However, considering that we have in various parts of the Lake Superior region and on the north shore of Lake Huron the same number of clastic series, having the same unconformable relations with the Basement Complex below and the Cambrian above, it seems highly probable that the corresponding series are of equivalent age. If this be true, after the deep erosion of the Basement Complex a great region was three times overridden by the sea, subjected to epeirogenic and orogenic movements, and three times deeply eroded, before the great Cambrian transgression. While no general correlation of formations within the Lower Huronian can be made for the entire Lake Superior region, in districts which are comparatively close together, as the Marquette and Menominee districts, the formations composing the series can be equated with a reasonable degree of certainty. In the Upper Huronian of the Penokee, Mesabi, and Animikie districts there are the same number of formations, of like character and in like order, and these can be regarded with a high degree of probability as of the same age and as once continuous.

PRINCIPLES ILLUSTRATED

All, or nearly all, of the principles discussed in Part I are well illustrated in various parts of the Lake Superior region. Indeed, it was by means of a study of this region and of the Appalachian region that these principles have been most largely formulated Therefore, an attempt to discuss fully the illustration of each principle would greatly expand this paper. It seems advisable, however, to mention some of the localities where various important principles are well exemplified.

In many parts of the Basement Complex and in some of the Huronian districts, the material yielded to the orogenic forces without perceptible fracture, and in these areas all the phenomena of folding without crevicing may be seen. The Huronian rocks during their deformation were very largely in the lower part of the zone of combined fracture and flowage. It follows that while major faults are not common, they do occasionally occur. Two are known in the Penokee district, one in the Marquette, and one in the Steep Rock Lake district. While the material in a large way obeyed the law of flowage, and was therefore folded, in a minor way many of the beds were in the zone of fracture. (Pl. CXIV, fig. 1.) The great beds of mud, which were the thickest formations of the Huronian, were deformed for the most part with little fracturing. On the other hand, the beds of sandstone, dolomite, and cherty iron carbonate and alteration forms were fractured through and through, and recemented (fig. 145), and in many areas autoclastic rocks developed. (Pl CXIV, fig. 2.) The widespread fracturing of these formations is perhaps best illustrated in the Lower Huronian of the Marquette and Steep Rock Lake districts.

In all of the series and districts the folding is complex. The complexity increases in passing downward from newer to older series. The great east-west Keweenawan synclinorium has important but gentle cross folds. The Upper Huronian of the Penokee, Mesabi, and Animikie districts is almost as simply folded. The folding of the Lower Huronian rocks is exceedingly complex, and in some districts the Upper Huronian rocks are included in the complex deformation. In these districts the character of the folding has been worked out only in the Marquette and Steep Rock Lake areas. In the first the chief longitudinal fold is an abnormal upright synclinorium, the abnormal character of the folding being due to the unequal rigidity and the consequent differential movements between the Archean and the Lower Huronian (fig. 146). The transverse folding is also severe, so as to give steep dips in places. A map of the outcrops of the formations in the more closely crumpled areas is extremely complex (fig. 147). The folds are often overturned (fig. 148). In the Steep Rock Lake district, as shown by Smyth, the Lower Huronian was first bent into a steep monocline, which was subsequently closely buckled by

FIG. 145.—Shattered slate cemented by vein quartz in Wewe slate of Lower Marquette series.

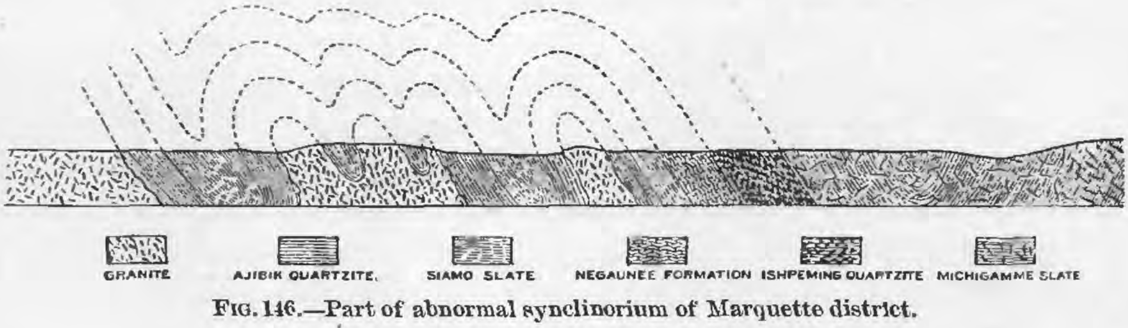
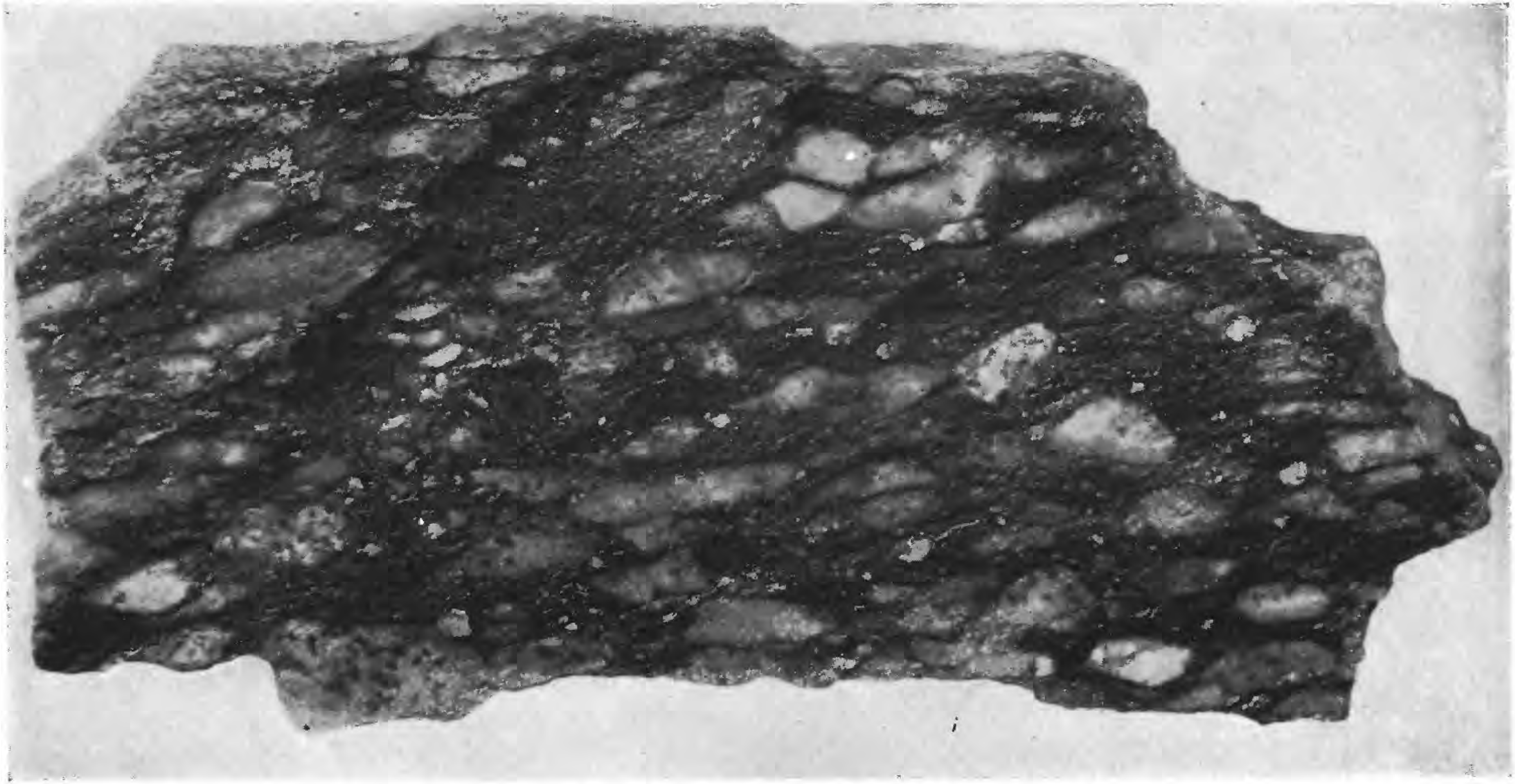


FIG. 146.—Part of abnormal synclinorium of Marquette district.

transverse forces. In many of the other districts, while as yet the character of the folding has not been worked out, it is certain that it is even more complex than in the Marquette and Steep Rock Lake areas. The anticlinoria and synclinoria in all of the complex districts are of a very composite type, having folds of a higher order superimposed on those of the next lower order up to microscopical plications.

Cleavage or fissility almost everywhere affects the Archean and the Lower Huronian rocks, and in some districts, as for instance in the



SCHIST-CONGLOMERATE FROM FELCH MOUNTAIN DISTRICT.

Marquette and Menominee districts, is fully developed in the Upper Huronian rocks. Cleavage often occurs in a soft layer and is absent in a harder one (fig. 149). All the different varieties of cross and parallel cleavage and fissility are exhibited, and all combinations of them. In the Baraboo quartzites, and especially at the Upper Narrows of the Baraboo River, fissility in shearing planes, diagonal stretching explained (pp. 651–655) as due to the unequal movement of the opposite sides of beds, and the relations of the same, are beautifully illustrated (figs. 150, 151, and 152).

In the Felch Mountain conglomeratic gneiss, mentioned below, the flattened pebbles in all stages of deformation and the schistosity are in perfect accordance, showing that the secondary structure developed normal to the pressure (Pl. CXV). Northwest of Lake Superior the peripheral cleavage, everywhere parallel to the intrusive batholites in each case, gives further fine illustrations of the development of a secondary structure normal to the pressure. The cleavage of the Berlin (Wisconsin) microgranite (see p. 789) is a beautiful illustration of the development of cleavage normal to the pressure in the case of an igneous rock. The fibrous structure found in the green schists of the Archean gives an illustration of a rock deformed where two of the principal stresses were nearly equal and the third less than these two (see p. 641).

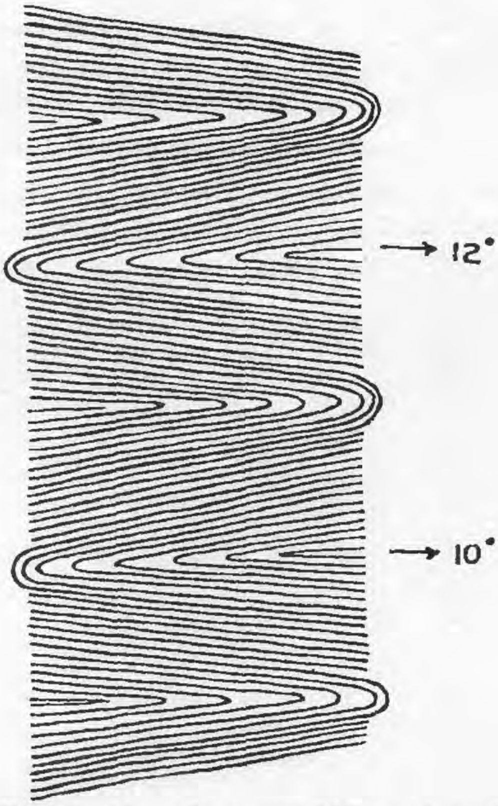


FIG. 147.—Map of outcrop of Wewe slate of Lower Marquette series southeast of Goose Lake.

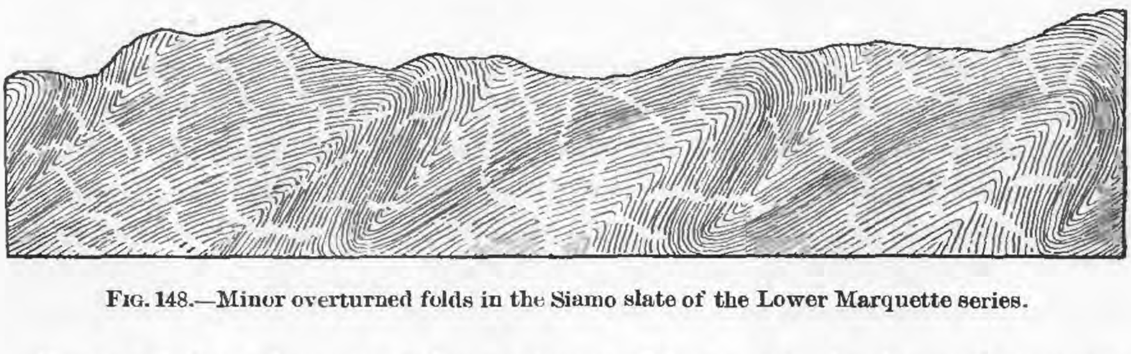


FIG. 148.—Minor overturned folds in the Siamo slate of the Lower Marquette series.

Some of the phases of the metamorphism of both the sedimentary and the igneous rocks are as follows: The rocks have everywhere been consolidated or welded. In many areas the sandstones have been cemented to quartzites, and in some cases in the Keweenawan the arkoses have been cemented by the growth of both quartz and feldspar. Certain of the volcanic tuffs, as at Kekekabik and Ogiski lakes, show also enlargement of hornblende. Metasomatic processes have everywhere affected the argillaceous, calcareous, and ferruginous rocks. Wherever cleavage and fissility occur, there the rocks have also been mashed, and slates or schists have been developed. Large porphyritic minerals, such as garnet, staurolite, chlorite, and chloritoid, have an extensive development, especially in the Upper Huronian mica-schists. In numerous localities the chlorite and chloritoid occur in crystals, the cleavage of which is at right angles to the cleavage of the rock, and this gives evidence of their development under static conditions after movement had ceased. Silicification has profoundly

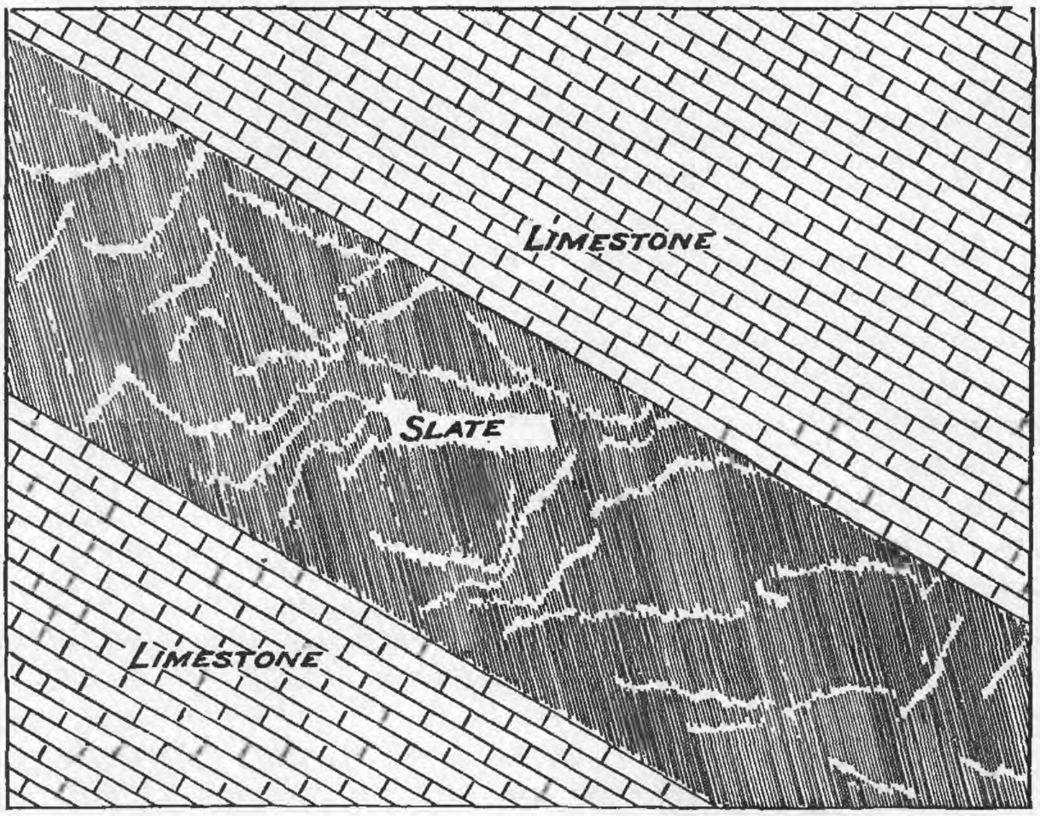


FIG. 149.—Cleavage in slate between two dolomite beds which do not show cleavage, in Kona dolomite of Lower Marquette series.

transformed the iron-bearing formations and the limestones. In the Felch Mountain district there are regularly banded mica-gneisses which can not be discriminated in the hand specimens from gneisses derived from a mashed granite. However, in the field they are traced step by step, both laterally and vertically, back to places where they become very distinctly a conglomeratic gneiss, bearing granite, quartz, chert, and other pebbles. In the closely folded mica-schist south of Michigamme Lake pegmatite veins in minute stringers occur, and a good deal of feldspar is found in the rock, so that it is now a veined mica-gneiss. As extraneous granitic injections have nowhere been discovered in the Marquette district, apparently the pegmatization was due to extreme dynamic metamorphism. In the Felch Mountain area of the Menominee district granite dikes occur in the Algonkian. In northeastern Minnesota and in Canada northwest of Lake Superior intrusive granites are found on a great scale, and the pseudo-conglomerates of intrusion are known at many places.

As a result of the alterations in the Lake Superior region, nearly every variety of metamorphic sedimentary and metamorphic igneous

FIG. 150.—Diagonal fissility of quartzite beds of the north range of Baraboo. Looking west.

rock mentioned in the discussion of principles is found at numerous localities.

All varieties of bedding and all degrees of obliteration of bedding are illustrated.

Basal conglomerates occur at various widely separated places in the Lake Superior region at four different horizons. The basal conglomerates at the lower horizons show all gradations of the process of obliteration.

As proofs of unconformity, all of the phenomena given as evidence of physical breaks (pp. 724–729) have been found at the four great unconformities existing in the region. Also in the Lower Huronian formations are found nearly all of the phenomena which might lead one to falsely infer unconformity. As one kind may be mentioned the dolomite of the Marquette district, the folds of which are truncated by dynamic action, the eroded edges being overlain by an autoclastic rock (fig. 153).

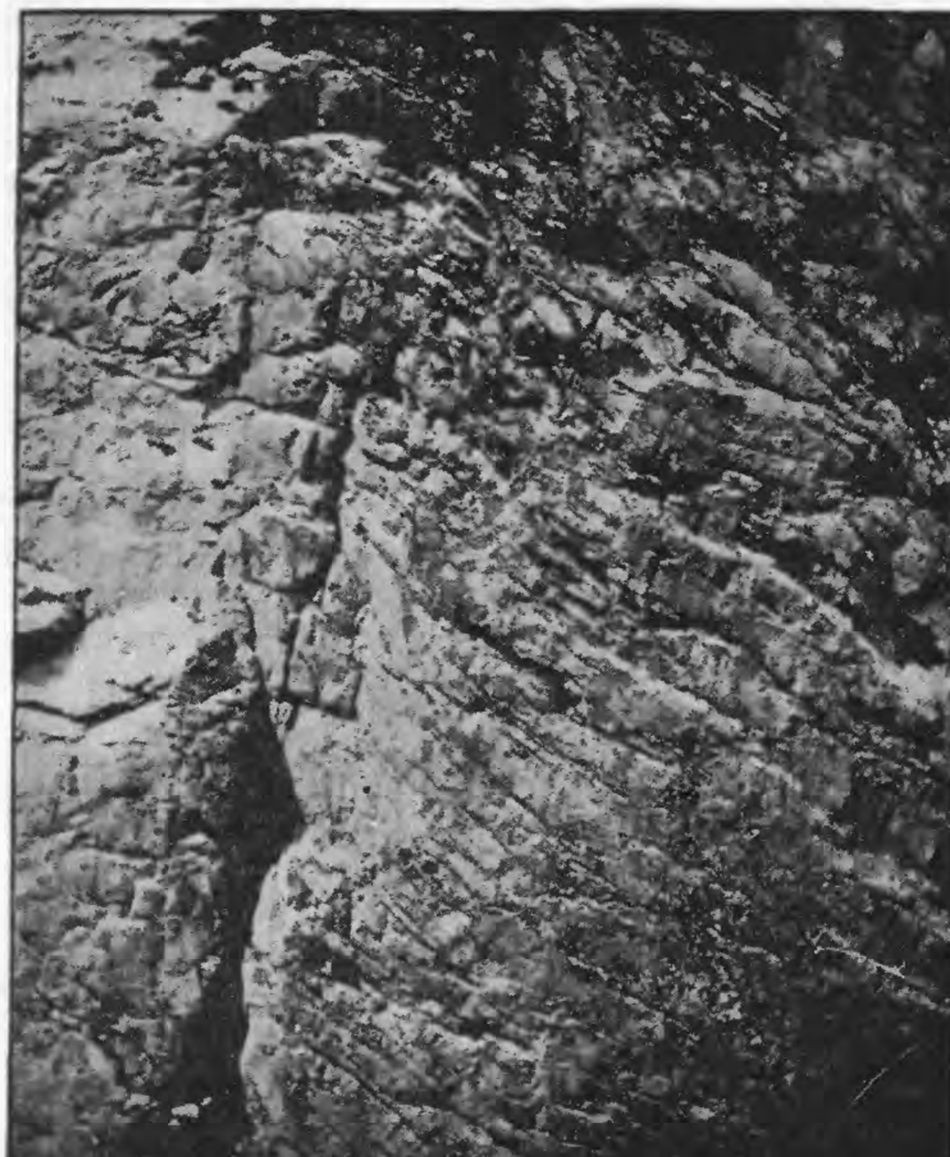


FIG. 151.—Details of one layer of fig. 150 having diagonal fissility. Looking west.

As the phenomena upon which the belief in unconformity is based are somewhat different at different horizons, each case may be mentioned separately. The statement that an unconformity exists between the Archean and the Lower Huronian is based upon: (1) the completely crystalline character of the former and the semicrystalline character of the latter; (2) the intricate folding of the former as compared with the latter; (3) the discordance of the foliation of the Basement Complex with the bedding of the Lower Huronian; (4) the presence in certain districts of abundant granitic intrusives in the Archean which nowhere penetrate the Lower Huronian; and (5) actual contacts at many places, basal conglomerates of the Lower Huronian being found to rest upon

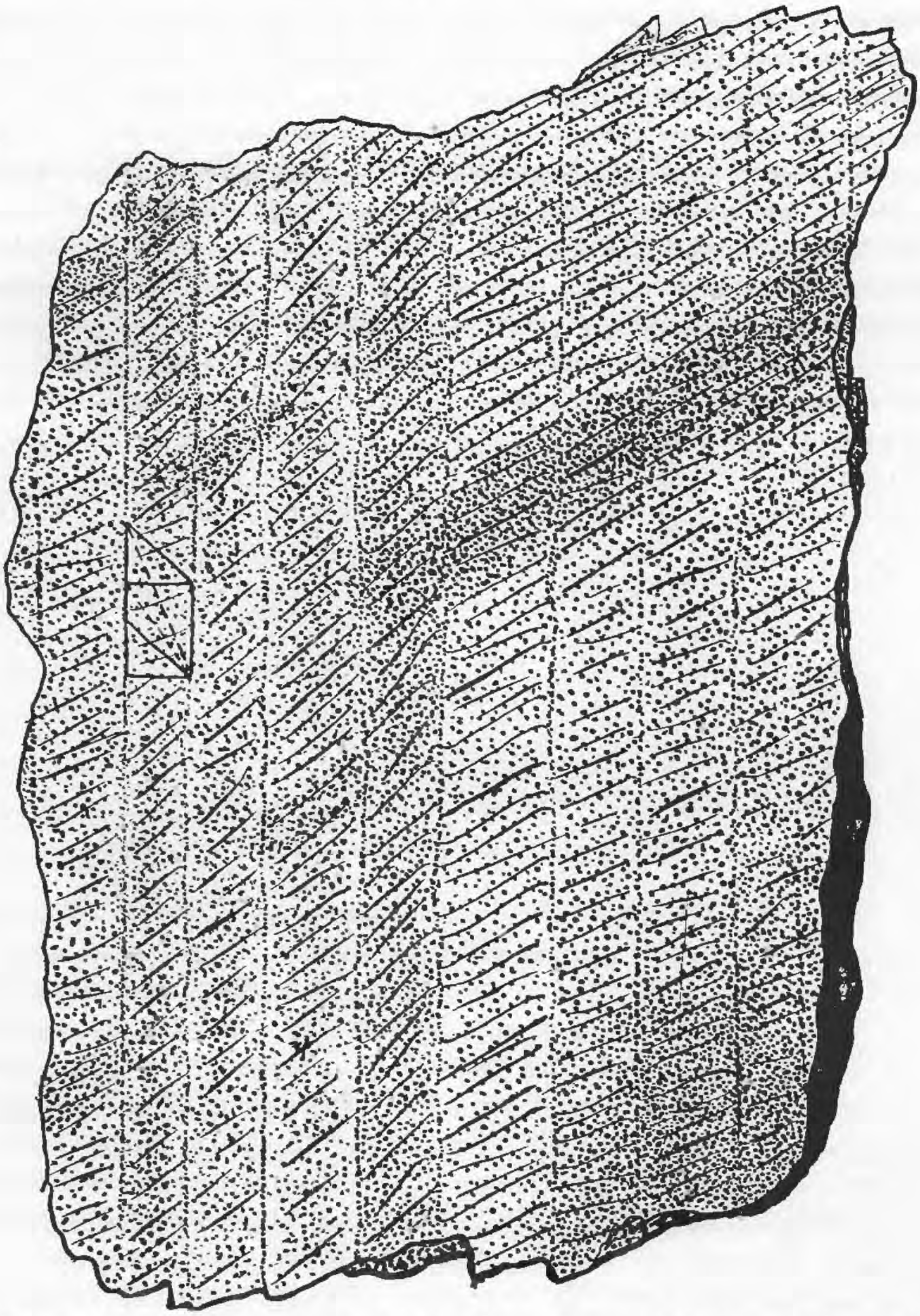


FIG. 152.—Diagonal fissility of quartzite beds of the north range of Baraboo. Looking east.

the foliated and truncated edges of the Archean and being composed wholly of detritus derived from it. All of these phenomena are found in some districts north and south of Lake Superior, but in some of the districts a part only have as yet been detected. As to the time represented by this unconformity, we have no definite knowledge, but it must have been great, since, whatever the origin of the rocks of the Archean, they were intricately folded, metamorphosed, intruded by various eruptives, and deeply truncated, before the Lower Huronian was deposited.

The unconformity between the Lower Huronian and the Upper Huronian is based upon the less crystalline character of the Upper Huronian as compared with the Lower Huronian, upon the very numerous contacts between the two, where discordance of bedding and basal conglomerates are found, and in some districts upon general field relations. The degree of crystallization would have but little weight alone, and it can be applied only in a broad way, for in certain areas in which the folding was intricate the Upper Huronian is more crystalline than is the Lower Huronian in other areas, so that in comparing the crystalline character of one with the other it must be in each case for the same locality. The contacts between the Upper Huronian and the Lower Huronian are found in scores of places. In some cases the formation below the Upper Huronian is a conglomerate, quartzite, quartz-schist, mica-slate, or mica-schist; in others a cherty limestone; in others the iron-bearing formation; and in

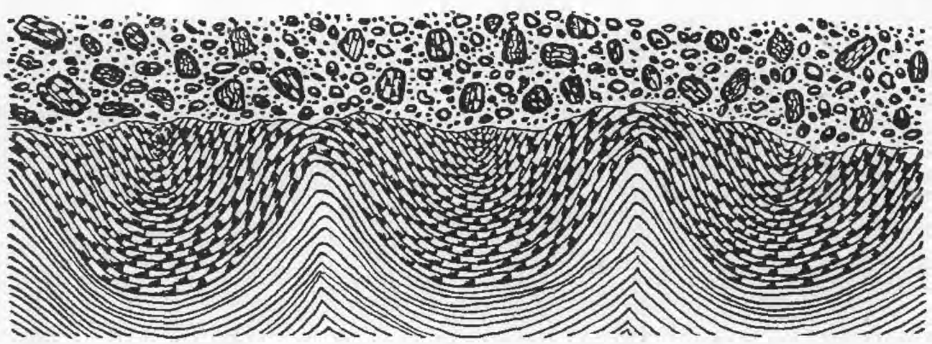


FIG. 153.—Chert-breccia, an autoclastic rock, resting upon truncated minor folds of limestone.

others the igneous rocks of the Lower Huronian. In other words, the inter-Huronian erosion cut to different depths, so that the basement formation of the Upper Huronian rests now upon one member of the Lower Huronian, now upon another. The most numerous contacts are between the Upper Huronian and the iron-bearing formation of the Lower Huronian. The predominant detritus of the basal conglomerate depends, of course, upon the formation with which it is in contact. The amount of discordance in bedding depends upon the closeness of the inter-Huronian folding. In some places the folding was so acute that the bands of jasper were plicated, and in this case the Upper Huronian beds cut those of the underlying jasper at any angle. The discrepancy varies from acute unconformity to but a slight discordance. The unconformity in the last case is discoverable only by the irregular erosion contacts and the basal conglomerate, rather than by discrepancy of strike and dip between the two series. In certain districts where the Lower Huronian is closely folded and the Upper Huronian gently folded, the field relations render the unconformity manifest. Where the Lower Huronian is entirely removed the Upper Huronian rests directly upon the Basement Complex or Archean (fig. 144). These series usually present glaring evidence of unconformity, nearly all the lines of proof being available in each district.

The unconformity between the Upper Huronian and the Keweenawan is based upon (1) broad field relations and (2) contacts. The folding of the Upper Huronian, while on a large scale, was, in the greater part of the region, in broad and simple rolls, so that while simple anticlinal mountains were raised and erosion removed a part or all of the Upper and Lower Huronian series, the formations of the Keweenawan were deposited with but little discrepancy in strike and dip. The discordance between the two was discovered by the fact that the basal parts of the Keweenawan in the same district here rest upon a high member of the Upper Huronian, there upon a low one, in other localities upon members of the Lower Huronian, and, finally, in other localities upon the various rocks of the Archean. This could occur only by the nondeposition of the higher members of the Huronian, or else by their removal between the time of the deposition of the Upper Huronian and Keweenawan time, and the latter is by far the more probable. This probability is made a certainty by the fact that at some localities erosion contacts are found between the two series.

The unconformity between the Keeweenawan and the Cambrian is based upon (1) general field relations, (2) difference in number of orogenic movements, (3) discordance of bedding, (4) basal conglomerates, and (5) relations with eruptives. The Cambrian is everywhere in a horizontal attitude or but slightly inclined, while the Keweenawan has dips which vary from 10° or 15° to as high as 90°, the higher inclinations chancing to be more common in the districts where the two series are together. These relations are due to the fact that the Keweenawan has suffered one orogenic movement, being folded into a great complex synclinorium, while the Cambrian is unfolded. Where the two series come in contact, as they do in many localities in northern Wisconsin, the horizontal Cambrian sandstone rests upon the inclined and truncated edges of the bedded lava flows of the Keweenawan. At these places basal conglomerates are very general. For many miles at various places on the south shore of Lake Superior the two series are contiguous, and the Keweenawan is everywhere interbedded with or cut by eruptives, which in no locality penetrate the Cambrian.

SECTION VIII.

THE GREAT NORTHERN REGION.

In the Great Northern region is included all of the vast area of pre-Cambrian rocks in the northern part of North America not heretofore considered. This area is as of great or greater magnitude than all other North American pre Cambrian areas, but as yet study of it has not gone beyond a reconnaissance. The Original Laurentian, Original

Huronian, and Lake Superior areas belong with this region, but because they have been somewhat carefully studied they are treated separately.

The Basement Complex or Archean occupies much the largest part of this vast region. So far as can be ascertained from the reconnaissance reports, this Basement Complex is in all essential respects like that described as occurring in the Original Huronian, Original Laurentian, and Lake Superior areas. All the varieties of rocks found in these areas occur here, and the different kinds have both the areal and the structural complexities already described. It appears probable that the orthoclase-gneiss, which is the predominant rock in the Original Laurentian district, also predominates in the vast northern region.

At many places within the expanse of Archean are belts varying in width from narrowness to many miles, consisting largely of sedimentary rocks. These sedimentary rocks vary in alteration from those which are merely consolidated to those which are transformed to crystalline schists. As in the Original Laurentian, Original Huronian, and Lake Superior areas, the sedimentary rocks are in many district closely associated with intrusive and extrusive, basic, intermediate, and acidic igneous rocks of many kinds.

For the most part it is impossible to give any definite lithological or structural account of the numerous districts in which these rocks have been mentioned as occurring. However, a little is known of the Hudson Bay district. At various areas about the bay fragmental rocks, such as sandstone, quartzite, shale, slate, slate-conglomerate, and limestone occur. These are associated with imperfect gneisses, a great variety of schists, and schistose and jaspery iron ores. According to Bell, above these rocks at Little Whale River and Richmond Gulf are formations consisting of beds of siliceous conglomerate, of red and gray sandstone, with some red shales. Unconformably overlying this intermediate series is the Manitonnuck series, which consists of argillaceous and siliceous limestones, sandstones, quartzites, shales, amygdaloids, basalts, and clay-ironstones. It thus appears probable that in the Hudson Bay region the Basement Complex and three series of pre-Cambrian clastics occur. This is the same number that are found in the Lake Superior region. The uppermost series of Hudson Bay is very similar to that of the Lake Superior Keweenawan, and in the two regions the lower two series have a somewhat general similarity. On the Copper Mine River and at Doobauly Lake occur traps, amygdaloids, and porphyries, associated with sandstones and conglomerates, constituting a series which are lithologically similar to the Keweenawan of Lake Superior.

Therefore, from the somewhat scanty information available as to the Great Northern Area of Canada, it may be considered as possible that the succession of series as worked out about Lake Superior and Lake Huron will be found to extend far to the north and west, perhaps covering the vast region which includes Hudson Bay, Copper Mine River, and Doobauly Lake.

At various localities in northeastern and eastern Canada are great areas of igneous rocks in all respects similar to the anorthosites of the Original Laurentian. Crystalline limestones are also found in certain of these districts in which anorthosites occur.

The succession which here obtains is possibly similar to that in the Original Laurentian district.

SECTION IX.

EASTERN CANADA.

In eastern Canada there are areas of pre-Cambrian rocks in the eastern townships, in the Gaspé Peninsula, in Central New Brunswick, in southern New Brunswick, in Cape Breton and northwestern Nova Scotia, and in southeastern Nova Scotia. Large areas of pre-Cambrian rocks also occur in Newfoundland. These areas are separated from one another and from the Great Northern Area of Canada by post-Algonkian rocks, and as they are devoid of fossils, there is no satisfactory basis upon which to make comparisons between them. The salient facts determined for each district will be independently summarized.

THE EASTERN TOWNSHIPS.

The eastern townships constitute the northeastward extension of the Green Mountains of Vermont, and occur in a long belt from the boundary between Vermont and Canada to north of the central part of the State of Maine. The oldest rocks found consist mostly of alternations of chloritic and micaceous schists and gneisses. Associated with these at various localities are slates, quartzites, and limestones. These have not been separated from the gneissic and schistose series, but they may be of later age. According to Ells, resting unconformably upon the gneissic and crystalline schist series is a set of semicrystalline schists. These comprise limestones, slates, sandstones, quartzites, quartziferous schist, and conglomerates, some of which are basal. The unconformity between this series and the crystalline series is based upon the presence of the basal conglomerates, upon the difference in crystalline character, and upon the sharply defined line either of overlap or fault between them. Both the crystalline and semicrystalline series are unconformably below Cambrian rocks bearing Olenellus fossils. The crystalline and semicrystalline rocks of the district are intruded by granites, diorites, and anorthosites, and volcanic rocks also occur.

No certain evidence is available as to the exact position which the above series of rocks occupies in the time scale. If the clastics closely associated with the crystalline schists belong to the same series, in all probability we have no rocks in this area older than the Algonkian. If, on the other hand, the associated clastics really belong with the unconformably overlying clastic series, the lowest rocks may be Archean. The semicrystalline series, although placed by Ells with the Lower Cambrian, because of its unconformity below the Olenellus Cambrian is believed to be Algonkian.

GASPÉ PENINSULA.

In the Shickshock Mountains, on the Gaspé Peninsula, are garnetiferous gneiss, hornblendic, chloritic, and micaceous schists, slates, limestones, and serpentine. Intruded in these rocks are found great masses of granite and dikes of trap newer than the Silurian or Devonian, as shown by inclosed fragments of these rocks. No attempt has been made to subdivide the rocks of this area into series. The character of the rocks mentioned makes it probable that Algonkian rocks occur here, and the Archean may also be represented.

CENTRAL NEW BRUNSWICK

In central New Brunswick are numerous areas of granites, gneisses, and schists, associated with other rocks which are plainly of sedimentary origin, including mica schists, quartzites, and slate. Felsites are also found. Granite, syenite, and diorite in certain places are intercalated with the sedimentary rocks, and in other places cut them. From the descriptions it appears clear that there are Algonkian rocks in this area. Whether crystalline rocks older than the Algonkian also exist can not be decided from the information available.

SOUTHERN NEW BRUNSWICK

Much has been written about the geology of southern New Brunswick, and detailed areal maps have been published. Yet the pre-Cambrian succession is not clear. As nearly as can be made out the order from the base upward is as follows: (1) Wholly crystalline granites, gneisses, syenites, diorites, and gabbros; (2) mica-schist, gneiss, quartzite, and limestone; (3) semicrystalline Coldbrook series, consisting of chlorite schists, black slates, shales, argillites, sandstones, conglomerates, diorites, amygdaloids, and other volcanics; (4) little altered Coastal and Kingston series, consisting of conglomerates, clay-slates, chloritic grits and schists, micaceous slate, shales, argillites, limestone, felsites, and diorites; (5) Lower Cambrian.

Some of the massive rocks at the base of the succession are intrusives, as shown by all of the phenomena characteristic of eruptive rocks, and some of them are probably as late as Carboniferous. It does not follow that the main masses of the gneissoid granite may not antedate the clastic series. At certain of the localities the gneisses associated with the granites are described as conformable with the limestone series. The phenomena are similar to those between the Grenville and Gneissic series in the Original Laurentian area, and they may be explained by obliterated unconformity, progressive metamorphism, or subsequent intrusion of the gneiss. Since it is unknown whether or not there are any rocks older than the oldest clastic series, it can not be stated whether the Archean or Basement Complex is represented in southern New Brunswick. Divisions 2, 3, and 4 belong to the Algonkian. The second and third divisions are said to be in conformity, the differences between them being mainly lithological, and especially the presence of volcanics in the Coldbrook series. Between the Coldbrook series and the Coastal and Kingston series there is a slight unconformity. Along the line of contact it is not uncommon to find coarse breccia-conglomerates, the fragments of which are derived from the felsites of the inferior series. Also the lower series has a steeper inclination. That there is a pronounced unconformity between the Coastal and Kingston series and the Lower Cambrian is agreed to by all.

NORTHWESTERN NOVA SCOTIA AND CAPE BRETON

In the area of northwestern Nova Scotia and Cape Breton is the following ascending succession, as given by Fletcher: (1) Syenites, gneisses, felsites, and quartzites; (2) George River series, consisting of crystalline limestone interstratified with mica-schist, quartzite, conglomerates, felsite, syenite, and diorite. By Fletcher and by Gilpin the George River series is regarded as resting unconformably upon the lower series. From the descriptions it is clear that some of the syenites and other massive rocks intrude the sedimentaries, but whether any older rocks than those of sedimentary origin are to be found in the region is undetermined. We conclude, therefore, that while the presence of Algonkian rocks has been demonstrated for this area, whether Archean rocks also occur is as yet unknown.

SOUTHEASTERN NOVA SCOTIA

In southeastern Nova Scotia is an area believed to be pre-Cambrian, occupying 6,000 or 7,000 square miles. The sedimentary rocks, which are estimated to have a thickness of 15,000 feet, consist of conglomerates, quartzites, clay slates, mica-slates, and mica-schists. The lower 11,000 feet is chiefly quartzite, and the upper 4,000 feet is a graphitic and ferruginous slate. These sedimentary rocks are intruded by great masses of granite, and adjacent to them, and due to their metamorphic influence, are the mica-slates and mica-schists. The slates and quartzites are folded into sharp undulations, and are cut by a regional slaty cleavage. In the more disturbed parts of the area the bedding is not easily recognized. In these slates occurs the fossil form which has been described as Eophyton.

The slates and quartzites are not found in any structural relations with the early fossiliferous rocks. Hence, so far as definite knowledge is concerned, they may be as late as Cambrian, but it is believed that the probability is strongly in favor of their Algonkian age. Bearing in this direction is the abundance of fossils in the Lower Cambrian of southern New Brunswick and in the Lower Cambrian of Newfoundland to the northeast. The extreme scarcity of fossils in the series in question renders it probable that they are older than the fossil-bearing Cambrian rocks of the same region. Also in Newfoundland the Lower

Cambrian rocks rest unconformably upon a great series of slates and quartzites, in most respects similar to the gold-bearing series of Nova Scotia. In Newfoundland these are certainly Algonkian, and it seems highly probable that the similar rocks in Nova Scotia were deposited at the same time, the two districts being parts of the same geological province.

NEWFOUNDLAND.

The rocks of Newfoundland are largely of pre-Cambrian age. The main area of Newfoundland has been but little studied, but the southeastern part, especially the Peninsula of Avalon, has been carefully mapped. At the base, and occupying much the largest area of pre-Cambrian in the main area of Newfoundland, are masses of syenites, granites, porphyries, and gneisses. At certain localities in this area graphitic crystalline limestones and anorthosite rocks are found. In the southeastern part of the main area of Newfoundland and on the Peninsula of Avalon a pre-Cambrian sedimentary series occupies most of the country. These are quartzites, slate-conglomerates, slates, and sandstones, with diorites. They may be called the Avalon series. The series was found by Murray to be over 11,000 feet thick. It is intruded by granite, syenite, porphyry, and trap, which occur interbanded with the sedimentary beds and cutting them. The latter are more abundant in the main area than on Avalon. Where the intrusive rocks occur the Avalon series is more than usually metamorphosed. These intrusions are particularly well seen in the area between Trinity and Bonavista bays. In the western part of the Peninsula of Avalon volcanic conglomerates and volcanic ashes occur. In the sedimentary series two fossils have been found, *Aspidella terranovica* and *Arenicolites spirales.*

The Avalon series is cut by a cleavage, the angle of which is usually steep, being never less than 45°, and the strike usually being parallel to the strike of the beds, but not invariably so. Resting unconformably upon the upturned and altered Avalon series are found the unaltered horizontal Olenellus Cambrian rocks.

As in New Brunswick and Nova Scotia, there is no clear evidence available as to the relations of the Avalon or other sedimentary series to the main areas of granitic and schistose rocks. It is certain that a portion of the granites and gneisses are intrusive in them, but it is not improbable that a close structural study would detect an older series of rock upon which the Avalon series was deposited. However, in the present state of knowledge, it can not be asserted that Archean rocks exist in Newfoundland, though this is highly probable. The Algonkian is, however, represented by the Avalon series, and also by the small series of limestones and associated rocks in the main area. Whether these and the Avalon rocks belong to the same or to different series is not determined.

In all probability the Avalon series, as explained on a previous page, is equivalent to the quartzites and slates of southeastern Nova Scotia. Both of these may be equivalent to one or both of the clastic series of southern New Brunswick. In degree of metamorphism and in the presence of volcanic rocks the areas are somewhat similar. However, this suggested correlation can be considered as no more than a possibility.

SECTION X.

ISOLATED AREAS IN THE MISSISSIPPI VALLEY.

In the Mississippi Valley pre-Cambrian rocks, surrounded by the fossiliferous series, are found in the Black Hills of South Dakota, in central Missouri, and in central Texas. As these are unconnected with one another and with the pre-Cambrian to the east and west, they are considered separately.

THE BLACK HILLS.

In the Black Hills is a great series of Algonkian rocks, composed chiefly of mica-slates, with quartzites, schist-conglomerates, and ferruginous chert, and smaller areas of mica schists and mica-gneisses of unknown although probably of great thickness. They extend over an oval area 60 miles long and 20 miles broad. These rocks are folded into close rolls, with north-south axial planes, and are cut by a regional cleavage which is usually nearly vertical. The ordinary metamorphism is believed to be largely due to the folding. The sedimentary rocks are cut by various masses of intrusive granite and basic rocks of Algonkian age, and also by later eruptives. The largest granite mass is 8 or 10 miles long and nearly as broad. A number of other masses are of considerable size. Adjacent to these batholites numerous large dikes of granite occur. In passing away from them dikes become less abundant and smaller in size, until they finally disappear. Close to the larger granite masses the dikes have typical granitic structures; farther away they grade into pegmatitic rocks, and these, by a lessening of the feldspar, grade into ordinary quartz veins, showing at places a banded structure. There can be little doubt that the dikes are dependent upon the batholites of granite. There is equally little doubt that the quartz veins are water impregnations. Between the two there appear to be gradations. (See pp. 686–688.) About the great batholites the sedimentary rocks are thoroughly crystalline, being transformed to mica-schists and mica-gneisses, with secondary structures parallel to the intrusive masses, and the original structures being destroyed. In places the mica-schists and mica-gneisses are thoroughly pegmatized. The zonal belt of schist passes by gradation into the ordinary cleaved slate of the district. Resting unconformably upon the deeply denuded edges of the Algonkian schists and granite is the nearly horizontal Potsdam sandstone. In degree of folding, character, and mineral composition the sedimentary rocks resemble in some respects the Lower Huronian of the Lake Superior region. The Black Hills afford one of the best instances known of the metamorphic effect of great intrusive masses of granite. The metamorphism is not contact metamorphism in the ordinary sense, but seems rather to combine cementation, injection, metasomatism, and mashing. The deep-seated mass of granite had an effect far beyond its border. This is probably explained by the radiating granite dikes and by the thermal waters, rich in solutions, produced in connection with the intrusive. Also the intrusion resulted in extended interior movement of the materials of the schists, and hence produced dynamic metamorphism. The production of peripheral cleavage parallel to an intrusive magma, and therefore normal to the pressure, is as finely illustrated here as anywhere in America.

MISSOURI.

In Missouri are a number of pre-Cambrian islands surrounded by Cambrian sediments. These consist mainly of granites, felsites, porphyries, and porphyritic breccias. Haworth describes gradations between the granitic and porphyritic rocks. At Pilot Knob and in the adjacent area are found water-deposited rocks, which comprise porphyry-conglomerates and the iron ores and associated rocks of Pilot Knob. The unaltered horizontal Cambrian rocks rest upon the deeply eroded pre-Cambrian igneous and sedimentary rocks.

There is, then, in central Missouri a pre-Cambrian clastic series, and, therefore, a member of the Algonkian system. Whether any of the crystalline rocks are older than the Algonkian there is no certain means of judging.

There are also no certain data upon which to parallelize this Algonkian series with series of the nearest pre-Cambrian region—that of Lake Superior. Upon the whole, the lithological character of the series more nearly resembles that of the Keweenawan than any other. This is indicated by the porphyries and porphyry-conglomerates. The parallelism is rather strengthened by the fact that the Upper Huronian quartzite outcrops of southern Wisconsin are associated with and cut by porphyries. But a reference of the Missouri rocks to either the Keweenawan or the Upper Huronian has a very uncertain value, and it is not impossible that it rather represents the period of erosion which separates the Keweenawan and Upper Huronian.

CENTRAL TEXAS

In Texas is a series of sedimentary rocks, named Llano by Walcott, which consists of alternating beds of shales, slates, sandstones, quartzites, limestones, ferruginous rocks, carbonaceous or graphitic schists, mica-schists, and chlorite-schists. There also occur in this area granites and gneisses, a part of which are placed as a separate system by Comstock, but which are regarded by Walcott as intrusive in the sedimentary rocks. Whether all of the granites or gneisses are intrusive or not, it is agreed by both that the clastic series are cut by numerous eruptives, both basic and acidic, of which granite is the most prominent. Comstock also divides the sedimentary rocks into two series, between which he believes there is an unconformity. Resting unconformably upon the deeply eroded pre-Cambrian are the Potsdam Cambrian rocks.

It is clear that in Texas there is one, and possibly two, series of Algonkian rocks, but whether the Archean is also represented is as yet undetermined. The sedimentary rocks of the Texas area have been correlated by Walcott and Comstock with the Algonkian of the Grand Canyon region.

INDIAN TERRITORY

In the Indian Territory is an extensive area of granite, called by Hill the Tishomingo granite, which appears to be of pre-Paleozoic age, but whether Archean or Algonkian is undetermined.

SECTION XI.

THE CORDILLERAS.

In the mountain systems of the western part of the United States to which the term Cordilleras is applied are many great areas of pre-Cambrian rocks. The axial cores of the majority of the mountain ranges are composed of ancient rocks, although in certain districts they are of more recent, igneous origin. The more important areas in which pre-Cambrian rocks are known to occur are as follows: In Wyoming are the Laramie, Medicine Bow, Park, Big Horn, Rattle Snake, Sweetwater, Wind River, Gros Ventre, Wyoming, and Teton ranges. The central and southwestern parts of Montana and the adjacent parts of Wyoming, Idaho, and British Columbia are mainly occupied by great areas of pre-Cambrian rocks. In Utah and Nevada are the Uinta and Wasatch mountains, and numerous Basin Ranges, among which are the Promontory, Fremont Island, Antelope Island, Oquirrh, Aqui, Raft River, Ibenpah, Ombe, Gosi-Ute, Schell Creek, Washoe, Pequob, Egan, Franklin Butte, Humboldt, Seetoya, Piñon, Cortez, Wah-weah, Toyabe, Shoshone, Fish Creek, Havallah, Augusta, Pah-ute, West Humboldt, Montezuma, Pah-tson, Pah-supp, Pogonip, Snake, Sahwave, Truckee, Granite, Lake, and Peavine ranges. In Colorado and northern New Mexico are the Front, Wet, Sangre de Christo, Park, Sawatch, Elk, and Uncompahgre ranges, and areas along the canyons of the Grand and Gunnison rivers. In Arizona and western New Mexico are the Buro, Pimaleno, Apache, Pinal, Colorado, Black, Virgin, Granite, Santa Rita, Sandia, Zuni, Music, and other ranges, and areas along the Grand Canyon of the Colorado. In the many ranges of California, Oregon, Washington, and British Columbia, crystalline rocks occur, and in certain areas these appear to be of pre-Cambrian age. The only area in North America south of the United States in which possible pre-Cambrian rocks have been reported is in Guatemala.

In the majority of the Basin Ranges and in the Wet, Sangre de Christo, and Elk mountains the rocks consist mainly of granite, but in some ranges syenite, diorite, and gabbro occur. The more important Basin Ranges in which the rocks are mainly massive are as follows: Laramie, Rattle Snake, Oquirrh, Aqui, Raft River, Ibenpah, Ombe, Gosi-Ute, Schell Creek, Washoe, Pequob, Egan, Franklin Butte, Seetoya, Piñon, Cortez, Wah-weah, Toyabe, Fish Creek, Havallah, Augusta, Pah-Ute, Pah-supp, Pogonip, Sah-wave, Granite, Wet, Sangre de Christo, and Elk ranges. The core rocks of these ranges have been classified as Archean, but in some cases there is evidence that they are post-Cambrian eruptives. In each of the remaining areas listed there is a great variety of crystalline rocks, including massive and schistose kinds, having all the intricate lithological and structural characteristics of the Archean. The more important of these are as follows: Medicine Bow, Park, Big Horn, Rattle Snake, Sweetwater, Wind River, Gros Ventre, Wyoming, Teton, Uinta, Wasatch, Promontory, Antelope and Fremont islands, Humboldt, Shoshone, West Humboldt, Montezuma, Pah-tson, Truckee, Lake, Peavine, Front, Sawatch, and Uncompahgre ranges, central and southwestern Montana, with adjacent parts of Wyoming, Idaho, and British Columbia, and the canyons of the Grand and Gunnison rivers.

In a number of the above cases the complex referred to the Archean rests below a series of pre-Cambrian sedimentary rocks, which in turn are overlain by the Paleozoic. In some instances the pre-Cambrian clastics are unconformably above the Archean, and in others appear to grade into it. The pre-Cambrian clastics in some instances are unconformably below the Cambrian, and in others are conformable with it. The massive rocks of the Archean are granites, syenites, diorites, gabbros, and other igneous rocks, the acidic varieties being by far the more abundant, and being the core rocks of many ranges. The predominant schistose rocks are gneissoid granite, but finer-grained schists are abundant. In numerous cases the massive rocks are clearly intrusive within the schistose ones, while in other cases there are undoubted gradations between them, due to dynamic action. For instance, at many places granites are traced step by step into gneissoid granites, these into well-laminated gneisses, and these into fissile schists. Perhaps most frequently in passing from the schistose to the granitic rocks there first appear in the schist thin belts of gneiss, which become more and more prominent, until the rock is predominantly a gneiss, and thus by imperceptible stages passes into a granitoid gneiss, then into a granite. A part or a whole of the laminated rocks may be cut by granite veins, while oftentimes there are considerable masses of granite in the schists of the same character as the main granite mass, the contacts being exceedingly sharp. Also in the massive granites not infrequently fragment-like areas of the schists occur. Such relations show that at least a portion of the granite is intrusive, but they do not decide the question as to how much of the gneissoid granite is more ancient than the associated schistose rocks. To fully describe the Basement Complex would be but to repeat the general characterization given at the beginning of Part II, and so like in essential characteristics are rocks of each of the ranges which are certainly Archean that a description of one would be but a description of most of the others. Therefore those ranges in which Archean rocks only are known will not be further described.

However, at various places, besides the Archean, Algonkian rocks are present, and these districts will be separately treated. The areas in which Algonkian rocks probably or certainly occur are as follows: The Medicine Bow range in Wyoming; large areas in southwestern Montana and in British Columbia; in Utah, the Uinta, and Wasatch mountains, Promontory Ridge, Antelope and Fremont islands, and the Aqui Mountains; in Nevada, Schell Creek, Egan, Pogonip, and Piñon ranges; in Colorado, the Front range, Sawatch range, and Uncompahgre Mountains; in Arizona, the Grand Canyon district; and in Guatemala.

MEDICINE BOW MOUNTAINS

The larger part of the Medicine Bow Mountains is an intricate basement complex of Archean rocks. However, in the area of Medicine and Mill peaks a clastic series occurs. This consists from the base up of slates and slate-conglomerates bearing granite pebbles, above which are thick layers of quartzite, and above these are cherts and cherty limestones. These rocks appear to be in isoclinal folds overturned toward the west. The conglomerates are much mashed and the quartzites approach quartz-schists. On the east side of the mountain, one finds, in passing from the Archean toward the Algonkian, that the granite becomes less plentiful and the gneiss more laminated, grading into banded gneiss, which appears to change by imperceptible stages into fine-grained green schist, and finally into black slate. On the west side, at the base of the sedimentary series, are found the slate-conglomerates which bear granite pebbles. It is believed that the facts are best explained by regarding the Medicine Bow series as unconformably upon the Archean. The apparent gradations are on the east side of a fold with an eastward-dipping axial plane. Therefore the junction between the two series is here a horizon of great accommodation, and one where the sedimentary rocks were rendered crystalline. A parallel schistose structure was produced both in the sedimentary rocks and in the Archean. On the west side, however, where the shearing was less intense, the clastic character of the series is still discoverable.

If the above interpretation is correct, the Medicine Bow range affords another locality in which there is apparently complete gradation between a sedimentary and a crystalline series. If the facts of the gradation were taken by themselves they would be explained by some geologists as proof of the intrusive character of the gneissoid granite in the Algonkian; by others they would be taken as evidence of the progressive metamorphism of the Algonkian rocks into the Archean. But it has been seen that the more probable explanation is that the two are really unconformable, but have been mashed and metamorphosed until there is gradation between the two and conformity of secondary structures.

SOUTHWESTERN MONTANA

In southwestern Montana the predominant rocks are, as usual, those of the Basement Complex, or Archean. The gneissoid granite of this system is magnificently exposed in the canyon of the Madison. Here the banded gneissoid granite, cut by granitic and basic rocks, has a foliation in the same direction for many miles (fig. 154). A suggested explanation of the phenomenon is given on pages 664–668. Associated with the Archean gneisses along Cherry Creek on the west side of the Madison River is an area, 8 miles long and 4 miles wide, which consists of crystalline limestones, mica-schists, quartz-schists, and gneisses, very highly inclined. This may be called the Cherry Creek series. So far as seen, the structure of the series is conformable with the lamination of the gneiss and granite. The truncated edges of all the above are traversed by the little-disturbed Cambrian. Besides this clastic series there is in southwestern Montana, along the East Gallatin River, in the canyon of Jefferson River, in the Bridger range, and in the Little Belt Mountains, a great thickness of sedimentary rocks, called the Belt series, which rests upon the Archean unconformably. This series in the Bridger range has a thickness of 5,000 or 6,000 feet, and in the Little Belt Mountains is estimated by Davis to have a thickness of from 10,000 to 15,000 feet. It consists mainly of micaceous slates, micaceous sandstones, and conglomerates. Near its base at the East Gallatin River bands of siliceous limestone occur. Resting conformably upon the top of the series is a hard, persistent belt of quartzite 100 to 150 feet in thickness. This is called the Flathead quartzite. Conformably above this quartzite is a limestone, which carries a Cambrian fauna. Peale states that while there is no unconformity between the Flathead quartzite and the Belt series, there was an important epeirogenic movement between the two, the entire area of the Three Forks sheet being submerged at this time.

The completely crystalline sedimentary rocks of Cherry Creek clearly belong to the Algonkian. As these are described as inseparable from the Archean gneisses, we have no certain evidence as to their real relations. The district has not been closely enough studied to ascertain whether the gradation is real or apparent. In these relations we have the same problem as in so many other regions. The apparent conformity of the Cherry Creek series and the Archean may in the future be explained by any one of three hypotheses: obliterated unconformity, downward metamorphism, or intrusion of the gneissic series.

While the Cherry Creek Algonkian is not anywhere in contact with the Belt series, its extreme metamorphism and common structure with the Archean gneisses make it highly probable that it is unconformably

FIG. 154.—Regularly laminated gneissoid granite of Madison Canyon.

below the Belt series, since the latter rests upon the truncated edges of the Archean gneiss. As to the age of the Belt series, nothing definite can be said, for no fossils have been found in it.

In this series we have a problem of correlation somewhat different from that of any area before considered. A set of clastic rocks bearing Cambrian fossils passes conformably downward into a great series of rocks devoid of fossils, which from their lithological characters ought to contain an abundant fauna. Repeated search for fossils has been made by skilled paleontologists in the area, and in other areas correlated with the Belt series, but always without success. It is possible that in the future a fauna will be carried down through this series of rocks. Such a fauna may prove to be Cambrian, or it may so change in character as to be properly called a pre-Cambrian fauna. Lacking definite evidence, and considering the fact that the pre-Cambrian sedimentary rocks are so generally devoid of abundant fossil remains, it has seemed to me that it is somewhat more likely that the Belt and equivalent series in this region will prove to be Algonkian rather than Cambrian.

Occupying a position similar to that of the Belt series are great series of sedimentary rocks in the Uinta Mountains, in the Wasatch Mountains, and in British Columbia. These in all probability are contemporaneous with the Belt series, and together mark a continuous area of deposition, and therefore a geological province, in early Cambrian or late Algonkian time

BRITISH COLUMBIA

In British Columbia the basal rocks are granites, gneisses, and mica-schists. These are said by Dawson to be overlain conformably by a great series consisting of argillites, argillite-schists, quartzites, conglomerates, and some limestone. In the Bow River district, in the upper part of this series the Olenellus fauna is found, and thus there seems to be a conformable gradation from the Olenellus Cambrian to the basal rocks. It appears highly probable that the great thickness of sedimentary rocks, or a part of them, below the Olenellus Cambrian is equivalent in age to the Belt series of southwestern Montana, and is therefore probably of Algonkian age. Whether the lower crystalline rocks belong with this series, are unconformably below them, or are igneous rocks intrusive within the sedimentary series, is undetermined. Therefore, as yet it can not be asserted that the Archean is represented in this region, although this is probable.

THE UINTA MOUNTAINS

In the Uinta Mountains the basal rocks comprise a small area along Red Creek Canyon. They consist of intricately folded, white, gneissoid granites, cut by dikes of basic eruptives, now changed to hornblende-gneiss. The whole was intricately folded after the intrusion of the basic rocks and before the Uinta series was deposited, producing complicated secondary structures and plications. This basement complex is referred to the Archean. Resting upon its truncated edges and occupying a large part of the area of the Uinta uplift is a great series of sedimentary rocks, estimated by Powell to be 12,500 feet thick, and called the Uinta series. This series consists of shales, red sandstones, and quartzites. The whole is exceedingly ferruginous, and contains seams of clay-ironstone. While much time was spent by Powell in the search for fossils, none were found. Resting unconformably upon the Uinta sandstone, with an intervening erosion sufficient to carry away at least 3,000 feet of strata, is the Lodore formation, belonging to the

Carboniferous. On account of the absence of fossils, and because unconformably below the Carboniferous and unconformably above the Archean, it is thought to be most probable that the Uinta series is to be correlated with the Belt series of Montana, and that it is therefore probably of Algonkian age. However, there is no definite proof that it may not be Cambrian or Silurian.

THE WASATCH MOUNTAINS

In the Wasatch Mountains the typical granite gneiss-schist Basement Complex constitutes a broad belt in the northern part of the area. The schists and gneisses are cut by pegmatitic granite veins in the most irregular manner. For instance, in the lower part of Saw Mill Canyon the Archean is a series of schists. In going up the canyon granite begins to appear, cutting the schists, and becomes more and more prominent, until it is the most abundant material. It is here exceedingly coarse, and the whole appearance is that of an intrusive which has cut the schists and gneisses by numerous apophyses.

Resting unconformably upon this Archean complex is a great series of sedimentary rocks. These consist of mica-slates, mica schists, argillite, and intercalated siliceous schists, 800 feet thick; and above these is a great quartzite formation 12,000 feet in thickness. Conformably above the quartzite are 250 feet of shales, which according to Walcott contain Olenellus fauna. Walcott says that this lower series, although in a most excellent condition for affording fossils, did not reveal any. The pre-Olenellus series may be called the Wasatch series. The Wasatch series is rather gently folded, although the dips are sometimes steep. The metamorphism of the rocks is largely by consolidation and cementation, although the quartzites everywhere show the effects of orogenic movements, and in places approach quartz-schists.

In the southern part of the Wasatch area, in the Little Cottonwood district, is a great mass of white, laminated granite, the lamination being due to the parallel arrangement of many of the mineral particles. This granite has been regarded by certain geologists as constituting the basement upon which the Cambrian was deposited, while others have regarded it as intrusive within the Paleozoic.

However this may be, we have the Archean in typical development in this region, and a great series of sedimentary rocks in a position exactly similar to the Belt series in southwestern Montana, and which are therefore doubtless equivalent to them, and probably belong with the Algonkian.

PROMONTORY RIDGE, FREMONT ISLAND, AND ANTELOPE ISLAND.

In the range composed of Promontory Ridge and Fremont and Antelope islands the Archean rocks occur in typical development. Resting on these, according to Hague, is a conformable series of quartzites and mica-schists containing a zone of calcareous sandstones and several beds of limestone, the whole estimated to be 3,800 feet in thickness. No fossils are found in these rocks, and they are presumably the equivalent of the Wasatch series, and are therefore probably Algonkian.

THE AQUI MOUNTAINS.

In the Aqui Mountains is a granitic core which is presumably Archean. Resting upon this granite is a series of quartzites 6,000 feet thick, containing beds of conglomerate with argillaceous schists and imperfect mica-schists. This series, on account of its great thickness and the absence of fossils, was correlated with the Wasatch series by Emmons, and if this correlation is true it is probably Algonkian.

SCHELL CREEK, EGAN, POGONIP, AND PIÑON RANGES.

The Schell Creek, Egan, Pogonip, and Piñon ranges are given by the King survey as among those in which the Archean is mainly granitic. Resting unconformably upon this granite are quartzites, several thousand feet in thickness, which are conformable below the Olenellus Cambrian. These rocks are therefore probably equivalent to the Wasatch series, and may with plausibility be referred to the Algonkian.

In the Schell Creek range the probable Algonkian is represented by heavy bodies of quartzite. In the Egan range the probable Algonkian is represented by a series of thoroughly vitrified quartzites several thousand feet thick, containing quartzitic and micaceous schists. In the Pogonip range it is represented by micaceous, arenaceous, and argillaceous slates and shales and by vitreous quartzite, the series being of undetermined thickness. In the Piñon range it is represented by quartzites underlain by mica-schists and quartzitic schists, having a total thickness of 5,000 feet.

FRONT RANGE OF COLORADO.

By far the greater portion of the Front Range of Colorado is composed of the typical Basement Complex, or Archean, and intrusive granites. In the central part of the range gneissoid granites are predominant, but in some places along the eastern border this gneissoid granite varies into a great series of completely crystalline schists. Taking schistose structure for bedding, King estimated the thickness of the series at Clear Creek to be 25,000 feet. However, the structure is, without doubt, foliation, and the figure given only serves to show the extent of the schistose area.

In the district of Coal, Boulder, and Thompson creeks, on the east side of the range, is a narrow belt of mica-schists, quartzites, quartz-schists, and schist-conglomerates, containing abundant pebbles of white quartz and fewer of gneissoid granite, the thickness being unknown; but if foliation corresponds to bedding this thickness has a maximum of at least 1,000 feet. The clastic character of this series is unmistakable. The higher members of the series are quartz-schists alone, but in passing downward mica-schists and quartz-schists are interstratified with beds of conglomerate. At the base the mica schists become interlaminated with gneiss, which rock becomes more and more abundant, and upon Coal Creek pegmatitic granite veins cut them. Nowhere between the clastic and gneissoid series has any discordance been discovered, there appearing to be a somewhat rapid gradation between them. The series has been subjected to such intense dynamic action as to almost entirely obliterate the clastic characters, with the exception of the schist-conglomerates, and even in these the matrix is a completely crystalline schist, the only unmistakable evidence of the sedimentary character being the greatly mashed and flattened pebbles. This clastic series is unconformably overlain by the Triassic. As in other districts of the Front range, little-metamorphosed Cambrian rocks are found resting discordantly upon the Archean and the crystalline schists associated with them. It is believed that this border series is of Algonkian age.

In this locality we have therefore another case of apparent gradation between the Archean and the Algonkian. It is believed to be most probable, however, that there is a real unconformity between them. This is indicated by the horizon of schist-conglomerate near the base of the series, and by the fact that the mica-schists below this conglomerate are cut by abundant pegmatitic granite veins which do not penetrate the Algonkian sediments.

In the Pikes Peak district Cross describes very numerous masses of quartzite included in and cut by granite. The largest of these, in Wilson Park, is 4,000 feet thick, stands on edge, and is exposed for 5 miles along the strike. Other large masses occur in Cooper and Blue mountains. These quartzites and the intersecting granite, which occupies a far greater area than the quartzites, Cross refers to the Algonkian.

THE SAWATCH RANGE

In the Sawatch range the Archean, or Basement Complex, again occurs in all its typical complexity. Near Salida, Cross describes a volcanic series of hornblendic, micaceous, and chloritic schists of great thickness, which are cut by granitic and pegmatitic veins as well as by dikes of porphyry. At Marshall Pass what is thought to be a continuation of these hornblende schists is found. At Tin Cup and Tin Cup Pass, interbedded with the green schists and fine-grained gneissoid rocks, is a highly crystalline marble, showing that metamorphosed sedimentary rocks occur among the crystalline schists of the Sawatch range. This series rests unconformably below the Cambrian, but the relations to the Archean have not been determined. From the facts observed, Cross concludes that the schists and massive rocks of the Salida area are a series of Algonkian lavas.

UNCOMPAHGRE MOUNTAINS

In the Uncompahgre Mountains the usual typical Basement Complex occurs. The red and white gneissoid granite is cut by or interlaminated with numerous black bands of hornblende-gneiss, which occur in dike-like forms. In the Quartzite Mountains is a large area composed of rather pure vitreous quartzite, in places conglomeratic, and occasionally showing more or less of a slaty appearance. In this quartzite dikes of hornblende-gneiss are nowhere found. The quartzite is somewhat closely folded, the dips being usually high. Very considerable dynamic metamorphism attended this folding, quartzites and conglomerates being transformed to semicrystalline schistose quartzites and schist-conglomerates. As this series occurs in typical development along the Rio Animas, it may be called the Animas series. In the Animas section there is no evidence of a transition between the quartzite series and the Basement Complex on either side of the quartzite area. In both of these localities the two series were found a few paces apart. At the southern boundary there is a marked discordance in the strike and dip of the schistose structure of the gneissoid granite and a set of beds of quartzite adjacent to it which are in sharp anticlines and synclines.

South of Ouray, along Red Mountain Creek and along one of the branches of the Uncompahgre, is also exposed a great series of slates, quartzites, and conglomerates, which in lithological character is identical with the clastic series of the Quartzite Mountains. The formations are repeated by close folding. These rocks may be called the Red Creek series. Just south of Ouray the Juratrias is found in an almost horizontal position upon the truncated edges of the slates and quartzites. This unconformity, in the distance at which it may be observed and the mass of rocks exposed, is most striking. Conformably below the Juratrias at Ouray is the Carboniferous. Hence the semicrystalline clastic series is certainly unconformably below the Carboniferous. As the Cambrian rocks, wherever they occur in this southwestern region, are unfolded and are conformable with the Carboniferous, it is certain that the Animas and Red Creek series are pre-Cambrian. Also these series are almost certainly unconformably above the Archean. This is indicated by their relations where found near together, and by the fact that the numerous dikes which cut the Archean nowhere penetrate the sedimentary series. Therefore the series are regarded as Algonkian. These series of clastic rocks are far from the sedimentaries of the Grand Canyon region, and are also a great distance from those of the Wasatch region. They may be equivalent with the Algonkian of either of the latter regions or of both of them. If the latter should prove to be the case, the Algonkian sea, which included southwestern Montana, part of British Columbia, the Uintas and the Wasatch, and the eastern portion of the Basin Ranges, must have extended far south to the Quartzite Mountains and the Grand Canyon of the Colorado.

THE GRAND CANYON OF THE COLORADO

Walcott gives the following in reference to the Grand Canyon of the Colorado: At the base is the Archean. On the north side of the Grand Canyon south of Vishnu's Temple is a set of micaceous schists and quartzites, cut by granite, which is called the Vishnu terrane, and is doubtfully referred to the Algonkian. Resting with a great unconformity upon the Vishnu is the Grand Canyon series, 11,950 feet thick. The Grand Canyon series is divided into two terranes: the Unkar, 6,830 feet thick, and the Chuar, 5,120 feet thick.

The Unkar series consists of sandstones and limestones interstratified with basalts, and has at its base a conglomerate composed largely of pebbles derived from the upturned edges of the pre-Unkar strata. Resting upon the Unkar terrane with a slight unconformity is the Chuar terrane. It consists of shales, sandstones, shaly limestones, and limestones. In the middle of the lower portion of the shales and limestones of the Chuar terrane is a sparse fauna, consisting of a minute discinoid or patelloid shell, a small lingula-like shell (which may be a species of Hyolithes), and a fragment of what appears to be the pleural lobe of a segment of a trilobite belonging to a genus allied to the genus Olenellus, Olenoides, or Paradoxides. There is also a Stromatopora-like form that is probably organic. Resting with a great unconformity upon the Chuar is the Tonto or Middle Cambrian sandstone. During the time represented by this unconformity the sediments of the Grand Canyon series were elevated, faulted, somewhat flexed, and eroded, so that the entire series was cut through, and the area, including the more resistant Vishnu terrane, was base-leveled. The length of time required by this unconformity is believed to be longer than the period of Lower Cambrian sedimentation, and the Grand Canyon series is therefore placed in the Algonkian. The Grand Canyon series has lithological analogies with the Keweenawan of Lake Superior and the Llano series of Texas, but there is no certain evidence, in the absence of fossils, by which it can be equated with either.

The fauna of the Chuar terrane, although so meager, furnishes the largest number of fossils yet found in any pre-Cambrian series. While not sufficient to give a basis for correlation, it gives legitimate hope that a more satisfactory pre-Cambrian fauna may be found in the future.

GUATEMALA.

Sapper describes and maps considerable areas of Azoic formations in Guatemala.[1] The lowest formations are gneiss and the higher formations are mica-schists and phyllites, associated with which are crystalline limestones, actinolite-schists, and quartzites. Closely connected with these schistose rocks are ancient eruptive rocks, including granite, gabbro, diabase, etc. Whether these Azoic formations are pre-Paleozoic or not can not as yet be asserted. If they are pre-Cambrian the Algonkian is certainly, and the Archean possibly, represented in this State.

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[1] Grundzuge der physikalischen Geographie von Guatemala, by Carl Sapper. J. Perthes Geog Anstalt, Erganzungsheft Nr 113, 1894, pp 5–6 With 4 maps

SECTION XII.

THE EASTERN UNITED STATES.

In the eastern part of the United States are great areas of semicrystalline and holocrystalline rocks, which vary in age from the Archean to the end of the Paleozoic. Included in this great complex are the larger parts of the States of Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut, considerable parts of New York, New Jersey, Pennsylvania, and Maryland, and a broad belt, in greatest width more than 100 miles, in the southern Appalachians and the Piedmont Plateau, and running through the States of Virginia, western North Carolina, eastern Tennessee, western South Carolina, northern Georgia, and northeastern Alabama. These rocks have all been called Archean, using Archean to include the Laurentian and Huronian as these terms were formerly applied.

However, wherever areas have been closely studied it has been ascertained that this great complex of crystalline and semicrystalline rocks must be distributed from the Archean to the Paleozoic. Lithologically the rocks comprise almost every variety of semi-metamorphosed and completely metamorphosed sedimentary rocks; igneous rocks of the greatest variety and abundance, basic, intermediate, and acidic, plutonic and volcanic, the latter including both lava flows and tuffs; and many varieties of crystalline schists of undetermined origin. The igneous and metamorphosed sedimentary rocks vary in age from the Archean to the Carboniferous. Williams recently strongly emphasized the great variety and abundance of these volcanic rocks, which he traced from Maine to Alabama. Many of them have heretofore been regarded as metamorphosed sedimentary rocks. Great batholites of granite of Paleozoic age are also known to be intrusive in the sedimentary rocks. Emerson has described in detail those which occur in the central part of Massachusetts. In places these granites are cut by coarse-grained granites which are apparently of later age. About the batholites are zones of mica-schists, which have been produced from argillites. The most intense metamorphism next to that of the granite is marked by the development of muscovite, hornblende, and feldspar, the next zone by staurolite and garnet, and the outer zone by fibrolite and chiastolite.

As the present state of knowledge of this great eastern area of partly or wholly crystalline rocks is so imperfect, it is impossible to give any satisfactory account of the region as a whole, or of considerable parts of it. At present it therefore seems best to confine definite statements to a few small areas which have been accurately mapped, and the stratigraphy of which has been unraveled.

Within the eastern region are illustrated all of the principles of pre-Cambrian North American geology given in Part I, and many of them at various points. No attempt will here be made to recapitulate them, but it may be said that the Appalachian system shows as well as any mountain system in the world the general tendency which sometimes prevails for the formation of monoclinal folds, and, in the crystalline areas, of uniformly dipping cleavage. (See pp. 664–668.) The axial planes of the folds and the cleavage very generally dip to the southeast. Over extensive areas the inclination is so great as to form overturned folds, and where overturned folds do not occur it is very generally true that the northwest limbs are steeper than the southeast ones.

GREEN MOUNTAINS OF VERMONT

Recent close work by Whittle in the Green Mountains of Vermont apparently justifies the following statements, which are summarized from his results: The lowest rocks described are Algonkian, which are divided into two series, in ascending order called the Mount Holly series and the Mendon series. Above the Mendon series is a Lower Cambrian quartzite.

The structure of the Mount Holly series is so complicated, the different rock types vary so greatly, and the series has been subjected to such a multiplicity of orogenic movements, that no definite stratigraphy has been made out. Some of the prominent rocks of the series are biotite-schist, muscovite-schist, garnetiferous schist, vitreous quartzite, augen-gneiss, and various kinds of limestone. The limestones are in irregular lenses, and are extremely local. There may be two horizons of limestone or a dozen. The series, because of the undoubted areas of sedimentary rocks which have escaped destruction, are regarded as clastic. Associated with the above rocks are very abundant schistose igneous rocks, comprising both dikes and sheets.

The Mendon series consists, in descending order, of the following members. Mica-schist, with a maximum thickness of 1,000 feet; micaceous quartzite, having a maximum thickness of 500 feet and carrying several thin beds of crystalline limestone; crystalline limestone, with a maximum thickness of 400 feet; conglomerate-schists and quartzite, with a maximum thickness of 700 feet. At Mendon the section has an approximate thickness of 1,300 feet, and in some localities there may be 2,000 feet of strata in the series.

The Mount Holly and Mendon series are regarded as unconformable for the following reasons: Between the two there is great lithological difference; the Mount Holly series has been cut through by eruptive rocks in a complicated fashion, and these do not occur in the Mendon series; the Mount Holly series is folded in a much more intricate manner than the Mendon series, and secondary structures have developed to a far greater degree; at the bottom of the Mount Holly series is a widespread formation of conglomerates and gneiss. The schistosity of the two series is parallel, but this is regarded as due to disintegration before the Mendon series was deposited and to post-Mendon folding.

That the Mendon series and the Lower Cambrian quartzite, although apparently conformable, are really unconformable, is supported by the following reasons, among others: The extreme lithological diversity of

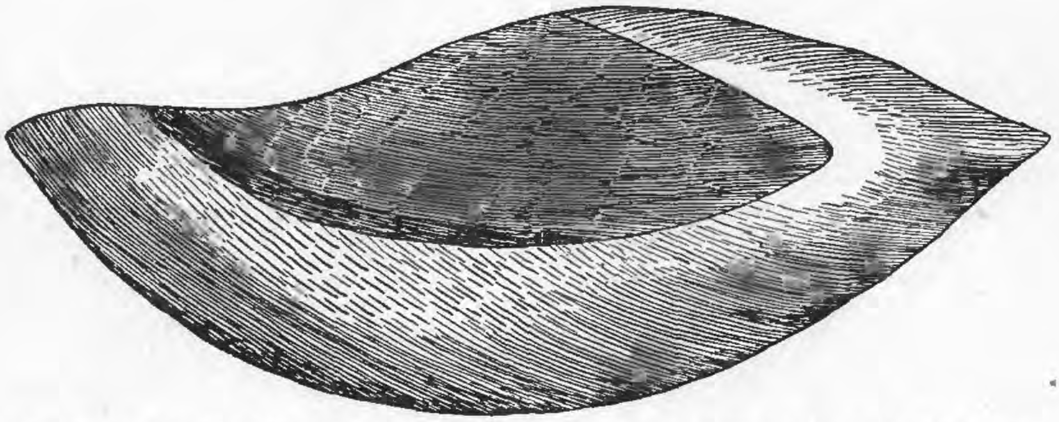


FIG. 155.—Indented pebble from schist-conglomerate; from Plymouth, Vt. After Hitchcock.

the Mendon series as compared with the quartzite; a close folding in the Mendon series not observed in the quartzite; and the fact that the quartzite reposes discordantly upon granitoid gneiss to the southward.

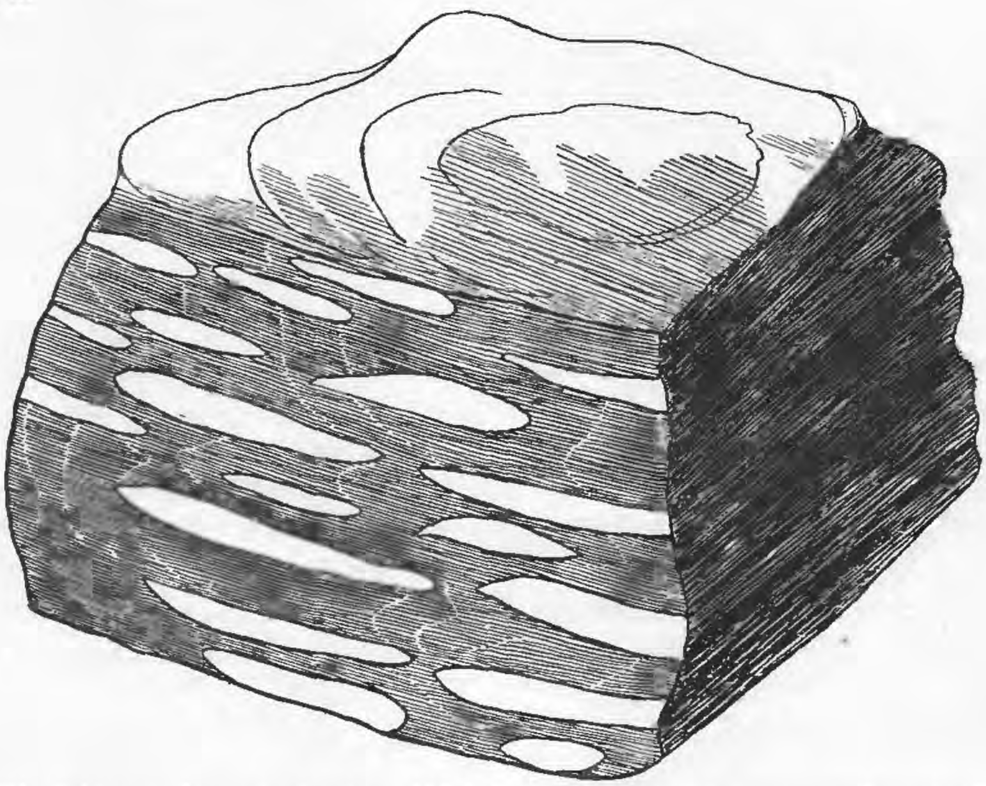


FIG. 156.—Schist-conglomerate, showing pebbled character when cut transverse to the major direction of elongation and gneissoid character when cut in other directions; from Plymouth, Vt. After Hitchcock.

The main axis of the Green Mountains is described as a series of sharply compressed folds striking approximately north and south and overturned to the west in most localities, so that induced schistosity and stratification dip eastward.

The Green Mountains are of great interest in geology as furnishing one of the first published instances (1861) of complete proof of the development of a crystalline schist from a fragmental rock. Hitchcock described at Plymouth a schist-conglomerate in which the pebbles are elongated very much in the direction of their strike. He says they are flattened, but not so strikingly as elongated; they are indented deeply into one another (fig. 155); they are sometimes a good deal bent; they are cut across by parallel joints and fissures. At times the process has gone so far as to merge the pebbles together so that they scarcely present the appearance of ordinary pebbles. If the conglomerate-schist is looked at on the edge corresponding to the dip, nothing is seen but alternate folia of quartz and mica, and the rock would be pronounced a good example of a mica-schist (fig. 156). But a fracture at right angles reveals the flattened pebbles and shows that their edges are what have been regarded as folia. If the process of flattening had been carried a little further no evidence would remain that they were ever pebbles.

WESTERN MASSACHUSETTS

Although in former years nearly all of the Green Mountain area of Massachusetts was placed in the Laurentian or Huronian divisions of the Archean, under the old usage of these terms, recent study has shown that only isolated patches of pre-Cambrian rocks occur in the area. The following information is kindly furnished me by Prof. B. K. Emerson. The succession is given from the top downward:

(1) Washington gneiss. This is a rusty, highly crushed, saccharoidal rock. Besides quartz and orthoclase it contains biotite, muscovite, and allanite. Interspersed laminæ of blue quartz are also seen. These apparently formed after the mashing of the rock.

(2) Tyringham gneiss. This is a highly mashed biotite-gneiss.

(3) East Lea gneiss. This is a heavy, black, hornblendic rock, immediately underlying the Hinsdale limestone.

(4) Hinsdale limestone. This is a coarsely crystalline rock, containing chondrodite, phlogopite, and coccolite.

(5) Hinsdale gneiss. This is a coarse, porphyritic, epidotic, and allanitic gneiss, in which microcline is abundant and some blue quartz is found. In many places it is much mashed.

These pre-Cambrian rocks are known in 13 areas in western Massachusetts, as follows: The Clarksburg Mountain area, the Hoosac Mountain area, the Hinsdale Township area, the Colesbrook Township area, the Tyringham Township area, the Bear Mountain area, 6 small areas in New Marlboro Township, and the Hartland area of Connecticut, which extends into Tolland Township, Mass.

Since the granitoid gneiss of these various areas is of similar lithological character, and since the Hinsdale limestone is presumably of sedimentary origin, Emerson tentatively places the whole in the Algonkian system.

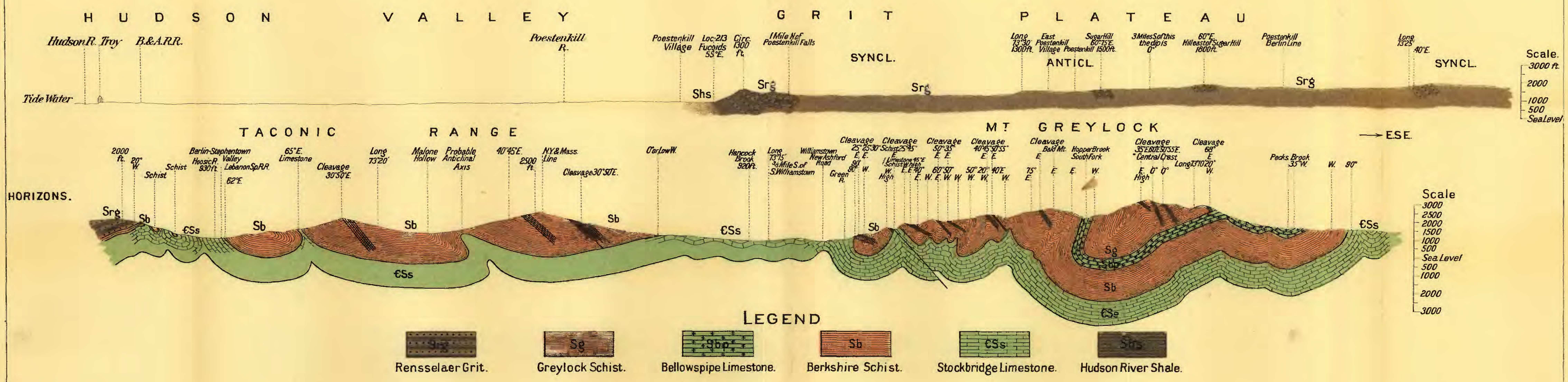
Resting with conformable secondary structures upon the pre-Cambrian rocks of this district are great thicknesses of completely crystalline Cambrian, Silurian, and Devonian rocks, which include gneiss, quartzite, limestone, and schist. In occasional areas of relief, as at the top of Hoosac Mountain and at the brook south of the Dalton Mountain club-house on the old Hinsdale-Dalton road, the basal formation is a quartzite-conglomerate which bears numerous fragments of the underlying gneissoid granite. This quartzite-conglomerate, and the fact that a basic dike was discovered which cuts the granitoid gneiss, but stops abruptly at the quartzite, the quartzite sagging down into its place, showing that it had been disintegrated before the deposition of the quartzite, are considered by Pumpelly as definite proof of an unconformity between the Hoosac granitoid gneiss and the Cambrian quartzite.

That the Algonkian is represented in western Massachusetts is made highly probable by the crystalline limestone, but it does not follow that all of the gneissoid granite is of the same age. Much of it may be Archean. The unconformity at the base of the Cambrian was discovered with the greatest difficulty, and even if two unconformable series exist within the pre-Cambrian this might not be discovered with the present state of knowledge. It seems safer to place in the Algonkian only the pre-Paleozoic rocks, which are certainly of sedimentary origin, and to call the others pre-Cambrian (see pp. 714, 765).

It is beyond the scope of this paper to consider the succession of the crystalline Paleozoic rocks of Massachusetts. The district is, however, one of great interest as illustrating the principles of Part I as fully as any in North America. In working out its structure important contributions to these principles were made and others of them were exemplified. Some of the more important of the principles illustrated are as follows:

In general the rocks of the district when deformed were in the zone of combined fracture and flexure, although some of the deeper-seated granitoid gneisses constituting the core rocks may have been in the zone of flexure and flowage only. On account of the very great difference in the depth of burying and of the different resisting powers, the softer formations yielded mainly by flexure, while the harder formations yielded largely by fracture. In many cases certain formations as a whole obeyed the law of flexure, while in a minute way they were fractured through and through.

The published sections of the district show the folds to be composite and complex. The complex folds in cross-section, if taken in a large way, are found to be normal anticlinoria and synclinoria. As an illustration of this may be mentioned the great anticlinorium extending from the east flank of Mount Greylock across the Green River to the west side of the Taconic range, the structure of which was worked out by Dale (Pl. CXVI). The Green River Valley is the center of the anti-



GENERAL SECTION RENSSELAER PLATEAU, TACONIC RANGE & MT. GREYLOCK,

From the East Foot of the Greylock, Mass. to the Hudson Valley at Poestenkill.

by T. Nelson Dale

Natural Scale $\frac{1}{62.500}$. 1 inch = 1 mile.

clinorium, Mount Greylock being a synclinorium of the second order upon the eastern flank of the great primary anticlinorium, while the Taconic Mountains are another synclinorium upon the western flank of the same. The axial planes of the secondary folds of Mount Greylock, as compared with the axial planes of the secondary folds of the Taconic range, diverge upward and converge downward. Carrying the section still farther east (fig. 157), the Greylock folds and the secondary folds on the west side of Hoosac Mountain may be considered as a normal synclinorium, the axial planes on the opposite sides of the synclinorium converging upward and diverging downward. If Hoosac Mountain be taken by itself, and the secondary folds on its flanks making a part of the synclinorium be considered as a part of the Hoosac anticlinorium, the folds are again in a normal position and Hoosac Mountain is a normal anticlinorium. In the sections secondary folds are not figured as occurring on the eastern flank of Hoosac Mountain. As another illustration of a normal anticlinorium may be mentioned Mount Washington, of Massachusetts, the structure of which has been worked out by Hobbs. The central section is a typical normal anticlinorium (fig. 158).

Fig. 157.—Transverse section through Greylock and Hoosac mountains. After Pumpelly.

Fig. 158.—Cross-section of Mount Washington, Mass. After Hobbs.

These composite folds are also complex, the transverse folding in some cases being rather severe. This cross-folding is well illustrated by Hoosac Mountain, by Greylock Mountain, and by Mount Washington, and perhaps best of all by the flexures of the Riga schist, worked out by Hobbs (fig. 159). At many localities folds of many orders may be seen, from the greatest anticlinorium mentioned, the Green River anticlinorium, to microscopic plications. On any of the mountains above mentioned the different orders of folds may be well observed.

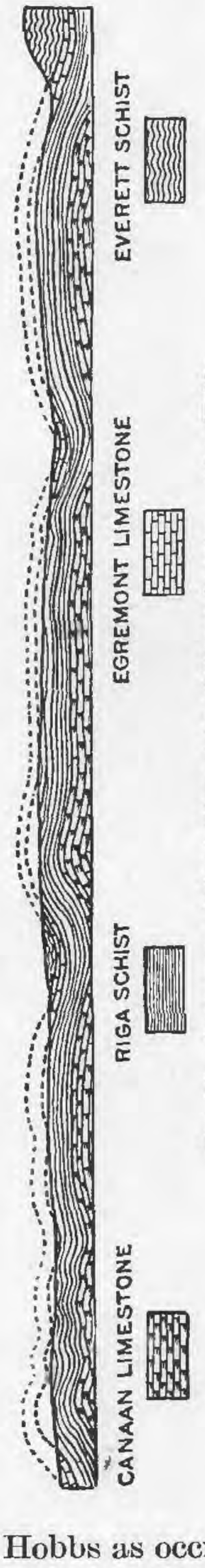
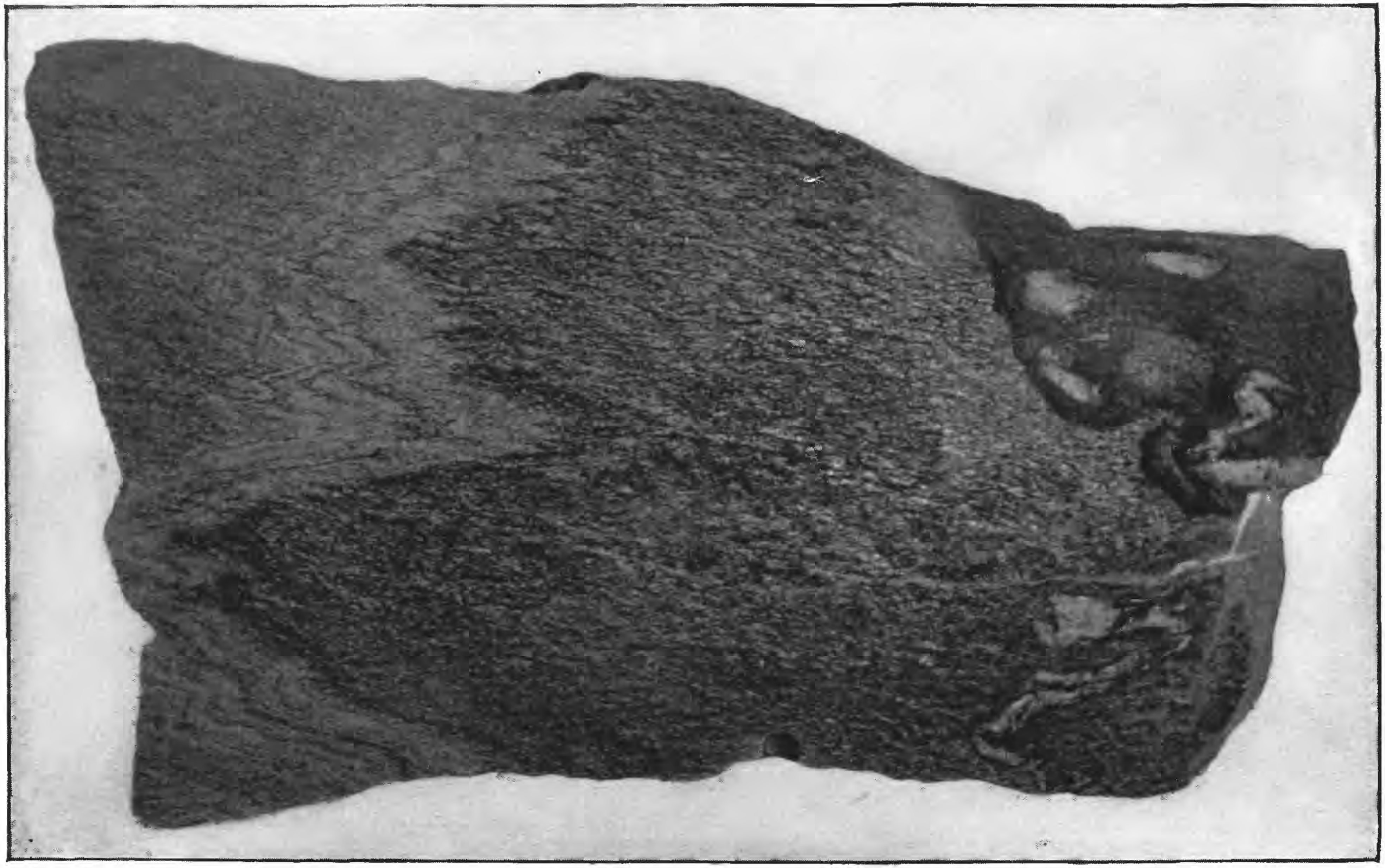


FIG. 159.—Transverse folds of Riga schist of Massachusetts. After Hobbs.

The rules for the working out of the structure of complexly folded districts are fully exemplified. At the north and south ends of Hoosac Mountain and south of Clarksburg Mountain, because of the cross folding, transverse strikes characteristic of pitching folds may be found (fig. 160). The folding of the Riga schist (fig. 159) shows the advantage of examination of the crests of ridges. The low ground at the north and south ends of Hoosac and Greylock and the south end of Clarksburg Mountain illustrate the cross topographic breaks which are likely to occur in districts which are complexly folded. In the schists of Greylock Mountain the discordance between the strike of cleavage and the strike of bedding may be observed. On the flanks of Washington, Hoosac, and Greylock mountains are found many minor folds, the degree and direction of the pitch of which correspond with the major folds.

The obliteration of unconformity by folding is nicely illustrated at Hoosac Mountain upon the flanks of the fold. The structure of the granitoid gneiss and that of the Cambrian quartzite are identical, and one appears to grade into the other; and yet on the crest of the anticline, which is an area of little differential movement, there is, as has already been said, complete evidence of unconformity.

Nearly all of the relations described between cleavage and fissility and the original structures and their different methods of production are illustrated at many localities in this district. Many of these have been described by Dale, others by Hobbs. Dale has especially illustrated fault-slip cleavage, or, as it is here called, fissility (figs. 161, 162; see also figs. 90 and 91, Dale, in previous paper, pp. 563–564). The modification of the secondary structures by infiltration, thus producing banding, has been described by Hobbs as occurring at Searles quarry in a gneiss (Pl. CXVII), and by Dale, in a slate. The Searles gneiss is at the bottom of a syncline, where the primary and secondary structures are likely to be found cutting each other, while upon the legs of the fold a short distance away the two



BANDED GNEISS NEAR HOPKINS-SEARLES MARBLE QUARRY AT GREAT BARRINGTON, MASSACHUSETTS

The plicated layers are probably beds, and these are cut by the secondary banding Photograph by Hobbs.

structures are in accordance. The relations of faults to fissility or slip cleavage are well illustrated by the accordance of the fissility with the *repeated faults in the Housatonic Valley, described by Hobbs.*[1]

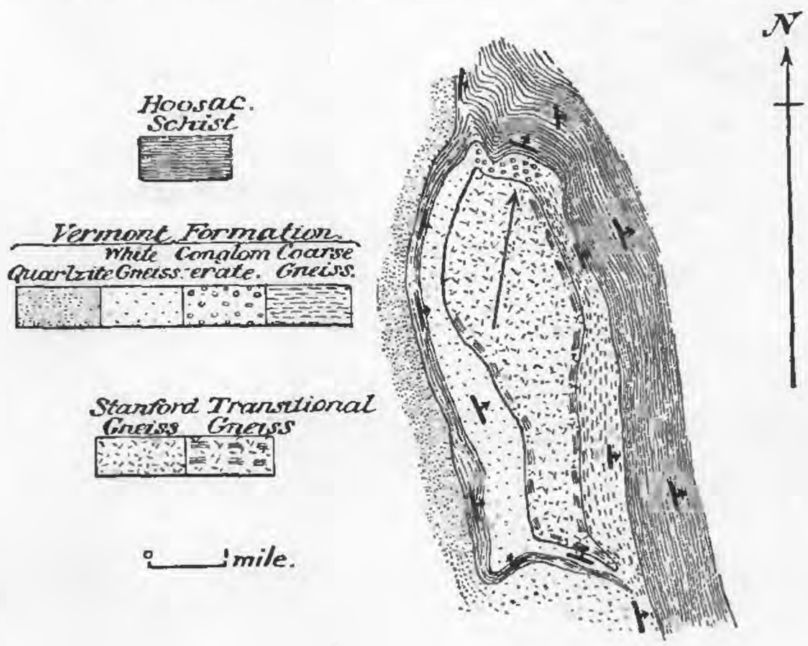


FIG. 160.—Map showing the transverse strike at the ends of the pitching folds at Hoosac Mountain. After Pumpelly.

All of the processes of metamorphism of sedimentary rocks are well illustrated in the various districts. They have been described with particular fullness of the areas of Hoosac, Greylock, and Washington

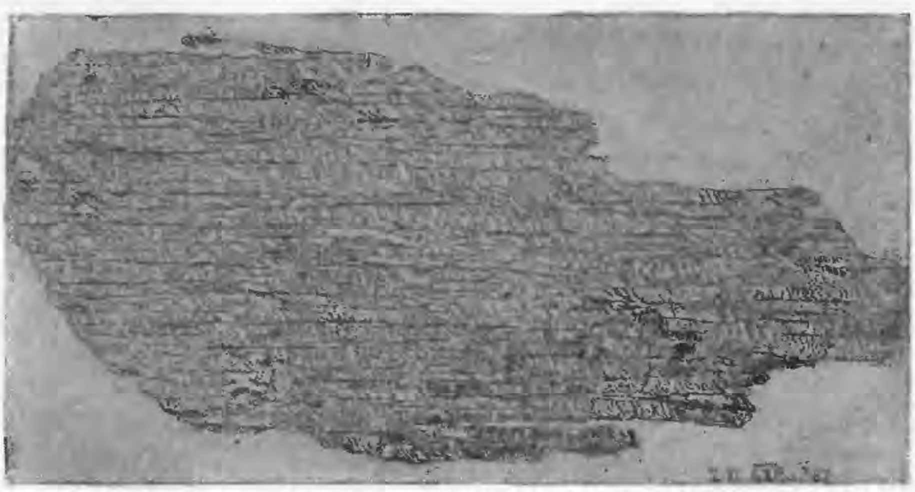


FIG. 161.—Thin section showing cross fissility in Greylock schist. After Dale.

mountains and of the Housatonic Valley. To point out in detail the particular localities in which each principle is illustrated, and in what manner it is illustrated, would very greatly extend this paper.

[1] The Geological Structure of the Housatonic Valley, by William H. Hobbs, Jour. of Geol., Vol. I, pp. 780-802, especially Pl. VI, p. 789.

SOUTHEASTERN NEW YORK.

In southeastern New York the following summary has been kindly furnished me by Mr. F. J. H. Merrill:

The crystalline rocks of southeastern New York occur in Dutchess, Putnam, Westchester, and New York counties east of the Hudson River, and in Orange and Rockland counties on the west of that river. The lowest rock in this district is a coarse hornblende-granite, which forms the central axis of the range of mountains known as the "Highlands of the Hudson." On the flanks of these granite masses, which are probably intrusives of great age, are laminated biotitic and hornblendic gneisses, consisting chiefly of quartz and orthoclase feldspar.

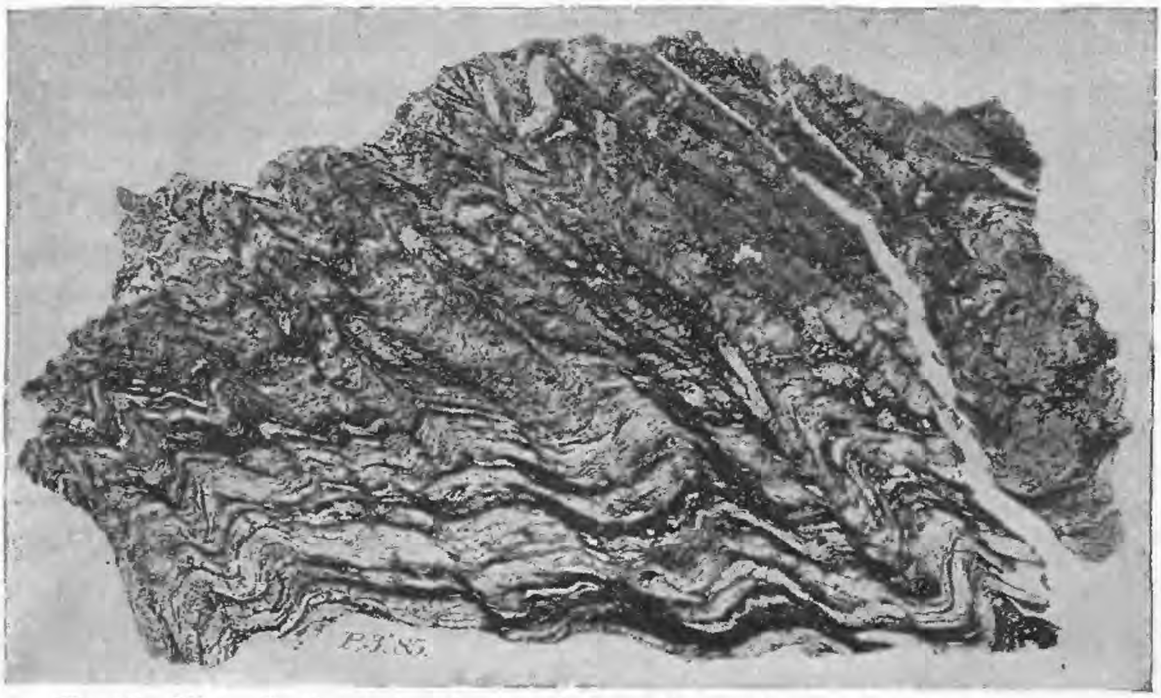


FIG. 162.—Minor plications in trough of Greylock syncline cut by cross fissility. After Dale.

These gneisses contain numerous masses of magnetic iron ore. They are probably of pre-Cambrian age.

On the northern slope of the "Highlands" these gneisses at many places in Dutchess County are overlain unconformably by a basal quartzite, which is believed to be of Lower Cambrian age. The quartzite is bordered by Ordovician limestone, and over this are schists or slates. To the southward, in Westchester and New York counties, the old gneissoid granite, which has been called the Fordham gneiss, is found in anticlinal folds trending northeast and southwest. This is overlain by two formations, limestone and mica-gneiss. These occur in synclines between the anticlinal ridges. Beneath the limestone is a thin layer of quartzite, rarely exceeding a foot in thickness, which may be regarded as the base of the Paleozoic in this district. The limestone designated the Inwood limestone is dolomitic, and in general is highly metamorphosed, coarsely crystalline, and at many places contains silicates. At most localities it exceeds 1,000 feet in thickness. The overlying mica-gneiss, called the Manhattan gneiss, differs in general from the lower gneisses in the great abundance of mica, garnet, staurolite, fibrolite, and cyanite are frequent accessories.

The relations of the basal quartzite, Inwood limestone, and Manhattan gneiss to the Fordham gneiss are precisely similar to those of the Paleozoic strata in Dutchess County to the subjacent gneiss. It is therefore inferred that the Inwood limestone and Manhattan gneiss are equivalent to corresponding rocks in Dutchess County. The age of the limestone there has been determined, by the work of W. B. Dwight and others, to be Calciferous-Trenton. The overlying schists and the micaceous gneisses are presumed to be of Hudson River age.

Besides the old granite first mentioned, there are within the district numerous eruptive rocks of considerable areal importance. Red granite intersects the older gneiss at various points from Sing Sing southward, and at Sing Sing it cuts the overlying limestone. In Yonkers Township is a large area of reddish gneissoid granite, which is surrounded by the Fordham gneiss, and may be regarded as a portion of the red granite above mentioned.

The Manhattan gneisses have been especially subjected to igneous intrusions, and within their area occur the Cortland series of diorites and norites described by J. D. Dana and George H. Williams. In the town of Harrison are extensive outcrops of mica-diorite, and near Port Chester and New Rochelle are areas of serpentine, which is evidently an altered plutonic rock. Serpentines also occur on Staten Island and at Hoboken. In Eastchester and Westchester townships the schists are divided by domes and bosses of gray granite, and in this area they are almost everywhere injected with veins, lenses, and dikes of pegmatite, amphibolite, and pyroxenite.

In a synclinal valley of the "Highlands" which crosses the Hudson River a little below West Point is a crystalline limestone associated with the gneisses, and containing magnesian silicates. These have been hydrated at many points and converted into serpentine, which appears in irregular masses in the limestone. The age of this limestone has not been determined.

In a general way, I have studied the rocks of Manhattan Island and vicinity. Their folding is of the most complicated character. The synclines and anticlines are highly composite, having folds of a second order upon those of the first, and upon these those of the third order, and so on to microscopic plications. In some places the secondary anticlinoria and synclinoria are overturned or recumbent. Moreover, the folding is highly complex, since the longitudinal folds are transversely folded, giving pitches in places as high as 60° or 80°, but ordinarily having lower pitches, in some places not exceeding 18° or 20°. The pitch of the folds is shown by innumerable minor plications. As a consequence of the pitch the Inwood limestone wraps about the ends of the areas of the Fordham gneiss at various places, and at such places a depression is sure to occur. Thus the principle of the relations of complex folds and topographic cross-breaks is beautifully illustrated. In some places such topographic breaks occur even where the limestone is now absent, the cross valley apparently having first formed upon the limestone. Subsequent erosion removed the limestone, so that the valley is now upon the gneiss, and in such cases the minor folds of the Fordham gneiss may be seen to pitch on either side toward the cross valley. The schistosity of the Manhattan gneiss accords very nearly with bedding upon the limbs of the folds, but upon the crests and troughs nearly vertical schistosity may be seen to intersect the minor folds of the minutely plicated bedding layers of the gneiss.

It is plain from the foregoing that this district is one of the best known in which to study the principles of highly complex folding and the relations of primary and secondary structures.

The Manhattan formation gives one of the best illustrations in America of a gneiss partly of aqueous and partly of igneous origin. About New Rochelle on the west end of Long Island Sound and certainly for a considerable distance east along the Sound the Manhattan schist is much injected by granite. This granite occurs in large domes, in veins and in dikes, and in parallel injections interlaminated with the schist, oftentimes a score occurring within a few inches. In many places this injection is so close as to change the rock from the ordinary Manhattan schist to a regularly banded gneiss. In other places the parallel bands of granite are wider, varying to several feet across. Some ledges are almost wholly of granite, containing little included schist, while others are almost wholly of schist, having been but little injected by granite. In the places in which the parallel injection is the closest the Manhattan schist to a remarkable degree simulates the appearance of the Fordham gneiss, which is of unknown origin. While this is true, there are certain differences, even when the two are most alike. In the Manhattan there is an abundance of mica and the characteristic minute lamination, while the Fordham has everywhere a certain density and uniformity which the Manhattan lacks. We thus have in this area a gneissic rock partly of sedimentary and partly of igneous origin, and in certain areas it is very difficult indeed to discriminate the metamorphic igneous from the metamorphic sedimentary material.

THE HIGHLANDS OF NEW JERSEY

The relations of the gneissoid granites and gneisses of the Highlands of New Jersey to the Potsdam sandstone are such as to make it certain that between them there is a great structural break. The rocks of the area consist largely of granitoid gneiss, in general very nearly massive, but having a laminated arrangement of the mineral constituents. The strike of the lamination conforms closely with the trend of the area as a whole, being east of north and south of west. The gneisses over large areas are graphitic. Interlaminated with them are beds of iron ore and apparently beds of crystalline limestone. They are cut by various basic and acidic eruptives.

The weight of opinion in former years has been in favor of the sedimentary origin of this gneissic series. Nason, who has recently been closely studying the limestones of New Jersey, finds that some of the white crystalline limestones which have been regarded as Archean grade into the blue limestones which are fossiliferous. Others insist that some of the white limestones belong with the gneisses. If all of these limestones were excluded from the pre-Cambrian, and this is a very doubtful assumption, the widely disseminated graphite and the magnetic iron ore would still remain as indications of the sedimentary origin of the Highland area. Magnetite is widely associated with certain belts of the gneisses of New Jersey, but this and its concentration in lenticular masses within the gneisses in the form of magnetite can hardly be considered as decisive evidence of their sedimentary character. The magnetites associated with the basal gabbros of the Lake Superior Keweenawan are in purely igneous rocks. The graphite of the graphitic gneiss is a point of more weight. The absence of graphite as an important constituent over large areas in any gneiss definitely determined to have been derived from granite, bears in favor of the sedimentary origin of the gneissic series. Recent studies by Wolff give further evidence for the view that the series is a sedimentary one. He finds that the rocks in the vicinity of Hibernia consist of distinct bands of gneiss. These layers were once nearly horizontal, and are folded into an anticlinal dome which has the characteristics of ordinary folds, and has a distinctly recognizable pitch. The rocks of the series have a top and bottom, the latter being at the center of the dome and the top ones at the periphery. One characteristic horizon, a garnet-biotite-graphite gneiss, must once have existed over a large part of the present area, and the same is probably true of the lower horizons.

If the Highland gneiss proves to be a sediment, it more nearly approaches a mashed eruptive than any other metamorphic sedimentary rock known. Upon the whole, in the regularity of its lamination, in its lack of extreme contortion and foliation, and in the presence of graphite, the Highland gneiss is not like the genuine Archean of Canada and the West. However, there are no certain criteria upon which it can be referred either to the Algonkian or to the Archean, although the weight of evidence is in favor of the former.

SOUTH MOUNTAIN OF PENNSYLVANIA

As shown by the recent work of Walcott, Williams, and Miss Bascom, the oldest rocks in South Mountain of Pennsylvania are felsites and basalts, the former being predominant. Both of these vary from compact to amygdaloidal, and are accompanied by tuffs and breccias.

The volcanics have been extensively transformed into slates and schists by dynamic action. These are unconformably overlain by quartzite-conglomerates and sandstones, or by shales, which bear the Olenellus fauna.

It therefore follows that the volcanic series of South Mountain is pre-Cambrian, although as yet no evidence is available to give the series a more definite place than this, and it may be Algonkian or Archean.

THE PIEDMONT PLATEAU OF MARYLAND

The structure of the Piedmont Plateau of Maryland, as given by Williams, is as follows.—The rocks composing the plateau are divisible into two classes, an eastern holocrystalline division and a western semicrystalline division. The rocks of the holocrystalline division comprise gabbro, peridotite or pyroxenite, and granite—all certainly eruptive—and gneiss, marble, and quartz-schist—all completely crystalline, and therefore exhibiting no certain traces of clastic structure. The gneiss is the prevailing rock. The eruptive rocks are intrusive in the gneiss, marble, and quartz-schist. The highly crystalline marbles are of the same age as the gneisses, and are infolded with them. The gneiss everywhere shows intense and repeated folding. Where the granites have been greatly foliated by the dynamic action, and are associated with gneisses, it becomes difficult to discriminate between them.

The western division of semicrystalline rocks consists of sandstones, slates, sericite-schists, limestone, and marble. At their western margin they are little altered, and have the same character as the sandstones, slates, and limestones of the Blue Ridge, of which they are believed to be the metamorphosed equivalents. The Blue Ridge sedimentary rocks have been determined by fossils to be of Paleozoic age.

The schistosity of the rocks of the Piedmont Plateau has a radiating or fan-like structure. The axial plane of the fan is diagonal to the boundary between the crystalline and semicrystalline rocks. The axis of the fan is throughout in the semicrystalline rocks, the western flank being made up of the least crystalline and the eastern flank of the most crystalline portion of the Piedmont district.

As to the age of the eastern or holocrystalline series Dr. Williams was inclined to believe it to be Algonkian on account of the presence of crystalline limestones. While it seems probable that there are Algonkian rocks in this crystalline complex, it can not be said to be at all certain that Archean rocks do not here also exist. The folding is so complex and metamorphism is so intense that it is difficult to everywhere discriminate between the gneiss supposed to be of sedimentary origin and the granite, which in its typical form is certainly of igneous origin. In the same way a clastic series of which the limestones are a part may be infolded with a more ancient Archean series.

THE BLUE RIDGE OF THE POTOMAC RIVER

The core rocks of the Blue Ridge where crossed by the Potomac River and in the adjacent areas of Maryland and Virginia, as described by Keith, consist of a rock called the Catoctin schist, which is intruded by granite, quartz-porphyry, and andesite. The Catoctin schist is an altered basic volcanic rock which varies in structure from rather massive to thoroughly schistose and from dense to amygdaloidal. Extensive areas of this schist are intruded in the most intricate manner by the granite. The schist is also intruded by rarer areas of quartz-porphyry and by andesite. The whole has been subjected to the most intense dynamic action, which in many places has transformed the eruptive basic rock and the granite alike to a completely crystalline schist. Keith's descriptions show that the deformation developing schistosity in connection with folding, and in the more rigid beds the deformation of faulting combined with folding, are well illustrated.

The whole of the Blue Ridge pre-Cambrian is referred to the Algonkian by Keith, but as there are no sedimentary rocks associated with the igneous series of the Potomac River, we have no certain evidence as to whether it is Archean or Algonkian. It therefore seems wiser at the present state of knowledge to assign it a place no closer than the pre-Cambrian.

THE SOUTHEASTERN AREA.

It has already been stated that in the Southern States is a belt of semicrystalline and holocrystalline rocks, in its broader parts 100 miles wide, including the Piedmont Plateau and a part of the Southern Appalachians, and running from northern Virginia to northeastern Alabama. All of the rocks of this area were regarded by the earlier geologists as pre-Cambrian, and by various writers have been distributed between the Huronian and the Laurentian. A closer study has shown, just as in the Northern Appalachians and in New England, that this complex mass of rocks probably varies in age from the Archean to the Paleozoic. As yet no maps or reports have been published of sufficient accuracy so that the stratigraphy can be said to be determined.

However, in making a cross-section of the plateau and the Appalachians at almost any locality, one finds belts of rocks which are alternately completely crystalline and semicrystalline. The completely crystalline areas consist mainly of gneissoid granite, with a great variety of other rocks. These include massive rocks, such as granite, syenite, gabbro, and diabase; and schistose rocks, such as mica-gneiss, hornblende-gneiss, chlorite-gneiss; and other varieties. All of these have most intricate structural relations. The semicrystalline series includes limestones, quartzites and quartz-schists, conglomerates and conglomerate-schists, mica-slates, and mica-schists. A great variety of basic and acid igneous rocks, massive and schistose, intrusive and extrusive, may be associated with any of these rocks. While the schistosity of the rocks of the semicrystalline and holocrystalline areas are frequently conformable, the change from one series to the other is in many places sudden and marked. In some areas, as for instance west of the Cranberry mine, as shown by Mr. Keith, a set of quartzites and conglomerates, with associated volcanic rocks, are sharply separated in their distribution from the surrounding gneissoid granites.

The gneissoid granite areas, in the wide variety of rocks of which they are composed and the complexity of their structures, have all the lithological aspects of the Archean. The rocks of the sedimentary areas are in most cases in all probability of later age than this granite-gneiss-schist complex, but as yet accurate determinations of their age have been made in only a single area. In central Virginia, as shown by Darton, some of them are Ordovician, as is proved by fossils contained. In other areas they may be even of later age, or as old as the Algonkian. In the present very imperfect state of knowledge, to call the whole Algonkian or Archean or even pre Cambrian is wholly unwarranted. To map them as belonging in any one of these divisons retards instead of advances knowledge, since it gives an impression that we have definite knowledge, and this tends to check further investigation.

On the western side of the Southeastern Area is a great series of rocks running from east of Knoxville to Alabama, named by Safford the Ocoee series, which has been generally referred to the pre-Cambrian. At the northeastern end of the area the rocks are less altered than in the southwestern part. The rocks of the Ocoee series in the unmetamorphosed district consist predominantly of conglomerates, quartzites, graywackes, slates with limestones, and in the metamorphosed districts these have been transformed to conglomerate-schists, quartz schists, mica-schists, mica-slates, and marbles. The following is taken from Keith. He divides the series into the following formations in ascending order: Wilhite slate, 300 to 400 feet thick; Citico conglomerate, 50 to 800 feet thick; Pigeon slate, 1,300 to 1,700 feet thick; Cades conglomerate, about 2,400 feet thick; Thunderhead conglomerate, about 3,000 feet thick; Hazel slate, about 700 feet thick, and the Clingman conglomerate, about 1,000 feet thick. The rocks of the Knoxville area at some places have been deformed by thrust faults and complex folds, and are metamorphosed. The transverse folds are described as having dips fully as steep as the longitudinal folds. As a result of the metamorphism there has developed slatiness or schistosity, which generally dips to the southeast from 50° to 60°. These secondary structures in some places coincide with bedding, but in other places do not.

As yet the age of this great series is undetermined. In some places it is faulted over the Paleozoic rocks; in others it overlies the Silurian rocks in apparent conformity and has been folded with them, but whether this is due to faulting and subsequent folding or to natural superposition has not been decided. The Ocoee series may be, so far as definite knowledge is concerned, either post-Silurian or Algonkian.

The Ocoee series furnishes one of the best exhibitions of regional metamorphism in the United States. The rocks vary from little altered limestones, slates, grits, and sandstones, to mica-slates or mica-schists, graywackes, quartzites or quartz-schists, and marbles. However, in most cases the metamorphism has not gone so far as to make the rocks completely crystalline schists; that is, they show microscopically if not macroscopically clastic characters.

During the folding of the rocks they were sufficiently buried so that they were in the zone of combined fracture and flowage. As the different clastic formations of the series vary from what were once soft and homogeneous muds to coarse-grained sandstones and conglomerates, as the amount of metamorphism is variable, and as the series is of great thickness, it would be expected that various phenomena of folding and of the relations of cleavage and fissibility to bedding in homogeneous and heterogeneous rocks would be well exhibited, and such is the case. A few of the principles best illustrated along the Hiwassee River between Thompson and Livingston are as follows:

The softer, more plastic layers obey almost perfectly the laws of flowage. The stronger, less plastic layers in their general deformation obey the laws of flowage rather than fracture, although their new positions are taken, in part at least, by numerous minute fractures. In the eastern, more gently folded area the heavier beds are in gentle curves, and in the closely folded part of the district they are turned back on themselves, oftentimes within their own radius, in some cases with no macroscopic sign of fracture.

The control which stronger layers have over weaker ones is beautifully illustrated. The thinner and weaker the beds, the more frequent and close are the plications. These strata were obliged to thicken and thin as demanded by the stronger rocks. In a given weak bed the plications are much more numerous along a trough or crest than along the limbs of the fold. On the contrary the strong beds in many cases were stretched upon the anticlines and synclines to the point of fracture. These fractures in the more closely folded anticlines are frequently radial, and have subsequently been filled by quartz veins. In all cases the limbs are the places where shearing due to accommodation was at a maximum. As a conseqnence the troughs and crests are now thicker than the limbs of the folds. This is true even where the troughs and crests were deformed by tensile fracture, for the beds are here separate pieces of full thickness joined by the infiltrated quartz (fig. 136). In the closely folded part of the section vein quartz which filled a first set of fractures was closely plicated by a second folding. This folding produced other fractures which were subsequently filled with quartz veins showing no dynamic effects. This indicates that the closely folded part of the district was subjected to two orogenic movements separated by a long interval of time.

Almost every principle given as to the relations of primary to secondary structures in the zone of combined fracture and flowage is beautifully illustrated. Some of these are the concentration of the major readjustments in the weaker beds; the formation of parallel cleavage and fissility in the weaker beds, and of diagonal cross-fissility in the stronger beds; the passage of one into the other by rotation; the prevalence of cross secondary structures at the troughs and crests of folds, and the tendency toward parallel structures on the limbs of the folds.

The early stages of the formation of pseudo-conglomerates are shown by the close infoldings of thin layers of hard material and thicker layers of soft material. The hard material was first dissevered by the movements into angular fragments. When the movement continued these were rounded.

In other districts in the South formations occur which by contained belts of schist-conglomerate are definitely proved to be of clastic origin, and these gradually pass into unmistakable crystalline schists. These transitions were clearly described and their meaning definitely pointed out by Emmons and Lieber, respectively, in 1856 and 1858.

More remarkable than this is the discovery by Emmons and Lieber that hornblende-schists and other schists are metamorphosed eruptives. These rocks are said sometimes to be as thinly laminated as paper, and are compared with slates; but their occurrence in dikes within the granites, and their gradations into the ordinary massive forms, demonstrate them to be later igneous rocks. These conclusions were not based upon petrographical work, but upon careful field study. The microscope in recent years has shown accurately the method of change; but that the change does occur from a massive eruptive rock to a thoroughly schistose one was proved beyond a doubt by these men before 1860.

Emmons and Lieber further appreciated that the gneissoid granites in their lithological affinities, as well as by actual transitions, belong with igneous granitic rocks rather than with the sedimentaries. Emmons also reached the same conclusion for the South which Emerson demonstrated many years later for the New England States, that there are two granites, one of which is more ancient than the clastics and the other intrusive within these. According to Emmons, the ancient form is predominant, but in certain localities granite was projected through fissures like other intrusive rocks.

The great discovery that regularly laminated rocks are produced by the metamorphism of eruptive rocks as well as from sedimentary rocks naturally carried the discoverer too far in the application of the principle. Emmons included in the metamorphic igneous rocks many mica-schists, slates, and limestones, for which he gave no evidence whatever. Lieber's discrimination between the metamorphic igneous and metamorphic-sedimentary rocks was much more satisfactory. But Emmons's general statements as to the small value of lamination alone in rocks as an evidence of origin and the method of stratigraphical work in the crystalline rocks can hardly be improved upon at the present day. Says this writer: "Rocks of igneous origin are often massive, but also are frequently laminated, and laminated rocks are frequently called stratified, but this latter term should be restricted to the sedimentary rocks. The metamorphic rocks are excluded from the sedimentary classification, because all rocks may become metamorphic, and a stratum metamorphic in one locality may not be metamorphic in another. The highest proof of the age of rocks is the order of superposition. When this method can be applied it is paramount, but paleontology may be used subject to proper principles."

FLOW AND FRACTURE OF ROCKS AS RELATED TO STRUCTURE.[1]

By Leander Miller Hoskins.

CONDITIONS OF FLOW AND OF FRACTURE.

I. NECESSITY OF ASSUMPTIONS REGARDING PROPERTIES OF ROCK MATERIALS.

In order to discuss the conditions under which rocks will rupture or flow, some assumptions must be made in regard to the properties of the material. These properties are but imperfectly known, even under the conditions prevailing at the earth's surface; much less can they be known under the conditions of great pressure and possible high temperature existing at great depths below the surface.

Experiments on the rupture of materials under simple conditions of stress are necessarily limited mainly to the application of great forces, either tensile or compressive, in a single direction. Such forces produce quite different effects in different substances. Certain general principles have, however, been established, which will be taken as the starting point of the following discussion.

II. PROPERTIES OF MATERIALS UNDER ORDINARY CONDITIONS OF PRESSURE AND TEMPERATURE.

If a body is subjected to normal stress in one direction, being unsupported in other directions, it is perfectly elastic until the intensity of normal stress reaches a certain limiting value, called the *elastic limit.* This "perfect elasticity" means that for stresses less than the elastic limit the deformation is not permanent, but disappears if the stress becomes zero.

If the intensity of stress exceeds the elastic limit, the deformation is partly permanent. On a removal of the deforming forces the body is found to have assumed a new form; there has been a flowage of the material. If the deforming forces be reapplied, the body exhibits prop-

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[1] The circumstances should probably be explained under which Professor Hoskins wrote this article. In repeated conferences and letters I explained to him, so far as I was able, the geological phenomena, and asked him to discuss the physical relations. This paper is the result. It has been of the greatest assistance to me, especially in the preparation of sections I and III. Without Professor Hoskins's paper these would have been far more imperfect than they now are. C. R. V. H.

erties very similar to those it possessed originally; it is elastic, tending to return to this new form, but the elastic limit has a new value.

If the deforming forces (and the accompanying normal stress) are increased, rupture will finally occur; the body will separate into two or more distinct parts. The greatest intensity of normal stress existing before rupture is the *breaking strength* of the material. The rupture may be either *normal* or *tangential;* i. e., the separation may occur along planes of normal stress or along planes of tangential stress. If the deforming forces are tensile, the rupture is usually normal; if they are compressive, rupture will be tangential, occurring by sliding along planes diagonal to the direction of normal stress.

These properties are not exhibited in perfection by rock materials under the ordinary conditions of experiment No well-marked elastic limit can be observed, and the rock will rupture without any observable amount of flowage. It is probable, however, that the long-continued application of forces not great enough to produce rupture would cause a distinct amount of flowage, resulting in a permanent deformation. This is evidenced by the sagging of stone beams which have been in place for long periods of time.

Time is thus an important element affecting the behavior of rocks under stress, and an element regarding whose effect we are in almost entire ignorance. It may, however, be assumed as probable that long-continued forces may produce flow without rupture, while greater forces would produce immediate rupture without sensible flow.

III PROPERTIES OF ROCK MATERIALS UNDER GREAT PRESSURES AND HIGH TEMPERATURES

The stress conditions of rocks buried beneath the surface of the earth are less simple than those above supposed. These conditions doubtless vary throughout any considerable volume, being dependent in general upon very complex causes. Throughout any small portion of the rock the stress condition may, however, be regarded as sensibly uniform. At any point three mutually perpendicular planes exist upon each of which the resultant stress is normal; these are the *principal planes* of stress. A cube of the rock with faces parallel to these three planes is under compression or tension in three rectangular directions. In general, the intensities of these three principal stresses are unequal. The difference between the greatest and least of them may be called the *stress difference.* If two of them are zero, the case is that already discussed. What relation must subsist among the three principal stresses in order that rupture may occur, and what in order that flowage may occur, are the questions to which the present discussion pertains.

First, it may be assumed that if the three principal stresses are equal there will be neither rupture nor flow, however great the intensity of the stresses. The density will decrease as the stresses increase, but no distortion nor breaking will result. Rupture and flow are in some way related to the *stress-difference.*[1]

Further, it seems reasonable to suppose that for a small difference between the principal stresses the body if solid will be elastic. If the stress-difference is gradually increased a limit will doubtless be reached at which there will be either permanent distortion (that is, flowage) or rupture. It may be that there will be first flowage and then rupture; or it may be that rupture will occur before there has been sensible flow. Again, it may be that whether or not there is flow before rupture depends upon the time element, so that flow would accompany a relatively small stress-difference if long continued, while a greater stress-difference would be accompanied by immediate rupture without sensible flow.

If the three principal stresses all become very great in intensity, what is the effect upon the properties of the body? The molecular structure is doubtless changed in some manner, but the effect of this change upon the elastic properties of the material must be largely a matter of conjecture. It seems probable, however, that the greater the pressures the greater the distortion that will take place before rupture, and that if the applied pressures exceed a certain limit rupture will be impossible. What this limit is there are no means of estimating. The body may still act as a perfectly elastic solid when the stress-difference is sufficiently small; there may still be a definite elastic limit, and its value may be comparable to that which exists under ordinary conditions. But beyond this limit permanent distortion begins, and continues indefinitely without rupture so long as the stress-difference exceeds the elastic limit.

Whether great pressure tends to aid or to prevent liquefaction can not be known apart from experiment. Certain known bodies (such as water) expand in solidifying; the solidification of such bodies is retarded by pressure. It is probable that the reverse holds true with the majority of bodies, including rock materials.[2] Probably, therefore, the enormous pressures to which deeply buried rocks are subjected tend to cause, or to maintain, a condition of solidity. On the other hand, the high temperatures existing at great depths doubtless tend to cause, or to maintain, a fluid condition. Our knowledge of the properties of rock materials is not sufficient to enable us to determine deductively the

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[1] "The precise circumstances under which elastic solids break have not hitherto been adequately investigated by experiment It seems certain that rupture can not take place without difference of stress in different directions One essential element therefore is the difference between the greatest and least of the three principal stresses How much the tendency to break is influenced by the amount of the intermediate principal stress is quite unknown The difference between the greatest and least stresses may, however, be taken as the most important datum for estimating tendency to break This difference has been called by Mr G H Darwin the 'stress difference'"—Thomson and Tait, Natural Philosophy, Part II, p 123, edition of 1890

[2] That this is true of diabase has been shown experimentally by C Barus (Bull U S Geol Surv, No 1031 The bearing of the results of Barus upon the question of the solidity of the earth is discussed by Clarence King in a paper on the age of the earth, American Journal of Science, 3d ser, Vol XLV, 1893, p 1

resultant effect of these two opposing tendencies. There is, however, indirect evidence that the earth possesses a high degree of rigidity. From a discussion of tidal observations, Prof. G. H. Darwin[1] concludes "that, whilst there is some evidence of a tidal yielding of the earth's mass, that yielding is certainly small, and that the effective rigidity is at least as great as that of steel." Other evidence pointing in the same direction has been discussed by Kelvin in several papers.

The stress-differences due to tide-generating forces not being permanent in intensity and direction at any given point in the earth's mass, the question might be raised whether the observed rigidity is that of a true solid or of a highly viscous liquid, it being well known that certain bodies are highly rigid under temporary deforming forces, even of considerable magnitude, while yielding slowly but continuously under much smaller permanent forces. That the earth is a true solid of considerable strength has been inferred from the magnitude of the surface inequalities. It is concluded by Darwin[2] that inequalities of the magnitude of Africa, the Atlantic Ocean, and America must, by the action of gravity, cause permanent stress-differences in the earth's interior comparable with the strength of the strongest known rocks. On the other hand, many geologists attribute these major inequalities of elevation to differences of density between the continental and the oceanic portions of the earth's crust.[3] While it seems unlikely that the distribution of density is such as to wholly relieve the interior portion of the earth from stress-differences, no reliable estimate can probably be made at present of the actual rock-strength necessary to sustain the surface inequalities. The supposition of solidity with a considerable degree of strength is, of course, not incompatible with the theory of isostacy.

If the properties of the rock are such as have been assumed above, it is obvious that there is no distinct separation into a zone of fracture and a zone of flow. Flowage and fracture may be going on simultaneously in the same region, a flow taking place under the action of forces not great enough to cause immediate rupture, while fracture is occurring where the rock is subjected to the action of greater forces.

IV. CONDITIONS FOR THE EXISTENCE OF CAVITIES

In considering under what conditions cavities could permanently exist in a rock mass, the rock will be assumed to possess the properties above described. Suppose that the stress conditions are uniform throughout some definite portion of the mass, that is, that the conditions are such that, if no cavities existed, the three principal stresses would be constant in direction and intensity. The *stress-difference* is

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[1] Thomson and Tait's Natural Philosophy, Part II, p 460, ed of 1890

[2] Philosophical Transactions, Vol 173, Part I See also Thomson and Tait's Natural Philosophy, § 832'

[3] Light is thrown upon this question by actual determinations of variations of density by means of pendulum observations on the intensity of gravity See papers by G R Putnam and G K Gilbert in Bulletin of the Philosophical Society of Washington, Vol XIII, pp 31-76

the difference between the greatest and the least of these three stresses. Assuming that rupture or flow depends upon the value of the stress-difference, let the *ultimate strength* be defined as the value of the stress-difference at which rupture will occur, and the *elastic limit* as the value of the stress-difference at which permanent deformation or flowage will occur. It is to be noticed that these definitions of ultimate strength and elastic limit do not assume that the values of these quantities are the same under all conditions of pressure. Some assumptions regarding their values under great pressures must be made in any numerical application. Suppose a cavity to exist at some point, within which there is a liquid under pressure, the bounding surface of the cavity being thus subjected to a uniform normal pressure which determines the normal stress in the rock immediately adjacent. These conditions being given, the problem is to determine the greatest stress-difference existing in the material.

It seems probable without mathematical analysis that no one of the three principal stresses in the general rock mass can exceed the pressure within the cavity by as much as the elastic limit or ultimate strength, without causing at the surface of the cavity a stress-difference great enough to cause flow or rupture. It is instructive, however, to consider mathematically certain special cases of the general problem.

The form of cavity that would offer greatest resistance to closing under any given stress condition is not apparent in the general case of three unequal principal stresses. Probably it would be the sphere in case the three principal stresses are equal, while for the case in which two principal lesser stresses are equal the most resistant form would perhaps be that of a cylinder or prism with axis parallel to the direction of greatest pressure.

The problem of determining the stresses at the surface of the cavity admits of exact treatment for the case of a spherical cavity for any values of the three principal stresses in the rock mass. The solution does not, however, lead to definite practical results, because it involves the ratio of the two elastic constants of the material, which is a quantity of very uncertain value. This general solution will not, therefore, be given here; but it may be remarked that so far as any conclusion can be drawn from it, it is consistent with the general conclusion stated below after the discussion of special cases.

The mathematical discussion which follows is limited to two special cases which admit of comparatively simple treatment, and which have the advantage of leading to results independent of the elastic constants of the material. These cases are, first, that in which the three principal stresses are equal and the cavity spherical; and, second, that in which two of the principal stresses are equal and the cavity has the form of a circular cylinder whose axis is parallel to the direction of the third principal stress and whose length is considerable in proportion to its diameter.

CASE I.—THREE PRINCIPAL STRESSES EQUAL.

Let the cavity be a sphere of radius a', and let the hydrostatic pressure per unit area within the cavity be p'. At all points of a spherical surface concentric with the cavity the stress conditions are exactly similar. Consider a shell whose outer surface is a sphere of radius a, and whose inner surface is that of the cavity. From symmetry it is evident that the resultant stress on any element of the outer spherical surface is normal and is equal in intensity over the whole sphere. Let p denote the intensity of this normal pressure.

One of the three principal axes of stress at any point has the radial direction, the other two being any two rectangular lines perpendicular to the radius. Let p_1 denote the normal compressive stress in the radial direction, and p_2 the normal compressive stress in any direction perpendicular to the radius. By symmetry it appears that p_1 and p_2 depend only upon r, the distance from the center of the cavity.

Following the method employed in Minchin's Statics,[1] the following results may be reached:

$$p_1 = \frac{a^3}{a^3 - a'^3}\left(1 - \frac{a'^3}{r^3}\right)p - \frac{a'^3}{a^3 - a'^3}\left(1 - \frac{a^3}{r^3}\right)p' \quad \ldots\ldots(1)$$

$$p_2 = \frac{a^3}{a^3 - a'^3}\left(1 + \frac{a'^3}{2\,r^3}\right)p - \frac{a'^3}{a^3 - a'^3}\left(1 + \frac{a^3}{2\,r^3}\right)p' \ldots\ldots(2)$$

$$p_2 - p_1 = \frac{3\,a^3\,a'^3}{2\,(a^3 - a'^3)\,r^3}\left(p - p'\right) \ldots\ldots\ldots\ldots(3)$$

The last equation shows that the stress-difference increases as r decreases; it will have its greatest value when $r=a'$. Let q' denote the value of p_2-p_1 when $r=a'$, and q its value when $r=a$; then

$$q' = \frac{3a^3}{2\,(a^3 - a'^3)}(p-p') = \frac{3\,(p-p')}{2\left(1 - \frac{a'^3}{a^3}\right)} \ldots\ldots\ldots(4)$$

$$q = \frac{3a'^3}{2\,(a^3 - a'^3)}(p-p') = \frac{3\,(p-p')}{2\left(\frac{a^3}{a'^3} - 1\right)} \ldots\ldots\ldots\ldots(5)$$

Equation (5) shows that as $\frac{a}{a'}$ increases, q decreases very rapidly, approaching zero as $\frac{a}{a'}$ increases without limit. Practically, q becomes negligible for comparatively small values of $\frac{a}{a'}$. Thus, if $\frac{a}{a'}=10, q=\frac{p-p'}{666}$.

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[1] 3d ed ,Vol II, p 436

The greatest stress-difference, q', approaches the value

$$\frac{3}{2}(p - p')$$

as $\frac{a}{a'}$ increases without limit, so that $\frac{a'}{a}$ approaches zero. As a limiting value, therefore,

$$q' = \frac{3}{2}(p - p') \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

This value would hold very nearly for comparatively small values of $\frac{a}{a'}$.

$$\text{If } \frac{a}{a'} = 10, q' = \frac{1000}{999} \cdot \frac{3}{2}(p - p').$$

The condition that flow takes place is

$$q' = Q = \text{elastic limit};$$

that is (assuming (6) to hold),

$$p - p' = \frac{2}{3} Q \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

The condition that rupture takes place is

$$q' = S = \text{breaking strength};$$

or

$$p - p' = \frac{2}{3} S \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

CASE II.—TWO PRINCIPAL STRESSES EQUAL.

If two only of the principal stresses are equal, the solution for a spherical cavity is less simple and the result less useful, for the reasons stated above. Assume, therefore, a cavity whose form is that of a circular cylinder whose axis is parallel to the axis of unequal stress, and whose length is considerable in proportion to the diameter. Strictly the solution applies only when the length is infinite; practically it will hold very nearly for very moderate lengths.

The stress condition is symmetrical with respect to the axis of the cylinder. One principal axis of stress at any point is radial, another is parallel to the axis of the cylinder, the third being perpendicular to these. Let a' be the radius of the cavity, and a the radius of a cylinder coaxial with the cavity. Let p_1 denote the normal compressive stress in the radial direction (at distance r from axis); p_3 the normal stress parallel to the axis of the cylinder, and p_2 the third principal stress. Also let $p_1 = p$ when $r = a$, and $p_1 = p'$ when $r = a'$.

Methods analogous to those used in the preceding problem lead to the following results:

$$p_1 = \frac{a^2}{a^2 - a'^2}\left(1 - \frac{a'^2}{r^2}\right)p - \frac{a'^2}{a^2 - a'^2}\left(1 - \frac{a^2}{r^2}\right)p' \ldots\ldots (9)$$

$$p_2 = \frac{a^2}{a^2 - a'^2}\left(1 + \frac{a'^2}{r^2}\right)p - \frac{a'^2}{a^2 - a'^2}\left(1 + \frac{a^2}{r^2}\right)p' \ldots\ldots (10)$$

$$p_3 = \text{constant} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

The stress-difference is the greatest of the three quantities

$$q_3=p_2-p_1 \dots\dots\dots\dots (12)$$
$$q_1=p_3-p_2 \dots\dots\dots\dots (13)$$
$$q_2=p_3-p_1 \dots\dots\dots\dots (14)$$

As r varies from a' to a, the principal stresses vary as follows: p_1 ranges from p' to p; p_2 ranges from

$$\frac{2\,a^2 p-(a^2+a'^2)\,p'}{a^2-a'^2} \text{ to } \frac{(a^2+a'^2)\,p-2\,a'^2\,p'}{a^2-a'^2}\text{; } p_3 \text{ remains constant.}$$

If $\frac{a}{a'}$ is infinite (practically if $\frac{a}{a'}$ is moderately great),

$$p_2 \text{ ranges from } 2p-p' \text{ to } p.$$

Hence the range in the values of q_1, q_2, and q_3 may be taken as follows:

$$\begin{array}{llll} q_1 \text{ ranges from} & (p_3-p')-2\,(p-p') & \text{to} & p_3-p; \\ q_2 \quad\text{"} \quad\quad \text{"} & p_3-p' & \text{"} & p_3-p; \\ q_3 \quad\text{"} \quad\quad \text{"} & 2\,(p-p') & \text{"} & 0. \end{array}$$

If any one of these values exceeds the elastic limit Q, flowage will occur; if any one exceeds the ultimate strength S, rupture will occur. The magnitude only, not the sign, is important in considering these values.

The value p_3-p may be disregarded, since if this exceeds Q or S there will be flow or rupture independently of the existence of a cavity. The values of the stress-difference which must be considered are therefore

$$q_1=(p_3-p')-2\,(p-p') \dots\dots\dots\dots (15)$$
$$q_2=p_3-p' \dots\dots\dots\dots (16)$$
$$q_3=2\,(p-p') \dots\dots\dots\dots (17)$$

Equations (16) and (17) show that the limiting condition for flow is that one of the following equations is satisfied:

$$\left.\begin{aligned} p_3-p' &= Q \\ \text{or}\qquad p\ -p' &= \tfrac{1}{2}Q \end{aligned}\right\} \dots\dots\dots\dots (18)$$

The limiting condition for rupture is

$$\left.\begin{aligned} p_3-p' &= S \\ \text{or}\qquad p\ -p' &= \tfrac{1}{2}S \end{aligned}\right\} \dots\dots\dots\dots (19)$$

Equation (15) would give as the condition for flow

$$p_3-p'= Q+2\,(p\ -p') \dots\dots\dots\dots (20)$$
$$\text{or}\qquad p\ -p'=\tfrac{1}{2}Q+\tfrac{1}{2}\,(p_3-p') \dots\dots\dots\dots (21)$$

(since the result is the same whether q_1 becomes $+Q$ or $-Q$).

So long as p and p_3 are both greater than p', equations (20) and (21) can not be satisfied for less values of these quantities than equation (19). If, however, $p-p'$ is negative, equation (20) makes $p_3-p'<Q$; and if p_3-p' is negative, equation (21) makes $p-p'<\frac{1}{2}Q$. Under such conditions, therefore, rupture or flow would be facilitated; that is, would occur with less absolute values of p_3-p' or $p-p'$ than would be required by equations (18) or (19).

If $p_3 = p$, the stress conditions in the rock mass are the same as those assumed in Case I. The discussion thus shows that a cylindrical cavity would begin to close under a less stress than a spherical one when the three principal stresses are equal.

The conclusions to be drawn from the above discussion are the following:

1. If the three principal stresses in any region of a rock mass are equal, a spherical cavity can not exist permanently if the normal stress in the rock exceeds the pressure within the cavity by as much as two-thirds the elastic limit or the ultimate strength.

2. If two of the three principal stresses are equal, a cylindrical cavity of considerable length whose axis is parallel to the third direction can not exist permanently if either of the equal principal stresses exceeds the interior pressure by as much as half the elastic limit or the ultimate strength, or if the third principal stress exceeds the interior pressure by as much as the elastic limit or ultimate strength.

Although the discussion has been confined to these special cases, it seems safe to state the following general proposition as at least probably true:

3. *No cavity can exist permanently in a rock throughout a considerable portion of which the normal stress in any direction exceeds the pressure within the cavity by as much as the elastic limit or ultimate strength of the rock.*

It is important to notice that the above propositions relate to the *permanent* existence of cavities. In the light of the preceding discussion of the properties of rock material it appears that the closing of a cavity may be an exceedingly slow process. If the stress conditions in a certain region are undergoing a very gradual change, there may be at certain times rupture, producing cavities, while at other times flow is taking place, tending to close the cavities.

V DEPTH AT WHICH CAVITIES MUST CLOSE

There remains the further question as to the depth within the earth at which the stress conditions become such as to make impossible the permanent existence of cavities. If the earth were a homogeneous flat solid of infinite horizontal extent, gravity being constant in direction and intensity throughout every portion of the mass, the intensity of stress on any horizontal plane would be equal to the weight of a column of the rock of unit cross-section extending from the surface to the given plane. It is perhaps sufficiently evident that this must be practically true in the actual case for depths which are small in comparison with the radius. It may be well, however, to give a discussion of the problem, taking account of the sphericity of the earth and of the possible existence of lateral stress. The mathematical discussion will be given only in outline.

Assume the earth to be a sphere, of which the outer portion, for such depths as are to be considered, is a solid of uniform density and elastic properties. Taking a set of rectangular coordinate axes, with origin at the earth's center, the differential equations for the strain displacements are:[1]

$$(\lambda+\mu)\frac{d\theta}{dx}+\mu\left(\frac{d^2u}{dx^2}+\frac{d^2u}{dy^2}+\frac{d^2u}{dz^2}\right)=-X$$

$$(\lambda+\mu)\frac{d\theta}{dy}+\mu\left(\frac{d^2v}{dx^2}+\frac{d^2v}{dy^2}+\frac{d^2v}{dz^2}\right)=-Y$$

$$(\lambda+\mu)\frac{d\theta}{dz}+\mu\left(\frac{d^2w}{dx^2}+\frac{d^2w}{dy^2}+\frac{d^2w}{dz^2}\right)=-Z$$

In these equations λ and μ are the elastic constants of the material; u, v, and w are the displacements parallel to the three axes, respectively, of a point whose coordinates are x, y, and z; X, Y, and Z are the axial components of the bodily forces (in this case the force of gravity) acting upon unit volume of the material, and θ is the dilatation at the point (x, y, z), defined by the equation

$$\theta=\frac{du}{dx}+\frac{dv}{dy}+\frac{dw}{dz}.$$

To express the values of X, Y, and Z, let w denote the weight of unit volume of rock at the earth's surface; n the ratio of the earth's mean density to the surface density; a the radius of the earth; r the distance of the point (x, y, z) from the center (i. e., $r^2=x^2+y^2+z$). The weight of a unit volume of rock at distance r from the center is easily shown to be

$$P=\frac{wa^2}{nr^2}\left(n-1+\frac{r^3}{a^3}\right);$$

and the values of X, Y, and Z are

$$X=-\frac{Px}{r}=-\frac{wx}{na}\left(1+(n-1)\frac{a^3}{r^3}\right)$$

$$Y=-\frac{Py}{r}=-\frac{wy}{na}\left(1+(n-1)\frac{a^3}{r^3}\right)$$

$$Z=-\frac{Pz}{r}=-\frac{wz}{na}\left(1+(n-1)\frac{a^3}{r^3}\right)$$

Using these values in the three differential equations above given, these equations are to be integrated subject to the conditions of the problem. The problem is identical in form with one solved in Minchin's Statics.[2] Following the method there outlined, the following results may be reached:

Let the intensity of normal stress in the radial direction at distance r from the center be p_1, and in the horizontal direction p_2, these being regarded as compressive. Then

$$-p_1=\left(\lambda+\frac{2}{3}\mu\right)B-\frac{4\mu C}{r^3}+\frac{wa}{n(\lambda+2\mu)}\left[\left(\frac{\lambda}{2}+\frac{3\mu}{5}\right)\frac{r^2}{a^2}-\left(n-1\right)\lambda\frac{a}{r}\right]$$

$$-p_2=\left(\lambda+\frac{2}{3}\mu\right)B+\frac{2\mu C}{r^3}+\frac{wa}{n(\lambda+2\mu)}\left[\left(\frac{\lambda}{2}+\frac{\mu}{5}\right)\frac{r^2}{a^2}-\left(n-1\right)\left(\lambda+\mu\right)\frac{a}{r}\right]$$

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[1] See Minchin's Statics, 3d ed , Vol II, p 430

[2] Vol II , pp. 441, 442.

In these equations B and C are undetermined constants, to determine which two conditions are needed. They may, however, be expressed in terms of the values of p_1 and p_2 at some given point. Before proceeding to this, an approximation will be introduced, simplifying the discussion.

Since the results of this discussion are applicable only to depths below the surface which are small in comparison with the radius, the ratio $\frac{r}{a}$ differs from unity by a very small fraction. Let

$$\frac{r}{a}=1-h;$$

then we may write with sufficient accuracy

$$\frac{a}{r}=1+h,$$

$$\left(\frac{a}{r}\right)^m=1+mh,$$

$$\left(\frac{r}{a}\right)^m=1-mh;$$

and the above values of p_1 and p_2 become

$$-p_1=\left(\lambda+\frac{2}{3}\mu\right)B-\frac{4\mu C}{a^3}\left(1+3h\right)+\frac{wa}{n\,(\lambda+2\mu)}\left[\left(\frac{3}{2}-n\right)\lambda+\frac{8}{5}\mu-\left(n\lambda+\frac{6}{5}\mu\right)h\right]$$

$$-p_2=\left(\lambda+\frac{2}{3}\mu\right)B+\frac{2\mu C}{a^3}\left(1+3h\right)+\frac{wa}{n\,(\lambda+2\mu)}\left[\left(\frac{3}{2}-n\right)\lambda+\left(\frac{6}{5}-n\right)\mu-\left(n\lambda+\left(n-\frac{3}{5}\right)\mu\right)h\right]$$

Let p' and p'' be the values of p_1 and p_2, respectively, at a point for which $h=h_0$. Then B and C may be expressed in terms of p' and p'' by means of the following equations:

$$-p'=\left(\lambda+\frac{2}{3}\mu\right)B-\frac{4\mu C}{a^3}\left(1+3h_0\right)+\frac{wa}{n(\lambda+2\mu)}\left[\left(\frac{3}{2}-n\right)\lambda+\frac{3}{5}\mu-\left(n\lambda+\frac{6}{5}\mu\right)h_0\right]$$

$$-p''=\left(\lambda+\frac{2}{3}\mu\right)B+\frac{2\mu C}{a^3}\left(1+3h_0\right)+\frac{wa}{n(\lambda+2\mu)}\left[\left(\frac{3}{2}-n\right)\lambda+\left(\frac{6}{5}-n\right)\mu-\left(n\lambda+\left(n-\frac{3}{5}\right)\mu\right)h_0\right]$$

Solving for B and C and substituting the values thus found in the above expressions for p_1 and p_2, all powers of h and h_0 above the first being neglected,

$$p_1=p'+wa\,(h-h_0)+2(p'-p'')\,(h-h_0)$$

$$p_2=p''+\frac{\lambda}{\lambda+2\mu}wa\,(h-h_0)-(p'-p'')\,(h-h_0)$$

The last term in each of these equations may be neglected, since $(p'-p'')\ (h-h_0)$ is very small in comparison with p' or p''. The term $wa\ (h-h_0)$ is, however, comparable in magnitude with p' and p''. The equations may therefore be written (if r_0 is the value of r corresponding to $h=h_0$),

$$p_1-p'=wa(h-h_0)=w(r_0-r)\ \ldots\ldots\ldots\ldots\ldots\ldots\ (A)$$

$$p_2-p''=\frac{\lambda}{\lambda+2\mu}\,wa(h-h_0)=\frac{\lambda}{\lambda+2\mu}\,w(r_0-r)\ \ldots\ldots\ldots\ (B)$$

In interpreting these results it must be kept clearly in mind that the discussion has referred only to the effect of gravity, whereas the actual stress conditions are in general due to the combined action of various causes. Moreover, the displacements of the particles which the above discussion assumes are those which would bring every element of the body into its present configuration from that configuration which would be assumed if gravity ceased to act, the body being supposed to be perfectly elastic for this assumed deformation. It is obvious, however, that this supposition of perfect elasticity for the hypothetical deformation can not be realized throughout a great depth of the rock mass, unless the elastic limit is much higher than seems probable from such knowledge of the properties of bodies as can be gained by experiment.

If by "natural configuration" is meant the configuration which any given portion of the body would assume if all deforming causes ceased to act, so that the stress became zero on every plane, then the natural configuration changes whenever the stress-difference exceeds the elastic limit. The displacements assumed in the mathematical theory of elasticity are always to be reckoned from the *present* natural configuration. Supposing a body to have initially any definite configuration; let any new cause of deformation become active. The theory of elasticity may be applied, to determine the effect of this new cause, up to the point at which flowage or permanent deformation begins. If, after this permanent deformation, the body again acts as an elastic solid, but with new values of the elastic constants, the theory of elasticity may be again applied to compute the further deformation and the accompanying stresses, until the elastic limit is again reached. But a permanent deformation, or change of "natural configuration," always introduces a discontinuity into the problem.

For the purposes of the following discussion it is convenient to introduce a new constant in place of λ. The elastic properties of an isotropic body (within the elastic limit) are completely known if the values of two constants are given. These may be variously chosen, but will be here taken as the *bulk modulus* and the *modulus of shear.* The former measures the resistance of the body to change of volume, the latter its resistance to shearing or distortion.[1] The modulus of shear is the quantity μ in the above discussion. If the bulk modulus is denoted by k, then the λ of the foregoing discussion is defined by the equation

$$\lambda=k-\frac{2}{3}\mu.$$

Introducing this value in place of λ, equation (B) becomes

$$p_2-p''=\frac{k-\frac{2}{3}\mu}{k+\frac{4}{3}\mu}w\,(r_0-r)\;\ldots\ldots\ldots\ldots\ldots\ldots(\mathrm{B}')$$

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[1] See Thomson and Tait's Natural Philosophy, § 680; Minchin's Statics, 3d ed., Vol. II, pp. 412-415.

Equation (A) is unchanged, being independent of the elastic constants.

Proceeding now to the examination of the values of p_1-p' and p_2-p'', notice first the meaning of the quantity $w\ (r_0-r)$. Since w is the weight of unit volume of rock, $w\ (r_0-r)$ obviously denotes the weight of a column of rock of unit cross-section and of height r_0-r.

VARIATION OF RADIAL STRESS WITH THE DEPTH.

Equation (A) shows that the difference between the values of the radial stress (per unit area) at any two points is equal to the weight of a column of rock of unit cross-section and height equal to the vertical distance between the two points considered, for the value of p_1-p' is independent of the elastic constants, so that the radial stress varies with the depth in the same way, however the rigidity of the rock may change. Since the radial stress is zero at the surface, its value at any depth is equal to the weight of a rock column of unit cross-section extending to the surface.

VARIATION OF LATERAL STRESS WITH THE DEPTH.

This can not be determined so simply, since equation (B′) involves the elastic constants k and μ. The deformation required by the above mathematical theory will undoubtedly be much beyond the elastic limit of the rock throughout the greater portion of the mass. Moreover, the elastic properties (the values of k and μ) doubtless vary with the depth, because of changes in temperature and pressure. For both these reasons equation (B′) fails to represent the true difference between the values of the lateral stress at two given depths, if k and μ retain their usual meanings. If, however, two points very near together be considered, so that the properties of the rock are sensibly the same at both, equation (B′) may be applied if proper values are given to k and μ. The value of k may probably be regarded as comparable with the true values of the bulk modulus under ordinary conditions; but the value of μ must generally be taken as much smaller than the true value of the shear modulus. The value to be used for μ must, in fact, express the ratio between the actual shearing stress and the total shearing deformation, the latter being measured, not from the *present* "natural configuration," but from that assumed in the mathematical discussion above explained. If the elastic limit has been greatly exceeded, this value of μ is obviously much smaller than the actual value of the shear modulus for deformations within the elastic limit. The more the elastic limit has been exceeded the smaller the values to be used for μ in the formula. But the smaller μ becomes in comparison with k the more nearly the quantity $\frac{k-\frac{2}{3}\mu}{k+\frac{4}{3}\mu}$ approaches to unity. If, therefore, the deformation has very greatly exceeded the elastic limit, equation (B′) becomes very nearly

$$p_2-p''=w\ (r_0-r) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (\mathrm{B}'')$$

if $r_0 - r$ is small, so that p_2 and p'' denote values of the lateral stress at two points very near together. If $\mu = o$, equation (B″) is exact, the body becoming practically a fluid. (For a fluid, the truth of the equation is obvious from the principles of hydrostatics.) Since equation (B″) is independent of the elastic constants, it is applicable to two points at a considerable vertical distance apart, if the elastic limit has been greatly exceeded at all intermediate points, variations in the elastic properties between the two points not invalidating the equation.

Near the surface, however, the deformation required by the above mathematical theory may be within the elastic limit, and equation (B′) indicates that the lateral stress may decrease less rapidly than the radial stress. How greatly this variation may differ from the law of hydrostatic increase (represented by equation (B″)) depends upon how great μ may be in comparison with k. As the ratio of μ to k increases from zero, the coefficient of $w\,(r_0 - r)$ in (B′) decreases from unity. It is not probable that μ ever greatly exceeds $\frac{3}{5}k$; if $\mu = \frac{3}{5}k$, equation (B′) becomes[1]

$$p_2 - p'' = \tfrac{1}{3}\,w\,(r_0 - r) \quad \ldots\ldots \quad (\mathrm{B}''')$$

The true rate of variation of the lateral stress with the depth is probably everywhere between limits not greatly different from the values given by equations (B″) and (B‴).

APPLICATION.

In applying to the actual problem presented by the earth the results reached by the solution of the above ideal problem, there are important modifying conditions to be considered. First, it is obvious that throughout an outer shell of considerable thickness the effect of surface irregularities will be important, and will introduce so many elements into the problem as to make its exact treatment impossible. Very complex stress conditions doubtless exist in many localities. But throughout any region in which the surface irregularities are only moderately great over a considerable horizontal area, the principle above deduced regarding the variation of radial stress with the depth will undoubtedly hold as an average result. Any local decrease of stress will be accompanied by a corresponding increase in some neighboring portion of the rock mass.

Again, the outer crust of the earth has not (as assumed in the mathematical theory) been brought to its present configuration by the action of gravity upon an elastic solid spherical shell. If the whole mass was originally fluid, both the radial and the lateral stresses followed the hydrostatic law of variation with the depth, expressed (for depths small in comparison with the radius) by equations (A) and (B″). This stress condition was subsequently modified by solidification and contraction by cooling, the nature and amount of this modification depending upon

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[1] The relation $\mu = \frac{3}{5}k$ is exactly satisfied for so called "perfect" solids See Minchin's Statics, 3d ed, Vol II, p 442

the change of volume accompanying solidification, upon the rate at which solidification proceeded with the depth, upon the rates of cooling of the solid crust at different depths, and upon the value of the coefficient of expansion with temperature. The present law of variation of the lateral stress with the depth may therefore be widely different at different depths. These considerations do not, however, invalidate the general conclusion above stated as to the limits between which the rate of variation will probably lie. And the actual value of the lateral stress can nowhere permanently differ from that of the radial stress by more than the elastic limit of the material.

In estimating the actual depth beyond which cavities can not permanently exist, it may be assumed, in accordance with the conclusion above reached, that the intensity of stress upon a horizontal plane at any depth is equal to the weight of a column of rock of unit cross-section extending to the surface. There may also be a lateral stress, differing from the radial by any amount from zero up to the elastic limit. If the lateral stress is equal to the radial, the depth of closing will probably be less than if the lateral stress is zero. The following numerical estimate is based upon the supposition of no lateral stress.

The numerical value of the required limiting depth can not, of course, be determined with certainty because of uncertainty as to the elastic limit of the rock. Under ordinary experimental conditions, no distinction can be made between the elastic limit and the ultimate strength, since the rock specimen always ruptures without sensible previous deformation. If the elastic limit is comparable in value with the crushing strength as determined by experiment, it is probable that 25,000 pounds per square inch, or say 17,600,000 kilograms per square meter, may be taken as a sufficiently high value. If the density of the rock mass is taken at 2.7 times that of water, the weight of a cubic meter is 2,700 kilograms. Therefore, if d is the required depth,

$$d=\frac{17{,}600{,}000}{2{,}700}=6{,}520 \text{ meters.}$$

If cavities are filled with water under pressure, the maximum value of this pressure may be taken as that due to a column of water extending to the surface; or, at a depth of d meters below the surface, the interior pressure would be, as a maximum, 1,000 d kilograms per square meter. If the condition for the closing of cavities is as heretofore stated, the greatest normal stress in the rock may exceed this interior pressure by as much as the elastic limit (or ultimate strength) before closing will occur. That is, if d is the depth necessary for closing,

$$2{,}700\ d-1{,}000\ d=17{,}600{,}000,$$

or

$$d=\frac{17{,}600{,}000}{1{,}700}=10{,}350 \text{ meters.}$$

STRAIN AND STRESS.

I STRAIN

The following discussion is not designed as an exhaustive treatment of the subject of strain, but only as a presentation of such principles as seem to have an important bearing on the causes of rock structure.

A body is said to be *strained* when the relative positions of its particles undergo any change. A rotation or translation of the body as a whole may accompany a strain, but forms no part of it.

Strain proper changes either the *form* or the *volume* of the body, or of some portion of it. Change of form is called *distortion*, and change of volume *dilatation;* the latter being positive or negative, according as the volume increases or decreases.

A strain is *homogeneous* when any two portions of the body which are similar in form and similarly oriented before the strain are also similar in form and similarly oriented after the strain. The following discussion relates mainly to homogeneous strain.

If all lines having a certain direction are elongated or shortened in some definite ratio, while lines perpendicular to that direction are unchanged in length, the two sets of lines remaining unchanged in direction, the strain is a *simple elongation* or *simple shortening.* (A shortening may be regarded as a negative elongation.) Any spherical portion of the body is changed by a simple elongation into an ellipsoid of revolution, prolate if the elongation is positive, oblate if it is negative.

If a body receives successively *two simple elongations* in directions perpendicular to each other, a sphere will be changed into an ellipsoid; if the two elongations are equal it will be an ellipsoid of revolution, otherwise an ellipsoid of three unequal axes. It is also true that three simple elongations in mutually perpendicular directions change a sphere into an ellipsoid, the ratios of whose principal axes depend upon the ratios of the three elongations. The principal axes of the ellipsoid coincide in direction with the three elongations.

It is known that any homogeneous strain may be produced by three simple elongations or shortenings of the body in directions perpendicular to one another, followed, in the most general case, by a rotation of the body as a whole. The three lines of the body which pass through any point and are parallel to the three directions of simple elongation are called the *principal axes of the strain* at that point. These three lines are perpendicular to one another both before and after the strain, but may or may not change their directions relative to the earth or to any other assumed reference-body. If their directions remain constant the strain is called *pure* or *irrotational;* if not, the strain is *rotational.* Since a rotation of the body as a whole does not change the relative positions of its parts, such a rotation may be disregarded in studying the nature of the strain proper, and any homogeneous strain may be analyzed into three simple elongations.

If the direction of any line in the body be specified by the angles it makes with the strain-axes, the direction of a line not parallel to one of the axes will in general be changed by the strain. A sphere will be changed into an ellipsoid whose principal axes are parallel to those of the strain. A rectangle whose edges are originally parallel to two of the axes of the strain will become a rectangle with edges unchanged in direction. A rectangle whose edges are oblique to the principal axes of the strain will in general become an oblique parallelogram.

If equal lines parallel to the three principal axes of strain are equally elongated or shortened, the strain is a *simple dilatation*. The ellipsoid into which the sphere is transformed is in this case a sphere. Neglecting rotation of the body as a whole, every line remains unchanged in direction, but all lines are elongated in the same ratio. Every figure is unchanged in form, but undergoes a change of volume.

If the ratios of elongation and shortening in the three principal directions are so related that the volume is unchanged, the strain may be called a *simple distortion*. This obviously requires that the three simple elongations be not all of the same sign. The algebraic sum of the volume-changes due to the three axial strains must be zero.

Any homogeneous strain may obviously be produced by the combination of a simple dilatation and a simple distortion; it is often useful to study these separately.

As a special case, the strain in one of the three principal directions may be zero; in this case the strain may be called *two-dimensional*. In analyzing a two-dimensional strain it is sufficient to consider a plane perpendicular to the axis of zero strain. Every point in such a plane may be taken as the representative of a line perpendicular to the plane, and every straight line as the representative of a plane parallel to the axis of zero strain. Even in the case of three-dimensional strain, it is often instructive to direct the attention to a plane perpendicular to one of the strain-axes. The two-dimensional strain occurring in such a plane may then be combined with the elongation perpendicular to it, and the nature of the actual strain is thus readily understood. The study of strains in two dimensions is thus of considerable importance.

The effect of two or more successive homogeneous strains whose axes do not coincide is a matter of some importance. Consider first two successive simple elongations, both positive, in directions not perpendicular to each other nor parallel, and direct the attention to a plane parallel to the two directions of elongation. A circle lying in this plane is changed by the first strain into an ellipse whose major axis is parallel to the direction of elongation. This ellipse is changed by the second strain into another whose major axis is intermediate in direction between the two elongations. The two elongations are together equivalent to a two-dimensional strain whose axes coincide with the principal axes of the final ellipse. The positions of these axes relative to the directions of the two given elongations can be found mathemat ically when the ratios of elongation are known, but the above qualitative statement is sufficient for the purposes of the present discussion. (It is to be noticed that even if each of the two given elongations occurs without rotation, the resultant strain is in general rotational—that is, the lines which become axes of the final ellipse have not the same direction after the strain as before. This is important if the absolute position of the axes of the total strain is in consideration.)

In a similar manner the result of any succession of homogeneous strains may be estimated. The total result is a homogeneous strain; but the positions of the strain-axes, both in the body and in space, may, by reason of the successive strains, undergo any series of changes.

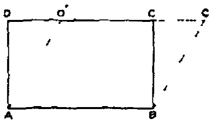

Fig 163 —Simple shear

If a rectangle ABCD (fig. 163) is strained into a parallelogram ABC'D' whose base and altitude are equal to those of the rectangle, the strain is called a *simple shear*. All lines parallel to AB move parallel to themselves through distances proportional to their distances from AB. Planes parallel to AB and to the axis of zero strain are called *shearing planes*.[1] Any two such planes slide relatively to each other an amount proportional to their distance apart. The *amount* of the shear is measured by the amount of relative sliding of planes at unit distance apart. Thus $\frac{DD'}{AD}$ is the amount of the shear represented in fig. 163. Since the area of the parallelogram ABC'D' is equal to that of the rectangle ABCD, the shear is evidently an undilatational strain, or a *simple distortion.*

It may be proved that any two-dimensional homogeneous strain which leaves the volume unchanged is equivalent to a shear combined with a displacement of the body as a whole.[2] It will be well to give here the proof of this proposition, since the nature of a shearing strain and its relation to the principal axes of elongation and shortening are matters of importance in the applications to rock structure.

Let a body receive any two-dimensional homogeneous strain which leaves the volume unchanged, and let XX' and YY' (fig. 164) be the principal axes of the strain. Let AC be any length taken on XX' before the strain, and let its strained length be A'C'. On YY' let BD, equal to A'C', be laid off before the strain, and let its strained length be B'D'. If the volume is unchanged B'D' must equal AC, because the rhombus ABCD is strained into A'B'C'D', and by construction BD is equal to A'C'. Now, having regard solely to the *relative* positions of the particles of the body, and not to their absolute positions in space, it is evident that ABCD may be transformed into A'B'C'D' by

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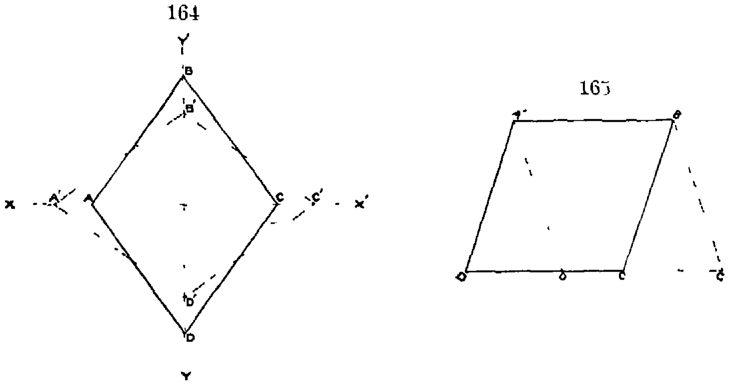
[1] These planes are also designated as *planes of sliding* and as *undistorted planes* The term "shearing planes" as here used must not be confused with "plane of the shear" By the latter is meant a plane parallel to the motion of every particle of the body during a simple shear. The plane of the shear is perpendicular to the planes of sliding

[2] See Thomson & Tait's Treatise on Natural Philosophy, Part I, §§ 169–170, pp 122–124, 1890

a shear. Thus, if ABCD is moved until AB coincides with A′B′ (fig. 165), CD will be collinear with C′D′, and a sliding parallel to A′B′ will bring A′B′CD into coincidence with A′B′C′D′.

There is evidently another way in which ABCD (fig. 164) can be changed into A′B′C′D′; namely, by bringing BC into coincidence with B′C′ and then sliding AD and all parallel lines until they coincide with corresponding lines of A′B′C′D′. That is, in every shear there are two sets of planes, either of which may be regarded as shearing planes.



FIGS 164 and 165 —Two dimensional strain equivalent to shear

The two processes are equivalent in total result. The actual series of deformations undergone by any element of the body is, however, different in the two cases.

When a shear is known with reference to one set of shearing planes, the determination of the other set is a matter of some importance. Let XX′ and YY′ (fig. 166) be parallel to the known direction of sliding, and let BB′ be the amount of sliding of YY′ relatively to XX′. Assuming every point of XX′ to remain stationary, the point originally at B moves to B′, and a line BA moves into B′A. If A is so taken that AB equals AB′, the length of every line originally parallel to AB is the same after the strain as before. Hence, such a parallelogram as ABCD may be brought into its strained position by first moving it bodily until AB falls into AB′ (CD then falling at C″D″), then bringing AB′C″D″ into coincidence with AB′C′D by a shearing motion parallel to AB′. It is thus seen that lines originally parallel to AB represent the second set of shearing planes.

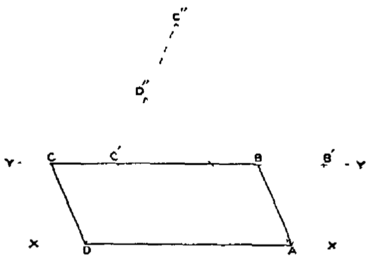


FIG 166 —Relation of two sets of shearing planes

Another problem of importance is the determination of the principal axes of elongation and shortening in the case of a shearing strain, the shearing planes being supposed known. From figs. 164 and 165 it is evident that these axes bisect the angles between the two sets of shearing planes; the obtuse angle (before strain) being bisected by the axis of elongation, and the acute angle by the axis of shortening.

The effect of a shearing strain in deforming a circle is shown in fig. 167. In the two sets of shearing planes are taken equal lengths, AB and BC. The rhombus ABCD is strained into the equal rhombus ABC'D' by a shearing motion parallel to AB. The point O, the intersection of the diagonals of ABCD, is taken as the center of a circle whose radii in the directions of greatest elongation and shortening are OM and ON. These are strained into O'M' and O'N', which are therefore the principal semidiameters of the ellipse into which the circle is strained. Let BE be a line perpendicular to AB before strain, then BE' is the strained position of BE, the distance EE' being equal to CC'.

No shearing or sliding of parallel planes over one another takes place in the case of a simple dilatation, for such a strain changes every figure into a similar figure, while the sliding of planes relatively to one another would deform a rectangle into an oblique-angled parallelogram.

Every two-dimensional strain is equivalent to a shear combined with a simple dilatation, followed by a displacement of the body as a whole (strains in the third dimension being disregarded); for any such strain transforms a circle into an ellipse; but a circle may by a dilatation be made equal in area to any ellipse, and by a shear it may then be made similar to the given ellipse. (It is to be understood that a dilatation may be either positive or negative.)

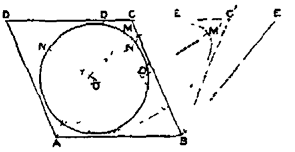


FIG 167.—Deformation of sphere by simple shear

In the foregoing discussion of strain only the initial and final configurations of the body have been considered. The successive steps by which the final configuration is reached from the initial are disregarded. In fact, if the initial and final form and size are alone given, there are no means of ascertaining these intermediate steps. Referring to the case of a shear illustrated in fig. 166, the parallelogram ABCD is supposed to be strained into the parallelogram AB'C'D. This change *may be* produced by a continued sliding or shearing parallel to AD; the same final result (so far as the *form* of the figure is concerned) *may be* produced by a sliding or shearing parallel to AB. This is what is meant by the statement that AB and AD are both shearing planes. It is not meant to assert that simple sliding has necessarily taken place along either of these sets of planes in order to produce the supposed result. In fact, simple sliding can not have occurred continuously parallel to both AB and AD. A little consideration will show that, if rotation be disregarded, at any given instant during the process of strain simple sliding is taking place along two sets of planes which are at right angles to each other, while simple elongation and shortening are occurring in directions inclined 45° to the planes of sliding. In undergoing any given change of form, the body passes through a continuous series of intermediate forms. The total strain is thus the sum or resultant of a series of smaller strains. Now consider a strain of very small amount. For a very small strain the figures ABCD and A′B′C′D′ (fig. 164) are very nearly squares. If the strain be taken smaller and smaller, approaching zero as a limit, the figures ABCD and A′B′C′D′ will in the limit become squares; but AB and BC represent the two sets of shearing planes. Hence, the simple sliding at any instant takes place along two sets of planes at right angles to each other and inclined 45° to the directions of elongation and shortening at that instant.[1] In the production of a given strain of finite amount, it is not necessary that the directions of elongation and shortening or either

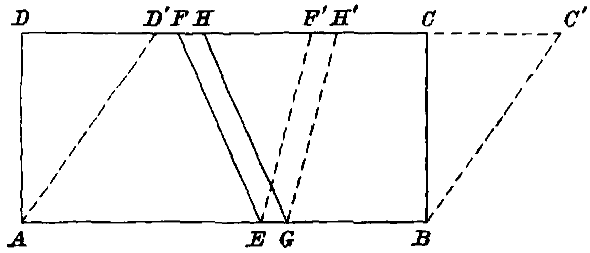


FIG. 168.—Planes of instantaneous sliding.

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[1] The planes defined as shearing planes are not the only ones along which there is sliding. Any parallel planes (not perpendicular to a strain axis) slide over one another during the process of strain. That which distinguishes the shearing planes is the fact that their total relative motion is equivalent to a *simple* sliding—that is, a sliding unaccompanied by change in their dimensions or in their distances apart. It is also true that the total amount of sliding is greater for these planes than for any other set.

Consider, for example, a simple shear of finite amount such as illustrated in fig. 168, the rectangle ABCD being changed into ABC′D′ by a continued simple sliding parallel to AB. Lines parallel to AB remain constant in length, and their distances apart are unchanged, but parallel lines having any other direction undergo a continuous change in length, and at the same time either approach or recede from each other. Thus EF and GH move into the positions EF′ and GH′, and during the process they at first decrease and then increase in length, while their distance apart first increases and then decreases. They have at every instant a sliding motion relative to each other, as may be seen by comparing any two successive positions of the parallelogram EFHG, but the sliding is not *simple*. At a single instant, however, the relative motion of EF and GH is a *simple* sliding; this is when they are perpendicular to AB. At this instant their length and their distance apart are neither increasing nor decreasing, so that they are in the same condition as lines parallel to AB.

Evidently ABCD may be changed into ABC′D′ in many other ways than that which has been assumed. Simple sliding may not be continuous parallel to AB; indeed AB may not be a shearing plane at any time during the process. But if at any instant simple sliding is occurring parallel to AB, it is also occurring along those planes which are at that instant perpendicular to AB.

The proposition, above proved, that any finite homogeneous two dimensional strain that leaves the volume unchanged is equivalent to a shear, and that there are two sets of shearing planes, refers only to total results, not to the actual process by which the results are accomplished. Such a strain *may be* produced by simple shearing along a constant set of parallel planes (accompanied, of course, by a rotation), and for a strain of given amount there are two sets of planes, either of which *may be* the set along which continuous simple sliding occurs, but the given result may be produced without there being at any instant simple shearing along any set of planes, and simple shearing can not be continuous along more than one set. In order to apply to the process of strain at any instant, the proposition must take the following form:

If at any instant a body is undergoing a two dimensional homogeneous strain of such a character that the volume is not changing, there is simple shearing along each of two sets of parallel planes, these sets being at right angles to each other and inclined 45° to the directions of elongation and shortening.

of the directions of sliding should remain constant during the process. In fact, they can not all remain constant,[1] and in general all of them change. In the application of the foregoing principles to the explanation of cleavage structure, to be given below, the question of chief importance is the total effect of a given finite strain upon the form of any small portion of the rock mass. To determine this effect it is not necessary to know all the steps of the actual process by which the final result is produced. Any process which would produce the same total strain may be treated as if it were the actual process. For certain purposes it is instructive to study a strain with reference to the planes of total shearing, while for other purposes the attention may be directed to the axes of total elongation and shortening.

The simple strains above treated—elongation, dilatation, and shear—are the most important elements in the analysis of homogeneous strains. Any homogeneous strain may be produced by a suitable combination of these elements, with or without a rotation of the body as a whole. The analysis of any given strain into its elements may be made in various ways, the most useful method depending upon the particular problem in hand.

Heterogeneous strain.—In heterogeneous strain different elementary portions of the body receive unlike deformations. In any case, however, unless there is a surface of discontinuity due to the actual separation of the body into two or more parts, the strain throughout a volume sufficiently small is sensibly homogeneous, and the variation of the strain is gradual throughout the body. The strain of every small element is thus equivalent to three simple elongations (positive and negative), combined with a rotation; but the directions of the three principal elongations, and the amount of the rotation, in general vary in passing from point to point of the body.

The variation of the rotation especially needs notice. In homogeneous strain, since all elements of the body are equally rotated, the result is necessarily a rotation of the body as a whole, forming no part of the strain proper. In heterogeneous strain, however, different elements may be unequally rotated, so that the total result of the rotations may be a true strain—a change in the relative positions of the parts of the body. If, however, there is no surface of discontinuity, the rotation, as well as the other elements of the strain, varies gradually throughout the body.

In studying the relations of strain to rock structure, the results reached in the analysis of homogeneous strain will apply also to heterogeneous strain so far as the *nature* of the effects is concerned; but the resulting structure will vary continuously in passing from one part of the body to another, instead of being uniform as in the case of homogeneous strain.

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[1] This statement refers to directions as determined by definite lines of particles in the body. The directions in space along which elongation, shortening, and sliding take place may or may not remain constant.

II STRESS.

The action and reaction between any two adjacent portions of a body constitute a *stress*. Considering any two such portions separated by a plane, the forces exerted between them may have any direction relatively to that plane. It is convenient to consider these forces as resolved into components normal and tangential to the plane. The stress made up of the tangential components is called a *shearing stress*, and may have any direction in the plane considered. The normal stress is a *tension* if it resists a tendency of the two portions of the body to separate, and a *compression* if it resists a tendency of the two portions to approach each other.

Whatever stress condition exists at any point of a body, there are always three rectangular planes upon each of which the resultant stress is normal. Three intersecting lines perpendicular to these three planes, respectively, are called the principal *axes of stress.*

Upon any plane not perpendicular to a principal axis the stress has in general a tangential component. It may be proved that, for planes parallel to one principal axis, the tangential or shearing stress has the greatest intensity[1] upon planes inclined 45° to the other two principal axes.

III. RELATION OF STRESS TO STRAIN

The condition of stress existing at any point of a body depends upon its state of strain and upon the properties of the body. It is important to understand what is meant by "state of strain" as here used. This state of strain is to be reckoned from what is called the "natural configuration" of the body. By the "natural configuration" is meant the form and size which the body would assume if freed from all deforming forces so that the stresses at the point considered became zero upon every plane. If the body is acted upon by external forces sufficiently great, a permanent deformation will result, and the natural configuration will be changed. It is evident, therefore, that the stresses existing at any instant can not be estimated from a knowledge of the total strain which a body has undergone from some previous condition, unless it is known that no permanent deformation has been produced. If a body is isotropic and the strain is small and within the elastic limit, the relation of stress to strain can be expressed rather simply.[2] But a strain of large amount will for most bodies be accompanied not only by a permanent deformation but by a change in the elastic properties of the body. For an isotropic body and for strains within the elastic limit the principal axes of the stress coincide with those of strain; and doubtless this is at least approximately true for very great defor-

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[1] By *intensity* of stress is meant stress per unit area In the following discussion the word stress alone is sometimes used in the sense of stress intensity, when the meaning seems obvious, in order to avoid circumlocution Some writers define stress as force per unit area, but this usage can not be regarded as established

[2] See Minchin's Statics, 3d ed , Vol II, p 416

mations, so that if a great shortening is observed in a certain direction it can be inferred that the predominating stress has been a compression in that direction. A complete account of the stress conditions through which any particle of a body has passed can not be given without a knowledge of much more than the total deformation it has undergone. It requires, further, a complete knowledge of every step of the process of strain and of the properties of the substance at every stage. It is evident, therefore, that the stress conditions which accompany the deformation of rocks can not be determined except in the most general way.

IV GENERAL REMARKS ON STRAIN AND STRESS.

The foregoing discussion of strain and stress is of course far from complete, but includes the main elementary principles from which the complete theory is developed. The attempt has been made to present these principles in a form intelligible to the non-mathematical reader.

Perhaps the matter of fundamental importance to the geologist in considering the various mechanical theories advanced to explain rock structures, is a clear conception of the nature of tangential or shearing strains and stresses and of their relation to other elementary stresses and deformations. The language sometimes used in the discussion of geological theories seems to imply that tangential stresses and strains must be due to exceptional conditions. But a study of elementary principles shows that only under exceptional conditions can there be strain without the occurrence of sliding along certain planes, or stress without the existence of tangential stress on certain planes. The only case in which shearing stresses are absent is that in which the normal stress has the same intensity on all planes, whatever their directions. The only case in which there is no sliding or tangential strain is that of a simple dilatation—the elongations or the shortenings in all directions being equal.

APPLICATIONS TO ROCK STRUCTURE.

I. CLEAVAGE

It is not designed here to discuss exhaustively the causes of cleavage in rocks. It is probable that different causes have been operative, either separately or in combination, to produce the observed results. The foregoing discussion of homogeneous strain seems, however, to throw light on at least one of the important agencies concerned in the production of cleavage.

In a body absolutely homogeneous, even to the minutest portions, it seems improbable that cleavage would be developed by any possible strain. The tendency of certain rocks to rupture with great readiness along certain planes or to cleave seems to be due to the fact that the small particles of which they are composed are flat parallel to that direction. This flatness not only facilitates rupture along these planes, but by the overlapping of the flat particles tends to prevent smooth fracture in directions not parallel to the flatness. That this flatness exists in the case of rocks showing distinct slaty cleavage is shown by observation.

To account for the flatness of the small particles and their parallel arrangement, various theories have been proposed, the most prominent being that of Sorby and that of Sharpe and Tyndall. These theories both assume that the cleavage structure has been produced by the action of great compressive forces, causing a shortening of the rock mass as a whole in one direction, the cleavage being developed along planes perpendicular to the direction of shortening. On the theory of Sharpe and Tyndall this shortening is participated in by every small particle of the rock, both the flatness of the particles and their parallel arrangement being thus accounted for.[1] Sorby's theory, on the other hand, assumes the previous existence of the flat particles, and explains their parallel arrangement by a rotation due to the supposed shortening of the rock mass in one direction and corresponding elongation perpendicular to that direction.

The relation between the two theories may be otherwise expressed by the statement that one supposes a homogeneous strain of the whole rock mass, including every constituent particle, while the other assumes a homogeneous strain of the rock mass as a whole, not participated in by the flat particles, but causing them to assume parallel positions.

Without attempting an exhaustive discussion of the merits of the two theories, it may be remarked that the theory of Sharpe and Tyndall is the simpler, and is probably the true explanation of a considerable part of the observed phenomena of cleavage. It is hardly supposable that in all cases the flatness observed in the particles of rocks showing slaty cleavage existed in all the particles of the original sediment. The simplest supposition is that every small particle participated in the strain undergone by the whole mass; that is, was shortened perpendicularly to the cleavage planes and elongated in directions parallel to these planes.[2] Taking a sphere as the type of a particle in the original sediment, it would be flattened into an ellipsoid; and this flattening, if experienced by all particles, is sufficient to account for the cleavage structure. A very close, smooth, slaty cleavage would develop only in a very fine-grained rock; but the same sort of structure on a different scale may be observed in coarse-grained schists. In fact, in some cases the directions of the three principal axes of strain are plainly evident from the form of the fragments, and a tendency to cleavage exists along planes perpendicular to the greatest shortening. It is to

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[1] Sharpe supposed the expansion parallel to the cleavage planes to take place mainly in the direction of the cleavage dip This, however, is not essential to the theory

[2] It has been seen that every strain is equivalent to a dilatation (positive or negative) combined with a distortion. In the case of rocks accessible to study by the geologist, it is probable that the amount of dilatation will never be great A great shortening parallel to one strain axis must be accompanied by a compensating elongation in at least one of the other axial directions

be observed that on this view a fibrous structure might develop under certain conditions, there being approximately equal shortening in two axial directions and an elongation in the third.[1] A tendency to this structure is seen in certain schists. But probably in the majority of cases there is a predominant pressure in one direction, causing a shortening in this direction and an elongation in all directions perpendicular to it. (Pl. CXV.)

This seems a simple and adequate explanation of the development of slaty cleavage in any small volume of rock, since the strain is practically homogeneous throughout a volume sufficiently small. It can not be supposed, however, that this homogeneity exists throughout any considerable volume. If a body of rock of great extent is subjected to a great compression in a certain direction, there will be not only a tendency to shortening in that direction but generally also a tendency to bending, because of unequal support in transverse directions. The result will be that, simultaneously with the shortening, there will be folding of a more or less complex character. If the supposed conditions continue for a sufficient time, the shortening in the direction of

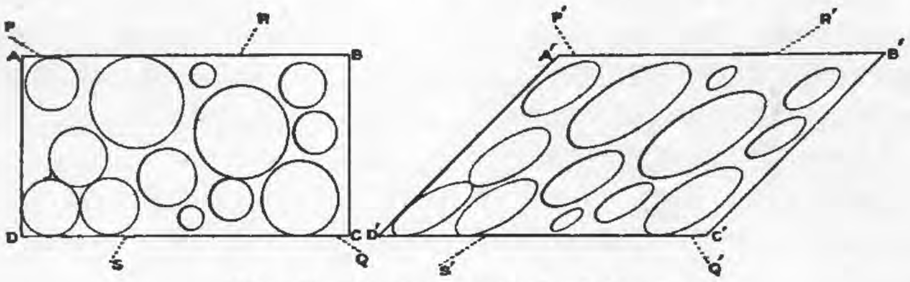

FIG. 169.—Cleavage due to simple shear.

the prevailing pressure may ultimately so far predominate that cleavage will develop in approximately parallel planes, irrespective of minor deformations of the particles due to the folding. On the other hand, there will doubtless be cases in which the local deformation predominates over the general, or is at all events of sufficient amount to modify the direction of greatest shortening of the particles, and thus to produce local variations in the direction of the cleavage planes. It is, indeed, possible that cleavage should be wholly due to local deformation, and should therefore affect only limited volumes. In discussing this local variation in the direction of cleavage, it is useful to consider the relation of cleavage to the shearing planes.

In fig. 167 let the circle represent a small spherical fragment of a sedimentary rock, and let it be supposed that the rock is under such conditions that it flows without rupture and that it undergoes a shearing strain such as is represented in the figure; the spherical fragment becomes an ellipsoid, one of whose sections is the ellipse shown. If the process of shearing were continued, the ellipsoid would be still

[1] See paper by Alfred Harker "On Slaty Cleavage and Allied Rock-Structures," British Association Reports, 1885, p. 820.

further flattened, and its major axis would become more nearly parallel to AB. If the rock is composed of particles all of which are deformed in a similar manner, cleavage will tend to develop in planes parallel to AC′. Such a result is shown in fig. 169, in which ABCD represents a portion of rock which by shearing is changed into A′B′C′D′. Spherical fragments are strained into ellipsoids whose longer axes have the direction R′S′. The result of the shear is the same as if the body ABCD had been shortened in the direction PQ and elongated in the direction RS, and then rotated until PQ took the direction P′Q′. Similarly, in fig. 167 it is seen that the final result is the same as if the sphere were shortened in the direction ON and elongated in the direction OM, and then rotated until these lines coincided with O′M′ and O′N′. This, however, does not necessarily describe what has actually taken place. Assuming AB to be a plane of simple sliding throughout the whole process, then at any instant the directions of elongation and shortening are inclined at 45° to AB, and sliding is taking place not only along planes parallel to AB but along planes perpendicular to AB.

The above would seem to furnish an explanation of the relation of cleavage structure to bedding sometimes observed in the case of folded strata. When parallel strata are folded without rupture there must be a parallel readjustment between them; in other words, shearing parallel to the bedding must take place. The amount of this shearing is greatest at the limbs of the folds and becomes zero at the crests. On the above theory the cleavage structure, so far as determined by the local shearing deformation, would tend to develop along planes diagonal to the bedding. If the amount of the shear were known, the direction of the cleavage planes could be predicted, being such as to bisect the acute angle between the two sets of shearing planes in their final positions (the angle BAD′ in fig. 167). If the amount of sliding is different in different portions of the bedding, the direction of the cleavage will vary correspondingly, being most nearly parallel to the bedding at points where the sliding has been greatest (fig. 131). It is to be noticed that the cleavage planes may be much more nearly parallel to the bedding than are lines originally perpendicular to the bedding. Thus, in fig. 167 the line BE′, originally perpendicular to the bedding, falls into BE′, while AC′ represents the position of the cleavage planes.

This local tendency to the development of cleavage planes diagonally to the bedding may be combined with a general tendency to the production of cleavage in some direction, as already discussed; if so, the final result will be a cleavage intermediate in direction between those which would be due to the two causes acting separately.

The foregoing explanation of the production of cleavage has assumed that all particles yield equally to the deforming forces. A rock may, however, be composed of particles of different degrees of rigidity. In such a case the strain can not be regarded as homogeneous throughout a volume containing particles of unequal rigidity, and the theory above given needs modification. The result will, however, be the same in kind, though not in degree. As the simplest case, suppose the rock to be subjected to a simple compression whose direction remains constant while the rock mass undergoes a deformation of great amount. The various particles will be flattened unequally, but their shorter axes will be parallel, and cleavage will tend to develop along planes perpendicular to the direction of these shorter axes. Or, consider the same process with reference to the shearing planes. It has been shown in the preceding discussion of strain that a simple shear produces the same final result as an elongation and shortening along some pair of axes, together with a rotation of the body as a whole. If the rock contains particles of unequal rigidity, they will participate unequally in the elongation and shortening, but equally in the rotation. The direction of the cleavage planes is thus unaffected by the unequal rigidity of the fragments.

If the rock contains originally a great number of particles already flat, the conditions exist which are assumed in the theory of Sorby. If these particles are originally parallel, or nearly so, their parallelism is not destroyed by homogeneous strain, and they may be a factor in the production of cleavage. If, however, they have originally random directions of orientation, they will not be made parallel by any amount of homogeneous strain of the rock mass, although a compressive strain of great amount will cause them to approach parallelism, except those whose shorter axes are originally nearly or quite perpendicular to the direction of compression. Flat particles, even with an original random arrangement, may thus become a factor in the development of cleavage.

II FISSILITY.

Fissility, as the term is here employed, is due to the actual separation of the rock along certain planes. Such separation requires that the rock be under different conditions from those supposed in the development of cleavage; that is, the condition of stress and the properties of the body must be such that rupture will occur instead of unlimited deformation.

Actual separation of adjacent parts of a body may occur either by tension or by shearing. If it occurs by tension, the surfaces of separation are usually approximately plane and perpendicular to the axis of greatest elongation. If rupture occurs by shearing, it will occur along planes diagonal to the axes of greatest and least normal stresses. As a rule, rupture by shearing does not occur unless the greatest principal stress is compressive. Thus, an isotropic prism subjected to longitudinal tension and free from transverse stress will usually rupture along a surface which is approximately normal to the axis of tension. In exceptional cases, however, a prism under such conditions is found to rupture by shearing along a diagonal plane. If a longitudinal compression is substituted for the tension, rupture by shearing along a diagonal plane is the rule. If the body is under compression in all directions, the only possible rupture is by shearing. The exact conditions determining rupture in this case are unknown, but the difference between the intensities of the greatest and least principal stresses may be taken as the most important factor.[1] The question of most importance to the present discussion is in regard to the relations of the planes along which rupture will occur.

In ordinary engineering practice it is usual to assume that the liability to tangential rupture is greatest along planes of maximum intensity of shearing stress. This, however, overlooks the important consideration that the existence of normal stress on any plane may increase or decrease the resistance it can oppose to shearing. Experiments on the rupture of prisms by longitudinal tension or compression indicate that a compressive stress across any plane increases its capacity of resisting shearing rupture, while a tensile stress has the opposite effect.

Rupture by shearing occurs along planes for which the intensity of normal compressive stress is less (or of tensile stress greater) than exists on the planes of maximum intensity of shearing stress. Thus Hodgkinson[2] found as the average result of 21 experiments on the rupture of cast-iron cylinders by compression that the surfaces of rupture made angles of about 35° with the axis of pressure; while experiments by Kircaldy[3] on tensile rupture of steel showed that when rupture occurred by shearing the surfaces of rupture were inclined at angles of 65° with the axis of tension.

If these principles hold in the case of rocks under pressure, rupture by shearing would be expected to occur along planes oblique to the axes of greatest and least intensity of compressive stress, but (if the material is isotropic) inclined at angles of less than 45° to the axis of greatest stress. In such a case two intersecting sets of planes of rupture may develop, cutting each other at an oblique angle, the greatest pressure bisecting the acute angle. It seems improbable that such rupture would occur in a regular manner, so as to develop parallel planes of fracture throughout large volumes, although there might be considerable regularity throughout limited volumes. If, however, a structure such as cleavage already exists, the cleavage planes may determine the direction of fracture, even if they differ considerably in position from the planes which the rupture would follow in an isotropic body. The result may be a single prominent set of planes of fissility, following the original cleavage planes with considerable regularity. And a similar result may be reached, even if the original structure is not sufficiently regular and well marked to be called a true cleavage.[4]

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[1] See footnote 1 on page 847

[2] British Association Reports, 1837, p 349

[3] See Encyclopædia Britannica, article "Strength of materials," Vol XXII, p 601 By J A Ewing

[4] The figure shown by Sorby (Proc Q J Geol Soc, p 73, fig 4) illustrating "close joints" cleavage strongly suggests such an explanation as the above

In case two sets of planes of fissility are produced by tangential rupture, the relation between the two structures may be changed by subsequent flowage, so that their angle of inclination may range widely in value. Even without flowage, the angle would doubtless vary considerably in different rocks and under different stress conditions. In some cases the two sets of planes might intersect nearly at right angles. From the nature of the problem, however, it is evident that no exact principle governing the value of the angle of intersection can be stated.

Again, it is probable that in some cases there may be a considerable flowage, followed by rupture. It is not clear just how the nature of the rupture will be affected by previous flowage. It is possible that, even in a homogeneous body, flow will destroy the isotropy. It has been maintained that in a body originally homogeneous a pronounced and visible structure may result from flow unaccompanied by fracture.[1] It is not easy to see what the nature of the structure thus produced would be, nor what would be its relation to the axes of the strain and to the forces causing it. If, however, the rock is not originally homogeneous, flowage may produce a structure which will influence the mode of rupture. Thus, if the rock is finely granular, the result of the flow may be a flattening of the particles, as in the first stages of the development of slaty cleavage. The planes of rupture may then be partly determined by the structure thus developed. It is also to be remembered that during any finite strain the relation between the direction of maximum pressure and the axes of total strain may vary, and the planes of flattening may, at the instant of rupture, have any direction relative to the axis of greatest pressure.

Actual separation of the rock along planes of maximum compressive stress can not occur. What is ordinarily referred to as rupture by compression is in reality rupture by shearing. Thus, a short prism of a brittle material like cast iron or any ordinary building stone, if subjected to longitudinal compression, will rupture by shearing along surfaces oblique to the direction of compression. Usually the surfaces of rupture do not show great regularity of form or position.

If the above view is correct, the occurrence of a series of parallel planes of fissility showing great regularity of form and direction, throughout large volumes of rock, is usually to be attributed to a previously developed structure in the rock. Rupture by tension might, however, produce parallel planes of separation of considerable regularity, though probably not throughout any considerable extent of rock nor very close together. The occurrence of actual tensile stress in rocks near the surface of the earth is by no means improbable. A bending of strata would tend to cause tension near the convex surface of the fold. Contraction by cooling may in some cases account for rupture by tension.

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[1] "The Cleavage of Rocks," August Laugel Bull Soc Géol de France, 2d series, Vol XII, 1854-55, pp. 363-368 "Finite Homogenous Strain, Flow, and Rupture of Rocks," G F Becker, Bull Geol Soc Am, Vol IV, 1893, pp. 55-56

SUMMARY OF THE PRIMARY TRIANGULATION EXECUTED BY THE UNITED STATES GEOLOGICAL SURVEY BETWEEN THE YEARS 1882 AND 1894.

BY

HENRY GANNETT,
CHIEF TOPOGRAPHER

SUMMARY OF THE PRIMARY TRIANGULATION EXECUTED BY THE UNITED STATES GEOLOGICAL SURVEY BETWEEN THE YEARS 1882 AND 1894.

By Henry Gannett.

Since the inception of topographic work by the United States Geological Survey in the spring of 1882, primary triangulation has been carried on upon an extensive scale, for the purpose of furnishing ultimate control for maps. To convey an idea of the magnitude of these triangulation operations, it may be stated that during these thirteen years no fewer than 1,295 primary points have been located, furnishing control for fully a half million square miles of country, or one-sixth of the area of the United States, excluding Alaska.

Since the primary purpose of this work has been to control maps upon scales not ordinarily exceeding 1 mile to 1 inch, the extreme of accuracy has not been sought, but only such degree of accuracy as would insure that no errors perceptible upon the scale of the map could accumulate.

Whatever work has been done by other organizations which is deemed to be of sufficient accuracy for the control of the maps of the United States Geological Survey has been utilized, both immediately for the control of topographic work and also for the extension of triangulation therefrom by the United States Geological Survey. The work of the United States Coast and Geodetic Survey has been largely used in this manner, especially in the eastern part of the country. The maps in New England, New York, New Jersey, and Pennsylvania rest in large part directly upon the triangulation of that organization, while in the Appalachian region triangulation has been extended by the United States Geological Survey from points determined by the United States Coast and Geodetic Survey in its great Appalachian belt. The work of the United States Lake Survey, and that of the New York State survey under Mr. J. T. Gardiner, have been extensively utilized in a similar manner. In the interior of the country and in the far West, where no work by other organizations exists, primary triangulation has been done ab initio by the United States Geological Survey; astronomic determinations of positions have been made, base lines measured, and expansions effected by it.

As was stated above, 1,295 points have been determined by primary triangulation during the past thirteen years. These are distributed over thirty-three States and Territories, as appears from the following table, which gives the number determined in each State and Territory in which work has been done:

Maine	20	Michigan	7
New Hampshire	11	Arkansas	84
Vermont	1	Missouri	13
Massachusetts	13	Kansas	291
Rhode Island	12	Texas	236
Connecticut	16	South Dakota	19
New York	60	Montana	65
Pennsylvania	42	Wyoming	17
Maryland	5	Colorado	10
Virginia	44	New Mexico	32
West Virginia	32	Arizona	27
Kentucky	39	Utah	2
Tennessee	21	Nevada	12
North Carolina	23	Idaho	29
South Carolina	5	Oregon	4
Georgia	14	California	86
Alabama	3		

The methods and instruments employed in this work have developed as the work has progressed. This development has been in the direction of economy and efficiency as well as of accuracy, so that at the present time a much higher degree of accuracy is obtained than at the outset, together with a diminished expenditure upon field and office work.

In the early years of the work, base-lines were measured with secondary base bars. These were used up to the year 1887, when long steel tapes, 300 feet in length, under constant tension, were substituted, and have since been employed. They have been found more advantageous for the following reasons: The ground requires less preparation; the base can be measured much more rapidly, and, owing to the diminished number of contacts, with quite as great accuracy. By making the measurements upon cloudy days or at night, the correction for temperature is believed to be determined quite as accurately. Longer bases are measured, thus simplifying the expansion; and bases are measured more frequently, thus affording a greater number of checks upon the triangulation.

During the thirteen years in which this work has been going on, twelve base-lines have been measured in different parts of the country. Their localities, the date and means of measurement, and their approximate lengths are set forth in the following table:

Base-lines measured by the United States Geological Survey.

Locality	Year	Means of measurement	Length in miles
Wingate, N Mex	1881	Bars	4 20
Bozeman, Mont	1883	Bars	4 56
Austin, Tex	1884	Bars	6 40
Fort Smith, Ark	1887	Tape	2 84
Little Rock, Ark.	1888	Tape	3 72
Spearville, Kans	1889	Tape	7 10
Albany, Tex	1889	Tape	9 00
Sierra Blanca, Tex	1890	Tape	4 60
Boise, Idaho	1890	Tape	4 75
Aspen, Colo	1891	Tape	1 00
Laramie, Wyo	1892	Tape	2 50
Rapid, S Dak	1893	Tape	5 00

In early years the instruments used were vernier theodolites reading to 10 seconds, with circles 6, 7, 8, 10, and 11 inches in diameter. In 1889 there were substituted for these, 8-inch theodolites reading by microscope to 2 seconds, and these have since been employed universally in the primary triangulation.

While there is no question that the results from the instruments first used were amply accurate for the purpose, greater care was required in using them, a larger number of readings was necessary than with the present instruments, and the results were adjusted by least squares, which tedious operation is rendered unnecessary by the use of the better instruments. Indeed, it is believed that the instruments at present employed are of as high a grade as those in use in any part of the world, and that, by employing sharper signals, by exercising more care in the selection of times for observations, and by taking a larger number of measurements of angles than have heretofore been employed results can be obtained with them equal to the best secured in geodetic work.

The signals used differ with the facilities afforded by the neighborhood. The commonest form, and that which is generally in use in a settled country, is the ordinary tripod and pole, the tripod being swathed in cotton to facilitate finding it. In a wooded, unsettled region, tripods composed of three trees trimmed up are sometimes employed, or a single tree found upon the summit of a station is trimmed up and utilized as a signal. In the Rocky Mountain region a common signal is a cairn of stones upon a summit.

The permanent marks which have been left to indicate the stations also differ widely with the facilities afforded by the country for obtaining the necessary material. Of the total number of stations (1,295), 921 have been marked in a manner which may be regarded as permanent, 253 in a less permanent manner, while 121 have no mark of any degree of permanency. The permanent marks consist of copper bolts set in ledges, holes drilled in ledges, stone posts, buried bottles with stones set over them, and cairns of stones, upon the largest of which inscriptions have been marked. Iron bolts and pipes set in the ground have been used. In many cases upon the plains section corners of the General Land Office surveys have been located, and in this case the section corner serves as the permanent mark. Buildings of various sorts also serve this purpose in numerous cases. Less permanent marks are marked trees, tripod signals, etc.

Triangulation has been carried on in the following areas in the years named:

New England, in the years 1887 to 1890, and in 1892.
New York and Pennsylvania, from 1889 to 1894
Southern Appalachian region, from 1882 to 1890
Upper peninsula of Michigan, in 1889.
Arkansas, from 1887 to 1891
Texas, from 1884 to 1893.
Kansas, from 1885 to 1887, and in 1889 and 1890.
Montana, in 1883 and 1884, 1886 to 1889, and in 1891
Wyoming, in 1892
Colorado, in 1893 and 1894
New Mexico and Arizona, from 1882 to 1890.
Idaho, from 1889 to 1892
California, from 1882 to 1893.
South Dakota, in 1891 and 1893.
Oregon, in 1894

There has been expended upon this triangulation, including base measurement and expansion, and also all salaries and other expenses connected therewith, about $400,000, an average per year of $30,000, and an average per station located of a trifle over $300. The average expense of primary triangulation per square mile of area triangulated is about 80 cents. This item differs widely, however, in different parts of the country, being far greater in heavily timbered, level country, where the triangle sides are short and the expenses of clearing and signal-building heavy, while in the Rocky Mountains, when the triangle sides are long and when there is no clearing necessary, the cost is far below the above average.

As the simplest method of characterizing the degree of accuracy of this primary triangulation, the following table of average closure errors of triangles is presented. It is to be understood that in all cases the station adjustments and correction for spherical excess had been made prior to footing up these errors of closure. The work in Texas prior to 1887 and in other areas prior to 1889 was done with vernier theodolites, while the work in those and subsequent years was done with micrometer theodolites.

Closure errors of triangles.

Year	Number of triangles	Closure errors	Year	Number of triangles	Closure errors
Central Texas			New Mexico		
1884	......	8 50	1886	42	9 50
1886	40	7 77	1889 and 1890	29	10 00
1887	50	5 22	Montana		
1888	14	8 08	Early years	48	19 10
1889	38	7 08	1891	74	3 39
1890	54	4 00	Kansas		
1891	41	4 43	1885	62	7 95
1892	16	7 83	1886	20	15 80
1893	15	8 71	1889	71	3 49
Western Texas			1890	*40	1 73
1892	36	9 85	1890	†62	2 07
California			Arkansas		
1886	34	18 86	1887-88	103	8 14
1887	9	13 46	1889	43	6 66
1889	24	6 93	1890	38	7 54
Arizona			1891	48	9 18
1883	13	12 46			

* Spearville belt † Northern belt

The work in New England, New York, and Pennsylvania has been mainly supplementary to the work executed by the United States Coast and Geodetic Survey, and that in New York to the work of the United States Lake Survey and the New York State survey. In some places it has been found necessary to extend triangulation from the existing work of these organizations in order to furnish control for areas to be surveyed in other localities, and in certain cases the stations in preexisting work were too far apart to serve the purposes of the topographer, and it was therefore necessary to multiply stations within preexisting triangulation. The work done in these States by the United States Geological Survey is, therefore, not in compact bodies, but consists of a little work here and a little there.

The work in the Appalachian Mountain region south of Mason and Dixon's line is very extensive, spreading from the Blue Ridge westward across the valley and over most of the Cumberland Plateau. Its northern limit is Mason and Dixon's line, and its southern limit is the neighborhood of Atlanta, Ga., and Birmingham, Ala. This work rests upon stations of the United States Coast and Geodetic Survey along the Blue Ridge and the outlying ridges to the eastward, known as its Appalachian Belt. Most of the stations of the United States Coast and Geodetic Survey on the Blue Ridge from Maryland to Georgia have been occupied by the United States Geological Survey as initial points for triangulation. The work in this region has been done throughout with 6-inch and 7-inch vernier theodolites reading to 10 seconds, and has been subjected to least square figure and station adjustments.

A little triangulation has been done on the upper peninsula of Michigan for the purpose of controlling surveys of the Marquette iron district. This triangulation rests upon two stations of the United States Lake Survey, near Marquette.

The northwestern quarter of the State of Arkansas has been quite well covered by triangulation This was initiated by a base measured in the eastern part of Indian Territory, near Fort Smith, Ark., the site being a tangent of the St. Louis and San Francisco Railroad. The base is 2.84 miles in length. It was measured at night with a 300-foot steel tape. After expanding, triangulation was carried eastward to the neighborhood of Little Rock, opposite which, near Argenta, a second base, 3.72 miles long, was measured in a similar manner upon the roadbed of the St. Louis, Iron Mountain and Southern Railroad. The angles in the triangulation were measured with a 7-inch vernier theodolite reading to 10 seconds.

From stations in the eastern portion of this belt, work was extended northward across the Arkansas and over the Ozark Plateau to the Missouri boundary, thence returning southward near the west boundary of the State, and closing upon stations in the western part of the belt. Angles in this work were measured with an 8-inch micrometer theodolite.

The triangulation in Kansas is in three detached belts, each of which starts from a line of the transcontinental triangulation of the United States Coast and Geodetic Survey. The southern belt begins with the line Fulton-Hutton Mound, some 20 miles east of the Missouri-Kansas boundary, and proceeds nearly due west in a narrow belt of triangles and quadrilaterals until the Arkansas River is reached at Hutchinson; thence the general course of the river is followed as far as Larned, at which point the conditions favored a detour southwestward to Dodge, after which the river was followed to its present terminus, near Hartland.

The first part of this belt was executed in 1885 with a Gambey 11-inch vernier theodolite. In 1889 the belt was continued westward as far as Spearville with a Fauth 8-inch micrometer theodolite. At Spearville a base 7.1 miles in length was measured with a 300-foot steel tape, with a probable error of 0.39 of an inch. The next year work was resumed at Spearville and continued westward to the present terminus of the belt, at Hartland.

A second belt of triangulation was executed in 1886, work being based upon the United States Coast and Geodetic Survey line, Blue-Mound-Eckman, near Lawrence, Kans. This belt runs northwestward and then westward. Angles were measured with the Gambey 11-inch theodolite above referred to.

A third belt, lying west of that just described, uses for initial positions three stations of the United States Coast and Geodetic Survey, Blind Creek-Frey Wilman. This belt first proceeds northward about 40 miles, and then takes a general westward course to its present terminus, near Leland, Kans. It consists of a series of well-proportioned quadrilaterals of larger size than the other two belts, the increase in size being rendered possible by more favorable topographic conditions. The instrument used was a Fauth 8-inch micrometer theodolite. Angles were read by the method of direction, both singly and combined, in such manner as to give check observations on each angle which entered into the position. Adjustment by least squares was made in the earlier work, when vernier theodolites were employed; but in the later work, when better instruments were employed, it was considered unnecessary Nearly all the signals consisted of tripods built of lumber. In connection with this triangulation a large number of section corners were located, usually by measuring directions and distances from the triangulation stations.

Triangulation has been carried on in Texas in two localities, namely, middle Texas, between longitudes 96° 30′ and 101°, and western, or trans-Pecos, Texas. The work in the latter section extends from the western point of the State as far eastward as longitude 103°, and from the Rio Grande to the New Mexican boundary line, inclosing an area of about 15,000 square miles.

The triangulation in middle Texas covers an area of about 50,000 square miles, nearly rectangular in shape. The work in this region was commenced in the neighborhood of Austin in the summer of 1884. A base-line 6.4 miles in length was measured with four-meter bars, and was connected with the astronomical determination of the United States Coast and Geodetic Survey at Austin. Work was carried on continuously until 1889, covering the area closely. In the latter year a verification base was measured near Albany, in the northern part of the State This Albany base is about 9 miles in length, and was measured twice with a 300-foot steel tape under a tension of 20 pounds. The instruments used in the triangulation were 8 inch theodolites with verniers reading to 10 seconds, up to and including 1886, and during the remainder of the work an 11-inch theodolite reading by microscopes to single seconds was employed. The work done with the first named instruments was adjusted by least squares; that subsequently done was not subjected to this adjustment. The signals were mainly tripods made from sawed lumber, with an interior scaffold for the support of the instrument whenever it was necessary to raise it from the ground.

In trans-Pecos Texas triangulation was commenced in the spring of 1890 A base-line was measured on the roadbed of the Texas and Pacific Railway, and an astronomic determination of position was made at Sierra Blanca. In this region the triangulation stations were usually the summits of sharp and well-defined mountain peaks, which were marked by piles of stones that served as signals.

Triangulation in the Black Hills of South Dakota originated in a base line in the valley of Box Elder Creek, about 4 miles northeast of Rapid. This base is nearly 5 miles in length and was measured with a 300-foot steel tape under a uniform tension of 20 pounds. The probable error of the measurement is 0.84 of an inch. The initial astronomic point is a pier in the county court-house at Rapid, the position of which was determined in 1890. The instrument used in the triangulation was an 8-inch theodolite reading by microscopes to 2 seconds. The signals consisted of tripods of lumber with a signal pole in the center, under which the instrument was placed.

A little triangulation has been done in the Elk Mountains of Colorado for the control of a small area about Aspen. This work rests upon a base-line 1 mile in length measured along one of the streets of Aspen, and for astronomical position the work was connected with a station of the United States Coast and Geodetic Survey on Treasury Mountain. Angles were measured with an 8-inch vernier theodolite.

Triangulation in southern Wyoming rests upon a base-line about 2.5 miles in length measured along the roadbed of the Union Pacific Railroad just north of the town of Laramie. The initial position is an astronomical station in Laramie determined in 1872 by the Wheeler Survey. The instrument used in this triangulation was an 8-inch micrometer theodolite.

Triangulation in Montana covers an area of about 50,000 square miles. A base line located just west of the town of Bozeman, which was measured by officers of the Wheeler Survey in 1877 with a steel tape, was remeasured in 1883 by the United States Geological Survey with a secondary base apparatus. It was expanded and the work carried southward, to include the area of the Yellowstone National Park, during 1883 and 1884. In subsequent years the work was carried eastward, northward, and westward over much of central and western Montana. The angles were measured with an 8-inch vernier theodolite. In 1889 the triangulation was extended eastward down the valley of the Yellowstone to the neighborhood of Fort Custer, using an 8-inch micrometer theodolite.

Triangulation in Idaho covers an area of about 15,000 square miles, forming a parallelogram about 100 miles in breadth by 150 in length, extending from the longitude of Hailey on the east to the western boundary of the State. Work was begun in the summer of 1889 and continued until 1892, inclusive. It rests upon a base-line 1.75 miles in length measured near Boise with a 100-foot steel tape, and the resulting probable error of different measurements was 0.19 of a foot. The initial astronomic position is in the city of Boise. The instruments used in this triangulation were at first a 7-inch vernier theodolite, and during the seasons of 1891 and 1892 a 10-inch micrometer theodolite. The work done with the vernier theodolites was adjusted by least squares; that executed with the 10-inch theodolite was not subjected to this adjustment.

Triangulation in California, Nevada, and Oregon is in three distinct parts, which may be distinguished as the Cascade section, in northern California and southern Oregon; the Gold Belt section, including the Sierras in the latitude of Red Bluff, the Yosemite Valley, and from the Sacramento Valley eastward into Nevada; and the southern California section.

The work in the first section was begun in 1882 and continued until 1887. All distances, azimuths, and positions depend on the line Lassen-Shasta, as determined from unclosed triangles of the United States Coast and Geodetic Survey. The instrument used in this portion of the work was an 8-inch 10-second vernier theodolite. Natural points mainly were sighted, since sharp peaks were generally used. The work was adjusted by least squares.

In the Sierra Nevada, work was commenced in 1885. This work rests upon the line Marysville Butte-Pine Hill of the United States Coast and Geodetic Survey. Other lines determined by the same organization were used as check lines. During the first year the angles were measured with a 7-inch vernier theodolite. Subsequently work was done with similar instruments having an 8-inch circle. Upon most of the stations on this work signals were built, and in many cases these were very high and difficult to construct.

Triangulation in southern California was begun in 1891, and covers an area of about 5,000 square miles. The line Southeast Base-San Juan, as determined by the United States Coast and Geodetic Survey, serves as a base-line for this work. The instrument used was an 8-inch micrometer theodolite.

The triangulation in the plateau region of northern New Mexico and Arizona and parts of adjacent States depends on a base measured at Fort Wingate, N. Mex. This was measured in 1881 with four-meter bars, and was expanded and triangulation depending upon it was carried forward until 1890. The initial position, which is Fort Wingate, was located in 1883. The instrument used in the triangulation was a 10-inch vernier theodolite, prior to 1890, in which year an 8-inch micrometer theodolite was used. Many of the signals of this triangulation were natural points, consisting of high, sharp peaks. In other cases cairns of stone or trees were used. This triangulation, being carried on in a region of high mountains, consists of very large figures, lines of 100 miles in length being not uncommon. The area covered by this triangulation is approximately 94,000 square miles.

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CHARLES D. WALCOTT, DIRECTOR.
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for the fiscal year
1894–95.
Compiled by Henry Gannett.
LEGEND.
Surveyed by U. S. Geological Survey 1894-5, Scale 1:62.500
" " " " " 1:125.000
" " " in previous years, Scale 1:62.500
" " " " " " 1:125.000
" " " " " " 1:250.000
Surveyed by other organizations.
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INDIAN TERY.
MAINE
INDIANA
OKLAHOMA
KENTUCKY
OHIO
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ARIZONA
NEW MEXICO
MONTANA
CALIFORNIA
TEXAS
C A N A D A
(B R I T I S H P O S S E S S I O N S)
P A C I F I C
A T L A N T I C O C E A N
G U L F O F M E X I C O
ENGRAVED BY U.S.G.S.
Scale
300 STAT. MILES
LITH. BY A. HOEN & CO. BALTIMORE, MD.