The publications of the United States Geological Survey are issued in accordance with the statute approved March 3, 1879, which declares that—

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ANNUAL REPORTS.


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MONOGRAPHS.

Monograph I is not yet published.


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V. The Copper-bearing Rocks of Lake Superior, by Roland Duer Irving. 1883. 4°. xvi, 494 pp. 15 pl. 29 pl. and maps. Price $1.55.

VI. Contributions to the Knowledge of the Older Mesozoic Flora of Virginia, by William Morris Fontaine. 1883. 4°. xi, 144 pp. 54 pl. Price $1.95.


X. Geological History of Lake Lahontan, a Quaternary Lake of Northwestern Nevada, by Israel Cook Russell. 1885. 4°. xiv, 288 pp. 46 pi. and maps. Price $1.75.


XII. Geology of the QuickSilver Deposits of the Pacific Slope, with atlas, by George F. Becker. 1888. 4°. xix, 486 pp. 7 pl. and atlas of 14 sheets folio. Price $2.00.


In preparation:

XV. Younger Mesozoic Flora of Virginia, by William M. Fontaine.

XVI. Paleozoic Fishes of North America, by J. S. Newberry.

XVII. Description of New Fossil Plants from the Dakota Group, by Leo Lesquereux.

XVIII. Geology of the Eureka Mining District, Nevada, with atlas, by Arnold Hague.


Geology of the Eureka District, Nevada, with atlas, by Arnold Hague.

Sauropoda, by O. C. Marsh.

Stegosauria, by O. C. Marsh.

Brontotheria, by O. C. Marsh.


Flora of the Dakota Group, by J. S. Newberry.

The Glacial Lake Agassiz, by Warren Upham.

Geology of the Potomac Formation in Virginia, by W. M. Fontaine.

BULLETINS.

Each of the Bulletins contains but one paper and is complete in itself. They are, however, numbered in a continuous series, and may be bound in volumes of convenient size. To facilitate this, each Bulletin has two pagination, one proper to itself and another which belongs to it as part of the volume.


2. Gold and Silver Conversion Tables, giving the coining values of troy ounces of fine metal, etc., computed by Albert Williams, jr. 1883. 8°. 8 pp. Price 5 cents.

3. On the Fossil Faunas of the Upper Devonian, along the meridian of 78° 30', from Tompkins County, N. Y., to Bradford County, Pa., by Henry S. Williams. 1884. 8°. 36 pp. Price 5 cents.


18. On Marine Eocene, Fresh-water Miocene, and other Fossil Mollusca of Western North America, by Charles A. White. 1886. 8° 26 pp. 3 pl. Price 5 cents.
24. List of Marine Mollusca, comprising the Quaternary fossils and recent forms from American Localities between Cape Hatteras and Cape Horno, including the Bermudas, by William B. Ives. 1885. 8° 336 pp. Price 25 cents.
27. Report of work done in the Division of Chemistry and Physics, mainly during the fiscal year 1884-85. 1885. 8° 80 pp. Price 10 cents.
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In press:
49. On the Latitudes and Longitudes of Certain Points in Missouri, Kansas, and New Mexico, by R. S. Woodward.
50. Formulas and Tables to facilitate the construction and use of Maps, by R. S. Woodward.
51. Invertebrate Fossils from California, Oregon, Washington Territory, and Alaska, by C. A. White.
53. Geology of the Island of Nantucket, by N. S. Shaler.

In preparation:
— Notes on the Geology of Southwestern Kansas, by Robert Hay.
— On the Glacial Boundary, by G. F. Wright.
— The Gabbros and Associated Rocks in Delaware, by F. D. Chester.
— Geology of the Pacific Coast, by W. H. Malville and Waldemar Lindgren.
— Report of work done in the Division of Chemistry and Physics, mainly during the fiscal year 1886-87.
— The Grenatome Schist Areas of the Menominee and Marquette Regions of Michigan, by George H. Williams; with an Introduction by R. D. Irving.
— Bibliography of the Paleozoic Crustacea, by A. W. Vogdes.
— The Viscosity of Solids, by Carl Barus.
— On a Group of Volcanic Rocks from the Tewan Mountains, New Mexico, and on the occurrence of Primary Quartz in certain Basalts, by J. P. Iddings.
— On the relations of the Traps of the Jura-Trias of New Jersey, by N. H. Darton.
— Altitudes between Lake Superior and the Rocky Mountains, by Warren Upham.
— Mesozoic Fossils in the Permian of Texas, by C. A. White.

STATISTICAL PAPERS.

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

In preparation:

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LETTER OF TRANSMITTAL.

DEPARTMENT OF THE INTERIOR,
UNITED STATES GEOLOGICAL SURVEY,
Washington, D. C., October 1, 1886.

SIR: The report of the operations of the Geological Survey for the fiscal year ending June 30, 1886, is herewith transmitted.

I have the honor to acknowledge with gratitude the many favors received at your hands and to express my thanks for the earnest support you have given to the work under my charge.

I am, with great respect, your obedient servant,

[Signature]
Director.

Hon L. Q. C. Lamar,
Secretary of the Interior.
At the time the Geological Survey was organized the field geologist found within his reach maps of very few portions of the country that he could utilize in delineating geologic phenomena; accordingly, as has been fully set forth in previous reports, recourse was had to existing statutory authority for the organization of a geographic division. The chief functions of this division are: First, the prosecution of a topographic survey of the entire country; second, the preparation of topographic maps thereof, on such scales as are required for the accurate delineation of geologic structure; and, third, geodetic co-ordination of the topographic surveys in such manner that when they are completed and the topographic maps are combined they will constitute an accurate geographic map of the entire country, showing, with a good degree of exactness, its extent; its relations to contiguous countries; the boundaries of states, counties, &c.; the positions on the earth's surface of cities, towns, railways, highways, and other public cultural features; the creeks, rivers, lakes, coast lines, and other hydrographic features; and the mountains, hills, valleys, canons, plains, and other hypsographic features.

The prosecution of this topographic survey, unlike the original research of the geologist, is to a large extent a work of applied science; and, after the adoption of suitable methods
and standards, the surveys and the preparation of maps can be carried forward with few changes in organization save those demanded by changes in the field of operation. Experience has shown, however, that there is a constant improvement in methods and an elevation of standards.

Anterior to the organization of this division of the Geological Survey, topographic science and topographic art had received high development through other organizations in this country and in Europe; but to a large extent such work had been prosecuted with the object of producing charts for military purposes on the one hand or for fiscal purposes on the other; thus the art had been directed to the production of military maps and cadastral maps. During the last half century the science of geology, because of its great industrial importance, has been greatly developed; and as all the civilized nations of the earth have promoted and endowed geologic research and as geologic maps are among the most important results arising therefrom, the need for topographic maps as a basis for geologic maps has largely modified the map-making systems of the world. Yet the earlier purposes for which they were made largely prevailed, with the result of still producing maps chiefly valuable for military or cadastral uses. Now, such maps are on scales too large for general industrial purposes, and must represent such a variety of facts as to make them exceedingly complex; still further, the multiplied data presented are to a large extent ephemeral, and the maps which represent them must be frequently revised by re-survey, redrawing, and re-engraving.

In developing the topographic work of the Geological Survey, especial attention has been given to the industrial purposes for which maps are made; for the best topographic map for geologic purposes is also the best for other scientific and industrial purposes.

If a good topographic map of the country be constructed, having in view the representation of three classes of facts: first, public cultural features; second, hydrographic features; third, hypsographic features, such a map is a proper basis for a geologic map. It is also a proper basis for all other maps
designed for industrial purposes; it is a proper basis for general military maps, and provides the fundamental data for cadastral maps. And such a map of the United States is now in process of construction.

Having decided the scale and the class of facts to be represented upon the map, the survey in the field must be adjusted thereto for economic considerations; and this fact has been kept persistently in view in the organization of this branch of the service.

Although the method of representing relief in contours or grade curves has long been in vogue in this and other countries, these conventions have usually been supplemented by hachures or brush shading whenever it became necessary to represent widely diverse types of topography on the same map. To a certain extent, therefore, the plan of representing the relief of all parts of the surface of a country upon a uniform series of maps by means of contours alone was an innovation; and it is a source of gratification to find that this plan, which has been fully set forth in preceding reports, is eminently successful.

The objections to the use of hachures and brush shading are manifold: they obscure the map and conceal the conventions employed for the representation of other conditions and features of the surface; they easily degenerate into generalized conventions for imperfectly ascertained facts of relief, and thus fail to convey accurate information; they lead to the development of special artistic styles by the several draughtsmen employed upon the work, and thus do not have a uniform meaning from sheet to sheet; in districts of complex topography they are difficult of interpretation; and they represent reliefs only in a qualitative manner.

Another potent reason for the rejection of hachuring methods of representing topographic reliefs inheres in their excessive cost. The drawing and engraving of topography with hachures is many times more expensive than the drawing and engraving of the same in contours. In fact, hachure drawing and engraving almost equal in expense the field work by which the facts are collected. In the preparation of a map of a
region so great as the United States—three million square miles in area, exclusive of Alaska—questions of economy are of prime importance.

The method of hachuring has gained, and yet maintains, a strong hold among geographers because of its artistic capabilities; for by means of hachures alone, or in combination with either brush shading or contours, or both, it is possible to produce maps that have much artistic beauty and as forcibly express the artistic conceptions and individuality of their authors as do paintings and statuary. But therein lies the imperfection of the system; for in so far as the finished map expresses the individuality of the author, in just so far does it defeat the purpose for which it was designed, namely, the accurate representation of a portion of the earth's surface.

The cartographic conventions, i. e., the symbols to be used on the maps for the representation of the cultural, hydrographic, and hypsographic facts, have been reduced to the greatest possible simplicity, in order that the maps may be easily understood and be of value to all classes of people. As the cost of the Survey is borne by all the people of the United States, it was not deemed just that a map system should be adopted with a view to subserve the wants of trained engineers only. Still it is believed that while the system selected is so simple as to be easily used by all, it yet represents with precision and accuracy all the topographic facts desired by the engineer.

The maps already completed and engraved by the Survey include a great variety of topographic types, but all of these have been reduced to the uniform standard of cartographic representation adopted at the commencement of the work. The experience gained in the prosecution of the surveys upon which these maps are based and the preparation of the maps themselves demonstrate that the method of representing relief by contours not only enables the topographer to express the condition of the earth's surface quantitatively, but that within certain definite limits it permits the expression of artistic conceptions, and hence the production of maps which are highly
but not obtrusively artistic and at the same time strictly accurate.

The recognition and delineation of the features of the earth's surface by the topographers of the Survey has become a highly developed art, depending on experience and mechanic skill, the training and co-ordination of the eye and the hand, and the development of artistic perception of the reliefs diversifying the land. The value of the reliefs and the character of the topographic forms determined thereby vary from place to place, and the features of the surface are variously concealed by forests; and the methods of surveying in different localities are modified by the topography, the degree of concealment by forests, the facilities for travel and subsistence, and various other conditions. So the character of the special training of the topographer varies locally. Nevertheless, special work in any field is beneficial, and in a measure prepares the surveyor to enter upon other fields of work intelligently and promptly; and accordingly the retention of skilled topographers is found to be highly advantageous. Hence the changes in organization of this division of the Survey required from time to time, as the work is completed in certain areas and initiated in other areas, do not generally involve material changes in the personnel.

Under the statutes relating to the Geological Survey there is no provision for the general publication of purely topographic maps. These maps can be published only as a basis for "geological and economic maps illustrating the resources and classification of the lands," but a small edition is necessarily printed for the use of the employés and collaborators of the Survey in the prosecution of field work.

The demand for topographic maps has grown to great proportions, and it may be found advisable to ask the authority of Congress for their general distribution.

Although the topographers employed by the Survey are necessarily competent draughtsmen and usually construct their own maps, it has been found desirable, in order (1) to secure uniformity in style and character and (2) to obviate the necessity for employing the topographers in the office during months
REPORT OF THE DIRECTOR.

in which they might more profitably be employed in the field, to organize a section of topographic drawing. In like manner, as set forth in an earlier report, the necessity for the adoption of uniform standards for the astronomic and geodetic work required in the co-ordination of the topographic surveys has led to the organization of an astronomic and computing section. Finally, it has been found economic, both in time and money, to establish a section in which are made the repairs of the large number of instruments constantly required by the division.

THE GEOLOGIC DIVISIONS.

It became necessary at the outset of geologic investigation to develop a system of taxonomy applicable to American rocks and a system of conventions whereby these rocks might be properly distinguished upon maps issued by the Survey and properly designated and defined in the accompanying letterpress. But there are difficulties in the way of developing such systems of taxonomy and graphic conventions. In the first place, there has grown up with geologic science a conventional language involving a taxonomy and a method of graphic representation which is based on the phenomena of other countries, and which is accordingly to some extent inapplicable to American rocks; it is nevertheless desirable to adhere as closely as possible to this conventional language because of its wide adoption. In the second place, it is manifest that a great portion of the rockmasses to be classified and represented on the maps have not yet been discovered. It has accordingly been necessary to devote much labor and thought to the development of a cartographic system which shall meet the following among other conditions: (1) it must be sufficiently definite to be readily intelligible to all users of the geologic maps published by the Survey, whether their interests lie in the scientific relations of the phenomena represented or in the economic resources of the areas mapped; (2) it must be sufficiently elastic to yield to the requirements not only of the tentative classification of the rocks now in vogue but of such final classification as may be evolved after the extension of geologic operations over the whole country; and (3) it must be sufficiently com-
prehensive to represent, without duplication of conventions and symbols, all rockmasses of the entire dominion of the United States which it may at any time become necessary to discriminate for scientific or economic reasons.

Pending the completion of a cartographic system suitable for present and future needs, geologic investigation of course has continued; and indeed the results of such investigation, as developed from time to time, have served an important purpose in determining the limitations and requirements of the cartographic system. Moreover, questions as to the taxonomic positions of the rockmasses discriminated in the field have arisen from time to time and will continue to arise in the future. The cartographic system devised to meet the various considerations involved must, therefore, be applied from time to time, as research progresses; and the rockmasses discriminated by each geologist in the field have to be correlated with those discriminated by every other geologist, and the entire sum of observations has to be combined and built up into a single comprehensive and symmetric system. To this end exhaustive study of the current and antecedent literature of American geology and occasional field investigations in critical areas are required.

The general work of systemization and co-ordination is the legitimate function of the administrative head of the Survey, but the amount of detailed labor involved has proved so great that it has become necessary to obtain the aid of one of the assistants of the Survey; and for this purpose a portion of Mr. W J McGee's time during the past year has been given to the collection of the data to be used in this work.

The Geological Survey inherited much unfinished work of different surveys in the Western Territories previously prosecuted under the auspices of the Government. Since it seemed desirable to carry forward and complete these surveys as rapidly as possible, investigations were continued in the fields covered by them, and thus the early organization of the Survey was determined in part by antecedent geologic work. At the same time, however, demands for local geologic and mineralogic investigations came from various portions of the country, including the older and long settled States, and as soon as the
legality of such action was established the geologic operations of the Survey were extended into the older States, and a number of divisions were organized and intrusted with the investigations.

It should be explained that by its organic law the Geological Survey is inhibited, both implicitly and directly, from making a geologic survey upon a cadastral plan, i. e., from making investigations relating to the value of properties of individuals. Accordingly, its work in economic geology is limited to the observation and mapping of the formations within which mineral resources lie; the general distribution and characteristics of coal beds, ore bodies, and other valuable mineral deposits; and the investigation of questions relating to the origin and taxonomic relations of the formations themselves and of their contained minerals.

Within the above limitation it has been found possible to make the scientific investigations of the Survey of high economic value, (1) by extending its operations into those portions of the different States in which the natural resources have not yet been fully developed, and (2) by developing and applying such systems of classification of the formations as will at the same time enable and compel the geologist to discriminate in the field and clearly distinguish on the maps of the Survey those rockmasses which are economically important. Both of these means of rendering these investigations of the Survey of maximum value to the country have been adopted. Moreover, friendly relations exist between the United States Geological Survey and the geologic surveys prosecuted under the auspices of different States of the Union; and in many cases partial co-operation with these States has been effected in such manner that the State geologists leave to the Federal Survey the investigation of such general scientific questions as involve operations beyond the limits of their own States as well as within them and avail themselves of the results of this investigation, and in return permit the general Survey to utilize the results of their own more strictly economic studies.

Many of the investigations undertaken within the public domain are purely economic in character, and all give promise
of results of economic importance—either immediately through the discovery and development of natural resources, or remotely through the additional knowledge gained from them as to the modes of origin and laws of distribution of ore deposits, the relations between geologic structure and agricultural capabilities, &c.

For various requirements a number of distinct geologic divisions have been organized, and the occasion for each is demonstrated in the work which it has accomplished.

THE ACCESSORY DIVISIONS.

Ever since the birth of geologic science the importance of the fossils found in the rocks as a guide to geologic classification has been recognized; indeed, a large proportion of the questions which the geologist is called upon to answer cannot be answered without their aid, and paleontology, therefore, is now, as it ever has been, an essential part of geologic science. But geology is differentiated into many departments, and its progress has been along many lines; a large fund of special knowledge is required of the student in each; and the literature in each has become voluminous. Accordingly, it is no longer possible for the geologist, whose function it is to study the relations of the rocks themselves, to adequately investigate the relations of the fossils contained in these rocks. Division of labor is required: the geologist investigates the rocks and ascertains their physical characteristics and relations to contiguous rockmasses; while the paleontologist, studying the fossils collected from the same rocks by the geologist, determines the relations of these rocks to rockmasses in all parts of the earth. To meet this imperative demand for paleontologic investigation a number of divisions have been created; and although paleontology is but a subordinate branch of geologic science, and the results of paleontologic investigation are hence but means to an end, the publications growing out of the work in these divisions are among the most valuable contributions to science already published or to be published in the near future by the Survey.
Another class of criteria for determining the relations of rocks is found in their chemic constitution. Most of the questions concerned in geologic technology or in the application of geologic science to the arts involve a knowledge of the chemic constitution of rocks; and in addition requests for the chemic examination of various rocks, minerals, ores, soils, waters, gases, and natural oils, required for the proper prosecution of important public works, reach the Survey from time to time. To meet these various demands, a division of chemistry was early organized by the Survey, as specified in previous reports. There is connected therewith a physical laboratory, in which are prosecuted researches relating to the effects of temperature, pressure, moisture, &c., upon rocks, and the causal conditions of crystallization, segregation, and secondary alterations of various kinds such as have during the geologic ages resulted in the formation of mineral veins, the metamorphism of rocks, &c.

A third class of criteria valuable in ascertaining the interrelations of rockmasses and the presence therein of economically valuable minerals is found in their minute structure, discoverable only with the aid of the microscope; and in this and other countries microscopic petrography has rapidly grown to be one of the most important and promising lines of geologic research. The microscopic examination of rocks, however, involves cutting, grinding, and mounting of slides by means of delicate and costly machinery, and in some cases the separation of the rock constituents by means of fluids of variable specific gravity. This work, as well as the examination of the material thus prepared, requires skill of a high order and the permanent employment of the specialists entrusted with the work. In pursuance of its general policy of utilizing the latest discoveries in science and art whereby geologic investigation may be promoted, a petrographic laboratory has been organized in which all work of this character is done.

To meet the constant demand for information respecting the economic and industrial results of geologic investigation and the development of the mineral resources of the country,
a division of mining statistics and technology has been established, as set forth in a previous report.

Some of the most important questions of the day, from both a scientific and an economic standpoint, are those involved in the relations of the soils and vegetation of the earth to the rocks which they conceal and from which the one is derived and by which the other is supported. Moreover, the distribution of the forests of this country is one of great and ever increasing importance to its people. Now, in the prosecution of the topographic surveys there is incidentally collected a vast amount of information relating to the forests of the different States in the Union which can be rendered available at small expense; and, in obedience to the statute relating thereto, there has been established a division of forestry, the functions of which are the collection and diffusion of data relating to the forests of the country, their extent and value, their proximity to routes of transportation, and our national resources in timber, lumber, ornamental woods; fuel, tan bark, and the various other forest products.

A division of illustrations has been established, and was described in a preceding report from this Office.

The tools of the field geologist are the hammer, trowel, compass, clinometer, and magnifying glass; but the no less essential tools of the same geologist when employed in elaborating the results of his field studies are books; for no original investigator regards his work as complete until he has ascertained the results of researches in the same or related fields by all other investigators. Thus a library is a necessary part of the equipment of the working geologist. The literature of the science has become so voluminous that the purchase and maintenance of an adequate library by the individual geologist is a burden too great to be borne unless his means are ample, and students are compelled to avail themselves of extensive public libraries. It has been found economic of time, labor, and money to build up a carefully selected library of such strictly geologic works as are required from time to time by the officers of the Survey. The library now contains no less than 17,255 books and 19,600 pamphlets, together with
9,000 maps. These come from all parts of the world, as indicated by the fact that they are printed in no less than nineteen languages, and include not only current scientific publications of private and public institutions, but the most important serial publications and also nearly all the standard contributions to telluric science that have ever been published. It is maintained chiefly by exchanges.

Since the material sent out in exchange consists of the publications of the Survey, a division has been established whose functions are the care of the library and the distribution of publications. That the work of this division is very great may be readily inferred from the facts that the publications have already reached 41 in number and are issued in various editions, aggregating 225,900 copies, in large part distributed by the Survey; that the library now contains no less than 36,855 books and pamphlets, besides 9,000 maps, and that a vast correspondence is involved in the elaborate system of exchange.

SCHEDULE OF ORGANIZATION.

Although the organization of an institution devoted to original research can never be considered final, the present differentiation of labor in the Geological Survey may be regarded as definite and comparatively thorough. It is as follows:

**Geography.**

In charge.

Division of Geography ...................... Henry Gannett.

Northeastern Section of Topography ........ Marcus Baker.

Massachusetts Subsection of Topography.

New Jersey Subsection of Topography ..... George H. Cook, State geologist.

Appalachian Section of Topography ........ Gilbert Thompson.

District of Columbia Section of Topography.

Central Section of Topography ............ Jno. H. Renshawe.

Western Section of Topography ............ A. H. Thompson.

Texas Subsection of Topography.

Arizona Subsection of Topography.

Gold Belt Subsection of Topography.

Cascade Subsection of Topography.

Montana Subsection of Topography.

Section of Topographic Drawing .......... Harry King.

Astronomic and Computing Section ......... R. S. Woodward.

Section of Instruments ..................... Edward Kübel.
REPORT OF THE DIRECTOR.

Geology.

In charge.

Division of Archean Geology .................... Raphael Pumpelly.
Atlantic Coast Division of Geology............... N. S. Shaler.
Appalachian Division of Geology ................. G. K. Gilbert.
Lake Superior Division of Geology ............. R. D. Irving.
Division of Glacial Geology ................... T. C. Chamberlin.
Montana Division of Geology ................... F. V. Hayden.
Yellowstone Park Division of Geology ........... Arnold Hague.
Colorado Division of Geology .................. S. F. Emmons.
California Division of Geology ................ G. F. Becker.
Division of Volcanic Geology ................... C. E. Dutton.
Mississippi Division of Geology ............... L. C. Johnson.
Potomac Division of Geology ................... W J McGee.

Paleontology.

Division of Vertebrate Paleontology.............. O. C. Marsh.
Paleozoic Division of Invertebrate Paleontology... C. D. Walcott.
Mesozoic Division of Invertebrate Paleontology... C. A. White.
Cenozoic Division of Invertebrate Paleontology... W. H. Dall.
Division of Paleobotany ........................ L. F. Ward.
Division of Fossil Insects ....................... S. H. Scudder.

Miscellaneous.

Division of Chemistry and Physics ............... F. W. Clarke.
Division of Petrography ........................ The Director.
Division of Mining Statistics and Technology... D. T. Day.
Division of Forestry ............................ G. W. Shutt.
Division of Illustrations ....................... W. H. Holmes.
Division of the Library and Documents .......... C. C. Darwin.

TOPOGRAPHIC WORK.

During the year topographic surveys have been carried on in accordance with plans previously adopted and described in earlier reports, and satisfactory progress has been made. The area surveyed was 81,829 square miles, and the average cost was about $2.75 per square mile.

The distribution of the work is shown graphically in Plate I;1 and the aggregate area surveyed in the several States and Territories into which the operations of the geographic division have been extended, the scales upon which the work has been executed, and the vertical distances sepa-

1See pocket at the end of this volume.
rating the contours by which relief is shown in the different areas are given in the following table. Other details of the work are fully set forth in the administrative report of Mr. Gannett, who has charge of this division of the Survey.

Areas surveyed during the fiscal year ending June 30, 1886.

<table>
<thead>
<tr>
<th>State</th>
<th>Scale of publication</th>
<th>Contour interval</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alabama</td>
<td>1:125000</td>
<td>100</td>
<td>3,933</td>
</tr>
<tr>
<td>Arizona</td>
<td>1:125000</td>
<td>200</td>
<td>8,000</td>
</tr>
<tr>
<td>California</td>
<td>1:125000</td>
<td>200</td>
<td>4,400</td>
</tr>
<tr>
<td>Do</td>
<td>1:125000</td>
<td>100</td>
<td>2,248</td>
</tr>
<tr>
<td>District of Columbia</td>
<td>1:62500</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>Georgia</td>
<td>1:125000</td>
<td>100</td>
<td>2,442</td>
</tr>
<tr>
<td>Kansas</td>
<td>1:125000</td>
<td>50</td>
<td>13,700</td>
</tr>
<tr>
<td>Kentucky</td>
<td>1:125000</td>
<td>100</td>
<td>2,380</td>
</tr>
<tr>
<td>Maryland</td>
<td>1:125000</td>
<td>100</td>
<td>895</td>
</tr>
<tr>
<td>Do</td>
<td>1:62500</td>
<td>20</td>
<td>119</td>
</tr>
<tr>
<td>Massachusetts</td>
<td>1:125000</td>
<td>20</td>
<td>2,500</td>
</tr>
<tr>
<td>Missouri</td>
<td>1:125000</td>
<td>50</td>
<td>7,700</td>
</tr>
<tr>
<td>New Jersey</td>
<td>1:62500</td>
<td>20</td>
<td>1,843</td>
</tr>
<tr>
<td>Nevada</td>
<td>1:125000</td>
<td>200</td>
<td>2,000</td>
</tr>
<tr>
<td>North Carolina</td>
<td>1:125000</td>
<td>100</td>
<td>650</td>
</tr>
<tr>
<td>Oregon</td>
<td>1:125000</td>
<td>200</td>
<td>3,600</td>
</tr>
<tr>
<td>South Carolina</td>
<td>1:125000</td>
<td>100</td>
<td>600</td>
</tr>
<tr>
<td>Tennessee</td>
<td>1:125000</td>
<td>100</td>
<td>3,445</td>
</tr>
<tr>
<td>Texas</td>
<td>1:125000</td>
<td>50</td>
<td>8,000</td>
</tr>
<tr>
<td>Virginia</td>
<td>1:62500</td>
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<td>Do</td>
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<td>5,103</td>
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<tr>
<td>West Virginia</td>
<td>1:125000</td>
<td>100</td>
<td>3,000</td>
</tr>
<tr>
<td>Wyoming</td>
<td>1:125000</td>
<td>100</td>
<td>1,000</td>
</tr>
<tr>
<td>Yellowstone National Park</td>
<td>1:125000</td>
<td>1,600</td>
<td>2,600</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1:125000</strong></td>
<td><strong>1,600</strong></td>
<td><strong>81,829</strong></td>
</tr>
</tbody>
</table>

During the year the general plan for the preparation and engraving of the topographic sheets constituting the general atlas contemplated by the Survey, which was fully described in the last annual report, has been fully tested and put in execution; and already there have been engraved 57 sheets. The geographic distribution of these sheets is shown graphically in Plate I; and their distribution by States, the area covered in each State and Territory, and the scales of the work are exhibited in the appended table:
Table showing distribution, &c., of engraved atlas sheets.

<table>
<thead>
<tr>
<th>State</th>
<th>Number of sheets</th>
<th>Scale</th>
<th>Contour interval</th>
<th>Area Sq. miles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alabama</td>
<td>2</td>
<td>1:125000</td>
<td>100</td>
<td>1,905</td>
</tr>
<tr>
<td>Arizona</td>
<td>10 + 1 in part.</td>
<td>1:250000</td>
<td>200</td>
<td>48,190</td>
</tr>
<tr>
<td>California</td>
<td>1</td>
<td>1:250000</td>
<td>200</td>
<td>3,580</td>
</tr>
<tr>
<td>Kansas</td>
<td>4 + 2 in part.</td>
<td>1:125000</td>
<td>50</td>
<td>4,485</td>
</tr>
<tr>
<td>Missouri</td>
<td>6 + 2 in part.</td>
<td>1:125000</td>
<td>50</td>
<td>6,985</td>
</tr>
<tr>
<td>Montana</td>
<td>3</td>
<td>1:250000</td>
<td>200</td>
<td>0,765</td>
</tr>
<tr>
<td>Nevada</td>
<td>3 + 1 in part.</td>
<td>1:250000</td>
<td>50</td>
<td>13,556</td>
</tr>
<tr>
<td>New Mexico</td>
<td>2</td>
<td>1:250000</td>
<td>200</td>
<td>7,720</td>
</tr>
<tr>
<td>Tennessee</td>
<td>4</td>
<td>1:125000</td>
<td>100</td>
<td>3,682</td>
</tr>
<tr>
<td>Texas</td>
<td>2</td>
<td>1:250000</td>
<td>50</td>
<td>2,065</td>
</tr>
<tr>
<td>Utah</td>
<td>17</td>
<td>1:250000</td>
<td>250</td>
<td>63,135</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>164,235</strong></td>
</tr>
</tbody>
</table>

GEOLOGIC WORK.

THE INVESTIGATION OF THE ARCHEAN ROCKS.

The rocks of the earth are divisible into three great classes: (1) the crystalline or azoic masses (often denominated Archean), which form the base of the geologic column and are destitute of fossils and are generally without traces of organic life; (2) the clastic or fragmentary strata, which constitute the greater part of the geologic column and represent nearly the whole of that portion of the history of the earth with which geologists have become familiar, and which generally contain the remains of animal and vegetal organisms by which they may be classified; and (3) the volcanic rocks, which have been erupted at various stages of the world's history and are intercalated in various parts of the geologic column.

The great mineral wealth contained in the first of these systems of rocks renders their study one of the most important in the whole field of economic geology. Moreover, they represent one of the most interesting and at the same time obscure stages in the geologic development of the globe; but, by reason of their general concealment beneath newer rocks, as well as by reason of the absence of fossils and the dearth of other criteria for their genetic and chronologic classification, the relations of these rocks to one another, to the clastic and...
volcanic series, and to their contained minerals, are little understood. There are even grave doubts whether the best methods of investigating these rockmasses and the best criteria for their classification have yet been developed. The Archean rocks, therefore, offer one of the most promising subjects for geologic study in this and other countries; and it was imperative, in view of both its scientific and its economic aspects, that such investigations should be commenced in this field as will result not only in the discovery and classification of phenomena, but in the general advancement of our knowledge of the principles involved in this branch of geologic science.

The investigations in Archean geology of the eastern portion of the United States were intrusted to Prof. Raphael Pumpelly. The character of his studies, his preliminary results, and the state of his work are indicated in his administrative report submitted herewith; and one of the first fruits of his survey, growing out of one of its collateral branches, is a memoir by Prof. W. M. Davis, one of his assistants, on the Triassic sandstones and traps of the Connecticut Valley, which constitutes one of the papers accompanying this report.

THE SURVEYS OF THE ATLANTIC COAST.

It is estimated that there are 100,000 square miles of coastal lands in this country which, subject to inundation by tidal and fluviatile waters, are valueless in their present condition. It would appear, from the experience of other countries, that by the employment of proper methods these lands might be reclaimed and rendered among the most valuable of the agricultural lands of the United States. But the relative altitude of land and sea is not constant: in some places the ocean is encroaching upon the land, and elsewhere the land is emerging from beneath the oceanic waters; and even where the level of the coastal lands is stationary, the shores are undermined and eaten away by the waves, and thus the sea gains upon the land in another way. Now it would be unwise to inaugurate expensive systems of reclamation of inundated lands without first ascertaining whether these lands are undergoing move-
ment, and if so in what direction; and, in order to guide engineering operations directed to such reclamation, a general investigation of the changes in level now in progress along the Atlantic coast has been undertaken.

Connected with these questions of oscillation of the land and the formation of coastal marshes is that relating to the origin and distribution of the bog ores, phosphatic beds, &c., now in process of formation in the marshes of the Atlantic coast, and, imbedded in the Cenozoic formations thereof, constituting one of the most important of the mineral resources of the Atlantic States.

These subjects of investigation and others of related character have been placed in the hands of Prof. N. S. Shaler. His preliminary results will be found elsewhere in this volume.

THE SURVEYS OF THE APPALACHIAN REGION.

By reason of its vast extent, its symmetry of structure, and the economic importance of the minerals contained in its rocks, the Appalachian mountain system has long been regarded as one of the most promising fields for geologic study to be found in any country. The publication of an elaborate treatise growing out of the investigations prosecuted under State auspices in Pennsylvania by H. D. Rogers, nearly thirty years ago, directed the attention of capitalists and scientific men to the portion of this field lying within that State, and the great development of the mineral resources of the Keystone State in the various forms of anthracite and bituminous coal, iron, petroleum, and natural gas must be attributed in large part to the stimulus afforded by these early scientific researches and the extensive publication of the results thereof; for the nearly commensurate mineral resources of Virginia, which were also investigated under State auspices about the same time by the equally eminent W. B. Rogers, the final results of whose researches were unfortunately never published, have remained to a great extent unknown.

The surveys instituted by the Geological Survey in the Appalachian region traverse the fields already occupied by the brothers Rogers and other geologists who have studied the re-
region, and in addition to their purely economic results these surveys promise to throw much light on various obscure questions in geology: e. g., the origin of the sediments of which a large portion of the rocks of the American continent are composed; the geographic configuration of the eastern portion of the American continent during different stages in its geologic development; the distribution of faunas and their modification by local conditions, and hence their value as bases for geologic classification; the petrographic diversity of formations laid down within the same geographic province; the origin and mechanism of mountain making movements and of continental oscillations; the metamorphism and other alterations of rocks produced by various causes; the genesis of coal and other carbonaceous minerals; and many other questions equally important in philosophic geology.

The economic results of these researches give equal promise. As will appear from the accompanying report of Mr. G. K. Gilbert, who has charge of the surveys in this region, two publications on subjects of economic importance have already grown out of the work and will shortly appear.

THE SURVEYS OF THE LAKE SUPERIOR REGION.

The copper-bearing rocks of the Lake Superior region (known among geologists as the Keweenaw Series) have been investigated in some detail by the State surveys of Michigan and Wisconsin; and the northward continuation of the same rocks has been examined by the officers of the Canadian Survey. But so long as geologists confined their attention to this single formation as an isolated congeries of phenomena, they were unable to ascertain its genetic and structural relations to the other formations of the country, and great confusion and uncertainty prevailed with respect to the copper-bearing series of rocks up to a very recent date.

When the operations of the Geological Survey were extended into the older States, Prof. R. D. Irving was employed to investigate these and associated rocks, not only within the limited area in which alone copper mines have been opened, but also in adjacent parts of Michigan, Wisconsin, and Minne-
sota; and, as previous reports have shown, his studies have already extended over a considerable area and have been productive of valuable results. During the past year his surveys have extended into the sparsely settled or altogether unsettled regions in Northern and Northeastern Minnesota, in which the only routes of travel are rivers and lakes and the sole means of progression light canoes; and extensive foot trips in neighboring regions were made by his assistants. Surveys in the Pene- kee-Gogebic region of Northern Wisconsin and Michigan were made for the purpose of supplementing and corroborating antecedent observations; the interesting succession of crystalline rocks about the western extremity of Lake Superior was examined in detail; and the notes of the last and previous field seasons have been assembled and digested, as set forth in the administrative report submitted herewith.

Professor Irving's studies in the Lake Superior region have led him to question the applicability of current systems of geologic taxonomy to that region without material modification. His views on this subject are clearly and forcibly expressed in a treatise constituting one of the accompanying papers of this report. These opinions, coming from such a source and representing as they do the outcome of years of study, carry with them great weight and are entitled to serious considera-

THE INVESTIGATIONS IN GLACIAL GEOLOGY.

One of the ultimate purposes of the Geological Survey is the classification of the soils of the country with respect to their agricultural capabilities. As a necessary preliminary thereto, extended investigations of the superficial deposits constituting the subsoils have been undertaken; for the soil is simply derived from the subsoil through the action of the sun, rain, frost, the products of vegetal decay, and other agencies, and any classification of the soils involves the classification of the subsoils. Experience in the various lines of geologic research has shown that the genetic classification of geologic products, involving as it does a thorough knowledge of the character thereof, is the only satisfactory one.
This work, which was commenced shortly after the inauguration of the Survey, was intrusted to Prof. T. C. Chamberlin. Hitherto, Professor Chamberlin has been compelled by practical considerations to confine his investigations to the glacial drift and its immediate derivatives; and since the immediate object of his studies was rather the discovery of the principles upon which soil classification may be based than the development of the classification itself, the results thus far attained have been scientific rather than economic. Some of these results have been published in earlier reports of the Geological Survey, and a treatise on one of the various phases of his multiform subject accompanies this report.

Professor Chamberlin's journeys and those of his assistants have already extended over a considerable portion of that northern third of the United States upon which the ice sheet deposited its burden of sand, clay, and bowlders. During the past year more or less extended observations have been made in Connecticut, Dakota, Idaho, Illinois, Maine, Massachusetts, Minnesota, Montana, Nebraska, New York, Ohio, Pennsylvania, Rhode Island, West Virginia, and Wisconsin. Within this vast area they have not been confined to a single order of phenomena, but have included careful studies of the drift itself; of the lateral and terminal moraines into which it sometimes rises; of the aqueous and glacio-aqueous deposits into which it merges; of the kames and drumlins locally developed within it in different regions; of the vegetal accumulations intercalated within its mass; of the rock surfaces upon which it rests, and the scoring, polishing, and striation of this surface, &c.; in short an attempt has been made to collate and thoroughly digest the entire range of widely diversified phenomena of the glacial drift and its derivatives.

Professor Chamberlin's work upon the glacial drift is the most comprehensive investigation of the class of phenomena involved ever undertaken in any country. It may now be regarded as approaching completion, and final reports upon different lines of the investigation will appear from time to time as the materials already collected are digested and elaborated.
THE SURVEYS IN MONTANA.

The mountain systems of the western part of the country are distinguished from those of the eastern portion by their greater irregularity and asymmetry, by their more recent origin, and in many other ways. Now, the structure of a mountain system is determined by its constituent rocks, and the first step in a comparative study of mountains is the determination of the age and structure of the rocks composing each of the systems compared. At the same time, the structure of the mountain system varies in a certain definite way from that of contiguous plains: the formations occupying vast areas in the plains are also represented in the mountains, where, by reason of their high inclination, they occupy small areas; the formations which in the plains are destitute of valuable minerals when traced into the mountains sometimes become metalliferous, &c. Moreover, the great vertical scale of rock exposure in mountains facilitates geologic investigation there; and so the succession of formations as developed in a single canyon of a mountain range frequently affords a key to the stratigraphy of a vast area of simple structure and plain topography.

With the foregoing considerations in view, investigations were undertaken, shortly after the establishment of the Geological Survey, in a specially interesting portion of the Rocky Mountain region lying within Montana. The work was intrusted to Dr. F. V. Hayden. The detailed operations of this division of the Survey are set forth in an accompanying administrative report; but it is worthy of note here that this investigation, undertaken primarily for scientific purposes, has resulted in the discovery and tracing out through considerable areas of important beds of coal, and has also enabled the officers of the division to convey valuable information to citizens interested in different mining operations within the Territory.

THE RESEARCHES IN THE YELLOWSTONE NATIONAL PARK.

Inquiries emanating from Congress and from different Departments of the Government from time to time have demon-
strated the desirability of ascertaining and making known to
the public the character and attractions of this great National
Park, in order that the purposes for which it was set aside
may be fulfilled. Something is indeed known throughout the
civilized world of its superb scenic features; the wonderful
geysers and the unique mineral deposits resulting therefrom,
the magnificent forests and the unique flora of this national pre­
serve; but it is important that exact knowledge concerning
this reservation for the use of the public set aside by a great
nation should be disseminated among its people. Moreover,
there are now in active operation within the National Park geo­
logic agencies related in kind and degree to those which have
been effective in the deposition of various minerals during
different geologic periods. Nowhere else in the known world
are the operations of nature's laboratory more thoroughly re­
vealed; and observations upon certain geologic processes here
promise to add much to existing knowledge of ore deposition
and kindred subjects.

This double object in thoroughly investigating the National
Park led to the establishment of a division for this purpose some
years ago. The division was placed in charge of Mr. Arnold
Hague, and a portion of the results of his investigation have
already appeared in different publications of the Survey.

During the past year Mr. Hague's researches have been pros­
ceuted energetically, as indicated by his administrative report
and by the appended memoir on Obsidian Cliff, by Mr. J. P.
Iddings, one of his assistants.

As appears from Mr. Hague's report, a portion of the field
season of 1885 was spent in conveying information to a Con­
gressional committee which visited the park for the purpose of
investigating its present condition and considering what legis­
lation is needed for its future maintenance, and in assisting a
special agent appointed by the honorable the Secretary of the
Interior to examine and report upon the present management
of the park.

THE SURVEYS IN COLORADO.

One of the uncompleted investigations inherited by the Geo­
logical Survey was that of the extensive mining regions in
Colorado, and work in that wide field has been continued ever since.

As set forth in the administrative report of Mr. S. F. Emmons, the geologist in charge of the work of that division, different lines of study have been pursued during the past year. The region covered by the investigation is of exceedingly complex structure, and a great variety of rock formations as well as mineral deposits exist. The formations represent all portions of the geologic column, from the crystalline rockmasses of the Archean at the base, through the extensive series of the Paleozoics and the enormously developed Mesozoics, to the vast series of lacustral deposits laid down in the Rocky Mountain region during different epochs of the Cenozoic. Extensive fields and masses of eruptive rocks also occur, associated with the sedimentary and non-volcanic formations in various ways. The precious metals of the region are accumulated in and distributed through many different formations, while valuable beds of coal are found in both the Mesozoic and the Paleozoic strata. A thorough knowledge of the geologic structure of the entire region is accordingly essential to a satisfactory exposition of the mineral resources of the State. Moreover, here, as in the Rocky Mountain region of Montana, there are represented different types of orographic structure, the study of which is demanded on broad scientific grounds, and the stratigraphy displayed in the mountains affords a key to the structure of the great area of plain topography and rare rock-exposure lying to the eastward. The investigations within the region have accordingly been made along different lines, as Mr. Emmons's report indicates, but the various lines converge and the different objects of the investigation are attained from time to time. Publications comprehending a portion of these results will appear at an early day.

THE SURVEYS IN CALIFORNIA.

The completion of an important series of investigations during the present year by Mr. George F. Becker is a source of gratification.

In 1883 Mr. Becker undertook the investigation of the quicksilver belt of Eastern California and Western Nevada. To a
certain extent the field was a new one; for although geologists had given some attention to quicksilver deposits in Spain and other countries, the mode of occurrence and the petrographic relations of the mineral in California are in part unique. The investigation therefore extended not only to the quicksilver and immediately associated rocks, but also to the various associated formations and eventually included many questions relating to the influence of pressure, temperature, &c., upon rock metamorphism and mineral deposition; and among the results of the investigation must be numbered many important additions to previous knowledge of the principles of dynamic geology. These investigations, too, indicate very clearly the intimate interrelations between geology and the sister sciences, and demonstrate the importance of that broad and comprehensive study which it has ever been the aim of the Geological Survey to foster; for among the results of Mr. Seeker's researches must be enumerated the discovery of new and important laws in both physics and chemistry. As will appear from his report, however, the general and purely scientific problems investigated have been subordinated to the primary purpose of the Survey, i. e., the discovery and the succinct exposition of the mode of occurrence and general distribution of the quicksilver deposits of the Pacific slope.

Mr. Seeker's energies are now concentrated upon a new field, the California gold belt. Preliminary studies of this belt were made some years ago by the then existing State Geological Survey of California, but these studies were never completed; and it is believed that further investigation will not only throw much light upon problems involved in the exploitation of the region and the development of its resources, but that they will at the same time direct attention to portions of the area which may be prospected with hope of success and prevent useless expenditure of time and money in hopeless prospecting in other portions.

THE RESEARCHES IN VOLCANIC GEOLOGY.

A single division of the Survey has been established for the purpose of investigating one of the three great classes of rocks
described in an earlier paragraph, the eruptives or volcanic rocks. It has been placed in charge of C. E. Dutton, captain of ordnance, U. S. A., who has been detailed to this Office by the honorable the Secretary of War under authority of a specific statute.

Volcanic rocks occur in all of the Western Territories, and, in less volume, in most of the older States. The lavas of which they are formed have been extravasated during various geologic periods; they have affected the different sedimentary formations with which they have been brought in contact in a great variety of ways; in certain portions of the country they are of vast thickness and areal extent; some of the precious metals and gems occur within them; they are important elements in the orographic structure of many mountain systems; the extravasation of their materials is intimately connected with orogenic movements, and they are consequently involved in the taxonomy of mountains; and by their constitution they afford some insight into the condition of the interior of the earth. It is therefore important upon many grounds, both scientific and economic, that researches upon this class of rocks should be as thorough and profound as the knowledge and capabilities of man will permit.

As indicated in his report, Captain Dutton's journeys during the past fiscal year have extended over considerable areas in California and Oregon, and have led him to such notable but little known points as Mount Shasta, Lassen's Peak, and Crater Lake, and over considerable portions of the Cascade and Sierra Nevada ranges. Much of the territory traversed is little settled or even totally unexplored, and portions of it are desert; and his observations and those of his assistants, therefore, contribute to our knowledge of the geography as well as to our knowledge of the geology of an interesting portion of the country.

THE INVESTIGATIONS IN THE LOWER MISSISSIPPI REGION.

One of the most recently established of the divisions of the Survey is that which has for its object the investigation of the iron ores, the sulphur and salt deposits, and the various other
mineral resources of the States of Mississippi, Louisiana, and Texas. It is in charge of Mr. Lawrence C. Johnson.

Mr. Johnson's efforts have been directed to the ascertain­ment of the geologic relations of the various beds yielding valuable minerals and the detailed structure of the entire re­gion; for in a region of such simple general structure as that of the Gulf States, it is possible to predicate the positions and depths beneath the surface of formations containing mineral deposits with a good degree of accuracy, provided the relations between the mineral deposit and its country rock have been determined. It is a source of gratification to find that while Mr. Johnson's investigations have not yet reached such a stage of completeness as to warrant publication, he has been able to impart valuable general information to individu­als interested in the material resources of the territory over which his operations have extended.

THE INVESTIGATIONS ON THE POTOMAC RIVER.

When the Geological Survey was organized very little was known of the geologic structure of the District of Columbia and contiguous portions of Maryland and Virginia; but as soon as possible after its organization geologic investigations were undertaken within this region, as has been mentioned in preceding reports. The work is in charge of Mr. W J McGee. During the past year his studies have covered a considerable area along the principal transportation routes between the north and south in Eastern Virginia and Maryland, and have also extended up the Potomac River well into the Appalachian region. Among the results reached in this division of the Survey may be mentioned the determination of the stratig­raphy and general structure beneath the National Capital, and their bearing upon the question of water supply. Some information relating to this subject was communicated to the Health Officer of the District of Columbia during the year.

Just after the close of the fiscal year 1885-'86, and pending the completion of this report, Mr. McGee undertook an inves­tigation of the geology of the region about the head of Ches­apeake Bay for the purpose of ascertaining the probabilities
of finding artesian water there. The area about the head of Chesapeake Bay is representative in geographic position and geologic structure of a zone upon which are located the cities of Trenton, Philadelphia, Wilmington, Baltimore, Washington, Alexandria, Fredericksburg, Richmond, Petersburg, Weldon, and others, in all of which the question of artesian water supply is important; and it was accordingly deemed wise to make the investigation as thorough as possible in order that its results might apply with only local modification to the various parts of this zone. Moreover, it seemed desirable that the investigation should be made public at the earliest possible day. Accordingly the requisite observations and studies were made as rapidly as possible and the report thereon is ready for publication as one of the general papers accompanying this report.

PALEONTOLOGIC WORK.

THE RESEARCHES IN VERTEBRATE PALEONTOLOGY.

It has been pointed out on a preceding page that paleontology furnishes the most important basis for general geologic classification and that paleontology is thus an essential part of geologic science. But one of the most important results of paleontologic research has been the development of the fact that the different classes of organic remains yield diverse units of geologic time. Thus, plants are little susceptible to the climatic and geographic changes that have occurred from time to time in the geologic history of the earth; modifications in vegetal organisms have consequently proceeded slowly; and hence the plant remains found in the rocks by their changes record great periods of time. The lower and less differentiated animal forms, the mollusca, radiata, &c., that inhabit the ocean, yield more freely to conditions of environment, and are much less stable than the plants; they have accordingly undergone greater and more rapid modification; and the chronologic units marked by these modifications are shorter. But the most sensitive geologic chronometer and that marking the shortest time units is afforded by the vertebrata, and especially by the more highly developed land animals. Now
in order to reduce the records of these different measures of geologic time and indices of taxonomic relations to a common standard, thorough investigation of the three great classes of fossils is demanded. Moreover, it frequently happens that formations containing plant remains are destitute of both vertebrate and invertebrate fossils; that beds yielding invertebrate fossils are without the remains of vertebrates or plants; and that great deposits characterized by vertebrate remains are destitute of the slightest traces of other, remains of life; and hence the determination of age and taxonomic relation depends now upon one, and again upon another, class of fossils. Thus different lines of paleontologic investigation have grown up in the Survey.

Among the rockmasses of the Western Territories, important by reason of their vast area and their immense thickness, there are many that were deposited in extensive lakes during late Mesozoic and Cenozoic time. These lakes were fed by great rivers; and within the sediment swept into these lakes there were preserved the bones of vertebrate animals that lived within the lacustral waters and upon the adjacent shores; and by means of comparative study of these bones the paleontologist is enabled to correlate the deposits laid down in different portions of the same lacustral area with each other and with the deposits of contemporaneous lakes, and at the same time to reproduce some of the most interesting scenes in the world's history. Prof. O. C. Marsh has had charge of the investigation of these remains for some years, and has already made several contributions to our knowledge of extinct animal forms, and brought to light data of importance in the development of geologic taxonomy. During the past year his investigations have extended into different portions of Nebraska, Kansas, Wyoming, and Colorado; and much work has been done in investigating and classifying his extensive collections, together with those made by other divisions of the Survey, in the paleontologic laboratory in New Haven.

**THE RESEARCHES IN PALEOZOIC INVERTEBRATE PALEONTOLOGY.**

The organic remains useful in correlating and classifying the lower third of the fossiliferous series of rocks are pre-
dominantly those of invertebrates, and accordingly this great class of fossils has been diligently studied, both in their biotic relations and in their relation to the strata within which they occur. This investigation is in charge of Mr. C. D. Walcott, whose paleontologic laboratory is in the National Museum.

As will appear from Mr. Walcott's report, the investigations of the division during the past fiscal year, which were sometimes made in conjunction with the geologic parties of different divisions, have extended into Alabama, Georgia, Nevada, Tennessee, Utah, and various parts of New York; and in addition there have been examined collections made by several geologists in other parts of the country. These studies have traversed the entire range of the Paleozoic groups, from the summit of the Carboniferous to the base of the Cambrian. Moreover, they have not been confined to the fossils themselves, but have in nearly all cases extended to the positions of the fossils in the strata and the development of the stratigraphy of the regions in which they were found.

One of the most important of the conclusions reached by Mr. Walcott and his assistant, Prof. H. S. Williams, relates to the local modifications of animal life by environment and the shifting of faunas from place to place with changing conditions in depth of water and configuration of shores, and consequent changes in sedimentation, in the Paleozoic ocean. These investigations are valuable in determining the limitations within which fossils are trustworthy criteria in the classification of rocks.

THE INVESTIGATION OF MESOZOIC INVERTEBRATE FOSSILS.

At its inception paleontology was little more than a set of empiric rules for the classification of formations by means of their contained fossils, viewed as accidental or petrographic characters; but in the present stage of geologic science the value of paleontology to the stratigraphist, as well as to the student of historic geology, depends largely on the power which it gives of restoring and mentally picturing the geographic, topographic, climatic, and other conditions prevailing in the various parts of the globe during each geologic epoch.
Studied in this broad way, fossils serve not only as data for the empiric correlation of the strata, but they enable the geologist properly to weigh and, in many cases, properly to interpret their own testimony, and thus mutually adjust the different time units of the three great classes of organic remains. It is with this view of the purposes of paleontologic investigation that researches by Dr. C. A. White have been made on the invertebrate fossils of the Mesozoic system of rocks in the United States.

During the past year Dr. White has performed field work in Utah, Wyoming, and Colorado, and has investigated collections from various parts of the country. One of the most important results of his field studies was the recognition of several distinct coal horizons within different early Tertiary and later Mesozoic formations. Another important result was the discovery of a large number of fresh water invertebrate remains associated with vertebrate fossils, which has added much to our previous knowledge of the continental invertebrate fauna of North America during Mesozoic time, and thus has been gained another vantage point from which insight may be obtained into the stratigraphic succession in the Rocky Mountain region and into the geologic history of the continent.

THE STUDY OF CENOZOIC INVERTEBRATE FOSSILS.

Fringing the Atlantic and Gulf coasts of the United States there is a broad zone of fragmental deposits, constituting the upper part of the fossiliferous column as represented in the American continent: the Cenozoic system of rocks. These deposits comprise a number of distinct formations representing different geologic periods. Within them are found the extensive greensand and phosphate deposits, which constitute the most important source of natural fertilizers in this country and which are thus far only partially developed. In the same formations there occur vast accumulations of iron ore, and some of the formations contain deposits of sulphur, salt, and other valuable minerals. Geologic investigation has already commenced within the portion of this zone covered by the operations of the Mississippi Division of Geology; but it is im-
portant that before extended geologic investigations are carried into this field a general study of its representative fossils shall be made, in order to facilitate prompt and trustworthy classification of the strata upon paleontologic grounds. This general investigation has been commenced by Mr. W. H. Dall. The details of his work in the important field to which he has been assigned, together with his collateral and accessory labors, are fully set forth in his administrative report.

THE RESEARCHES IN PALEOBOTANY.

Although plant impressions were among the first fossils to stimulate popular curiosity and attract scientific investigation they were among the latest to acquire importance as criteria for the classification of the rocks in which they occur. Their utility for such purposes is now generally recognized; and a division for their investigation has been established in the Geological Survey, and Mr. Lester F. Ward, whose extensive collections and laboratory are in the National Museum, is in charge of it.

In this, as in the other lines of paleontologic investigations pursued by the Survey, the primary object of study is not alone empirically to classify fossiliferous formations by means of their contained fossils in accordance with existing knowledge, but rather to develop the fundamental principles involved in the relations of rocks and fossils; and this necessitates a knowledge of the organisms fossilized, of the manner in which the fossils became imbedded, and of the various circumstances and conditions attending these processes. Thus the value of plants as indices of geologic vicissitude must be ascertained before their reliability as bases for a comprehensive geologic taxonomy can be determined. Accordingly, as sufficiently indicated by his report, Professor Ward's studies have thus far been general and philosophic, and his results are contributions to the science of paleobotany rather than applications of the science to geologic technology.

The investigations of the geologists of the last generation, during which there was great activity in geologic work in the Eastern United States, have shown that there is an important hiatus in the geologic column as represented in the Appalachian
Mountains and along the Atlantic coast. This hiatus occurs about the place of the lower and middle portions of the Mesozoic system of rocks; and it is impossible to form definite conceptions as to the succession of events in the geologic development of the continent until this gap is filled. Fortunately some epochs of the periods generally unrepresented in Eastern America are sometimes represented locally by stratigraphically and geographically unimportant formations. One such formation is the Trias of Connecticut, New Jersey, Pennsylvania, Maryland, and portions of Virginia; another is the probably distinct series of deposits of Southeastern Virginia, by some geologists regarded as the American equivalent of the European Rhætic; and a third is the formation intercalated between the Piedmont crystallines and the known Cretaceous rocks of the Atlantic slope, which probably belongs to a late Jurassic or early Cretaceous period unrepresented elsewhere in America, to which the name "Potomac formation" has been applied. The last two formations are practically destitute of animal remains, but each yields abundant traces of a unique and luxuriant flora; and with the hope of completing the geologic history of the American continent, the floras of these formations have been critically investigated in the division of paleobotany by Prof. William M. Fontaine.

Professor Fontaine's labors have already resulted in the preparation and publication of a monograph treating of the flora yielded by the older Mesozoic of Virginia; and, as set forth in his administrative report, his attention during the past year has been concentrated upon the equally interesting and yet more abundant flora of the Potomac formation of Virginia and contiguous portions of Maryland. His collections have been very large, and the material brought together will unquestionably add much to our knowledge of obscure points in American geology.

THE RESEARCHES IN FOSSIL INSECTS.

In accordance with the general theory held by the Survey, that collateral investigations ought to be simultaneously carried forward along as many convergent lines as possible, a
study of the fossil insects found in the Paleozoic and Mesozoic rocks in different parts of the country has been instituted. The investigation has been put in the hands of Mr. S. H. Scudder, the eminent specialist to whom the world is indebted for an important share of existing knowledge of the insect faunas of past ages. It is especially important that the study of fossil insects should be prosecuted in connection with that of fossil plants; for, as shown by the most eminent biologists, the history of plant life has been intimately connected with that of insect life; many of the most important modifications in plants are directly attributable to the agency of insects; and thus insects are as reliable indices of climatic and other conditions that have prevailed during the various geologic epochs as the plants themselves. Moreover, insects, like plants, tell of terrestrial conditions, while a large share of the other fossil remains that have been subjected to examination tell only of the sea and of aqueous conditions; and it is as important to geologists, whatever be the ultimate aim of their researches, to understand the various stages in the development of the land as to interpret the history of the seas. Professor Scudder's brief report on the initial work of his division appears in its proper place.

MISCELLANEOUS.

WORK IN THE DIVISION OF CHEMISTRY AND PHYSICS.

As will appear from the report of Prof. F. W. Clarke, chief of this division, satisfactory progress has been made in the analyses of rocks, ores, mineral waters, &c. These analyses cover materials from Arizona, California, Colorado, Illinois, Iowa, Kentucky, Louisiana, Maine, Massachusetts, Michigan, Montana, New Mexico, New York, North Carolina, Ohio, Utah, Virginia, West Virginia, Wyoming, Yellowstone Park, and several States and Territories not named above. While the chemic work of the Survey is ever regarded as subordinate to geologic investigation and its character and specific objects are determined from time to time by the needs
of the geologists of the Survey, original investigation in different collateral lines is encouraged, it is believed with beneficial results. Thus, during the past year interesting questions relating to the genesis of certain minerals and to the agency of certain waters in forming minerals have been investigated in this division of the Survey. Many of the researches carried on in this division have a direct practical bearing upon questions connected with the development of the mineral resources of the country. Among these may be mentioned the investigation of methods of salt manufacture by Mr. T. M. Chatard, submitted herewith among the special treatises prepared to accompany this report.

Hitherto the geologist engaged in the discussion of problems involving coefficients of friction, moduli of elasticity, constants expressing the effects of pressure, temperature, &c., upon rocks, and other questions such as continually arise in dynamic geology has generally been compelled to confine himself to the use of constants determined in connection with the arts; but such constants are unsatisfactory, since they are applicable only to a much more limited range of conditions than those encountered by the dynamic geologist. Accordingly, an adequate discussion of such phenomena demands more accurate determination of constants applicable under a wide range of conditions, and this involves the improvement of methods of determination and the devising of special apparatus therefor. These are the ends kept in view by Dr. C. Barus and his associates, the physicists of the division, and satisfactory progress has been made in their attainment.

RESEARCHES ON SEA LEVEL AS AFFECTED BY THE ATTRACTION OF ADVENTITIOUS MASSES.

The principal function of the astronomic and computing section and that which it was specifically established to perform is the making and reduction of such astronomic and geodetic observations as are required in the accurate determination of points lying within the areas topographically surveyed and in the co-ordination of the topographic sheets. Much work of this character has been performed in a satisfactory manner during the past year, and a special report thereon will
shortly be issued. But there arise from time to time important questions in physics and pure geology whose discussion involves the application of the higher mathematics, and the geologists are assisted in the investigation of such subjects by the astronomer of the Survey, Mr. R. S. Woodward.

One of the fields of original investigation inherited by this Survey and greatly expanded through its efforts relates to the ancient beaches and shore terraces that have been discovered and traced out in different parts of the country, far from the present shore lines. In many cases these ancient water lines are not horizontal. Now, it is important, upon purely scientific grounds as well as for utilitarian purposes, to ascertain the causes and the limits of the shifting of the great water bodies of the earth that these records indicate. It is also important that the different hypotheses which have been entertained from time to time as to the nature of this shifting should be tested by comparison with known facts. Among these hypotheses is that which attributes the shifting of the shore lines to the deformation of the sea level of the glacial period arising from the attraction of the northern ice sheet. The amount of deformation producible in the terrestrial spheroid by the attraction of a given ice mass is susceptible of determination to any required degree of precision by mathematic methods; but, in order to eliminate the possibility of error from the formulas of different investigators who have at various times dealt with related questions and to render practicable the numeric evaluation of the disturbing effects of local masses (either forming a part of the earth or superimposed upon its surface) on the sea level, it was necessary that the entire subject of the gravitative action of such masses should be critically reviewed. Such a review has been undertaken by Mr. Woodward during the past year, with valuable results. He has derived a new set of formulas, applicable not only to the discussion of the specific questions for which they were designed but to the entire class of questions to which these belong. Thus, the same formulas are of value in determining the relative positions of level (equipotential) surfaces in lake basins; they are applicable in determining the deformation of the ocean surface by contiguous continents;
within certain limits they are applicable in determining the relative density of different mountain ranges, or of mountain ranges and contiguous plains; and they are also applicable in discussions relating to the distribution of density in the earth's crust and other important problems in geology.

The results of Mr. Woodward's investigations will be published at an early day.

**WORK IN THE DIVISION OF MINING STATISTICS AND TECHNOLOGY.**

The principal function of the Geological Survey is the discovery of mineral resources before unknown and the collection of facts of importance to the industries involved. In order that this function may be properly performed it is necessary that attention shall be given to the technology of mining and that information relating to the best methods of mining different ores under various conditions shall be disseminated. Moreover, statistics of mining operations and of mineral products are essential to a thorough comprehension of the great mineral resources of the country, the mineral interests involved therein, and the industries that grow out of them. A division has been established for the performance of this work. The scope and character of the work of the division are clearly set forth in Mr. Albert Williams's final administrative report. The division is now in charge of Dr. D. T. Day.

The accompanying tables exhibit the quantities and values of the various metallic and non-metallic mineral products of the United States during the calendar year 1885.

*Metallic products of the United States in 1885.*

<table>
<thead>
<tr>
<th>Products</th>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pig-iron, long tons, spot value</td>
<td>4,044,525</td>
<td>64,712,400</td>
</tr>
<tr>
<td>Silver, troy ounces, coinage value</td>
<td>20,010,379</td>
<td>51,960,000</td>
</tr>
<tr>
<td>Gold, troy ounces, coining value</td>
<td>1,538,370</td>
<td>31,801,000</td>
</tr>
<tr>
<td>Copper, pounds, value at New York City</td>
<td>170,962,607</td>
<td>18,292,999</td>
</tr>
<tr>
<td>Lead, short tons, value at New York City</td>
<td>139,413</td>
<td>10,468,491</td>
</tr>
<tr>
<td>Quicksilver, flasks, value at San Francisco</td>
<td>32,073</td>
<td>970,189</td>
</tr>
<tr>
<td>Zinc, short tons, value at New York City</td>
<td>40,688</td>
<td>3,539,856</td>
</tr>
<tr>
<td>Nickel, pounds, value at Philadelphia</td>
<td>277,904</td>
<td><em>101,753</em></td>
</tr>
<tr>
<td>Aluminum, troy ounces, value at Philadelphia</td>
<td>3,408</td>
<td>2,550</td>
</tr>
<tr>
<td>Platinum, troy ounces, value, crude at New York City</td>
<td>550</td>
<td>187</td>
</tr>
<tr>
<td>Total value of metallic products</td>
<td></td>
<td>183,580,365</td>
</tr>
</tbody>
</table>

* Including copper from imported pyrites.*
REPORT OF THE DIRECTOR.

Non-metallic mineral products of the United States in 1885 (spot values).

<table>
<thead>
<tr>
<th>Products</th>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bituminous coal, brown coal, lignite, and anthracite mined elsewhere than in Pennsylvania, long tons</td>
<td>64,840,668</td>
<td>$82,347,548</td>
</tr>
<tr>
<td>Pennsylvania anthracite, long tons</td>
<td>34,228,548</td>
<td>76,671,048</td>
</tr>
<tr>
<td>Petroleum, barrels</td>
<td>31,842,041</td>
<td>19,183,694</td>
</tr>
<tr>
<td>Building stone</td>
<td>1,000,000</td>
<td>19,000,000</td>
</tr>
<tr>
<td>Lime, barrels</td>
<td>46,000,000</td>
<td>20,000,000</td>
</tr>
<tr>
<td>Salt, barrels</td>
<td>7,000,000</td>
<td>4,255,345</td>
</tr>
<tr>
<td>Cement, barrels</td>
<td>4,150,000</td>
<td>3,492,500</td>
</tr>
<tr>
<td>South Carolina phosphate rock, long tons</td>
<td>437,856</td>
<td>2,846,004</td>
</tr>
<tr>
<td>New Jersey marls, short tons</td>
<td>875,000</td>
<td>437,300</td>
</tr>
<tr>
<td>Limestone for flux</td>
<td>9,148,461</td>
<td>1,094,656</td>
</tr>
<tr>
<td>Mineral waters, gallons sold</td>
<td>9,148,461</td>
<td>1,094,656</td>
</tr>
<tr>
<td>Natural gas</td>
<td>4,854,200</td>
<td>4,854,200</td>
</tr>
<tr>
<td>Zinc white, short tons</td>
<td>15,000</td>
<td>1,050,000</td>
</tr>
<tr>
<td>Concentrated borax, pounds</td>
<td>5,000,000</td>
<td>489,000</td>
</tr>
<tr>
<td>Mica, pounds</td>
<td>2,000</td>
<td>181,000</td>
</tr>
<tr>
<td>Pyrites, long tons</td>
<td>49,000</td>
<td>220,500</td>
</tr>
<tr>
<td>Gold quartz souvenirs, jewelry, &amp;c</td>
<td>22,000</td>
<td>140,000</td>
</tr>
<tr>
<td>Manganese ore, long tons</td>
<td>23,258</td>
<td>190,281</td>
</tr>
<tr>
<td>Crople barytes, long tons</td>
<td>15,000</td>
<td>76,671</td>
</tr>
<tr>
<td>Other, long tons</td>
<td>3,000</td>
<td>43,575</td>
</tr>
<tr>
<td>Precious stones</td>
<td>310,000</td>
<td>89,900</td>
</tr>
<tr>
<td>Bronzes, pounds</td>
<td>13,000</td>
<td>66,000</td>
</tr>
<tr>
<td>Feldspar, long tons</td>
<td>2,700</td>
<td>40,000</td>
</tr>
<tr>
<td>Chrome iron ore, long tons</td>
<td>2,700</td>
<td>40,000</td>
</tr>
<tr>
<td>Asbestos, short tons</td>
<td>200</td>
<td>9,000</td>
</tr>
<tr>
<td>Slate, ground as a pigment, long tons</td>
<td>1,000</td>
<td>24,907</td>
</tr>
<tr>
<td>Sulphur, short tons</td>
<td>215</td>
<td>17,175</td>
</tr>
<tr>
<td>Asphaltum, short tons</td>
<td>2,000</td>
<td>15,500</td>
</tr>
<tr>
<td>Cobalt oxide, pounds</td>
<td>68,723</td>
<td>65,373</td>
</tr>
</tbody>
</table>

Total value of non-metallic products | $239,431,901 |

The commercial product, that is, the amount marketed, was only 63,569,284 tons, valued at $80,640,564.

The commercial product, that is, the amount marketed, was only 32,360,421 tons, valued at $72,374,544.

Including cobalt oxide in ore and matte.

Résumé of the values of the metallic and non-metallic mineral substances produced in the United States in 1885.

| Metals | $181,589,365 |
| Mineral substances named in the foregoing table | 239,431,901 |
| Estimated value of mineral products unspecified | 7,500,000 |
| Grand total | $428,521,356 |

WORK IN FORESTRY.

It is well known that the pineries of the Upper Mississippi and Great Lake regions, from which a large proportion of the lumber consumed in the country has been derived during past decades, are rapidly disappearing and that their complete ex-
haustion is a question of only a few years. It is therefore important that the eyes of the lumber manufacturer and of the lumber consumer should be directed to other regions of supply. Among such are the wooded portions of the Appalachian mountain system, the Adirondack region in New York, and other considerable areas in the Eastern United States which are naturally forested with woods available in the manufacture of various grades of lumber and within which the land is comparatively worthless for other purposes than timber growth. But the American people have now passed that pioneer stage in the settlement and utilization of the national domain in which man can avail himself of the fruits of the land without thought for the morrow. The time has come for considering questions of reproduction of ephemeral products and of perpetuating the natural supplies thereof. Moreover, the interests growing out of the various products of the soil are intimately but intricately connected with various other interests. It is therefore important not only to ascertain and classify the present forest resources of the country, but also to determine (1) what portions of the country can be profitably reserved for arboriculture and (2) what kinds of trees are best adapted to each region.

Such is the work of the division of forestry. In the administrative report of the chief of that division, Mr. George W. Shutt, the plan of operations and the preliminary results already secured are set forth in detail.

SUPERVISION OF PUBLICATION.

As stated on a previous page, the publications of the Survey already numbered 41 at the beginning of the fiscal year. Adding to this the number of monographs, bulletins, annual reports, and statistical papers since published or in various stages of completion, the total number is brought up to 58 at the present time. These publications, emanating from the several scientific divisions of the Survey, are varied in scope and frequently of a highly technical character. To secure clear and accurate statement in the material sent to press, careful proof-reading, and uniformity in the details of book-
making, as well as to assist the Director in exercising a general supervision over the publications of the Survey, it has been found expedient to provide a small corps to which work of this character may be intrusted; and Mr. Thomas Hampson has been placed in charge of it.

WORK IN THE DIVISION OF ILLUSTRATIONS AND IN THE DIVISION OF THE LIBRARY AND DOCUMENTS.

Attention is directed to the reports of the chiefs of these divisions, in which the operations for the past fiscal year are set forth in detail.

OFFICE OF THE SURVEY.

During the year the Survey offices, with the exception of the paleontologic and chemic laboratories, have remained in the F street building rented by the Government for the purpose; and it has been found that the transaction of business has been greatly facilitated by reason of the satisfactory arrangement of rooms, &c., in this commodious building. Most of the laboratories remain in the National Museum. The laboratory of vertebrate paleontology has been retained at New Haven, in one of the buildings of Yale College, for lack of space in the National Museum; and the offices and chemic laboratories of the Colorado and California divisions of geology are retained respectively in Denver and in San Francisco.

ACKNOWLEDGMENTS.

It is a pleasure to report that the relations of the various members of the Survey among themselves and with the Director have been most harmonious, and that there has been a complete co-operation between the several divisions. The Director desires to express his deep gratitude to the different gentlemen employed under his direction, who have so fully appreciated the ends of the Survey and so energetically carried out the plans whereby it is hoped these ends may be attained.

As heretofore, the Survey is deeply indebted to the honorable Secretary of the Smithsonian Institution, Prof. Spencer
F. Baird, for the use of laboratory rooms in the National Mu­seum and for the care and proper exhibition of the volumi­nous collections sent in from all parts of the country.

To the railroads of the United States the Survey is pro­foundly indebted not only for free transportation, whereby its work in some cases has been greatly facilitated, but for plans, profiles, and other valuable results of their surveys. Such data have been of incalculable service in the prosecution of the topographic surveys of this institution, as has been indi­cated in a preceding report.

FINANCIAL STATEMENT.

Amounts appropriated for and expended by the United States Geological Survey for the fiscal year ending June 30, 1886.

<table>
<thead>
<tr>
<th>Amounts appropriated</th>
<th>Geological Survey</th>
<th>Salaries, office of Geological Survey</th>
<th>Total appropriation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Services</td>
<td>$355,342.99</td>
<td>$96,700.00</td>
<td>$452,042.99</td>
</tr>
<tr>
<td>B. Traveling expenses</td>
<td>30,002.57</td>
<td>15,540.00</td>
<td>45,542.57</td>
</tr>
<tr>
<td>C. Transportation of property</td>
<td>5,455.00</td>
<td>3,741.73</td>
<td>9,196.73</td>
</tr>
<tr>
<td>D. Field subsistence</td>
<td>25,808.58</td>
<td>10,269.57</td>
<td>36,078.15</td>
</tr>
<tr>
<td>E. Field supplies and expenses</td>
<td>2,867.83</td>
<td>7,317.38</td>
<td>10,185.21</td>
</tr>
<tr>
<td>F. Field material</td>
<td>10,360.57</td>
<td>2,867.83</td>
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<td>G. Instruments</td>
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<td>5,574.55</td>
<td>19,316.28</td>
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<td>H. Laboratory material</td>
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<td>8,170.55</td>
<td>34,979.13</td>
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<tr>
<td>I. Photographic material</td>
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<td>6,792.76</td>
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<td>K. Books and maps</td>
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<td>L. Stationery and drawing material</td>
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<td>M. Illustrations for reports</td>
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<td>O. Office furniture</td>
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<tr>
<td>P. Office supplies and repairs</td>
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<td>Q. Storage</td>
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<td>879.61</td>
<td>1,759.22</td>
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<tr>
<td>S. Bonded railroad accounts: Freight, $1,496.24; transportation of assistants, $1,542.65</td>
<td>3,048.89</td>
<td>459,840.07</td>
<td>462,888.96</td>
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</table>

Salaries.

| Salaries          | 35,600.46       | 35,600.46                            | 71,200.92           |
| Balance unexpended | 7,889.33       | 530.54                               | 8,419.87            |
| Probable amount required to meet outstanding liabilities | 7,889.33 | 7,889.33 |

Total appropriation: $503,240.00
DEPARTMENT OF THE INTERIOR, UNITED STATES GEOLOGICAL SURVEY.

ADMINISTRATIVE REPORTS
OF
CHIEFS OF DIVISIONS
AND
HEADS OF INDEPENDENT PARTIES,
ACCOMPANYING THE ANNUAL REPORT OF THE
DIRECTOR OF THE U. S. GEOLOGICAL SURVEY
FOR THE
FISCAL YEAR ENDING JUNE 30, 1886.
REPORT OF MR. HENRY GANNETT.

DEPARTMENT OF THE INTERIOR,
U. S. GEOLOGICAL SURVEY,
DIVISION OF GEOGRAPHY,
Washington, D. C., July 1, 1886.

SIR: I have the honor to submit the following report of the operations of the Division of Geography during the fiscal year ending June 30, 1886:

During the year geographic work was carried on in all the areas occupied during the preceding year, including Massachusetts, New Jersey, the Appalachian Mountains south of Mason and Dixon's line, Kansas, Missouri, Texas, Arizona, the Cascade Range in Northern California and Southern Oregon, and in the Yellowstone National Park. Furthermore, work was begun, upon a scale of 1 mile to an inch, in the area adjoining the District of Columbia, and, upon a publication scale of 2 miles to an inch, in the Gold Belt, upon the western slope of the Sierra Nevada, in California. The total area surveyed during the season is 81,829 square miles, distributed as follows among the various areas under survey:

<table>
<thead>
<tr>
<th>Region</th>
<th>Scale of publication</th>
<th>Contour interval</th>
<th>Area</th>
</tr>
</thead>
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<tr>
<td></td>
<td>Feet</td>
<td>Sq. miles</td>
<td>Feet</td>
</tr>
<tr>
<td>Massachussets</td>
<td>20</td>
<td>2,500</td>
<td>20</td>
</tr>
<tr>
<td>New Jersey</td>
<td>20</td>
<td>1,843</td>
<td>100</td>
</tr>
<tr>
<td>Southern Appalachian region</td>
<td>20</td>
<td>1,843</td>
<td>100</td>
</tr>
<tr>
<td>Missouri-Kansas</td>
<td>20</td>
<td>1,843</td>
<td>100</td>
</tr>
<tr>
<td>Texas</td>
<td>20</td>
<td>1,843</td>
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<tr>
<td>Arizona</td>
<td>20</td>
<td>1,843</td>
<td>100</td>
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<tr>
<td>Gold Belt, California</td>
<td>20</td>
<td>1,843</td>
<td>100</td>
</tr>
<tr>
<td>Northern California and Southern Oregon</td>
<td>20</td>
<td>1,843</td>
<td>100</td>
</tr>
<tr>
<td>Yellowstone National Park and Northwestern Wyoming</td>
<td>20</td>
<td>1,843</td>
<td>100</td>
</tr>
<tr>
<td>Total</td>
<td>20</td>
<td>1,843</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>81,829</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 A map, Plate 1, exhibiting the areas surveyed, as tabulated above, in their relation to previous surveys, will be found in the pocket at the end of this volume.
The average cost of the work done during the year was, approximately, $2.75 per square mile.

There were completed during the year no fewer than ninety sheets of the General Topographic Atlas, several of which, although surveyed only last summer, are already engraved, while many others are in the hands of the engraver.

**ORIENTATION.**

The organization of the division was very similar to that during the preceding year. The work in Massachusetts and New Jersey, constituting the northeastern section, was until recently under my immediate supervision. On the 19th of April, 1886, Mr. Marcus Baker, formerly an assistant in the United States Coast and Geodetic Survey, was appointed geographer, and shortly afterward was assigned to the charge of the northeastern section.

All work done in the country south of Mason and Dixon's line and the Ohio River and east of the Mississippi, constituting the Appalachian section, was as heretofore in charge of Mr. Gilbert Thompson.

The work west of the Mississippi River (with the exception of that done in the Yellowstone National Park), including the Missouri-Kansas, Texas, Arizona, Gold Belt, and Cascade subsections, was in charge of Prof. A. H. Thompson.

The work done in the Yellowstone National Park and the region immediately adjacent thereto constituted a separate section, in charge of Mr. John H. Renshawe.

In the office there was a section of drawing, in charge of Mr. Harry King, and there was a section for the manufacture and repair of instruments, in charge of Mr. Edward Kübel.

**NORTHEASTERN SECTION.**

*Massachusetts subsection.*—The opening of the fiscal year found Mr. Summer H. Bodfish, with Messrs. C. C. Bassett, R. H. Phillips, Laurence Thompson, Clifford Arrick, E. B. Clark, W. J. Grambs, H. L. Smyth, and Van H. Manning, jr., at work in Bristol County, in the southeastern part of the State. Mr. Bassett was subsequently detailed to Mr. Johnson's party, and two additional assistants were added to Mr. Bodfish's party, making altogether ten men under his orders. These men prosecuted work during the season in Plymouth and Bristol Counties, and with such good effect that by the end of the season the area of these two counties was surveyed, with the exception of parts of the towns of Plymouth and Wareham, in the southeastern part of Plymouth County. There remained to be completed, however, in various parts of the region, small areas of swamp, marsh, ponds, &c., which could be surveyed to advantage during the winter, when frozen, and for this purpose two or three of the members of the party were left in the field during the winter, while the rest returned to Washington early in December. During the winter and early spring these swamp areas were sur-
MAP OF MASSACHUSETTS SHOWING AREAS SURVEYED UP TO June 30, 1886.

Scale: [Scales and symbols for completed work and areas traversed and leveled]
veyed, and the remaining parts of the towns of Plymouth and Wareham were completed. In the office the men were occupied in plotting the field notes, in drawing and lettering the maps, and in the preparation of copies for deposit with the State of Massachusetts.

Early in May of the present year Mr. Bodfish was ordered to the field, with the following assistants, including those who had been in the field during the spring, viz: Messrs. Laurence Thompson, W. J. Grambs, H. L. Smyth, E. B. Clark, Clifford Arrick, Van H. Manning, jr., and S. A. Aplin. Mr. Smyth was subsequently detailed to the party of Mr. W. D. Johnson, and Mr. Bodfish was authorized to employ temporarily three rodmen. Work was commenced upon Cape Cod, a large part of the area of which had been completed by the Coast and Geodetic Survey, and progress was also made toward the completion of the atlas sheets lying between latitudes 42° and 42° 15' and longitudes 70° 45' and 71° 30'. A beginning also was made in the sheet lying between latitudes 42° and 42° 15' and longitudes 71° 30' and 71° 45'. Altogether the area surveyed by this party during the year amounts to 1,200 square miles.

Mr. Natter's party, which at the opening of the fiscal year comprised, besides himself, Mr. J. H. Jennings, assistant topographer, and two field assistants, was engaged at that time upon the Boston sheet, the work upon which was very near completion. This sheet was finished by the middle of July, and Mr. Natter's party was at once ordered to Berkshire County, with directions to complete the area lying west of longitude 73° 15', from latitude 42° to 42° 45', including a belt the entire width of the State. Work was prosecuted during the rest of the season with great energy and good success, and early in December the entire area thus assigned was finished. During the winter Mr. Natter and his assistants, occupying rooms in the office of the Topographical Commission in Boston, completed the drawing of their field sheets, with the exception of the Boston sheet, and made copies of the work in Berkshire County for deposit with the State of Massachusetts.

Certain small areas in the Boston sheet were found to require revision, and the completion of this sheet was delayed until time could be had for the necessary examinations in the field.

Early in May of the present year Mr. Natter, with Messrs. J. H. Jennings, W. S. Hunter, C. B. Hepburn, and two field assistants, returned to the field. This party commenced work on the atlas sheet lying between latitudes 42° 15' and 42° 30' and longitudes 71° 15' and 71° 30'. At the present date they have completed an area on that sheet of 200 square miles. The total area surveyed by this party during the fiscal year is 590 square miles.

At the commencement of the last fiscal year Mr. W. D. Johnson, topographer, with two field assistants, was engaged in work upon the sheet lying between latitudes 42° 15' and 42° 30' and longitudes 71° 45' and 72°, a small area in the southern part of which had been surveyed dur-
ing the spring. As the season advanced, Mr. Johnson was authorized to employ additional assistants, and the work was pushed rapidly. The sheet in question was completed by the end of September, and his party was transferred to the northern part of Berkshire County, with directions to survey the sheet lying between latitudes 42° 30' and 42° 45' and longitudes 73° and 73° 15'. With three plane tables at work, this area was completed by the opening of winter, and early in December the party was established in winter quarters at Cambridge, Mass. The winter's work consisted in the completion of the plane table sheets of the two atlas sheets surveyed and in the preparation of copies of them for deposit with the State.

On the 1st of May of the present year Mr. Johnson, with his assistants, Messrs. R. D. Cummin and W. H. Lovell, was ordered to the field, and later Messrs. C. C. Bassett and H. L. Smyth, the latter having been detached from Mr. Bodfish's party, were ordered to join him, and three additional assistants were temporarily employed. Work was commenced upon the four atlas sheets lying between latitudes 42° and 42° 30' and longitudes 72° 45' and 73° 15', and is now being carried on with good effect. The total area surveyed by Mr. Johnson's party during the year amounts to 460 square miles.

Early in July, 1885, Mr. Anton Karl, topographer, with three assistants, was ordered to the field and directed to complete the atlas sheet lying between latitudes 42° 15' and 42° 30' and longitudes 72° 30' and 72° 45'. Shortly after reaching the field of his work, Mr. Karl was ordered to Colorado, for the purpose of taking part in the trial of the Maxwell Grant case as a Government expert. This detail, with its attendant delays, involving the absence of Mr. Karl for fully two months during the middle of the season, to a great extent crippled the work of his party. During the season the atlas sheet in question was completed, however, and the roads upon half of the sheet lying north of it were traversed by his assistants. During the winter Mr. Karl was engaged in the office at Washington in plotting his work and in making a copy of his sheet for deposit with the State of Massachusetts. His party has not yet taken the field for the current season. The total area surveyed during the season by this party comprises 160 square miles of finished work and a traversed area of about 116 square miles.

The entire area surveyed during the fiscal year in Massachusetts is 2,500 square miles. This, added to the area surveyed in 1885, makes a total of 3,750 square miles, or nearly one-half the area of the State.

*New Jersey subsection.*—This work was, as before, in the immediate charge of Mr. C. C. Vermeule, topographer, and under the general superintendence of Prof. George H. Cook, State geologist.

The parties were placed in the field in the spring of 1885, prior to the commencement of the last fiscal year. At that time Assistant Topographers F. W. Bennett, P. H. Bevier, W. H. Luster, jr., and George Hill, with four aids, were in the field engaged in leveling and contour-
The figures outlined on this map show the location of the several topographic maps with their numbers.

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Area surveyed to June 30th, 1885.

Survey completed during the year ending June 30th, 1886

Survey in progress
ing, while Messrs. W. D. Staats and Asher Atkinson were engaged in odometer surveys. On October 1 the latter force was increased by the addition of Mr. C. S. Sproul and another aid. During the month of October a party in charge of Mr. Bennett executed a detailed survey of a part of the Delaware River, from Philadelphia to a point 35 miles above that city. Field work closed on December 20. Five assistant topographers and two odometer recorders were retained in the office through the winter and were employed in plotting their work. This was completed April 5, 1886, and the parties resumed field work shortly after that date. At first, Messrs. Bennett, Bevier, Luster, Staats, and Atkinson, with assistants, were engaged in leveling and contouring, and N. B. K. Hoffmann and W. F. Marvin were employed in running traverse lines with the odometer. On May 5 a large party was organized and placed in charge of Mr. Bennett for the purpose of extending the detailed survey of the Delaware shore northward. This work was carried forward expeditiously and was completed on June 8, when the party was redivided into leveling and contouring parties. On the resumption of field work, in April, Mr. Sproul, with an assistant, was retained in the office for the purpose of plotting the traverse notes and furnishing plats to the level parties.

During the year Mr. Vermeule was occupied personally in the supervision of the work and in triangulation. The latter was extended over 1,800 square miles, in which fifty-three stations were located. The area which has been topographically mapped in this subsection during the year is 1,843 square miles, of which 1,453 have been plotted. An additional area of 570 square miles was traversed by meander survey, but not leveled or contoured. In the area surveyed there were 4,500 miles of traverse lines run and 3,500 miles of topographic levels, besides 571 miles of primary levels. (Pl. III.)

**APPALACHIAN SECTION.**

During the year the organization of the Appalachian section was quite similar to that of the preceding year. There was one triangulation party in the field, under Mr. S. S. Gannett, with six parties for topographic work, two of which have been carrying on triangulation also, in charge, respectively, of Messrs. W. T. Griswold, Morris Bien, Charles M. Yeates, Frank M. Pearson, Louis Nell, and Fred. J. Knight.

In addition to these, a party was engaged in making a map of the area adjacent to the District of Columbia, upon a publication scale of 1 mile to an inch. This party was under the immediate charge of Mr. John D. Hoffmann, topographer.

At the beginning of the fiscal year the party last mentioned was ordered to the field. It comprised, besides Mr. Hoffmann, Assistant Topographers Jere. Ahern and D. J. Howell and four field assistants. Instructions were given to survey the area lying between latitudes 38° 45' and 39° and longitudes 77° and 77° 15', excluding such part of the
50 ADMINISTRATIVE REPORTS BY

District of Columbia as lies within this area, that being now under survey on a large scale and in a great degree of detail by the U. S. Coast and Geodetic Survey. Adequate control for the location of topographic work was furnished by the triangulation of the Coast and Geodetic Survey, several stations of which lie within the area in question. The bench-marks of the Coast and Geodetic Survey were assumed as datum points for the location of contours, which were drawn at vertical intervals of 20 feet. The work was carried on by means of traverse lines, using stadia instruments supplemented by the plane table. During the season the Virginia portion of the area in question was completed in great elaboration of detail and with great accuracy.

Early in the spring of 1886 Messrs. D. J. Howell and George P. Money were directed to take the field for the purpose of continuing this work, under Mr. Hoffmann's direction, and subsequently Messrs. Emil Starek and Charles Bogan were similarly detailed. The work is being carried on by means of stadia lines. At the present date, the entire area of the sheet above designated lying outside of the District has been completed, and work is now being extended in the sheet east of it. The area surveyed by this party during the fiscal year was 308 square miles.

The triangulation party under Mr. S. S. Gannett took the field May 1, 1885, two months before the beginning of the fiscal year. The work during these two months consisted in the extension of the triangulation in the southern part of the valley in East Tennessee and the connection of this work in that region with the stations of the Coast and Geodetic Survey in Northern Alabama. On the 1st of July Mr. Gannett's field of work was changed to Southwest Virginia, in which area he continued, working northeastward between the transcontinental and Appalachian belts of the Coast and Geodetic Survey. During the season he occupied eleven stations in the southern area and twenty-five in the northern, being a total of thirty-six stations occupied during the season, covering an area within lines of 10,500 square miles. His party was disbanded on November 5. He was occupied during the winter in the reduction of his work.

On the 1st of May he was again ordered to the field for the purpose of closing up the area lying between the transcontinental and Appalachian belts of triangulation. This work being finished, Mr. Gannett was directed to continue the triangulation north of the transcontinental belt in West Virginia. Since taking the field this spring he has occupied nine stations, making a total for the year of forty-five stations, covering, within outside lines, an area of between 13,000 and 14,000 square miles.

The party under Mr. W. T. Griswold, topographer, was organized in two semi-independent parties, one under his immediate supervision and the other under Mr. Louis C. Fletcher, assistant topographer. The latter was directed to complete the unsurveyed portion of the atlas.
sheet lying between latitudes 39° and 40° and longitudes 79° and 80°, and thence to extend his work eastward, surveying a belt south of the area formerly occupied. The other party was directed to contour Berkeley and Jefferson Counties, in West Virginia, and Loudoun, Clarke, and Frederick Counties, in Virginia, taking advantage of certain surveys which had previously been made, notably those by Prof. H. F. Walling while connected with the U. S. Coast and Geodetic Survey. This party took the field on the 1st of June, 1885, and was engaged in triangulation up to the 1st of July, when an organization for the season was made. Work was prosecuted until the middle of November. An area of 3,500 square miles was mapped, completing the area lying between the parallels of 39° and 40° and the meridians of 78° and 80°, with the exception of the portions lying in Pennsylvania.

Mr. Griswold resumed field work on May 17, with Messrs. E. O. Barnard and H. O. Gordon as assistants. Mr. E. A. Oyster joined him a few days later. At the present date he has surveyed an area of 566 square miles, comprised in Loudoun and Fairfax Counties, in Virginia.

About the middle of May Mr. Merrille Hackett, assistant topographer, was ordered to the field in Northern Maryland for the purpose of examining and revising the work done in that region by Prof. H. F. Walling while connected with the U. S. Coast and Geodetic Survey. At this date a large area (895 square miles) has been revised, and the sheet comprising it is now being prepared for publication.

Mr. Fred. J. Knight, topographer, was placed in charge of the party formerly under Mr. W. A. Shumway, who resigned at the close of the preceding fiscal year. Mr. Knight's orders contemplated the mapping of the area embraced between the western limit of the work in Kentucky and the eighty-third meridian and between latitudes 37° and 38°, while south of latitude 37° he was to extend the work westward to longitude 84°, thus completing two atlas sheets. His work comprised both triangulation and topography. The party outfitted at Richardson, Ky., in the early part of July. It comprised, besides Mr. Knight, Messrs. D. C. Harrison and E. C. Barnard, assistant topographers, with two field assistants and the necessary laboring force. This party was successful in completing the work assigned to it, and disbanded at Woodbine, Ky., November 26, having surveyed an area of 3,300 square miles.

The party under Mr. Morris Bien, topographer, was instructed to complete the eastern portion of the atlas sheet lying between latitudes 37° and 38° and longitudes 81° and 82°, and, furthermore, to extend the work to the northeastward in Virginia, with the Blue Ridge as its east line, as far as the field season would permit. This party left for the field on July 10 and work was commenced five days later. It consisted, besides Mr. Bien, of Mr. R. C. McKinney, assistant topographer, five field assistants, and the necessary laboring force. Besides completing the atlas sheet above mentioned Mr. Bien surveyed the coun-
ties of Giles, Pulaski, Carroll, Floyd, and Montgomery, the entire area amounting to 3,675 square miles. The party disbanded at Pearisburg, Va., November 27.

The party under Mr. Frank M. Pearson, topographer, was instructed to complete the unsurveyed portions of atlas sheet 35°-84°, lying in East Tennessee, and to extend the work eastward into the Sequatchie Valley, including the east face of Walden's Ridge. The members of the party left Washington on July 12 and commenced topographic work three days later. The party was organized as follows: Mr. Frank M. Pearson, topographer, in charge, Messrs. H. B. Blair and A. E. Murlin, assistant topographers, with two field assistants and the necessary laboring force. On November 1 Mr. Pearson stored his camp outfit, discharged his camp hands, and with his principal assistants only continued work, subsistence being obtained at hotels and farm-houses. On November 21 he had completed the area assigned him and returned from the field. The total area surveyed by this party during the season is 3,325 square miles.

The party under Mr. Charles M. Yeates, topographer, was instructed to complete the atlas sheet 35°-83° and the northern half of 34°-83°. This party outfitted at Charleston, N. C., and was at work by July 4. It consisted, besides Mr. Yeates, of Mr. J. W. Hays, topographer, and Messrs. R. McC. Michler and H. S. Selden, assistant topographers, with three field assistants and the necessary laboring force. The work of the party was delayed somewhat by a series of accidents which befell Mr. Yeates, but in spite of them the area assigned to him was completed, and in addition the counties of Lumpkin, Georgia, and Oconee, South Carolina, the party having surveyed an area of 3,071 square miles. The success of this party was due in no small degree to Mr. Hays, who was placed in temporary charge during Mr. Yeates's disability, and who carried on the work excellently.

The party under Mr. Louis Nell, topographer, was directed to complete the atlas sheet 34°-86° and to survey the entire area of atlas sheet 34°-87°. This party was organized and took the field July 12. It consisted, besides Mr. Nell, of Messrs. R. M. Towson and E. A. Oyster, assistant topographers, and Messrs. C. E. Cooke and S. A. Foot, topographic assistants, with the necessary laboring force. Work was prosecuted during the season very successfully, although several members of the party suffered from malarial disease during the sickly season. The party was disbanded at Huntsville, Ala., November 20, some of the assistants remaining in the field a few weeks longer for the purpose of completing small areas previously left unfinished. The total area surveyed by this party during the season is 5,055 square miles.

For the reduction of barometric observations for altitude, base stations were established at Romney, W. Va., Wytheville, Va., and Roan Mountain, N. C. Through the courtesy of the Chief Signal Officer of
the Army, the observations taken at the signal offices at Knoxville and Chattanooga, Tenn., have been furnished, thus relieving this office from the necessity of establishing stations at those points. At our own stations observations were made hourly from 7 a.m. until dark, thus insuring coincident observations with those taken in the field. The barometers at these stations were carefully compared with the standard at the Signal Office in Washington, both before and after the field season, and the barometers used in the field were compared with those used at the base stations as often as possible and also with the barometers of the signal offices in Chattanooga and in Knoxville.

As will be seen from the above account, the work of this section during the past season has been eminently successful. The executive management has been brought to such a point of excellence that on an average the parties were in the field at work within four days from the time of leaving Washington. Not only did the area of work done show a very decided increase, but the improvement in quality has been even greater than the increase in quantity.

Since the inception of work in this region there has been surveyed an area of 56,350 square miles. This is distributed as follows among the several States:

<table>
<thead>
<tr>
<th>State</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alabama</td>
<td>6,013</td>
</tr>
<tr>
<td>Georgia</td>
<td>3,822</td>
</tr>
<tr>
<td>Kentucky</td>
<td>3,870</td>
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<tr>
<td>Maryland</td>
<td>2,155</td>
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<td>North Carolina</td>
<td>6,580</td>
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<td>South Carolina</td>
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<tr>
<td>Tennessee</td>
<td>11,515</td>
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<td>Virginia</td>
<td>10,780</td>
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<tr>
<td>West Virginia</td>
<td>11,000</td>
</tr>
<tr>
<td>District of Columbia</td>
<td>15</td>
</tr>
</tbody>
</table>

Total: 56,350

For map showing progress of triangulation in the Appalachian region, see Pl. IV.

WESTERN SECTION.

Missouri-Kansas subsection.—The work of this subsection was, as during the previous season, in charge of Mr. R. U. Goode, topographer. In the place of astronomic determinations for the correction of accumulated error in the surveys of the General Land Office, it was decided to substitute a gridiron system of triangulation, utilizing as far as possible the transcontinental belt of the Coast and Geodetic Survey, both immediately for the control of the work and also for the inception of our own triangulation. The work of triangulation was placed immediately in Mr. Goode's hands, and for carrying on the topographic work under the plan pursued during the preceding season two parties were organized, in charge, respectively, of Messrs. H. L. Baldwin and E. T. Perkins, jr., assistant topographers.

To Mr. Baldwin were assigned the two square degrees lying between latitudes 38° and 39° and longitudes 93° and 95°, comprising an area of
about 8,000 square miles. To Mr. Perkins were assigned the two square degrees lying between the same latitudes and the ninety-fifth and ninety-seventh meridians, together with an area of about 2,400 square miles, lying between latitudes 37° and 38° and the meridians of 96° 30' and 97°, being the unfinished portion of the sheet assigned to Mr. Peters during the previous season. Out of the area thus assigned to Mr. Perkins, however, Mr. Goode was directed to survey a strip some 18 miles in width, running east and west across the two northern square degrees, a work which he could carry on coincidently with his triangulation without sensible delay. Mr. Baldwin's area was traversed from east to west by the transcontinental belt of the Coast and Geodetic Survey, and required no further control. For the control of Mr. Perkins's area Mr. Goode was directed to carry a belt of triangulation, taking as its base line and initial azimuth the line between the two westernmost stations of the Coast and Geodetic Survey, and running thence nearly west across the middle of these two square degrees. The system of work as thus planned was successfully carried out. Mr. Goode, starting with the stations Fulton and Hutton Mound, of the U. S. Coast and Geodetic Survey, selected and occupied thirty-eight stations, carrying a belt of triangles and quadrilaterals through to a point within five miles of the ninety-seventh meridian. All these stations were connected, either by direct measurement or by minor triangulation, with the nearest section corners of the land surveys, connection being thus established between the two systems of survey. He also surveyed the 18-mile strip within which lay his belt of triangulation. (Pl. V.)

Although he found the plats of the General Land Office in his area very inaccurate and incomplete, Mr. Baldwin succeeded in supplementing their deficiencies of drainage and in adding the contours and culture to the entire area assigned him, and then, the season not being over, he extended his work northward to the Missouri River.

The area assigned to Mr. Perkins was mainly an open prairie region, and the Land Office surveys, being of later date than those in Mr. Baldwin's area, were much fuller with respect to drainage and were more carefully made; hence the difficulties which he encountered were very much less than those met with by Mr. Baldwin. He surveyed the entire area assigned him, and, several weeks remaining before the time assigned for the disbandment of the parties, he extended his work northeastward, and surveyed the counties of Wyandotte, Atchison, Jefferson, and Leavenworth, Kans., in addition to the area originally assigned.

The total area covered by this section is 21,400 square miles, of which about 2,000 were surveyed by Mr. Goode, 8,900 by Mr. Baldwin, and 10,500 by Mr. Perkins.

The parties disbanded in the latter part of November, stored their property, and returned to Washington for the winter. During the winter and spring they were engaged in plotting their field work and in reducing the triangulation.
SKETCH
SHOWING THE PROGRESS
OF THE
TRIANGULATION
IN THE
PLATEAU REGION

LEGEND
Triangulation East of 112° by A.P. DAVIS
West " - " H.M. WILSON
Light lines represent adjusted portion of the Tri-
angulation by Hayden and Powell Surveys
Texas subsection.—The organization of this subsection, with the exception of the field assistants, was precisely the same as during the preceding season. It remained in charge of Mr. E. M. Douglas, topographer, with Messrs. A. F. Dunnington and O. H. Fitch, as topographers in charge of parties.

The members of this subsection left for Austin, Tex., for the purpose of taking the field, about the middle of July. The work of outfitting was rapidly carried through and the parties commenced work with little delay. The areas assigned to the two topographic parties were as follows: First, the completion of the two square degrees lying between latitudes 30° and 31° and longitudes 97° and 99°, about half of which area had been surveyed during the preceding season; and, second, the survey of the area lying between the same latitudes and longitudes 99° and 99° 30' and that lying between latitudes 31° and 31° 30' and longitudes 98° and 99°. To Mr. Douglas was intrusted not only the supervision of these parties, but the duty of extending the triangulation to cover the area to be surveyed. (Pl. VI.)

These instructions were carried out. Mr. Douglas selected and occupied during the season twenty stations for triangulation, and Messrs. Fitch and Dunnington each surveyed an area of about 4,000 square miles. The parties continued work until late in November, when they disbanded and returned to Washington. During the winter the triangulation was reduced and the work plotted.

Early in May of the present year, Mr. Douglas was sent to the field, with instructions to continue the triangulation in advance of the topography. His reports recently received show that he has occupied and located eight stations during the current field season, making altogether during the year twenty-eight stations.

Arizona subsection.—The organization in Arizona, which had consisted the previous year of two parties, was reduced to one party, in charge of Mr. A. P. Davis, topographer, assisted by Mr. R. H. Chapman, assistant topographer. To this party was assigned the area lying between latitudes 34° and 35° and longitudes 111° and 113°, comprising an area of about 8,000 square miles. Mr. Davis was ordered to the field in the latter part of June, 1885, with directions to carry triangulation and topography over the above described area. The instructions were carried out, the work was completed, and the party left the field in the early part of November. (For a map showing triangulation in the plateau region, see Pl. VII.)

During the winter and spring this party has been engaged in office work.

Gold Belt subsection.—As an aid to the study of the gold-bearing rocks on the western slope of the Sierra Nevada, in California, it was decided to make a topographic map of this area upon a scale of publication of 1:125,000, or about 2 miles to an inch, with a contour interval of 100 feet. In accordance with this decision, Mr. H. M. Wilson, topographer, and Messrs. W. J. Peters and R. H. McKee, assistant topog-
Administrative Reports by

Raphers, were ordered to the field in June, 1885, with directions to outfit two parties for carrying on triangulation and topography jointly and survey the area lying between latitudes 39° and 40° and longitudes 120° 40' and 122°, or such part thereof as practicable during the season. It was the intention to initiate the triangulation from points determined by the U. S. Coast and Geodetic Survey, but upon arriving at the field of work the atmosphere was found to be so hazy that it was impossible to see the stations. Consequently, for temporary use, a base line was measured near Oroville, with a steel tape. Expansion was effected, and triangulation was carried on from this with the intention of connecting it with the points of the U. S. Coast and Geodetic Survey hereafter when the state of the atmosphere would permit. With this as a basis, topographic work was carried on. An area of 2,400 square miles was surveyed by the two parties during the season. The work was closed early in December, and the parties returned to this office.

On the 1st of May, 1886, Messrs. Wilson and Peters were again ordered to the field, mainly for the purpose of connecting their triangulation of the season before with the points determined by the U. S. Coast and Geodetic Survey, and also for the purpose of extending the triangulation as far as possible before the summer's haze should become troublesome. Reports recently received from them indicate their entire success. Connection had been established with the geodetic work of the U. S. Coast and Geodetic Survey, and the triangulation had been extended well in advance of the topography.

Cascade subsection.—In the spring of 1885 this subsection was placed under the charge of Prof. A. H. Thompson, the personnel remaining the same as during the preceding season. Early in May Messrs. M. B. Kerr and Eugene Riekseker left for the field, the outfitting point being, as heretofore, Red Bluff, Cal., and outfitted two parties for carrying on triangulation and topography. The instructions in regard to triangulation were to push it as rapidly as possible during the early part of the season, before the summer haze should become troublesome. Their instructions with regard to topographic work were to complete the survey of the country northward to the Oregon line and westward as far as longitude 123°, while certain unfinished areas in Northwestern Nevada were to be completed. The atmospheric conditions were very favorable to triangulation at the opening of the season, and Mr. Kerr succeeded in occupying Lassen's Peak and Mount Shasta and in obtaining the necessary angles from those points. Upon the latter peak, Mr. Kerr remained for three nights without fire and almost without shelter, one of these nights being passed in a snow storm, before he completed his work. Other points were occupied for triangulation with a greater or less degree of success, and this work was put in such shape that the topography was under fairly good control. The topographic work was eminently successful, as the two parties covered an area of about 10,400 square miles, completing all the parts of California and Nevada assigned.
to them and extending the work over a considerable area in Southern Oregon. The parties were disbanded early in November and returned to Washington, where the triangulation was reduced and the topographic work plotted during the winter.

Early in May of the present year the parties of Messrs. Kerr and Ricksecker were again ordered to the field, principally for the purpose of extending the triangulation in advance during the prevalence of clear weather. Reports received from these parties announce the occupation of nine stations, which will serve to control the topography over most of the present season's work.

YELLOWSTONE SECTION.

For the completion of the map of the Yellowstone National Park, including the extension of the surveyed area southward to latitude 44°, Mr. J. H. Renshawe, geographer, and Messrs. Frank Tweedy and S. A. Aplin, assistant topographers, were ordered to the field on May 22, 1885. Mr. Renshawe's instructions contemplated the organization of three parties for topographic work under the three gentlemen named. On the 1st of July Mr. W. H. Leffingwell, topographer, was ordered to the park for the purpose of reinforcing Mr. Aplin's party. Under this organization work was prosecuted rapidly, and the entire area assigned to the parties was completed during the month of September. The total area thus turned in is estimated at 3,600 square miles.

Upon the disbandment of these parties Mr. Leffingwell was ordered to proceed to Denver, Colo., and complete the survey of the Hogbacks, upon the east front of the mountains in Central Colorado, a work upon which he was engaged during the fall and part of the winter. He returned to Washington in March, and during the spring has been engaged in aiding in the preparation of the Yellowstone Park sheets.

DETERMINATION OF ALBUQUERQUE, N. MEX.

As accessory to the prosecution of geographic work in Arizona and New Mexico, it became necessary to determine the astronomical position of Albuquerque, N. Mex. For this purpose Mr. R. S. Woodward, astronomer, was detailed, with Mr. B. C. Washington, jr., as assistant. For the purposes of this determination, astronomical connection was had with the Washington Observatory, at Saint Louis, Mo., where the observations were taken by Prof. H. S. Pritchett. Seven telegraphic exchanges were made for time, with a mean result, uncorrected for personal equation, of $1^h 5' 47.34''$. For latitude, observations were made on ten nights; thirty-two independent pairs of stars were observed and one hundred and three results obtained. The weighted mean latitude is $35^\circ 4' 32.40'' \pm 0.09''$. The pier from which the observations were made in Albuquerque is the property of the Atlantic and Pacific Rail-
way Company, and is about 100 feet south of their general office building. This point was connected with several public buildings and with a land survey section corner.

SECTION OF TOPOGRAPHIC DRAWING.

During the year, from five to seven draughtsmen, under the direction of Mr. Harry King, chief draughtsman, have been in the employ of the office, and have been kept constantly occupied, mainly upon small pieces of work of a miscellaneous character. The large map of the United States, upon a scale of 16 miles to an inch, which has been in process of completion for the past three years, has been completed in respect to drainage and culture.

The compilation from original sources of the map of the State of New York, for the purpose of representing the geological results compiled by the State surveys, was commenced upon a scale of 1:300,000 and is now in a fair state of progress.

Besides these two pieces of work, the time of the draughtsmen was largely taken up in the preparation of copies of the original map sheets of Massachusetts for deposit with the State authorities and with the preparation of drawings and maps for illustrative purposes. The list of the latter is too long to admit of recapitulation here.

SECTION OF INSTRUMENTS.

During the year the work of adjustment and repair of instruments, and to a certain extent the manufacture of new instruments, has been carried on by Mr. Edward Kübel, the mechanician, with two, and during the spring three assistants. I am happy to be able to say that the employment of Mr. Kübel at a salary relieved the office from many of the difficulties and a large share of the expense attendant upon the repairs to the great number of minor instruments required.

ENGRAVING.

In my last report I noted the fact that contracts had been made by the Public Printer with Messrs. Julius Bien & Co., of New York City, for the engraving upon copper of one hundred sheets of the General Atlas of the United States. At that time seventeen sheets had been transmitted to Messrs. Bien & Co., and the engraving of them was in progress. Up to the present date the manuscript of seventy-six sheets has been furnished to the engraver, and of these fifty-seven have been engraved, comprising about 125,000 square miles. The completed copper plates of fifty-five sheets are now in our hands, and a small edition (250 copies) has been printed of forty-nine of these sheets for the use of the office.
The following is a list of the sheets thus far engraved:

List of atlas sheets engraved during the fiscal year ending June 30, 1886.

<table>
<thead>
<tr>
<th>State or Territory</th>
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<th>Designation of sheet</th>
<th>Area covered</th>
<th>Scale</th>
<th>Contour interval</th>
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## List of atlas sheets engraved during the fiscal year ending June 30, 1886—Continued.

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A further contract the engraving of twenty sheets has recently been made.

Very respectfully,

HENRY GANNETT,
Geologist in Charge of Geography.

Hon. J. W. POWELL,
Director U. S. Geological Survey, Washington, D. C.

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**REPORT OF PROF. RAPHAEL PUMPELly.**

**DEPARTMENT OF THE INTERIOR,**
**U. S. GEOLOGICAL SURVEY,**
**DIVISION OF ARCHEAN GEOLOGY,**
**Newburgh, N. Y., July 1, 1886.**

**Sir:** During the past year the permanent personnel of my division was as follows: Mr. Bayard T. Putnam, assistant geologist; Mr. John Eliot Wolff, assistant geologist; and Mr. A. O'D. Taylor, clerk and disbursing officer. In addition to these gentlemen Prof. W. M. Davis and Mr. T. Nelson Dale were employed temporarily in the field.

The season of 1885 was occupied in studying the structure of the Green Mountains, which undoubtedly contains the key to the geology of New England. There is in the whole range of American geology no more unsettled or more intricate and difficult problem. The experience gained already in our field work shows that the unraveling of this structure can be accomplished only step by step, by working from contact to contact, by correctly mapping all observations, and by taking nothing for granted. In this way in 1885 we worked out fully the structure of a long and important stretch of the Hoosac Mountain in Massachusetts and Vermont, and also made much progress on that of the Graylock mass. A large collection of working specimens was formed. Mr. Wolff has studied these lithologically, and during the winter his results and those of the field work have been correlated and
plotted on a scale of 5 inches to 1 mile. I hope that the end of the coming season will see us in possession of the solution of this great geological problem.

Mr. Davis made a study of the Triassic trap ranges of Massachusetts and Connecticut, the results of which appear as a contribution to your annual report.

All of the time that could be spared from the study and mapping of last season's work was given by Mr. Putnam and myself to editing and correcting the proof of the large volume of "Mineral Industries" for the Tenth Census.

I have the honor to be, sir, your obedient servant,

Raphael Pumpelly,
Geologist in Charge.

Hon. J. W. Powell,
Director U. S. Geological Survey, Washington, D. C.

REPORT OF MR. N. S. SHALER.

DEPARTMENT OF THE INTERIOR,
U. S. GEOLOGICAL SURVEY,
ATLANTIC COAST DIVISION OF GEOLGY,
Cambridge, Mass., July 1, 1886.

Sir: I have the honor to submit the following report of the work done in the division under my charge for the year ending June 30, 1886.

On the 1st of July, 1885, I began field work on the island of Nantucket. On the 1st of August I had finished the work of mapping the glacial drift and other deposits of that island as far as it could be done without making certain comparisons with the neighboring districts on the mainland and adjacent islands. My report on this island, with the accompanying geological map, is nearly ready for publication, and will be submitted to you before the 1st of September of this year. It will show the following points, viz: first, that the front of the ice during the last glacial period remained for some time over this district; second, that after the disappearance of the ice this region was very suddenly elevated above the level of the sea, after having been depressed below its level during the continuance of the glacial conditions; third, that since its elevation the land has undergone a considerable depression, amounting probably to 20 feet or more.

The only economic resource of importance discovered on the island is a bed of clay, appearing at various points on the north shore near the village of Nantucket, which will doubtless be found suitable for certain uses in the potter's art.

In the first days of August I resumed some long interrupted work on the island of Martha's Vineyard, which was begun in 1871, at the request
of Prof. Benjamin Peirce, but abandoned when he ceased to be the Superintendent of the Coast Survey. This work has been carried to the point where it can be published, and the memoir has been transmitted to you. The principal points which have been determined by this inquiry relate to the general history of the Tertiary strata in that district. It appears that these beds belong to a great delta deposit accumulated during the middle and later stages of the Tertiary age; they have been subjected to a considerable amount of dislocation by the action of mountain building forces; they thus indicate the action of these forces at a much later date than any for which they have been observed elsewhere on the eastern shore of this continent.

It appearing desirable to continue the study of the recent changes of level of the shore line on the coast of Maine (since that district might afford a chance of obtaining evidence as to the character of the movements by which the land recovered its position after the deep depression which the glacial period brought about), and the island of Mount Desert being peculiarly well suited for this research, it was chosen in August as the field of this investigation. It is a favorable place for this inquiry, for the reason that its hills rise to the height of over 1,500 feet above the sea and present steep faces inclined towards the open ocean. I hoped to find on these rock faces evidence sufficient to show whether or not the sea had acted upon them since the glacial period. The results of the inquiry were exceedingly satisfactory, as will be shown in the report on Mount Desert, which will be finished during the coming season. This report will sufficiently show that the surface of the island, at the time of the disappearance of the glacial sheet, was depressed to the depth of 1,000 feet or more below the surface of the sea, and that it emerged by a succession of sudden uplifts, each followed by a period when the sea was for a time in a stable position. As this research necessitated a very careful examination of the whole island, it was thought best to undertake the task of geologically mapping this area; the report will therefore show the structural geology of the district as well as the points which bear on its changes of level and the action of the glacial sheet upon its surface.

Among the interesting results of this inquiry into the geological structure of the island is the fact that, on its southern border, exposed not only on the main island, but also on Great and Little Cranberry Islands, which lie just south of Mt. Desert, we have an extensive series of volcanic ash beds, which were clearly formed in a subaerial position. These fragmental deposits have been found in the course of my work at several points along the shore between Eastport and Cape Cod. It appears likely that there is a fringe of these fragmental beds along the coast line between the several points where they have been observed, and that, being relatively soft beds, they have served by their erosion to determine in a measure the position of the shore line along this part of the coast. This problem will hereafter be made the matter of a special investigation.
Work on the island of Mount Desert was discontinued on the 20th
of September. From that time until the close of the field season I was
occupied in the study of the glacial phenomena in Rhode Island and
Southern Massachusetts. This work has resulted in the completion of
a map and relief models of a region of kame and terrace drift in the val­
ley of the Taunton River and in the partial preparation of a map and
report on the bowlder train from Iron Hill, in Cumberland, R. I., to the
island of Martha's Vineyard. The last named inquiry has led to results
which throw much light on the processes connected with the carriage of
glacial drift. It appears by this examination that a bowlder train origi­
nating in a hill, having a diameter transverse to the motion of the ice of
less than 1,000 feet, steadily widens from the point of origin until at a
distance of 15 miles from that point it is not less than 18,000 feet in
width. This bowlder train has been traced to the western end of
Martha's Vineyard, a distance of about fifty miles from its source. By
computing the amount of material contained in this train it seems pos­
sible to arrive at some conclusions concerning the amount of wear
brought about by the action of the ice on a surface of hard rock during
the glacial period, as will be fully shown in the forthcoming report.

On the 1st of January you deemed it best to add to the work of my
department that which is to be done upon the geological and phys­
ical conditions of the inundated lands of the United States. My expe­
rience in the study of the coast line of this continent has shown that
the greater part of our American swamps owe their origin to recent
changes of the coast line and that most of them are immediately contig­
ous to the sea and will have to be studied in connection with the coast
geology.

From the 1st of January I was in the main employed in organizing
the inquiries which it is necessary to make in this department. I made
a reconnaissance of the Dismal Swamp district of Virginia and studied
the fresh water marshes of Eastern Massachusetts. I also, through
the work of one of my private assistants, made some inquiries as to the
structure of the swamp of New Jersey.

By the aid of my valued assistant, Mr. R. A. F. Penrose, I was able
to make some advance towards the solution of an important problem in
the geological history of marshes, a matter which has occupied my atten­
tion for several years. It concerns the origin of the nodular and other
phosphates which are found in several parts of the Southern States, as
well as in foreign countries. It appears from these preliminary inquiries
that the superficial deposits of lime phosphate are accumulated beneath
marshes, and that their formation is in some way connected with the
physical and chemical conditions of those areas. The well known phos­
phatic character of iron ore deposits formed in swamps, as well as the
considerable amount of lime phosphate found in the earths deposited
beneath swamps, has an important bearing on this problem.
It seems likely that the dissolved lime phosphate brought into the swamp from the surrounding lands, in part at least, is taken from the water by the crustaceans which inhabit it, and that at their death it is brought into the mud in a state favorable to the formation of concretions. Mr. Penrose's researches are the result of two years of diligent and arduous labor prosecuted under my direction. As a result of this labor, he has prepared a valuable memoir on geological manures, with special reference to the deposits which are used in this country. This work is indeed the first synoptic treatise on the problem. When I became an officer of the Survey I asked your leave to study the problem of mineral manures as they occur in this country, a matter in which I have long been interested. Therefore, although Mr. Penrose himself defrayed the considerable cost of his inquiries, it seems to me that as it has been done in accordance with my plan of operation and under my supervision, it should be offered to you for publication by the Survey. On this account it is sent in as a part of the work of my division.

Besides the above mentioned assistance of Mr. Penrose, I received valuable, though uncompensated aid from five other special students, who worked under my instruction in preparing the details of my several reports. Their assistance will be properly acknowledged in the several reports. Although no part of the work done upon the marsh district of the United States is as yet ready for publication, my inquiries have shown that the inundated lands of this country afford a most important field for research. The area of lands in this country, excluding Alaska, which is rendered unfit for agriculture by a more or less permanent inundation probably amounts to nearly 100,000 square miles. By far the larger part of the swamps have a character which, as European experience shows, makes it easy to win them to agricultural use. Much of the best lands of Northern Europe and of England was, three centuries ago, in the condition of our American swamps. In this country lands of this class have been passed by, because hitherto there was so much good upland awaiting the tiller. Now that the fertile lands have been mostly occupied, we shall have to consider these vast reserves whence we are to win a great tillable area. The aim of the inquiry which I am seeking to make will be to ascertain the area and character of soil of each tract of inundated land which apparently affords conditions that make reclamation possible. As far as may be necessary the European areas will be compared, both as regards their nature and the means of improvement, with similar areas in this country and elsewhere which have been successfully treated.

The probable value of this inquiry may be judged from the fact, made plain by my examinations of the district, that the swamps bordering on Albemarle and Pamlico Sounds, containing an area of at least 3,800 square miles, are in the main reclaimable by a simple and inexpensive system of drainage; many detached portions of this area have been so
won to agriculture even by a rude and ill planned system of drainage ditches. The soil of these reclaimed swamps, as has been proved by long experience, is extremely fertile and enduring to tillage.

A condensed account of the more important part of the scientific results of my work in the district about Cobscook Bay, Maine, has, with your permission, been published in the American Journal of Science for July, 1886.

Very respectfully, your obedient servant,

N. S. SHALER,
Geologist in Charge.

Hon. J. W. POWELL,
Director U. S. Geological Survey, Washington, D. C.

REPORT OF MR. G. K. GILBERT.

DEPARTMENT OF THE INTERIOR,
U. S. GEOLOGICAL SURVEY,
APPALACHIAN DIVISION OF GEOLOGY,
Washington, D. C., July 1, 1886.

Sir: I have the honor to submit the following report of work in my division during the fiscal year ending June 30, 1886:

The scope of the work assigned by you to the division is the determination of the general geology of the Appalachian district, with the exception of the Archean rocks. Several States whose geology has been extensively studied are included in the district and many of the features of its geologic structure have been determined by earlier work. It has hence been possible to plan the work of the division in a more specific manner than could have been done in a virgin country. The work consists primarily of three parts: First, the investigation of the stratigraphy and structure of the belt of folded Paleozoic rocks lying immediately west of the Archean belt; second, the study of the Triassic formation, which lies in detached bodies resting for the most part on the Archean; and third, the study of the Tertiary and Quaternary history of the district, a history to be deduced partly from the levellying deposits that fringe the Atlantic and Gulf coasts and partly from the evidence of elevation and subsidence existing in the topography of the entire district.

The study of the later changes I have reserved for myself, and during the summer of 1885 I spent six weeks in the investigation of a system of shore traces marking the former extent of Lake Ontario and incidentally furnishing evidence as to the differential changes in altitude occurring in that region in post-glacial time. Later in the season I joined Professor Chamberlin in West Virginia, and with him continued the same line of investigation by studying the terrace system of the Monongahela, Alleghany, and Ohio Rivers. I also made three ex-
cursions in the Appalachian Mountains of Maryland, West Virginia, Virginia, Tennessee, and Alabama for the purpose of supervising and directing the work of my assistants.

The study of the Triassic formation was assigned to Mr. I. C. Russell, and he continued during the first part of the fiscal year the work begun by him in the spring of 1885. His field work continued from July 9 to October 24, and consisted of a reconnaissance of the various Triassic areas in North Carolina and Southern Virginia. At the close of the field season he had begun a preliminary examination of the greater Triassic area which extends from Northern Virginia northward into other States. It was found that this work could not be properly prosecuted without better maps than now exist; and, as it would not be economic to survey the isolated Triassic areas before they are reached in the general progress of the topographic work, it was decided to discontinue this investigation for the present and assign Mr. Russell other work. He prepared during the winter a preliminary paper on the Triassic area, which includes the Richmond coal field.

The belt of country in which the Paleozoic rocks are folded and otherwise displaced extends from Central Alabama northeastward to New England and constitutes approximately the Appalachian Mountains. The portion lying south of Pennsylvania and included in the States of Maryland, West Virginia, Virginia, Kentucky, Tennessee, North Carolina, Georgia, and Alabama is being surveyed by the Division of Geography and the mapping has reached such a stage that the work in general geology can be advantageously prosecuted. The portion of the belt in Pennsylvania has just received extensive study at the hands of the State survey and is therefore not included in our plan of operations, and the country traversed by the belt beyond Pennsylvania has not yet been topographically mapped. The work of my division has therefore been planned to develop the structure of the Appalachian Mountains in the States just enumerated southwest of Pennsylvania.

It is proposed to survey and measure with great care four sections crossing the belt at right angles. As the rocks to be studied are much disturbed, being in many places faulted and elsewhere crushed, a simple linear section does not afford sufficient guaranty of accuracy, and it has been decided to substitute for it the complete structural survey of a strip of country 20 miles broad. Four lines have been selected for such work: The most northerly lies within the basin of the Potomac, in Maryland and the Virginias; the next includes portions of the valleys of the Greenbrier and New Rivers, in West Virginia and Virginia; the third lies in Eastern Tennessee, crossing the Holston River and including a portion of the French Broad; the fourth, in Alabama, crosses the Coosa Valley in latitude 34°, and is to be surveyed in cooperation with the State geologists. When these sections have been finished and subjected to comparative study, it is believed that the structure of the intervening tracts of the belt can be unraveled with comparative ease and rapidity.
Mr. H. R. Geiger was assigned the Potomac section and has been engaged upon it during the fiscal year. He left the field early in November, spent the winter in office work arising in connection with his field notes, and resumed field operations early in May of this year. He began his survey in Western Maryland and is carrying the work progressively eastward.

Work has not yet been begun upon the Greenbrier section. The French Broad section was assigned to Mr. Bailey Willis. His field work began, in the spring of 1885, at the eastern edge of the Cumberland Plateau and was carried southeastward. It ceased on the 12th of October and was resumed early in May, the intervening time being devoted to the reduction of field notes. Mr. Ira Sayles, who had been previously engaged on the general geology of an adjacent district, continued field work until October, since which time he has devoted himself to the elaboration of his notes and the preparation of a report.

The Alabama section was assigned to Mr. Russell after the discontinuance of the investigation of the Trias, and he started for his field of operations in the latter part of April. His animals and camp equipment had been left the preceding autumn in Northern Virginia, and it was decided that he should travel with them to Alabama, continuing en route a research he had initiated the preceding summer in regard to the decay of rocks and its relation to climate. He reached his district in Alabama at the end of the fiscal year.

It was arranged that Prof. I. C. White, of the University of West Virginia, who had made an investigation under the auspices of the Survey of the stratigraphy of the Coal Measures in the valley of the Great Kanawha River, should incorporate the results of this investigation with material previously gathered by him in other parts of West Virginia and with portions of the published geology of Western Pennsylvania and Eastern Ohio, so as to present a comprehensive view of the sedimentary structure of that part of the Appalachian bituminous coal field contained in the three States. Certain discrepancies among the conclusions reached by the geologists who had studied different portions of this area made it necessary for him to visit several localities in each of the States, and he continued this work of review in the field from early in July until the first week in October. In Ohio he secured the co-operation of Prof. Edward Orton, the State geologist, who accompanied him in the re-examination of several important sections. In undertaking subsequently to arrange the material for publication, Professor White became satisfied that further field work was necessary, and the final preparation of the report has been postponed at his request until his data are complemented by additional observations.

The Appalachian district has been under observation for so long a period that the literature of its geology is copious and imposes great labor upon every new author who is unwilling to pass by the work of his predecessors without acknowledgment. If the literature were in-
dexed this labor would be materially abridged, and to this end I have undertaken to have executed what may be called a subject bibliography of the geology of the Appalachian district. A certain amount of experimental work was done by myself and by the permanent employes of my division, and the matter was finally placed in the hands of Mr. Nelson H. Darton, who has devoted five months to its prosecution. About 650 volumes have been treated, including the official literature of all the Appalachian States, and the work has produced nearly 6,000 bibliographic cards, each one referring to the pages in a specified volume on which a particular subject is treated.

In my last report an account was given of the condition of the various memoirs resulting from the investigation of the Quaternary history of the Great Basin. Although much labor has been devoted to these by Mr. Russell and myself, our progress cannot be indicated without going into details that would here be out of place. The report on Lake Bonneville is still incomplete, that on Lake Lahontau is still in press, and that on the Mono Basin awaits the preparation of a general map of the district.

Mr. E. H. Andrews, who had previously acted as Mr. Geiger's assistant, continued in that capacity until January 1, when he resigned; Mr. F. W. Geiger was afterwards engaged for the field season and reported for duty early in May. Mr. Willis has been accompanied this summer by Mr. William P. Trowbridge, jr., as volunteer assistant. A clerk was employed for four months to assist in the bibliographic work. During the field season Mr. Russell and Mr. Willis, subsisting on rations, have each given continuous employment to a cook and a teamster. Mr. Sayles employed a field assistant for four months and I had one for six weeks.

I remain, with great respect, your obedient servant,

G. K. GILBERT,
Geologist in Charge.

Hon. J. W. POWELL,
Director U. S. Geological Survey, Washington, D. C.

REPORT OF PROF. R. D. IRVING.

DEPARTMENT OF THE INTERIOR,
U. S. GEOLOGICAL SURVEY,
LAKE SUPERIOR DIVISION OF GEOLOGY,
Madison, Wis., July 1, 1886.

SIR: I have the honor to submit the following report of the operations of the division of the Survey under my charge for the year ending June 30, 1886. The work of this division is a general investigation of those enormously thick and difficult formations which in the Northwestern States underlie the basal fossiliferous or Potsdam sandstone of
the Mississippi Valley. The plan of operation under which my division works is set out at length in the Fifth Annual Report of the Survey (for the fiscal year 1883-84), pp.24-28 and 175-242.

FIELD WORK.

Besides my own work in the field during the year independent parties have been led by Assistant Geologists W. N. Merriam, C. R. Vau Hise, and G. H. Williams; in addition to which some brief studies, supplementary to the work done by him in previous years, were made in the field by Assistant Geologist C. W. Hall.

Mr. Merriam's party.—Mr. Merriam's field work for the season of 1885 lay entirely in the region of Northeastern and Northern Minnesota, where he spent the months of July, August, September, and October. During a portion of the time he was occupied in a repetition of the work of the previous year, his specimens and, in large measure, his notes also, having been destroyed by fire shortly after his return from the field in the fall of 1884; but he succeeded also in extending his observations over a very large amount of new territory. The total distance traveled by him in canoes during the four months named was over 1,000 miles, not counting the minor irregularities of his routes. The number of surveyed townships traversed was about eighty, besides which a large amount of unsurveyed country was crossed. The number of specimens collected was about eight hundred and fifty, most of which represent each a distinct rock exposure.

In accordance with my instructions, Mr. Merriam left Madison July 10 for Tower, Minn., via Saint Paul, Minn. At the latter place he was joined by Mr. H. B. Smith, who acted throughout the season as his field assistant. A stop of a day was made at Saint Paul in order to trace at the office of the United States surveyor-general at that place a number of plats of newly surveyed townships of Northern Minnesota needed in the summer's work. Leaving Saint Paul on the 12th, Mr. Merriam proceeded directly to Tower, stopping at Duluth only long enough to purchase provisions for the season. Having secured the necessary packers, canoe men, and canoes, the time until the 27th of July was occupied in a detailed examination of the shores of Vermilion Lake, this work being, in the main, a repetition of that of the previous year. At this time I joined the party, when we at once left Vermilion Lake, and proceeding thence eastward through Mud River, Mud Lake, Burntside Lake, Burntside River, Long Lake, Falls Lake, Farm Lake, and Mishishwi River, reached the western part of township 63, range 9 west of the Fourth Principal Meridian; thence, returning west for three miles, the party pursued a northerly and northeasterly route through a series of unnamed lakes and through Jasper Lake to Moose Lake, in township 64, range 9 west. From Moose Lake the route lay west and northwest through Wind Lake to Basswood Lake on the national boundary line; thence through Basswood Lake in a circuitous course to the
eastern end of Falls Lake, and thence through the same series of lakes as before named, but in reverse order, to Tower, which was reached August 16.

During this trip the rock exposures on the shores and in the vicinity of these lakes were examined closely, part of the ground having been covered by Mr. Merriam during the previous year. The next day Mr. Merriam with his party left Tower for a thirty days’ trip to the eastward through a region of country much of which was entirely virgin ground. His course lay at first in a southeasterly direction from the southeastern corner of Vermilion Lake through Gull, Eagle Nest, Bear Island, and Birch Lakes to Metawanga River, in township 60, range 12 west, in which vicinity a trip of two days was made away from the canoe route in order to study the relation of the Animiké formation and granite north of it to the great gabbro formation, all of which here present exposures in close proximity to one another. From Birch Lake the course lay northeasterly through one of the several arms of the singular lacustrine stream known to the Chipewas of this region as the Mishiwishiwi (or Big Beaver House) River, to the northern part of township 63, range 10 west. Thence turning into the main portion of this river, the course was southeastward and eastward as far as Reef Lake, at the northeastern corner of township 60, range 6 west. Returning thence to the northern part of township 62, range 10 west, the route lay next in a northerly and northeasterly direction through Moose to Snowbank Lake, and thence through Mountain and Carp Lakes to Knife Lake, on the national boundary line. From Knife Lake a southerly course was followed through several small lakes into Kekébak Lake from which Ogishkemanissi, Kabimitchikamak, and Sea Gull Lakes were reached, in which vicinity connection was made with the previous work of Mr. W. M. Chauvenet.

From Ogishkemanissi Lake the return trip west to Vermilion Lake was made by way of Knife, Carp, Basswood, Falls, Long, Burntside, and Mud Lakes, the village of Tower, on the south side of Vermilion Lake, being reached September 17. From the 17th to the 24th the party, dividing, was occupied in making a series of detailed sections of the iron formation in the vicinity of Tower and along the line of the Duluth and Iron Range Railway. On the 24th a fresh start was made from Vermilion Lake for the Lake of the Woods. The route now lay first northward from Vermilion Lake through Trout Lake, Loon River, and Loon Lake, on the national boundary line; thence eastward through Lac la Croix and Iron Lake to Crooked Lake, which had been reached from the eastward by Mr. Merriam’s party during the previous season. Turning westward again from Crooked Lake, the boundary chain of lakes, namely, Iron Lake, Lac la Croix, Loon Lake, Sandpoint Lake, Nameokan Lake, and Rainy Lake, was followed to Fort Francis, at the foot of Rainy Lake. Thence the course lay through Rainy River 80 miles to the Lake of the Woods, through which the course was northward to Rat Portage, on the Canadian Pacific Railroad, at the foot of the
lake, which was reached on the 20th of October. It being now too late
in the season to attempt to return by the same route, the party, in ac-
cordance with my instructions, returned via the Canadian Pacific Rail-
way to the Kaministiquia River, thence down that river in the canoes
to its mouth at Thunder Bay. The party disbanding, the packers re-
turned to Grand Marais on the Minnesota coast, Messrs. Merriam and
Smith returning via Duluth to Madison, which was reached October 29.
During this extended trip Mr. Merriam succeeded in gathering an im-
mensely amount of new material and in traversing a great deal of ground
not previously examined by any geologist even in the most cursory
manner.

Between May 19 and June 11 Mr. Merriam was occupied in photo-
graphing a number of important exposures in Northern Wisconsin and
Michigan, with especial reference to the preparation of illustrations for
a paper in this report on the classification of the early Cambrian and
pre-Cambrian formations.

**Professor Van Hise’s party.**—My last annual report left Professor Van
Hise in the field in the Penokee-Gogebic region of Northern Wisconsin
and Michigan, it having been determined, as explained in that report,
to attempt—in addition to the work previously done in this region by
himself during the season of 1884 and by the members of the Wiscon-
sin Geological Survey between 1873 and 1877—a general revision of the
whole iron-bearing belt between Lake Numakagon in Wisconsin and
Lake Gogebic in Michigan. Professor Van Hise, accompanied by three
packers, was continuously occupied in this work from June 24 until
September 5, at which time the party disbanded at Ashland, Wis.
Professor Van Hise returned at once to Madison, having succeeded in
visiting all of the important exposures of the iron-bearing formation and
of the underlying gneissie group within three miles of the iron-bearing
belt, in reviewing all of the Wisconsin work, and in obtaining a large
amount of new material (the number of specimens gathered being seven
hundred) to be used in preparing an account of the lithology of the
region. Professor Van Hise’s work was of a detailed character, every
exposure having been carefully located with reference to the section
lines. All of his traveling was necessary on foot, the region being
forest-clad, without roads, and impenetrable otherwise than on foot.

**Professor Williams’s party.**—Dr. George H. Williams, of the Johns
Hopkins University, having been appointed an assistant geologist and
assigned to this division, was instructed by me to devote his field sea-
son to a detailed examination, preparatory to an exhaustive microscopic
study, of two small areas, namely, the belts of greenish schist on the
Menominee River, in the vicinity of Quinnesec, in Michigan, and Pigeon
Point and its vicinity at the eastern extremity of the Minnesota coast
of Lake Superior. The first of these areas was selected as showing on
a large scale certain schists which may be taken as typical of a class of
rocks very widely distributed on both sides of Lake Superior. Any well-
established conclusions obtained with regard to the Quinnesec rocks
may, with entire safety, be extended to the corresponding rocks in other portions of the Lake Superior region. The Pigeon Point locality was selected as displaying on a grand scale a singular complex of sedimentary and eruptive rocks, such as obtains at numerous points in the wilderness of Northern Minnesota, in the vicinity of the junction of the Keweenaw and Animiké formations, but is nowhere else so favorably situated for study.

In accordance with my instructions, Dr. Williams, with Mr. W. S. Bayley, of Baltimore, as volunteer assistant, on the 1st of July left Chicago for Quinnesec, where his headquarters were kept until the 19th of that month, at which time, accompanied by Mr. Bayley, he left for Pigeon Point, via Duluth, Minn., where a camping outfit and supplies were obtained. Having provided himself also with a boat and with two Indian packers at Grand Marais, Dr. Williams established his camp on Pigeon Point, where he was occupied until August 25, at which date he returned, via Duluth and Chicago, to his home in Utica, N. Y. It should be said that, in his studies of the Quinnesec and Pigeon Point rocks, Dr. Williams has had the advantage, for the former place, of the detailed maps published by T. B. Brooks in the third volume of the Geology of Wisconsin, and, for the latter place, of a large scale contour manuscript map furnished by the courtesy of the Chief of Engineers of the United States Army.

My own field studies during the year included: (1) An examination of the Quinnesec schists, in company with Dr. Williams's party; (2) a study, in company with Professor Van Hise's party, of the contacts between the Penokee iron-bearing series and the gneissic formation lying to the south of it; (3) a study, in company with Mr. Merriam's party, of the vicinity of Vermilion Lake, in Northeastern Minnesota, and of the country for some 40 miles east and northeast of that lake, in which study I made an extended canoe trip through Vermilion, Mud, Burntside, Long, Falls, and Farm Lakes to White Iron Lake, and thence through the Mishiwishiwi River to township 64, range 9 west, thence northward through Jasper, Moose, and Wind Lakes to Basswood Lake, and thence through Basswood, Falls, Long, and Mud Lakes to Vermilion Lake; and (4) some brief studies of the Baraboo region of Central Wisconsin. The examinations in the Quinnesec and Penokee regions were made in July, those in the Vermilion Lake region during the latter part of July and August, and those in the Baraboo region in May.

OFFICE WORK.

The office work of the year included petrographic studies, mapping and other draughting, photography, the preparation of publications, and the general study and correlation of results. My own office work was partly at Madison, Wis., and partly at the general office of the Survey
in Washington, where I was occupied between December 28, 1885, and April 7, 1886.

Petrographic work.—Petrographic studies, particularly the microscopic study of thin sections, occupied much of my own time, as also most of the time given by Professors Van Hise and Williams to office survey work. We added to our collections during the year 2,300 hand specimens and 2,170 thin sections, of which latter 1,339 were made at Madison and 831 at Washington.

My own microscopic studies have been mainly in connection (1) with the question of the origin of the ferruginous schists and iron ores of the Lake Superior country, and (2) with our studies of the geology of Northern Minnesota, more particularly with reference to the mapping of the formations of that region. For the first of these studies I examined in detail some three hundred thin sections from all portions of the Lake Superior region, while for the second we have altogether over eight hundred sections. The latter have not all been studied in detail, but have in large measure been examined sufficiently to enable us to correlate the exposures they represent and to determine the several rock species of the region.

Professor Van Hise's microscopic work has been mainly in connection with the preparation of the volume on the Penokee-Gogebic region, to appear under our joint authorship. For this work he has studied in minute detail some five hundred thin sections, preparing full written descriptions of each. He has also prepared briefer descriptions of some four hundred thin sections representative of the granite and gneissic region of Central Minnesota. These descriptions were prepared, particularly at the present time, for the information of Prof. C. W. Hall, who has done the field work in this region and who was engaged during the past year in the preparation of a report of the results of his work. Professor Van Hise also aided me in my microscopic studies of the ferruginous schists of the Lake Superior region by preparing written descriptions of several hundred thin sections of this class of rocks.

Dr. Williams's petrographical work, done wholly in the petrographical laboratory of the Johns Hopkins University, was directly connected with the field work done by him, as already explained. In connection with the study of the greenish schists of the Quinnesec region he examined in detail 161 sections and in connection with the Pigeon Point work, 244.

Mapping and draughting.—The mapping and draughting work of the year was chiefly done, as heretofore, by Mr. W. N. Merriam. This work included the preparation of large scale working maps of various portions of the Lake Superior country, the plotting upon them of our field results, and the preparation of cuts and maps for publication.

Photography.—Mr. Merriam also continued to devote a portion of his time to photographic work, including the exposure of negatives in the

The preparation of the following papers for publication was also completed during the year: "The Classification of the Early Cambrian and Pre-Cambrian Formations," and "The Origin of the Iron Ores and Ferruginous Schists of the Lake Superior Region," both by R. D. Irving. The first of these papers appears in another place in this volume. The other paper will appear in the American Journal of Science for October, 1886. In addition to this much work was done during the year by both Professor Van Hise and myself in the preparation of a final memoir on the Penokee-Gogebic region. The field and microscopic work for this memoir is essentially completed, as is also much of the text of the memoir itself. It was expected that it would be ready by the 1st of July, but, in accordance with your instructions, my own work upon it was set aside in order that I might prepare the above named paper on the pre-Cambrian formations.

RESULTS.

Within the scope allotted to such a brief report as this it will not be possible to give any complete account of the year's work. Such an account can only be given in the shape of somewhat extended papers and memoirs. I may merely say that among the subjects to which special study has been given during the year the following should be named as having led to certain definite conclusions which are not only of some general scientific importance but have a direct bearing upon a satisfactory geological mapping of the region under survey—and indeed, are necessary pre-requisites to it.

The stratigraphy and lithology of the iron-bearing series of the Penokee-Gogebie region.—Our studies of this region, which has an exceptionally great importance as the best attainable type with which to compare the other iron-bearing formations of the Lake Superior region, are essentially complete.
The general geological structure of Northern and Northeastern Minnesota.—The great triangle of 24,000 square miles lying between Lake Superior, the national boundary line, and a line drawn southward from the Lake of the Woods to the vicinity of Little Falls, on the Mississippi River, has now been traversed sufficiently to enable us, by the further aid of our petrographic studies of the specimens gathered, to give a satisfactory account of its general geological structure. I had anticipated the presentation before now for publication of an account of the geology of this region, but our time being fully occupied otherwise it has been decided to set this aside and make a few additional studies in the least known portions of the district before publishing.

The origin of the ferruginous schists of the Lake Superior region and their accompanying iron ores.—The studies of the year led us for the first time to any satisfactory conception of the origin of these singular materials, which we may now say, I think somewhat confidently, can be demonstrated to have arisen in the main from the silicification of ferruginous carbonates, which were, in some measure, analogous to those of the Coal Measures. That these ferruginous materials were originally iron carbonates of some sort is a view which has often been advocated in the past, but no demonstration has ever before been offered nor does any conception of the nature of the process appear to have been reached.

The divisibility of the Archean formations.—The conclusion that the Archean formations of Lake Superior are divisible into two discordant members, to which Logan's terms Huronian and Laurentian should be applied, though with somewhat different limitations from those assigned them by geologists of late years, has been abundantly confirmed by new evidence gathered during the year. I think that we may say that we are now prepared on a definite principle to separate those two formations in mapping. Such a separation would differ from that indicated on the preliminary map of the Northwestern States, published by me in the Fifth Annual Report of the Survey, in that the areas to be colored for the Huronian would be greatly restricted in size. Most of the areas which on that map were provisionally colored for Huronian include, as was then suspected and as we now know, many schistose rocks which are an inseparable portion of the basement formation. Some of them possibly are wholly referable to that formation.

The origin of such chloritic schists as present themselves at the several falls of the Menominee River, on the boundary between Wisconsin and Michigan.—That such schists as these, which are typical of a kind having a very wide spread in the Lake Superior region, are the result of a metasomatic alteration, accompanying great pressure, of some sort of eruptive greenstone, we have suspected for some time, the field observations rendering such a conclusion very probable, as is set forth in my paper in the Fifth Annual Report of the Survey. We are now able, however, as a result of Dr. Williams's detailed studies in the Quinesec region, to announce such an origin for them with a great deal of confi-
Among the Quinnesec rocks Dr. Williams has distinguished three types of greenstone, namely, light colored gabbro, light colored diorite, and a dark colored diabase, with each of which are associated peculiar and characteristic schists. That these schists grade imperceptibly into their associated massive rocks and that they have originated from them by distinctly traceable mineralogical and structural changes the thin sections seem distinctly to demonstrate.

The origin of the upper mica schists of the iron-bearing series.—In both the Penokee and Marquette regions peculiar mica schists are largely developed in the upper horizons of the iron-bearing group. Professor Van Hise’s microscopic work enables us now to say that these mica schists have been developed from entirely fragmental rocks, composed mainly of quartz and feldspar, by a simple, easily traced process of metasomatosis.

As heretofore, Mr. Merriam is the only assistant on my division of the Survey who has been employed constantly throughout the year. The following have been employed on a per diem salary for such times as their services were needed or could be procured: Assistant Geologists C. H. Van Hise, G. H. Williams, C. W. Hall, and W. W. Daniells; also, as office assistants, T. A. Polleys, N. M. Thygeson, and J. R. Thompson; and as field assistants, W. S. Bayley and H. B. Smith, besides a number of canoe men and packers.

All of which is respectfully submitted.

ROLAND D. IRVING,
Geologist in Charge.

Hon. J. W. Powell,
Director U. S. Geological Survey, Washington, D. C.

REPORT OF PROF. T. C. CHAMBERLIN.

DEPARTMENT OF THE INTERIOR,
U. S. GEOLOGICAL SURVEY,
DIVISION OF GLACIAL GEOLOGY,
Beloit, Wis., July 1, 1886.

Sir: I have the honor to submit the following report of field and office work of the Glacial division during the fiscal year ending June 30, 1886:

My personal attention during the month of July was chiefly consumed in executive work incident to the beginning of the fiscal year and in the completion of a paper upon the driftless area for the Sixth Annual Report of the Survey. On the 1st of August, in association with Prof. R. D. Salisbury, a reconnaissance of the drift margin from the vicinity of Bismarck, Dak., to the national boundary line at the foot of the Rocky Mountains was undertaken. It was not thought wise in the present un-
settled condition of much of the territory to attempt a detailed tracing of
the drift border, but rather to determine a sufficient number of points to
fix beyond question the general course and character of the border of the drift in Northwestern Dakota and in Montana. The greater portion of
our time was spent in the delimitation of the drift in the Judith Basin
and the extreme Upper Missouri Valley and along the foot of the Rocky
Mountains, these regions being regarded as more fertile in significant
phenomena than the region intermediate between them and the well
known drift tract of Dakota. Determinations of the border were, how­
ever, made at two points west of Bismarck and east of the Little Mis­
souri River, and also in the Yellowstone Valley. It was ascertained
that the border of the drift, which in Southern Dakota lies nearly par­
allel to the Missouri River, on reaching the latitude of Bismarck turns
to the westward, passing about 10 miles north of Taylor, Dak., and
crossing the Yellowstone River about 20 miles below Glendive, Mont., or
60 miles above its mouth, though scattered bowlders occur several miles
to the southward in each case. The drift limit was found to cross the trail from Fort Maginnis to Stony Point on the Missouri River at about
18 miles from the latter. West of this the margin is deflected to the
northward, striking the Missouri River at the mouth of the Judith River,
west of which it swings again to the southward, and passing along the
northern foot of the Highwood Mountains crosses the Missouri River
above the mouth of the Sun River. Beyond this it curves rapidly to the
north, being here about 40 miles distant from the Rocky Mountains. As
traced northward it approaches them and passes the boundary at the
very foot of the mountains, as some years since determined by Dr. G. M.
Dawson, of the Canadian Survey. The drift area was reconnoitered for
considerable distances within the border, reaching at one point as far
back as Fort Assiniboine. The edge of the drift was found to be every­
where attenuated, nowhere terminating by ridged accumulations of the
nature of a terminal moraine. Conclusive evidence of its northeasterly
derivation was found. Incident to the discrimination of the northeast­
er drift some attention was given to the local "mountain wash" from
the Judith, Snowy, Mocassin, and Highwood Mountains, and more par­
ticularly from the great Rocky range. At the headwaters of the Teton
River impressive evidences of an ancient Rocky Mountain glacier were
found in the form of moutonnéed rocks and a well characterized mo­
raine, forming a loop around the débouchure of the stream from the
mountains. About the headwaters of the Marias River, another tribu­
tary of the Missouri, there was also found a magnificent terminal mo­
raine, marking the limit of a much greater ancient glacier, which moved
out upon the plains 25 miles from the mountains.
Parting from me upon the 29th day of August, Professor Salisbury
made a brief examination of the valley drift of the Yellowstone River
at Billings and in the vicinity of Glendive, with a view to distinguish-
ing this semi-local drift from that of the northeast as well as to deter-
ing the ancient fluvial conditions of the region.

In three days at the beginning of September spent on the eastern
slopes of the Rocky Mountains, in the vicinity of Helena and Marys-
ville, Mont., I found no unquestionable evidence of glaciation, but on the
western side, above Elliston, a well developed moraine was found indi-
cating a local valley glacier of considerable extent. On the 8th day of
September I discovered and explored a fine moraine on the northeast
side of the Mount Powell group, southwest of Garrison, Mont., formed
by an ancient glacier, which pushed forth some 5 miles beyond the foot-
hills of the mountain cluster. From September 9 to September 13 I
was engaged in reconnoitering the valley of Flathead Lake, giving
attention chiefly to the extensive moraines that were formed by glaciers
issuing from the Rocky Mountains and filling the greater portion of the
broad, flat bottomed valley. A curious phenomenon, consisting of a
series of parallel water marks of the nature of exceptionally slight ter-
races sweeping around the sides of the valley and encircling the isolated
hills within it, like gigantic musical staves, also occupied a portion of
my attention. My time from September 14 to September 24 was spent
in the region of Lake Pend d'Oreille, Idaho, where decisive glacial phe-
nomena are widely displayed. The more noteworthy objects of atten-
tion consisted of (1) the striated mountain sides bordering the lake on
the north and the west, and reaching thence northward through the
Kootenay Pass, a broad ancient river valley, to the Kootenay River,
and thence to British Columbia; (2) the drift-filling of this essentially
abandoned valley; and (3) the great overwash stream of gravel stretch-
ing from the southern extremity of Lake Pend d'Oreille into the Spo-
kane Valley, constituting the Spokane plains and blocking back the
waters which form the Cœur d'Alene Lake. From September 24 to
October 3 was given to observation in the Willamette Valley and in the
basin of Puget Sound. The subsequent fifteen days were spent at
private expense in observations on the glacial phenomena of British
Columbia and of the plains adjacent to the Canadian Pacific Railway,
for the purpose of comparative studies of drift phenomena.

Following a brief interval of office work my time from October 30 to
November 21 was given, in connection with Mr. G. K. Gilbert, to an
examination of the terraces of the Monongahela, Alleghany, Upper
Ohio, and Beaver Rivers, resulting in the gathering of important evi-
dence relative to the distinctness of the glacial epochs and the discrimi-
nation of the character and conditions of the formation of the terraces
in question. Between December 15 and December 23 I reconnoitered
the drift border in West Central Missouri. Between May 18 and May
25, 1886, I visited the areas of noted glaciated rocks at the eastern and
western ends of Lake Erie, notably the islands of the latter region, for
the purpose of studying the remarkable developments of grooving and
striation there so exceptionally developed and securing photographic.
illustrations of typical and unusual forms of glacial scorings. Between June 15 and June 25 I held field consultations with Mr. N. S. Shaler respecting the phenomena of drumlins and kames near Boston and of morainic accumulations and associated stratified deposits on Martha's Vineyard, and with Prof. J. D. Dana, of New Haven, and Prof. B. K. Emerson, of Amherst, Mass., respecting the terrace phenomena of the Connecticut Valley.

The remainder of the year was consumed in executive duties, the study of results, the preparation of the paper on glacial striation which appears in this volume, and with incidental minor studies.

During the winter Prof. R. D. Salisbury pursued at intervals his microscopic studies upon the residuary earths, loess, and glacial silts, with reference to determining the degrees of their assortment, the gradations in the size of their particles, and their mineralogical constitution. Some of the more important results were secured early enough to be incorporated in the proof of our joint article on the driftless area which appeared in the Sixth Annual Report.

Prof. J. E. Todd was occupied from the 1st to the 17th of July, 1885, in finishing a first draft of the manuscript for his bulletin upon the drift of Southern Dakota. On the latter date, with Mr. C. A. Love as assistant, he started for the field, and on the 21st began a brief re-examination of the region about the Bijou Hills and the mouth of Platte Creek, in Southern Dakota. On the 25th of July he began an excursion west of the Missouri River into the region south of the White River, with the object of determining the limit of the drift and the nature of the terraces of that region in connection with other glacial features. From the 1st to the 11th of August he was engaged in a re-examination of points between the Missouri River and the Wessington Springs, which resulted in the following determinations: (1) The existence of a driftless region occupying the northwestern portion of Buffalo County; (2) the occurrence of a bowldery terrace along the Missouri River at the Great Bend at the height of from 300 to 350 feet above the river; and (3) the existence of lines of very stony drift hills, resembling osars, in the more important valleys outside the moraine. The principal moraine was also found to form a nearly continuous line of hills along the eastern side of Box Elder Creek, while several miles to the northeast of it are three or four isolated clusters of high stony hills which bear evidence of having risen as islands through the ice sheet during its declining stages. Between August 11th and August 15th examinations were made between Wessington Springs and Madison, Lake County, resulting in (1) the location of the second moraine, a few miles west of Woonsocket, stretching southward toward Mount Vernon; (2) the discovery of a plain which was apparently an old lake bottom, occupying the eastern half of Sanborn County, extending, as was subsequently ascertained, to the vicinity of Mitchell and Alexandria. The principal deposit in this lake was, so far as could be determined, a bowldery clay,
scarcely distinguishable from glacier till. In the vicinity of Diana and Forestburg its surface is depressed, so that artesian wells are readily formed by piercing the boulder clay to a deposit of sand underneath. (3) From the eastern edge of this lake bed to Winfred there is a gradual rise of the surface, the streams presenting the peculiar feature of flowing at right angles to the general slope. (4) The range of high hills that extends along the East Vermilion River was found to decline in the eastern part of Lake County, forming an interlobate moraine similar to that of Turtle Point, near Wessington Hills, though less distinct. Between the 15th and the 28th examinations were made in the country east of Madison and southward as far as Palisade. It was ascertained (1) that the principal moraine, after forming a broad loop toward the southeast, nearly to Madison, turns northeastward along the north side of Battle Creek. This portion presents more abrupt knobs and more numerous lakes than any of the more southerly portions. (2) A plain was found extending eastward from Battle Creek, Lake Madison, and Skunk Creek to the vicinity of Pipe Stone, Minn., averaging in altitude about 1,700 feet above the sea. Remote from the principal streams this plain presents a more even surface than is usual in glaciated regions, there being few basins except along old water channels leading from gaps in the moraine. The western margin of the plain is not clearly distinct from the morainic surface except along Skunk and Battle Creeks. (3) Along the Big Sioux River, more especially in the bend north of Flandrau, there is a lower plain rising only to the height of 1,600 feet, presenting features more closely resembling those of an alluvial flood plain. (4) Upon the exposures of the red quartzites in the eastern part of Minnehaha County and adjacent parts of Minnesota glacial scratches were found to have diverse directions. This was especially marked near Pipe Stone, where the directions ranged from south 20° west to south 57° east, sometimes within a few feet. Farther south the directions range from south 30° east to south 75° east magnetic. (5) Along the Split Rock Creek, south of Pipe Stone, Minn., prominent knobs and clusters of knobs were visited, which presented kame-like contours whose interiors exhibit sand thinly covered with bouldery clay. (6) Along the eastern slope of the principal moraine in Minnehaha County systems of bouldery hills were noted within the valleys extending eastward from gaps or shallow outlet channels in the moraine. In their general relations and appearance they resemble those noted above.

A journey was taken from Mitchell to Fort Randall and an examination was made of the divide between the Missouri and Pouca Rivers. During this journey a section was constructed nearly at right angles to the moraines, reaching from within the second to the elevated Tertiary sandstone beyond the limit of the drift.

The week following September 3d was spent in visiting several localities in the contiguous portions of Iowa and Nebraska for the purpose of
examining the old drift deposits adjacent to the formations in Dakota, the terraces and the loess being the chief subjects of study. Field work closed on September 11th.

Between December 21st and January 1st an examination of the border of the drift in East Central Nebraska was made, during which the limit was ascertained to pass through the following towns: Friend, Seward, Brainard, Wisner, and Wakefield. Near Berks, Nebr., bowlder clay was found resting upon stratified sand beds without the slightest distortion of the latter. There was also found in the southern part of Seward County a deposit of volcanic ash intercalated between layers of stratified drift containing bowlders of red quartzite from Dakota.

Mr. Warren Upham was employed during the greater part of the year in an investigation of the area of the extinct Lake Agassiz, which is practically equivalent to the basin of the Red River of the North. His leading work was the determination of the precise extent of the ancient lake and of the altitudes formerly reached by its several portions, the object being to determine precisely the changes of water level that have taken place since the glacial epoch and that thus afford data for the solution of the larger problem of recent changes in drainage conditions. In connection with this investigation the extent of the ancient lake deposits which furnish the subsoil of that remarkably fertile and exceptionally smooth-surfaced tract was accurately mapped and a contribution was thus made to the study of the relations of soil and topography to agricultural methods.

In July and August, with Mr. R. H. Young as assistant in leveling, Mr. Upham determined the course and elevation of the highest beach line of this extinct lake from its mouth, at Lake Traverse, northwestern and northward through Northeastern Dakota to the international boundary. In the northern portion this shore line is found to coincide with the conspicuous promontory called the Second Pembina Mountain, which is the eastern edge of a plateau of Cretaceous shales mostly covered by drift deposits.

Instead of being now level, as at the time of its formation, this outer beach of Lake Agassiz shows, along its whole extent, as thus far surveyed, a gradual ascent northward, amounting to about 185 feet in this distance of about 225 miles. The area that was covered by this lake is now the vast plain widely famed as the Red River Valley of the North.

In September Mr. Upham examined the region about Red Lake, in Northwestern Minnesota, with a view to fixing some points on the border of the ancient lake in the wooded region, where continuous tracing and leveling are too tedious and expensive to be justified in advance of the settlement of the country.

In the interval between October 17th, 1885, and March 1st, 1886, in accordance with the provisions of his engagement, Mr. Upham was not employed upon the Survey. During the three months following he was
engaged in preparing his data for publication. As a part of his results
the material for a bulletin was submitted in June.

On the 15th of June he again took the field, devoting his attention
to an examination of the interior of the basin and a study of the lower
beach lines that mark stages of recession of the lake due to the cutting
down of its outlet. These observations, it is hoped, will give additional
evidence relating to changes of level and drainage conditions, since it
has already been ascertained that their rate of rise to the northward is
less rapid than that of the outer beach.

At the opening of the fiscal year Prof. George H. Stone was engaged
in field work in the vicinity of Kichmoud, Me., in continuation of his
previous special investigations of the gravels of that State, particularly
its remarkable osars. His attention was at first directed to the exami­
nation of a supposed terminal moraine on Swan Island, Kennebec River.
During the remainder of the month of July he was engaged in ex­
ploring the gravel ridges of Kennebec, Androscoggin, Cumberland, and
Oxford Counties. He traced out a large number of discontinuous gravel
ridges and gravel plains, a portion of which appeared to be clearly
parts of genetic systems, while other examples were without tracea­
bale connections. A large percentage of them were side-gravels, that
is, short ridges beginning on the south slope of a hill and running
down to the bottom and soon terminating. The glacial gravels in the
lee of the White Mountains were found to present characters quite
different from the long osars of the Penobscot region. Incidentally,
evidence was gathered relative to the changes of drainage of the An­
droscoggin basin during the Glacial and the Champlain periods. Au­
gust was occupied in investigations in the extreme southwestern portion
of the State, chiefly in Cumberland and York counties. A number of
remarkable gravel systems were traced out and mapped and many feat­
tures were noted that are peculiar to the gravel deposits of this region
in distinction from those of the eastern portion of the State. They
were found quite uniformly to take the shape of broad systems of closely
reticulated ridges or broad sheets very different from the definite
two-sided ridges of the eastern region. As a result of the difficulty of
sharply distinguishing these from valley drift, previous information was
found unusually defective and very important additions to existing
knowledge were made. One of the more interesting features of the
gravel systems of this part of the State is the way in which they divide
or branch outward toward the south like delta streams. Often there
is a second branching. Sometimes they send branches from east to west,
or the reverse, to join the neighboring systems. The gravel streams
here also climb to unusual heights and pass over cols occasionally three
or four hundred feet higher than the adjacent lowlands.

The first half of the month of September was occupied in further ex­
plorations of the southwestern corner of the State and in completing
details in the counties examined earlier in the season, embracing the
phenomena due to the submergence beneath the sea during the deposition of the gravels and the subsequent modifications wrought by it. During the month of June, 1886, Professor Stone again resumed the working out of the details of the gravel systems of Southwestern Maine. During the winter a portion of his time was given to the study of data and the preparation of maps and reports thereon.

The work of Prof. G. F. Wright on the Survey during the year was limited to twenty four days in the field and about an equal amount upon the completion of his report. His examinations were directed toward adding data to the large body of facts previously collected respecting the glacial border in Pennsylvania and the terraces of the Upper Alleghany River. A number of photographs were taken illustrating significant features of the formations examined. The report of Professor Wright upon this material and that previously collected is now essentially completed.

During the early portion of July, 1885, Prof. W. M. Davis made a careful and detailed study of the striation of Mount Monadnock for the purpose of determining the effect of such an isolated obstacle upon the ice currents that overflowed it. The result was a very satisfactory demonstration of the incurving of the currents in the lee of the mountain. The latter part of July was devoted by Prof. Davis to studies in connection with another division of the Survey. In August he made a brief study of two recent gorges near Canajoharie, N. Y., with reference to the time and method of their production, and also a brief inspection of the gorge at Little Falls, N. Y. His chief attention, however, was directed to the study of the remarkable parallel and dolphin-backed drift ridges of Wayne and Cayuga Counties, N. Y., which have been known variously as drums and drumlins, or lenticular, elliptical or mammillary hills. This region presents exceptional opportunities for the study of these peculiar forms of drift accumulation, since they here vary from the short mammillary type to those which are elongated to the extent of two or three miles. A considerable area was mapped and critically studied by Mr. Davis, both in respect to their shapes and positions and to their internal structure. In this work he was assisted by Mr. C. L. Whittle.

Mr. I. M. Buell continued his studies upon the bowlder trains of South Central Wisconsin, giving during the year sixty days to field work and the plotting of results. His work related almost entirely to the quartzite trains in Dodge, Jefferson, and Dane Counties, to which reference was made in my last administrative report. To the general purposes and objects of this special study there set forth, namely, the determination of (1) the amount of glacial abrasion of the parent quartzite knobs, (2) the amount of wear of the transported material in transit, as shown by the progressive degrees of rounding and reduction of the material found at different distances from the parent outcrop, (3) the lateral
dispersion of the material as it was borne onward, and (4) other characteristics of the trail as a whole, there were added, during the year, special studies on the topographic relations of the transported material and of its distribution through the body of the drift, in the endeavor to discern the laws of lodgment of the material. The area is characterized by drumlins, and also by kames, and the derivation of some data bearing upon the formation of these peculiar drift accumulations was also among the objects sought. It was necessary to spend a considerable portion of the time in the construction of a topographic map as a necessary means of representing the facts obtained.

During the month of June Mr. Frank Leverett was engaged in categorically collecting data regarding the drift deposits of Northeastern Illinois, chiefly in Boone, McHenry, Kane, and De Kalb Counties, preparatory to a contemplated study by myself of the obscure and complicated relations of the successive drift deposits of that region.

In connection with the special subjects of investigation of the Atlantic Coast Division, in charge of Prof. N. S. Shaler, considerable work relative to the glacial drift has been done by him or under his immediate direction, among which the following merit notice as a portion of the work of the year upon the glacial formations. Professor Shaler mapped in detail the glacial drift on the islands of Nantucket, Martha's Vineyard, and Mount Desert, and reports upon the same are in an advanced state of preparation. He also began and carried to an advanced stage the study of a bowlder train which extends from the deposit of ilmenite in Cumberland, R. I., to Gay Head, Mass., and caused to be prepared a map and model of the interesting kame district in the valley of the Taunton River near Steep Brook, Mass. Professor Shaler also had the drift area about Cohasset, Mass., carefully examined and mapped. In the above work he was aided by Messrs. T. W. Harris, A. S. Haskell, R. Hayward, J. P. Johnson, and C. S. Thompson.

Professor Shaler's work was directed toward the accomplishment of two ends, first, the mapping of the drift along the coast line, and, second, the study of certain selected problems which can advantageously be investigated in that part of the glacial field. The above named islands were chosen for the area work because the excellent Coast Survey maps afford the necessary basis for satisfactory delineation. The general subjects selected for examination included the glacial bowlder trains, the kames, esars, and terraces, and the action of the glacial sheet on the rock surface over which it moved. These inquiries have shown that the shore line of New England affords valuable data respecting several of the yet unsolved drift problems. A study of the glacial train from Cumberland Hill, in Rhode Island, makes it clear that there was a tolerably rapid lateral dispersion of the bowlders in that instance at least. The area overspread by the waste expands in the course of 15 miles from 1,000 feet to about 20,000 feet in width. The study of the kames led to the impression on the part of the investigator
that they were formed at or near the mouths of glacial streams and that the average distance to which the glacial waste was carried by these subglacial streams was much greater than that to which the adjacent till or ground moraine was carried. The general course of the ice movement is well indicated by the bowlder trains, it appearing from them, as well as from the less trustworthy indications of the glacial scratches, that both on the coast of Maine and on the southern coast of Massachusetts about Narragansett Bay, the ice, on escaping from the mainlands, where its course was in part determined by the north and south valleys, was considerably deflected to the eastward.

Considerable attention was devoted to the study of evidences indicating whether or not New England was depressed below the level of the sea during the glacial period, and the measure of its subsidence, if such occurred. Attention was also directed to the evidences indicating advances and recessions of the ice sheet during the glacial epoch.

It is fitting also here to note that in the pursuit of data relative to orographic changes, Mr. G. K. Gilbert, in charge of the Appalachian Division, traced out an ancient beach line of Lake Ontario from the vicinity of Watertown, N. Y., to the Niagara River, determining its altitude at frequent points along this extent, and demonstrating that the ancient lake had its outlet through the Mohawk Valley and was presumably blocked on the northeast side by the retiring glacier. This investigation showed differences in altitude between the eastern and western portions of the beach line amounting to 370 feet.

Respectfully submitted.

T. C. CHAMBERLIN,
Geologist in Charge.

Hon. J. W. POWELL,
Director U. S. Geological Survey, Washington, D. C.

REPORT OF DR. F. V. HAYDEN.

DEPARTMENT OF THE INTERIOR,
U. S. GEOLOGICAL SURVEY,
MONTANA DIVISION OF GEOLOGY,
Philadelphia, Pa., July 1, 1886.

SIR: I have the honor to submit the following report of operations of the Montana Division for the year ending June 30, 1886:

During the field season of 1885 the work of the previous season in the Gallatin Valley was extended, particular attention being paid to the southern end of the Bridger Range and the extension of its beds on the southern side of the Gallatin Valley. The field party was organized at Bozeman on the 22d of July. While the arrangements were being completed, Dr. A. G. Peale revisited Spring or Rocky Cañon and re-examined the section made by him in 1872.
After a week spent in work at this locality and in the vicinity of Mount Ellis, the study of the eastern side of the Bridger Range was begun. This occupied about two weeks. Bridger Creek was followed to its head and the divide to Brackett Creek crossed. The range was ascended at several points and the strata were carefully studied. The presence of the Devonian formation in this section was positively determined.

The coal beds, which are profitably worked near the Bozeman tunnel of the Northern Pacific Railroad, were found along the east side of the Bridger Range as far as our examination extended. The disturbances of the strata, due to violent uplift and overturning of the southern end of the range, have so crushed and distorted the coal beds that careful exploitation of the outcrops in each case will be necessary to determine whether mining will be profitable or not at particular localities.

After returning to the Gallatin Valley the range was ascended at several points from the western side and all the canons cutting into it were carefully examined. Evidences of glacial action were noted on both the eastern and western sides. The western foot-hills of the range, from Spring Hill southward to the Bridger Cañon, were found to be of gneisses, upon which rests the Potsdam sandstone, followed above by the Silurian and Devonian beds until the summit is reached, when the Carboniferous limestones are exposed, forming in most places the sharp, almost knife-like crest. In many places the beds are faulted and they are frequently completely overturned. Collections of fossils were obtained from a number of horizons that have been heretofore deemed non-fossiliferous.

The East Gallatin group (probably middle Cambrian) does not appear in this portion of the range, but from Spring Hill northward it forms the foot-hills on the west and a very considerable part of the main portion of the range itself.

During the latter part of August and the early part of September the upper part of the Silurian section and the lower Devonian beds of Dry Creek at the north end of the valley were examined and measured. This completed the detailed section up to the Carboniferous limestones.

A considerable portion of the earlier and later weeks of field work were devoted to the further study of the lake beds of the valley, with a view to determining, if possible, their exact age. During the winter some of the sands which form the so-called Pliocene lake beds, both at the north and at the south end of the valley, were subjected to microscopic examination, and they were found to be largely made up of volcanic glass, or pumiceous dust, which was probably carried by the winds from vents lying to the southward and deposited in the bottom of the lake that once spread over the Gallatin Valley. The sands and so-called marls form the lowest layers and rest upon creamy white limestones, and the particles of glass or pumice appear to be cemented.
by calcareous material. In the beds forming the central portion of the deposits there was but little if any material except the pumice. Some of the upper beds have fragments of crystalline rocks mingled with pumiceous particles. The former were evidently derived from the adjacent mountains, which undoubtedly formed a part of the shore line of the lake. Careful search of all these beds has been unsuccessful up to the present in regard to organic remains. Nothing of the kind has been found in any of the deposits of the Gallatin Valley, so we have no definite evidence to present as to their age. It is hoped that the more detailed study of their characteristics and comparison with the lake beds in other valleys of the Rocky Mountains, and perhaps with the known Pliocene and Quaternary lake beds of the plains east of the mountains, may eventually lead us to a correct conclusion as to their age. There are certain indications of a possible clue, which, if carefully followed out, will be productive of interesting results. The work of the next season promises to reveal some suggestive facts on this point, as it is proposed to undertake the examination of these lake beds in a more systematic manner. The areas about the Three Forks and between the Madison and Gallatin Valleys will be studied and their extensions determined, and it is hoped that in this direction the lines of contact with the underlying rocks may be better exposed.

During the season of 1885 only six weeks of actual field work could be accomplished. On the way to the field various mineral spring localities were visited and examined.

In the office the winter was mainly devoted to the study of the field notes. Dr. Peale has prepared a second paper on the statistics of the mineral waters of the United States, for publication in the next volume on the mineral resources, and he has also completed a bulletin on the mineral springs, giving complete lists with analyses. The bibliography of mineral waters has also been continued.

Very respectfully,

F. V. HAYDEN,
Geologist in Charge.

Hon. J. W. POWELL,
Director U. S. Geological Survey, Washington, D. C.

REPORT OF MR. ARNOLD HAGUE.

DEPARTMENT OF THE INTERIOR,
U. S. GEOLOGICAL SURVEY,
YELLOWSTONE PARK DIVISION OF GEOLGY,
Bozeman, Mont., July 1, 1886.

SIR: I have the honor to submit herewith the following report of field and office work conducted under my charge for the year ended June 30, 1886:

Field operations during the past year were confined almost exclusively to the area embraced within the Yellowstone National Park. On June
3, 1885, Mr. C. D. Davis left Washington for Bozeman, Mont., to equip a camp and make all the necessary preliminary arrangements for the season's field work. From Bozeman he proceeded to the Mammoth Hot Springs, where he established the first permanent camp for the summer. Accompanied by Mr. Walter H. Weed, I reached the Park June 24, meeting Mr. Davis at Cinnabar, the end of the railway, with transportation to take us directly to camp. Everything was in readiness for work July 1.

The party for the field season consisted, besides myself, of the following assistants, viz: Messrs. J. P. Iddings, Walter H. Weed, George M. Wright, and C. D. Davis. Mr. Samuel L. Penfield, of the Sheffield Scientific School, served most acceptably, rendering efficient aid as volunteer assistant for ten weeks during the college vacation.

The first geological work was a careful survey of the Gallatin Range, a reconnaissance of the region having been made the previous year. The party was placed in charge of Mr. Iddings, who commenced the survey near Mount Holmes, at the southern end of the range.

With the assistance of Mr. Wright, I examined the Madison Plateau from Mount Holmes, where the lavas abut against the Gallatin Range, southward as far as the Madison Canon and westward to the end of the great volcanic flow. Later I joined Mr. Iddings for several days, visiting the most salient points in the structural features of the range.

I returned to the Mammoth Hot Springs in time to meet the committee of the House of Representatives who visited the Park for the purpose of investigating its present condition and considering what legislation is needed for its future maintenance. I testified before the committee, presenting my views upon the necessity of the enlargement of the area of the Park, its proper boundaries, and the great importance of the region as a forest reservation to the whole country. I also met here Mr. W. H. Phillips, appointed by the Secretary of the Interior a special agent to examine and report to the Department upon the present management of the Park and what changes were necessary to insure an efficient management. With Mr. Phillips I made a tour of the Park, visiting all the more frequented resorts of travelers and the places where leases of ground for the accommodation of pleasure-seekers have been applied for or are most needed. I desired to give, as far as possible, the benefit of my experience to the Department in all matters pertaining to Mr. Phillips's visit. Mr. Phillips made his headquarters at my camp during his stay in the Park.

On September 1, I removed my main camp to Lost Creek, in the northwest corner of the Park, for the purpose of studying the Third and Grand canons and the region of country between Mount Washburne and the Yellowstone River. The details of the survey were assigned to Mr. J. P. Iddings and Mr. George M. Wright. From here Mr. Weed, accompanied by Mr. Penfield, started out for the annual examination of the different geyser basins, studying all changes that had taken place.
during the year in regard to temperature, periodicity, and amount of discharge, and noting all facts relating to their history, origin, and permanency.

I gave special attention to the later of the more massive lava flows and their relation to the so-called fossil forests and plant remains interbedded in the 2,000 feet of volcanic ashes, muds, and breccias. The value of the collection of Tertiary plants from the Park has been enhanced the past year, both by the addition of new species and by the amount and completeness of the material gathered. When our work is finished, these plants should throw considerable light upon the duration of the volcanic activity in the Park, which probably continued, with varying intensity and occasional periods of rest, throughout the greater part of the Tertiary and into Quaternary time.

On September 7, I left my main camp for a reconnaissance of the Absaroka Range, crossing the mountains near the headwaters of the Lamar River, an exceedingly rough and unfrequented portion of the country. I returned by the way of Clark's Fork and Soda Butte Creek, visiting the mining developments near Cook City, situated high up on the ridge between the two latter streams.

The continued study of the somewhat peculiar climatic conditions of the Yellowstone Park and my recent observations in the Absaroka Range only tend to confirm me in the opinion I have so frequently expressed to you of the great importance of this region as a forest reservation. I know of no tract in the Rocky Mountains where the necessity for the conservation of the forests appears so urgent, or the direct advantage to be gained so immediate, as right here on the Park Plateau at the headwaters of both the Yellowstone and the Snake River.

Owing to the extreme coldness of the season, the minimum thermometer falling to \(-5^\circ\) and \(-8^\circ\) every night, and the threatening appearance of the weather, I decided to close up the field work for the year on October 17. On that day I left the Park, accompanied by most of the members of my party, the others remaining to pack up the specimens and material gathered during the season, and later to transport the camp property to Bozeman, Mont.

Early in November all the members of this division of the Survey had returned to Washington and entered upon their regular office duties in working up and arranging the notes and material of the preceding summer.

During the year the collection of photographic negatives has been largely increased, and while among them there are but few showing the grander scenery of the Park, there is a great increase in the number of views illustrating the most interesting geological features which abound in that favored region. The negatives have proven to be exceptionally good pictures.

At the close of the fiscal year the topographical department was able to furnish me with photographic copies of the Yellowstone Park map from
Mr. Renshawe's original drawings. The map is in every way satisfactory and brings out all the varied and peculiar features of the Park in an admirable manner. It is not only suitable for geological purposes, but will meet all the requirements of travelers. In addition to the Park area as defined by law, the map extends southward to the forty-fourth parallel of latitude, adding a strip of country about eight miles in width along the southern border. This area, extending from the meridian of 110° to the meridian of 111° west of Greenwich, is a most interesting country, closely connected in its physical features with the Park. In a bill now before Congress it is proposed to include it within the Park domain.

With these completed sheets in the hands of the geological surveyors the work of mapping the country will be greatly facilitated and can now go forward without interruption. For detailed geological work an accurate map is an absolute necessity.

Recently Dr. F. A. Gooch, with the assistance of Mr. J. E. Whitfield, after an arduous and painstaking investigation, completed in the chemical laboratory of the Geological Survey a series of forty analyses of the waters of the more important geysers, hot springs, and rivers of the Yellowstone Park. The waters were carefully selected, with reference both to their geological significance and to the interest taken in them by the general public. Many of these waters forwarded to Washington were concentrated solutions, obtained by evaporation of large quantities of the natural waters at the place where they were collected. So many inquiries have been made as to the medicinal and curative properties of these waters by health-seekers and invalids, that the results of this chemical investigation will be of great value to geologists, chemists, physicians, and all interested in thermal waters. Included among the analyses are waters from the following geysers:

**Upper Basin.** — Splendid, Grotto, Beehive, Grand, Giantess. Old Faithful.

**Lower Basin.** — Fountain, Great Fountain.

**Norris Basin.** — Pearl, Fearless.

**Midway Basin.** — Excelsior.

Among the waters from the thermal springs analyzed are the following: Artemesia, Bench, Hillside, Hygeia, Coral, Schlammkessel, Cleopatra, Orange, Terrace, Soda Butte, Chrome, and Ink Pot.

In connection with his other duties during the past winter, Mr. Iddings, in investigating the acidic lavas of the Park, prepared for the Seventh Annual Report of the Director of the Geological Survey, a paper entitled "Obsidian Cliff, Yellowstone Park." It is the result of his studies upon the nature and mode of occurrence of the volcanic glasses forming so characteristic a feature of that region. The paper is well illustrated, and gives not only a description of Obsidian Cliff, but presents a résumé of all that is known as to the eruptions of obsidian in other parts of the world. During the year Mr. Iddings published
in the American Journal of Science a short paper on the occurrence of fayalite in the lithophyses of the obsidian in the Yellowstone Park. It was at the time the only instance known of the occurrence of this basic mineral in a natural acidic glass.

Very respectfully, your obedient servant,

ARNOLD HAGUE,
Geologist in Charge.

Hon. J. W. POWELL,
Director U. S. Geological Survey, Washington, D. C.

REPORT OF MR. S. F. EMMONS.

DEPARTMENT OF THE INTERIOR,
U. S. GEOLOGICAL SURVEY,
COLORADO DIVISION OF GEOLOGY,
Washington, D. C., July 1, 1886.

SIR: I have the honor to submit the following report of progress in the division under my charge during the fiscal year 1885-86:

The scientific corps of this division remains the same as at the time of my last annual report, except that Mr. W. F. Hillebrand, chemist, has been transferred to Washington, and the laboratory work at Denver since November 1, 1885, has been conducted by Mr. L. G. Eakins, who previously acted as his assistant.

Field work.—The field work of this division during the year has been carried on in the Gunnison or Crested Butte region and in the Denver Basin region, an area around Denver supposed to be underlaid by coal. I myself have taken no part in the field work, it having been judged best that I should remain at Washington to attend personally to the preparation of monographs for the press. I was, however, in constant correspondence with the members of the party in the field, keeping mental account of the progress of their work and offering suggestions from time to time in regard to its conduct. The summer field party consisted of Mr. G. H. Eldridge and Mr. Whitman Cross, geologists, with Mr. L. G. Eakins and Mr. W. B. Smith as assistants, and the necessary camp men. They left Denver with their pack train on July 1, and after stopping on the way—Mr. Cross at Buffalo Peaks to gather specimens for the Educational Series, Mr. Eldridge at the Monarch district and in the Arkansas Valley to gather fossils from the Paleozoic beds of those regions—reached the field of work on the 13th of the month. Work was carried on vigorously until the 21st of October, seriously interrupted only by a severe snow storm on the 10th of that month, which rendered work in the high mountain regions permanently impracticable until the following summer. As outlined in my former report, the plan of work was for Mr. Eldridge to map the sedimentary formations and Mr. Cross...
the eruptive masses, the work of the former thus including the deposits of coal and that of the latter most of the metalliferous deposits.

The structure of the region has proved so exceedingly complicated, even beyond expectation, that the simple outlining of the geological formations could not be completed during the summer, and another field season will be required for this alone.

Mr. Eldridge gathered further important and confirmatory data in regard to the non-conformities of which I spoke in my last report, adding considerably to the fossil evidence already obtained with regard to the relative age of the various formations, but had not proceeded sufficiently far in his work at the close of the season to form a satisfactory estimate of the extent and value of the coal fields in this important region.

Mr. Cross during the season collected over a thousand specimens of eruptive rocks, with many interesting minerals which it is thought will afford valuable data with regard to the origin of ore deposits, and took about forty excellent photographic views to illustrate the geology and topography of the region.

After the return of the party to Denver, about the end of November, Mr. Cross was engaged in office work, partly there and partly at Washington.

Early in November Mr. Eldridge took the field again to complete the laying down of geological outlines on the map of the Denver Basin, an area of 30 miles square, of which the city of Denver occupies about the center. At the same time Mr. W. H. Leffingwell was detailed to do the field work necessary to render the map of this region sufficiently detailed and exact to express the geological structure as indicated by these outlines. I had estimated that not more than two or three months would be required for the completion of this work, but—partly owing to the inclemency of the season, in consequence of which during the greater part of the time only a comparatively few days in the month could be profitably employed in the field, and partly owing to the unexpected complication in the structure, which necessitated most careful and detailed examination—this field work is at the present date not quite completed. It is my intention that the final writing up of the report of the region may be undertaken immediately after the close of the field season of this fiscal year, and, as certain chapters are already completed, I hope that the manuscript of the entire report may be ready for the printer in the coming spring.

Office work.—Contrary to my expectations, none of the various monographs of this division, which are in various stages of completion, have yet been published. Of that on Leadville, which has been so long delayed, I am now correcting the final pages of proof. The Ten-Mile, Silver Cliff, and Denver Basin reports are all partially completed, but it is as yet impossible to prophesy the date of their publication. As accessory work during the year, a number of interesting mineral inves-
tigations have been carried on by Messrs. Hillebrand, Cross, and Eakins, a portion of the results of which have appeared in scientific periodicals under the following titles:

"Widespread occurrence of allanite as an accessory constituent of many rocks," by J. P. Iddings and Whitman Cross.
"On emmonsite, a ferric tellurite," by W. F. Hillebrand.
"On allanite and gadolinite," by L. G. Eakins.

Reports of other investigations are in course of preparation, among the most remarkable of which is the study of the singular leucite rocks of the Leucite Hills of Wyoming.

Very respectfully, your obedient servant,

S. F. EMMONS,
Geologist in Charge.

Hon. J. W. Powell,
Director U. S. Geological Survey, Washington, D. C.

REPORT OF MR. GEORGE F. BECKER.

DEPARTMENT OF THE INTERIOR,
U. S. GEOLOGICAL SURVEY,
CALIFORNIA DIVISION OF GEOLOGY,
Washington, D. C., July 1, 1886.

SIR: The early portion of the past fiscal year was devoted to the completion of the field studies connected with my investigation of the geology of the quicksilver deposits of the Pacific Slope. The examination of Steamboat Springs, Nev., was finished in July. This locality is only six miles from the Comstock Lode, and the two districts possess many points of similarity. At Steamboat Springs, as at Virginia, diabase occurs, but while a large mass of this rock forms the hanging wall of the Comstock, it occurs at Steamboat only as pebbles in highly altered conglomerates, at least as old as the Tura-Trias series of the "Exploration of the Fortieth Parallel." These pebbles are macroscopically and microscopically identical with the hanging wall of the Comstock. The diorite of Mount Davidson or of the foot-wall of the Comstock, an older rock than the diabase, was not met with at Steamboat, where, however, the andesite series of the Washoe district is well developed. In both regions the pyroxenic andesites and the later hornblende andesites of my Comstock monograph are younger than an ordinary dense hornblende andesite. At Steamboat this relation is well exhibited by dikes. The chemical geology of Steamboat is of extreme interest, it having been shown, in part by field work and in part by subsequent analyses, that a variety of ores, including cinnabar, are still being deposited there.
The examination of New Almaden and Guadalupe was completed in August. Apart from the great production of this region it presents comparatively few peculiar points, most of its characteristics being common to the other quicksilver localities of the Coast Ranges of California. The occurrence here of a dike of rhyolite several miles in length, however, is of much interest, no other rhyolite being known in the Coast Ranges.

Since September Dr. W. H. Melville and I have been engaged in elaborating as rapidly as possible the material for my monograph on the geology of the quicksilver deposits. Messrs. H. W. Turner and W. Lindgren have also been employed during a great portion of the year in the same work. Mr. Turner is thoroughly familiar with the entire field work and the collections. Mr. Lindgren shared with me the arduous task of studying the microscopical lithology of the metamorphic and eruptive rocks, in which we had the assistance of analyses by Dr. Melville. On April 2 I left San Francisco for Washington, to complete the preparation of my report.

The preparation of this monograph is now in a very advanced state. It can be put into the hands of the printer a month after the completion of a little chemical work yet unfinished. Without this, however, no complete summary of the investigation can be submitted.

Messrs. Turner and Lindgren have begun upon the geology of the Gold Belt, which, according to your instructions, is to form the next subject of investigation by my party. They have been thus employed whenever they could be spared from the office, and have already mapped several hundred square miles of this region; the map, when completed, will embrace an area of 12,000 miles, on a scale of 2 miles to the inch.

Besides the statement of the main work of my division made above, I may call your attention to certain minor results. For the sake of comparison with Steamboat Springs and for the purpose of testing former conclusions, I visited the Washoe district, examining the surface and the new exposures in the mines as well as the principal older excavations. I had the gratification of finding my former results, published in Monograph III, very satisfactorily confirmed by these observations. The only correction which I should now make in that discussion is that a portion of the pyroxene of the diabase and augite andesite is hypersthene. Mr. W. Cross's fine discovery that hypersthene is a usual constituent of pyroxenic rocks was published after my discussion of the Washoe rocks had been completed and too late for me to reopen the subject. I should add that the augite andesite of my report is divisible into two successive eruptions, not separated by any other eruption, both of which occurred later than the outburst of "earlier hornblende andesite" and earlier than the "younger hornblende andesite" of my report. A long interval of time separated these two eruptions of pyroxenic andesite, of which the latter immediately preceded the eruption of later hornblende andesite. These last two rocks are connected by transi-
tions. I also examined the quartz porphyry, a pre-andesitic eruption, having five separations made of specimens from widely removed points. All of them showed a very small amount of plagioclase as compared with the orthoclase, confirming my previous conclusion that this rock is substantially orthoclasonic. Quartz porphyry has not been encountered either by the older or by the newer mine-workings north of Gold Hill or in the Sutro Tunnel.

Early in the year appeared my paper, Notes on the Stratigraphy of California, Bulletin No. 19, a companion to Dr. C. A. White's Notes on the Mesozoic and Cenozoic Paleontology of California, Bulletin No. 15. The field work for these papers had been done during the summer of 1884. They show, from structural and paleontological standpoints respectively, that a great and hitherto unsuspected non-conformity exists between the early and the late Cretaceous strata of the Coast Ranges and establish an identity between the older strata of the Coast Ranges and a portion of the Sierra Nevada, viz, the fossiliferous region, including the Mariposa estate, at the southern end of the Gold Belt. Hence also the Coast Ranges and the Sierra Nevada form portions of the same mountain system. These papers show further that there was continuity of life and of sedimentation from the Chico to the Tejon. The latter Dr. White considers, with Conrad and Heilprin, as Eocene, while the Chico is undoubted Cretaceous.

In view of the necessary delays in the publication of my monograph, I published in advance an abstract of my results on the Cretaceous metamorphic rocks of California. Nearly all the minerals forming important constituents of crystalline sedimentary rocks elsewhere enter into the composition of this interesting series, which is formed of granitic detritus, was deposited wholly or chiefly about the beginning of the Cretaceous, and was upheaved and metamorphosed about the close of the Neocomian. This series includes no interbedded eruptive rocks, but small specimens of the more highly metamorphosed rocks might easily be confounded with eruptive material. Many of these rocks carry fainophane. The serpentines of the Coast Ranges are in part the result of direct alteration of sandstones and are in part formed by the decomposition of other crystalline metamorphic rocks. None of the serpentine encountered is due to the alteration of olivine and none of it is an original precipitate. The metamorphic series of the Coast Ranges is interesting not only from its comparative recency but from the fact that it presents innumerable transitions to unaltered rocks which are fossiliferous at many points over a distance of 300 miles.

Studies connected with my notes on the stratigraphy of California also led me to the consideration of the fundamental shape of volcanic cones. It appears natural to suppose that as additions to a volcanic cone are made at or near its top, it will constantly tend to the loftiest

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form which the amount of material it contains can assume consistently
with stability. This form could, I found, be determined mathematically
with all possible definiteness. The result coincides in the most remark­
able manner with surveys and photographs of actual volcanic cones
in America and in Japan. The same investigation accounts for the ex­
traordinary height of the lunar volcanoes.

I also rediscussed the mechanical conditions of faulting, showing that
the results which I reached in an analysis of the faulting phenomena of
the Comstock Lode (Monograph III, chapter IV) are necessary deduc­
tions from the nature of friction. Incidentally I showed that frictional
problems may be brought under the general elastic problem, and are
not sui generis.

Chemical questions involved in the investigation of quicksilver led me
to a new general law of mechanics, which I have called a "theorem of
maximum dissipativity." According to this law there is in every sys­
tem a tendency to motions of a shorter period, and this tendency will
be the greatest possible when the motions of the system have periods
which differ considerably.

The chemical interpretation of this law forms a new law of thermo­
chemistry, according to which chemical energy will be degraded at the
highest possible rate. This result throws important light upon the
order of succession of minerals in volcanic rocks. It has also been of
great use to me in a study, still incomplete, of the solution and deposi­
tion of cinnabar and the other more important ores of California.

I may remark that every one of these inquiries has been forced upon
my attention by the demands of my investigation of the quicksilver
deposits, and that each of them has aided in the elucidation of that sub­
ject. By means of the results on the geometrical form of volcanic
cones, for example, I am able to show that the andesite lava in which
quicksilver occurs on the western side of Clear Lake is substantially con­
temporaneous with Mount Shasta. The same investigation shows that
both masses are later than had been supposed, and a discovery of fossils
at Clear Lake immediately below the andesite, which were determined
only a few days since by Professor Marsh, entirely confirms this result so
far as the Clear Lake lava is concerned, these remains indicating a very
late Pliocene date. The more general questions discussed have not
been allowed to interfere to any considerable extent with the routine
work of my division; indeed, since February, 1883, there has been, I
believe, but a single month during which my party has done no field
work.

In closing the record for the year, I may mention that a volume, Sta­
tistics and Technology of the Precious Metals, Census of 1880, Vol. XIII,
by Mr. Emmons and myself, appeared last autumn. The enormous
amount of work devolving upon the authors in the collection and dis­
cussion of these statistics was performed in addition to their duties as

members of the Survey, and, of course, gratuitously. It was completed in January, 1883, but publication was delayed by circumstances over which they had no control.

Very respectfully, your obedient servant,

G. F. BECKER,
- Geologist in Charge.

Hon. J. W. POWELL,
Director U. S. Geological Survey, Washington, D. C.

REPORT OF CAPT. C. E. DUTTON.

DEPARTMENT OF THE INTERIOR,
U. S. GEOLOGICAL SURVEY,
DIVISION OF VOLCANIC GEOLOGY,
In the Field, Ashland, Oreg., July 1, 1886.

SIR: Herewith I have the honor to transmit my report of the operations of the division of the Survey in my charge during the fiscal year ending June 30, 1886.

At the beginning of the year (July 1) my own party and that of Mr. J. S. Diller were already in the field in Northern California, having left our base station and outfitting camp at Red Bluff, Cal., and penetrated eastward as far as Lassen's Peak. Mr. Diller had already performed one season's work of a preliminary character and it was decided that he should spend the summer of 1885 in mapping the geology of that district. The topographic sheet which includes Lassen's Peak and the sheet lying to the west of it had been placed in our hands as photographed from the drawings, and it was hoped that the greater part of the geologic work could be advanced so far as to enable us to enter most of the geology upon the map. The sheet in question was chiefly compiled from the work of former surveys under the War Department, and was found to be wholly unsuited to geological work when compared in detail with the topographic features in the field. It was decided to make the best of it, however, and enter only those broader features of surface geology which are independent in some degree of accurate topography and to give the broader features and their areas as nearly as the map would permit. Mr. Diller was left to carry out the detail work, and in the course of the season he secured material to cover the whole map excepting a single small area. In addition to this he extended his detail studies beyond the limits of the map for the purpose of tracing to their natural limits formations and features which should be studied as wholes, and which, of course, have no such arbitrary boundaries as meridians and lines of latitude. His work, in short, extended as far southward as the north fork of the Feather River, which seems to form a natural boundary to the volcanic masses of the district. He also studied the general structure of the Sierra Nevada, which is of special interest in this vicinity,
for here is the northern end of that great range. In his report he will
discuss these structural features.

Leaving Mr. Diller I returned to Red Bluff and at once moved north­
ward across the Pitt River, up the Sacramento as far as Mount Shasta,
with a view to beginning a reconnaissance of the Cascade Range and
studying its broader orographic features; also, its relations to the Sierra
Nevada on the south and the Coast Ranges to the westward. At the
very outset it was necessary to know what constituted the Cascade
Range—where it began, what mountains should be included in it, and
what should not. Old maps are of no value for the determination of
these questions, and, as usually happens in such cases, the very definite
delineations and names which appear on such maps have no counter­
part in nature. The Cascade Range is usually represented as a north­
ward continuation of the Sierra Nevada. In reality an interval of quite
a hundred miles separates what may fairly be considered the southern
end of the Cascades and the northern end of the great Sierra; and,
furthermore, if the trend of the Sierra were continuous northwestward,
it would pass thirty or forty miles at least west of the Cascades. The
southern end of the latter range may be located with some approach to
precision as due east of the base of Shasta.

The interval between the Cascades and the Sierra is occupied by a
large field of volcanic rocks centering around Lassen's Peak, by a rather
extensive group of volcanic mountains immediately north of Lassens',
and still further northward by a tract of highly disturbed slates, meta­
morphic rocks, and Carboniferous limestones. Between the Pitt River
and the Cascades these old slates and metamorphic rocks are contorted
and thrown into the greatest confusion, without any persistent strike, but
with a varying one changing rapidly. The country is cut into a network
of ravines and gorges with intervening spurs and knife edges, which are
so sharp and steep that a passage through them is difficult to effect.
The slates and metamorphic rocks here form a belt of country trending
northwestward, and pass at length into those confused and still more
rugged mountains which form the Coast Ranges of Northern California.

Shasta is an outlier of the Cascade Range and stands a few miles
west of the southern end of it. It is an isolated volcano and its very
isolation gives it most of its exceptional grandeur.

So far as the Cascade Range was examined its structure was found
to be comparatively simple. The southern portion of it consists of
heavy masses of andesitic and basaltic lava covering Cretaceous strata
and perhaps also some very early Tertiary beds. It is, in its southern
portion at least, a great volcanic plateau. The lavas have been erupted
in the ordinary way from a vast number of vents, and some of them
have built up mountainous piles, all of which are extensively eroded.
Most of the mountainous accumulations of lava are of moderate dimen­
sions, but a large minority of them attain very dignified proportions.
In the southern Cascades the largest cone is Mount Pitt (locally called
McLaughlin). There are many other mountains of somewhat smaller proportions which are or have been large extinct cones, though greatly diminished now in bulk and altitude by a protracted erosion, such as Union Peak, Mount Scott, Mount Thielsen, and Diamond Peak. Some that are nameless rival or even exceed in mass those that are better known, and in fact the names have generally been given to those peaks which under the action of the degrading forces have assumed the most conspicuous and needle-like forms.

The plateau upon which these many volcanoes and lava fields occur is from forty to seventy miles in width. The plains which lie at its eastern base are much higher (4,000 to 5,000 feet) than those which lie along the western base (1,500 to 2,000 feet), while the average height of the general platform of the plateau itself may be about 6,000 to 6,500 feet. If we could imagine these great masses of lava taken away, leaving only the sedimentary beds on which they now lie, we should have a mental picture of the platform of the Great Basin region extending westward as a gently undulated plain as far as the western verge of the Cascade Plateau, not only preserving its altitude but slightly increasing it to the brink of the western wall. It does not appear as yet that any important part of the eminence of the Cascade Plateau above the plains of Fort Klamath, Klamath Lakes and the Modoc country to the southward is due to a greater upheaval or differential vertical movement, but it is due to the accumulation of volcanic extravasations. This statement, however, may be qualified slightly. The very gentle ascent from east to west of the sedimentary platform on which the volcanic masses rest appears at present to be the effect of a slight and very gradual increase in the amount of upheaval as we proceed across the range westwardly. The western front of the Cascades drops down very abruptly into a series of valleys. To comprehend the nature of these valleys and their relations, it is necessary to glance for a moment at the medley of mountains to the west of them which make up the Coast Range in these latitudes.

The belt of country between the shore of the Pacific and the Cascade Range is occupied by mountains which do not group themselves into distinct ridges, but which are crowded closely together and present forms altogether peculiar by reason of their irregularity, want of definite trend, and absence of anything approaching structural axes; they are also characterized by the extreme steepness of their slopes. There are a few valleys among them of small extent which have nearly level bottoms suited for agriculture; but in the main they are separated only by V-shaped gorges of extreme steepness, of great depth, and branching into numberless ravines. The altitudes of the peaks seldom exceed 7,000 feet and the summits are usually extremely sharp. The rocks which are found here are mostly metamorphic (?), with very ancient eruptives. Granite, gabbro, diorite of very coarse, almost "giant" crystallization, vast masses of slates or argillites, with now and then considerable
bodies of the Carboniferous limestone, form the greater part of the
country rock, while peridotites, passing apparently by metasomatic
changes into dark serpentines, also occur in large bodies. Ancient ba-
salts, which are believed to be older than the Carboniferous, are also
found in considerable quantities interbedded among the slates. On the
eastern border of this mountain belt, in Shasta Valley, a few remnants
of a littoral conglomerate, undoubtedly of late Cretaceous age, are seen
clinging to the more ancient rocks from which they have been derived,
as is plain from the character of the stones and gravels which compose
them. The attitudes of the older rocks disclose a scene of stratigraphic
confusion, displacement, and distortion such as I have never seen
equalled. It is a stratigraphic chaos. The terms dip and strike here
lose all significance, for everything like system or order in the arrange-
ment of the beds (or of what once may have been beds) has been ob-
literated by crushing or crumpling forces which have acted upon them.
The folding and distortion have not resulted here in a systematic plica-
tion like that of the Appalachians, as if by a force acting in a single or
two opposite directions, but by forces from every possible direction.

Turning now from this brief glance at the Coast Kanges to the Cas-
cades, we find the Upper Cretaceous beds rising from beneath the Cas-
cade platform along its western front and in the valleys below its west-
eru crestline, and as we proceed westward towards the Coast Ranges the
upward inclination of these beds is seen to increase, until they attain a
dip exceeding in many localities 35°, though generally not quite so great.
Thus on our westward course we cross their terminal edges, passing
lower and lower horizons, until at last we find the base of the series rest-
ning on the much more ancient masses of the eastern margin of the Coast
Range. And here is to be noted a very significant fact, viz, that these
Cretaceous masses forming the lower portions of the Cascade Plateau
and outcropping in the valleys beneath its western crest are composed
in great part of materials derived from the Coast Ranges. They are lit-
toral and inshore beds. The bulkier ones are conglomerates holding
wave-washed and rounded pebbles imbedded in sea sand and clay, alto-
gether too characteristic to be mistaken. As we ascend in this series
traces of volcanic sand and detritus appear, becoming more and more
abundant the higher we go, until many beds are seemingly composed of
it entirely. Sheets of contemporaneous andesite and basalt are occasion-
ally intercalated, until near the summit the lavas become the only
rock visible. From these relations of the sedimentary beds of the Cas-
cades to the Coast Ranges, the apparent inference to be drawn is that
near the close of Cretaceous time the Coast Range belt was a large land
area undergoing denudation and sending its detritus down into a Cre-
taceous sea to the east of it, where it accumulated in beds many thou-
sands of feet in thickness, and that these beds sunk pari passu with their
accumulation; that during the progress of this accumulation volcanic
eruptions were common, lasting into Tertiary time and becoming more
voluminous in their outpourings. As regards the period of principal activity of the volcanic forces, all that can be said here is that it was doubtless during Tertiary time, though with greater or less intensity it most probably prevailed throughout nearly the whole of that great era.

As yet too little has been seen of the country lying east of the Cascades to warrant any inference concerning the probable extension of the late Cretaceous and early Tertiary sediments in that direction. Whatever formations of those ages may exist, these are now well covered by Quaternary deposits, by recent lacustrine beds, and by young lavas, and few exposures older than these have as yet been seen in that quarter.

We should also note here the peculiarities of the valleys which occur in the Cascade system and in the country between it and the Sierra Nevada. Remembering that the country north of the Great Basin and possessing the Basin structure and topography drains chiefly into the Columbia River, while the Basin area itself does not for the most part have any drainage into the ocean, we note the fact that there is a small portion of this great geological province which does drain into the Pacific, but not through the Columbia. East of Lassen's Peak and of the belt of ancient slates to the north of it; east also of the southern portion of the Cascades, there is an extended tract whose waters find their way to the Pacific through the great mountain barrier which interposes. The North Fork of the Feather River, heading southeast of Lassen's, cuts across the northern end of the Sierra Nevada and enters the Sacramento Valley. Seventy miles northward the Pitt River, heading in many streams east of Shasta, cuts through the high barrier reaching from Lassen's to Shasta and joins the Sacramento; or rather the Sacramento joins the Pitt, for the latter is many times the larger stream. Most striking of all is the Klamath River. Forming the outlet of several large lakes strung along the eastern foot of the Cascades, it bursts through that plateau in a grand gorge and then breaks through the Coast Ranges to the Pacific. The Cascade barrier is not broken through again to the northward until we reach the Columbia. But it is deeply incised by streams which head at its divide and flow westward across the Coast Ranges to the Pacific. There are two such rivers, the Rogue and the Umpqua. This configuration of the drainage channels has prevented the formation of any great valley parallel to the southern Cascade Range along its western base. The valleys all run away from it, and in the course of their erosion have developed great "traverses," or short connecting ranges of mountains and hills, running from the Cascade platform to the Coast Range. These traverses have proved to be very serious obstacles to the construction of the railway along the western base of the Cascades to connect Portland and San Francisco.

But when we reach the sources of the Willamette we at length find a great valley parallel to the trend of the Cascades, just as the Sacramento and San Joaquin Valleys are parallel to the Sierra Nevada. On the
eastern side of the Cascades, too, we find the Des Chutes River, heading in the same mountains as the forks of the Willamette and flowing northward parallel to the base of the great plateau.

The Feather, Pitt, Klamath, Rogue, and Umpqua Rivers are admirable examples of antecedent drainage; of rivers which existed long before the great topographic features of the region they drain had any similitude to what they now are. They have maintained their positions amid profound changes both of displacement and of erosion. It is too early, however, to attempt to unravel the part which these rivers have played in determining the features of the country, though enough has been seen already to make clear the fact that it has been a most important one.

The lavas which occur in the Cascades, so far as yet seen, are almost wholly of the basic classes, andesite and basalt. In one locality only has a rhyolite been found, viz, at what is called Bogus Mountain, four or five miles south of the Klamath River, in the heart of the range. The andesites sometimes run into dacites but as a general rule they approach a basaltic constitution, while the basalts have a character which brings them near the andesites. Olivine is never abundant in the basalts, while the bisilicates of the andesites are usually hypersthenite and augite, though hornblende is not uncommon.

The season of 1885 proved to be very unsatisfactory for field work on account of the smoke, which obscured the air of the whole country. From the middle of July until late in September it was rarely possible to see six miles, and during the greater part of that time it was like working in a fog. General views of the country were never obtained. All that could be distinctly seen was what lay near the route traveled. In the course of the season I crossed the Cascades several times, and by zigzag courses reached as far north as Diamond Peak.

The succeeding winter was occupied in the office in Washington in making an examination of the rock specimens brought back and in reducing the observations made.

Early in May I made preparations for the season's field work, leaving Washington on the 17th of that month and reaching the outfitting camp at Yreka, in Northern California, on the 31st.

Considerable time was occupied in outfitting and also in making special preparations for a thorough examination of Crater Lake, which is doubtless the most striking feature of the Cascade Range and one which is destined to become famous throughout the world when it becomes better known and understood. With this view, I had constructed at Portland, Oreg., three boats, which are now about due by rail at this place (Ashland, Oreg.). When they arrive they will be hauled by wagons to the mountain on which the lake is situated and lowered down the walls of the crater to the water. I am under the greatest obligations to General Gibbon, commanding the Military Department of the Columbia, who, at my request, has most kindly sent
me an escort of ten enlisted men, in command of Capt. George W. Davis, Fourteenth United States Infantry, for the purpose of assisting me in the somewhat difficult task of lowering the boats down the cliffs to the water and rendering other indispensable aid in the work.

I must also speak in high terms of the work of Mr. J. S. Diller. His management of the lithological laboratory has been under your own eye as well as mine, and the excellent work done there is familiar to you. In the field he resumed recently the work which was not completed last season, and he will finish it and probably extend the detail work of mapping the geological formations into the volcanic region lying north of Lassen's Peak and perhaps as far as the Pitt River. He left Yreka on the 11th of June, visiting the great lava beds which lie east of the southern extremity of the Cascades and are well known as the Modoc lava beds. When last heard from he was on his way southward to the country which lies east of Lassen's Peak.

Very respectfully, sir, your obedient servant,

C. E. BUTTON,
Captain Ordnance.

Hon. J. W. POWELL,
Director U. S. Geological Survey, Washington, D. C.

REPORT OF MR. LAWRENCE C. JOHNSON.

DEPARTMENT OF THE INTERIOR,
U. S. GEOLOGICAL SURVEY,
LOUISIANA DIVISION OF GEOLOGY,
Washington, D. C., July 1, 1886.

SIR: The work assigned me for the fiscal year 1885-'86 was prosecuted mostly in the field, as follows:

Reaching Shreveport, La., about the 10th of August, 1885, pursuant to instructions, I immediately set about obtaining information as to the localities in which iron ores were known or supposed to be deposited.

As soon as my arrival and the purposes of the visit became known, letters containing this information, together with invitations, poured in from most of the parishes of Northern Louisiana, and before the end of the month I was fairly at work.

I deem it proper here to acknowledge the courtesy, and even zeal, exhibited by the press in giving notices and explanations to the public; and I should be glad, did space permit, to name the communities and the gentlemen to whom I was indebted for assistance, through the furnishing of transportation and in other ways. Although response to this generous liberality caused some loss of time, work was really promoted and the expenses were diminished.

Up to the end of the year 1885 the season was exceedingly fine for field operations, and all the more northerly parishes were visited before
the inclement weather came which marked the beginning of the new year. With more foresight these highland parishes might have been reserved to the last. However, to them belong the principal localities of the iron ore, and to this matter investigations were first addressed.

Upon special instructions the formations in the vicinity of Alexandria were visited in January. This, enabling me to get a starting point for the geology of the whole region, proved of great advantage afterwards in tracing and determining the genesis of the iron deposits and their relations to other formations.

The weather was bad for a month and very much crippled the efficiency of the researches on Red River and in the parishes of Rapides, Grant, Winn, and Natchitoches. Reaching Lincoln and Jackson Parishes in February, conditions were better, and this part of the survey was completed before the end of the month — that is, as far as under instructions, oral and written, I considered it necessary to proceed.

Under your direction I proceeded, January 27, 1886, to the assistance of Dr. Eugene A. Smith in the final preparation for the press of our paper on the Tertiary and Cretaceous Strata of the Tuscaloosa, Tombigbee, and Alabama Rivers. This occupied a large part of March.

By the 24th of March I reached Texas, and proceeded, in accordance with instructions of February 17, to make a reconnaissance of the iron fields of the eastern portion of the State. This was necessarily rather hasty and not as complete as could be desired. The counties of Robertson, Anderson, Cherokee, Rusk, Harrison, Marion, and Cass were examined in detail, and many others briefly visited. The observations made were in the main satisfactory, though likely to be modified by future investigations.

Very respectfully, your obedient servant,

LAWRENCE C. JOHNSON,
Assistant Geologist in Charge,
Hon. J. W. Powell,
Director U. S. Geological Survey, Washington, D. C.
of devising a cartographic system which shall be at the same time (1) sufficiently definite to be readily intelligible to all users of the geologic maps published by the Survey, whether their interests lie in the scientific relations of the phenomena represented or in the economic resources of the area mapped; (2) sufficiently elastic to yield to the requirements, not only of the tentative classifications of rocks now in vogue, but of such final classification as may be evolved on the extension of geologic operations over the whole country; and (3) sufficiently comprehensive to represent all rockmasses in the entire dominion of the United States which it may at any time become necessary to discriminate for scientific or economic reasons without duplication of conventions and symbols.

Acting under your specific instructions, and in constant conjunction with yourself, I have given much attention to the development of such a cartographic system; and the general geologic map of the United States, the experimental map, and the Thesaurus of American formations, described in preceding reports, have grown out of this study. A portion of the results of work in this direction has now been reduced to definite shape in the form of a bulletin entitled "A contribution to the areal geology of the United States." This bulletin comprises (1) your discussion of the principles of geologic taxonomy and cartography and description of the cartographic system of the Survey, as presented before the Congrès Geologique International at the Berlin session; (2) the experimental map and accompanying explanatory text, which are together designed to illustrate the application of the system in the representation of the terranes of a typical American area in which the rocks have already been classified and a nomenclature developed in accordance with different principles; (3) impressions of the general geologic map of the United States, printed in the colors of the two schemes now under consideration and test; and (4) a list of authorities consulted in the preparation of this map, together with a statement of the principles in accordance with which it was compiled. This bulletin is nearly ready for the press.

The International Congress.—The Congrès Geologique International, which was organized several years ago, largely through the instrumentality of American geologists, has for its principal function the improvement of methods and the unification of conventions employed in geologic cartography: a function so closely akin to the duty of the Geological Survey specified above as to render it highly desirable, if not imperatively necessary, that this institution shall remain constantly en rapport with that body. With this end in view I had the honor to attend the last session of the Congress at Berlin, September 28 to October 4, 1885, and present a formal communication to the Congress by you as the administrative head of a scientific institution of importance and magnitude, exhibiting a series of maps illustrating the plans, purposes, and preliminary results of the Survey, and participating in the
deliberations of that distinguished body as your representative. I was also present, as your accredited representative, at the meeting of the American committee of the Congress held in New York on January 8 last, and took such part in its proceedings as the published minutes of the meeting indicate.

The Thesaurus of American formations.—By reason of pressure in other directions, little work has been done during the past year upon the Thesaurus (described in your Fifth Annual Report, pp. 39, 40); but the plan for it is held in mind, suitable cards for the record of relevant data gleaned in current reading are kept constantly at hand, and thus material for it is slowly accumulating. Additional energy will, however, be concentrated upon it at an early day.

The geologic sketch of Texas.—The revision of this sketch has not yet been completed, because it seemed desirable to divert all available time and energy to the annotated bibliography of the region described in my last report. The preparation of this bibliography has proved a laborious undertaking, and the material for it has reached such volume that it is deemed expedient to issue it separately. Arrangements have been completed for sending each publication to press at an early day.

The Smith-Johnson Bulletin.—Early in the present year there was transmitted to this office for publication as a bulletin a manuscript report on the "Tertiary and Cretaceous Strata of the Tuscaloosa, Tombigbee, and Alabama Rivers," by Dr. Eugene A. Smith, State geologist of Alabama, and Lawrence C. Johnson, of this Survey; and, because of my familiarity with a phase of the subject (as set forth below), the manuscripts were placed in my hands for revision.

One of the formations described in this report is a series of peculiar sands, clays, and gravels, in which fossils have not yet been found, and the relations of which are therefore obscure. It is typically exposed on the Tuscaloosa River, in the vicinity of the city of the same name, and hence, at my suggestion, has received the name "Tuscaloosa formation." My interest attaches to this formation for the following reasons: One of the results of geologic investigation in the District of Columbia has been the discrimination of a distinctive formation, to which the name "Potomac" has been applied. As developed in the vicinity of Washington, it is of such origin and physical character as to be practically destitute of organic remains; and while both to the southward and to the northward it yields a unique flora (in the study of which Prof. William M. Fontaine is now engaged) of great interest to paleobotanists, it is everywhere practically without faunal relics. By reason of the absence of animal remains and the unique character of its flora, it has thus far been found impossible to satisfactorily correlate this formation in the usual manner with those already discriminated in this and other countries. Accordingly, the attempt has been made to determine its place in the geologic column through investigation of its physical relations, and to this end careful attention has been given to its composition, structure, attitude,
stratigraphic position, &c., and the geography, configuration of the sea bottom upon which it was deposited, topography of the adjacent land, depth of sea, and, in short, the general relations of sea and land during the epoch of its deposition, have been inferred. Definite conceptions of its genesis have thus been formed.

Now the preliminary description of the Tuscaloosa formation corresponded so closely with that found to apply to the Potomac formation as to suggest like conditions of genesis and (the stratigraphic relations being identical) presumptive chronologic equivalence of these formations. I therefore elaborated the portion of the report relating to the Tuscaloosa formation in accordance with this hypothesis, and returned the manuscript to the senior author in order that the hypothesis might be tested in the field and either disproved or corroborated by additional observation and study. Some weeks were spent by Dr. Smith in this supplementary investigation, and it is a source of satisfaction to find that his views and my own respecting this puzzling formation are now in perfect accord.

The report, which includes two chapters and some other matter contributed by myself, has at length been completed and is now ready for the press.

History of American State surveys.—The plan under which material for this history has been collected is such as to impose much labor on gentlemen in different parts of the country, many of whom have no official connection with the Survey; and although prompt and courteous acquiescence has in nearly every case met the requests for contributions sent out from the Survey, circumstances have prevented some of these gentlemen from completing their contributions at as early a day as they and we desired. The greater part of the requisite material has, however, been collected. Elaborate histories of the geologic surveys of two States (Missouri and New Jersey) have already been independently published in response to circulars and letters emanating from this Office, and manuscript sketches of the following surveys are now in my hands:

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<th>Region covered.</th>
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<tr>
<td>Arkansas and California, along 35th parallel</td>
<td>Exploratory and geologic</td>
<td>Jules Marcou, geologist.</td>
</tr>
<tr>
<td>Arkansas</td>
<td>Geologic</td>
<td>Richard Owen.</td>
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<tr>
<td>California</td>
<td>Geologic, mineralogic, and engineering</td>
<td>Henry G. Hanks, State mineralogist.</td>
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<td>Delaware</td>
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<td>James C. Booth, ex-State geologist.</td>
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<td>Indiana (first)</td>
<td>do</td>
<td>Richard Owen, ex-State geologist.</td>
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<td>Indiana (second)</td>
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<td>Indiana (recent)</td>
<td>do</td>
<td>R. T. Brown, ex-assistant State geologist.</td>
</tr>
<tr>
<td>Iowa, Wisconsin, and Minnesota</td>
<td>Geologic</td>
<td>Richard Owen, ex-assistant State geologist.</td>
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</tbody>
</table>
Region covered. | Character of survey. | Author of sketch.
---|---|---
Iowa (second, Hall) | Geologic | W J McGee.
Iowa (third, White) | do | Do.
Kentucky (first, D. D. Owen) | do | Robert Peter, ex-chemist to the Survey and State chemist of Kentucky.
Louisiana | Geologic and agricultural | Eugene W. Hilgard, ex-State geologist.
Michigan (early surveys) | Land, geologic, &c. | Alexander Winchell, ex-State geologist.
Michigan (third, Konringer, Pumppelly, and Brooks) | Geologic and mineralogic | Carl Konringer, ex-State geologist.
Minnesota | Geologic and natural history | N. H. Winchell, State geologist.
Mississippi | Agricultural and geologic | Eugene W. Hilgard, ex-State geologist.
New York, Adirondack region | Geodetic, geographic, and topographic | Verplanck Colvin, superintendent.

In some cases these sketches will be printed as contributed, under the signatures of their authors, and in all cases full credit will be given to the authors of the contributions.

It is with no small degree of pleasure that I express the profound obligations, not only of the Survey, but of geologic science as well, to the gentlemen who have generously turned aside from other duties and interests to collect and prepare material for our proposed history. Their assistance was invaluable. A large proportion of the essential data for the work has hitherto existed only in the memory and among the private records of a few individuals who were themselves instrumental in inaugurating, promoting, and accomplishing geologic research in this country; and from these individuals alone could such data be obtained. Ever since the commencement of the correspondence it has been a source of gratification to observe the cordiality and unanimity with which these veterans in American science have consented to co-operate in this work.

Efforts to have an exhaustive sketch of the geologic surveys of Iowa prepared either by officers of these surveys or by citizens of the State interested in scientific matters having proved unsuccessful, I undertook the task myself. The collection of data from official and private records necessitated a journey to Des Moines last May. The material is now in hand and ready for final revision for the press in conjunction with the sketches of other surveys.

The geologic map of New York.—On the completion of the base for the experimental map (forming one of the plates in the cartographic bulletin), the draughtsman by whom it was prepared, Mr. J. H. Kleunroth, was employed to construct a base map of New York upon which the geologic colors of the manuscript geologic map compiled during last year may be impressed. It is drawn on a scale of $4\frac{1}{2}$ miles to 1 inch.
The sheet is 81 by 84 inches in dimension. The drawing is about half done.

As soon as the base is completed the geology of the manuscript map will be supplemented by material recently collected, which will be transferred to it. It is proposed to reduce the scale to 6 miles to the inch in lithographing.

The bibliography of Texas.—On January 1, 1886, Mr. J. B. Marcou was transferred to my division by courtesy of Dr. C. A. White, and the collection of material for the annotated bibliography of Texas described in a preceding report was at once intrusted to him.

The work has been pushed forward as rapidly as possible. Some 1,500 titles (probably seven-eighths of the literature) have already been assembled and annotated, and only await final arrangement and revision for the press. The remaining fraction of the literature is, however, either ephemeral or buried beneath misleading titles, and therefore difficult to find, and in some cases the works not yet consulted are so rare as to be difficult of access. Thus the most tedious part of the task has yet to be done.

FIELD WORK.

The District of Columbia.—The topographic survey of the District of Columbia and contiguous territory, described in my last report, has been carried forward as rapidly as practicable under the direction of the chief geographer and under my own supervision in regard to certain details important in the geologic study of the region. It has not yet been completed; the area south and west of the Potomac is surveyed and mapped, and that north of the Potomac and west of the seventy-seventh meridian is surveyed; little has thus far been done on that half of the area lying east of the seventy-seven meridian.

Meantime, the geologic investigation has been prosecuted as energetically as appears expedient pending the completion of the topographic map, which, by reason of the special characters of the region and of its distinctive phenomena, must serve as the basis not only of the geologic and analytic maps required to elucidate the structure and development of the region, but, to an important extent, of the investigation itself; for many fundamental questions connected with the stratigraphy, erosion and transportation, and geotectonic movements of the area cannot be decided until the different phenomena have been projected upon a map accurately representing the vertical as well as the horizontal element in such manner as to exhibit their various relations at a glance. Evanescent exposures are, however, examined from time to time, and the collection of notes, drawings, photographs, and specimens representing them has increased materially during the year.

Virginia and Maryland.—During the latter part of July and August Prof. Lester F. Ward, Prof. William M. Fontaine, and myself united
in a journey through Eastern Virginia and Central Maryland, under­taken primarily for the purpose of extending our knowledge of the Po­tomac formation, the most important of the formations represented in the District of Columbia. My companions gave attention chiefly to the unique and abundant flora preserved in this formation at many points in Virginia and a few in Maryland; and the material collected in the course of the journey has been placed in the hands of Professor Fontaine for study. My own attention was divided between (1) the structure, composition, attitude, stratigraphic relations, &c., of the Potomac formation; (2) the discrimination and areal definition of associated formations, chiefly Cenozoic; (3) various Quaternary phenomena, including the marine terraces characteristic of the Potomac, Rappa­hannock, James, Appomattox, and other rivers; and (4) the post-Quater­nary orographic movements of the region; and in each of these lines of observation important results were secured.

Professor Fontaine has been for some years at work on the geology as well as the phyto-paleontology of Eastern Virginia: since I desire to avoid anticipating his results, and since my specific investigations relate primarily to the District of Columbia and immediate vicinity, and those prosecuted during this journey were only collateral thereto, I have placed my results at Professor Fontaine's disposal, and there is no probability that early publication under my name will grow out of the observations and studies of the journey.

The Blue Ridge and Catoctin Mountains.—During the past year the attempt to determine by means of lithologic study the relations of the rockmasses about the locus of passage from the known crystallines of the Piedmont region to the known Paleozoics of the Appalachian region, in the vicinity of Harper's Ferry and Beverton, has been continued, and a more complete series of rock specimens has been collected for microscopic examination. Unforeseen circumstances have thus far prevented me, however, from having the preparation and examination of the specimens completed.

Kansas.—During the first half of the fiscal year Mr. Robert Hay completed his field investigations in Southern Kansas and submitted a formal report embracing the results of his work, including a section extending through the little known region of Southern Central Kan­sas, from the westernmost members of the fairly well studied Paleo­zoics of the Mississippi Valley to the equally well known Mesozoic terranes of Eastern Colorado. The report is illustrated by a geologic map of the region traversed, by photographs, drawings, detailed sec­tions, &c.

Within a few weeks proofs of the topographic sheets of the survey representing Southeastern Kansas have been printed; I have visited the mapped region, and find its mineral resources of great value to the people of the State and already attracting the attention of capital­ists; and after a personal conference with Mr. Hay, I have employed
him under your instructions to classify and map the coal seams, hydraulic and pure limestones, gas yielding and petrolierous sandstones, building stone beds, and other formations of Southeastern Kansas, in accordance with such specific instructions as seemed to me required, in order that the results of his work might be at the same time of maximum value to citizens interested in local mineral resources and to the general geologist.

In accordance with my instructions, Mr. Hay began some preparatory work at his home in Junction City, Kans., on June 1, 1886; on June 17 and 18 a joint reconnaissance was made by Mr. Hay and myself in the vicinity of Fort-Scott, Kans., for the purpose of obtaining a general knowledge of the phenomena to be dealt with; and I have just received a monthly report from the field indicating satisfactory progress.

It should be mentioned that work on several lines was materially delayed, and the completion of certain tasks prevented, by serious illness during January, February, and March last.

As during previous years, some of my duties brought me into intimate association with yourself; and I have pleasure in acknowledging my indebtedness to you for much incidental suggestion and advice, as well as specific instruction, and in assuring you that whatever measure of value my work may possess has been greatly increased thereby.

I have the honor to be, sir, with great respect,

Your obedient servant,

W. J. McGee,
Geologist in Charge.

Hon. J. W. Powell,
Director U. S. Geological Survey, Washington, D. C.

REPORT OF PROF. O. C. MARSH.

DEPARTMENT OF THE INTERIOR,
U. S. GEOLOGICAL SURVEY,
DIVISION OF VERTEBRATE PALEONTOLOGY,
New Haven, Conn., July 1, 1886.

SIR: I have the honor to submit the following report of progress in this division during the past fiscal year:

In compliance with your letter of general instructions, I have continued the systematic work of collecting fossils in the West and investigating those new to science. In this work, I have had two objects especially in view: (1) to determine the geological horizon of each locality where a large series of vertebrate fossils was found, and (2) to secure from these localities collections of the more important forms sufficiently extensive to reveal, if possible, the life history of each.

The importance of the first object has been fully demonstrated, since
in many regions of the West the remains of plants and invertebrates are few in number, and even when abundant they often afford unsatisfactory evidence of the age of the strata in which they are found. The vertebrate fossils, on the other hand, especially of the higher types, are now known to form a more accurate and detailed record of the geological changes that occurred in the period in which they lived. The horizon, once determined, admits of approximate correlation with others at distant points, both in this country and in other parts of the world. The work thus demonstrates its practical value and justifies its prosecution, as geology is based largely upon accurate horizons.

The second object in view is of still more scientific importance, although at first sight of less practical use. It is intimately connected with the first, and follows as a natural conclusion of the work. The remarkable development of vertebrate life throughout the Rocky Mountain region in past ages, and the wonderful degree of preservation in which the remains are found, clearly indicate that some of the most important chapters in the history of life on the globe are recorded here alone, and the solution of many profound problems awaits the results of the investigation now commenced.

With such rich material at hand, it is clearly the duty of the Survey to make known to the world all the important facts brought to light by its current work and with them the conclusions that naturally follow. Such being the general scope of the work of this division, it remains to note briefly the progress made in its various sections during the past year.

The regions under exploration in the West were mainly those that proved so productive in previous years. One small party has been at work in the Pliocene deposits of Nebraska and Kansas, and at the close of the last season had practically exhausted the localities found. The collections secured are especially rich in the larger ungulate mammals, and the series of remains obtained in some groups will render the osseous structure of these almost as well known as that of existing species. With the opening of the present season, this work was extended northward into the Miocene of Dakota, and here the results promise to be equally valuable.

In the Jurassic beds of Wyoming, two parties have been at work, and continue to meet with good success. The remains of dinosaurian reptiles secured have been numerous, and they have been collected in so systematic a manner as to greatly increase their value and render the subsequent investigation less difficult. Important remains of Jurassic mammals have likewise been obtained by the same parties.

In Southern Colorado work has been prosecuted in essentially the same horizon during the greater part of the year and still continues with good results. The specimens secured are most welcome additions to those obtained in the previous year and largely increase our knowledge of several extinct groups.
The more difficult work of investigating and classifying the extensive
collections thus secured, and with them the vertebrate fossils incident­
ally obtained by other divisions of the Survey, has been carried on sys­
tematically at New Haven. The final results of all this work will be
brought together in the monographs now in preparation, and on these
volumes the progress during the past year has been continuous and
satisfactory.

Very respectfully,

O. C. MARSH,
Paleontologist in Charge.

Hon. J. W. POWELL,
Director U. S. Geological Survey, Washington, D. C.

REPORT OF MR. C. D. WALCOTT.

DEPARTMENT OF THE INTERIOR,
U. S. GEOLOGICAL SURVEY,
PALEOZOIC DIVISION OF INVERTEBRATE PALEONTOLOGY,
Washington, D. C., July 1, 1886.

SIR: In conformity with the request contained in your letter of Feb­
ruary 6, 1886, I have the honor to present the following report of opera­
tions conducted under my charge during the fiscal year ended June 30,
1886.

FIELD WORK.

The field operations for the year were: (1) The continuation of the
study of the Devonian strata and contained faunas in Southern and
Western New York; (2) the study of Cambrian strata in Alabama,
Georgia, and Tennessee, and the collecting of fossils from numerous
localities; (3) the examination of numerous sections of Cambrian
strata in Central Nevada and Northern Utah and the collecting of fos­
sils; (4) the taking of a section of the Permian formation in Southern
Utah and the collecting of fossils from three horizons in the section;
and (5) the examination of certain Middle Cambrian rocks in Columbia
County, New York, and the collecting of Lower Silurian fossils in Cen­
tral New York.

Prof. H. S. Williams confined his field work mainly to Cortland, Che­
nango, Broome, Otsego, and Delaware Counties, N. Y., and Susque­
hanna County, Penn. He spent about two months during the summer
with an assistant in endeavoring to interpret the order and succession
of the Devonian faunas in the strata of the region studied and in the
examination of twenty-three new stations.

The principal results were the clear determination of the change in
the faunas from the Ithaca section eastward, and the showing of a
marked Hamilton facies for the faunas following the zone of the black
shales (Genesee) in the eastern extension of these rocks, although the

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"Oneonto sandstones" were found to possess the typical lithologic and paleontologic characters of the "Catskill" deposits, and were found to occupy a position stratigraphically very nearly equivalent to that occupied by the Ithaca zone and fauna farther west.

One of the valuable results of this particular year's work is the clear demonstration of the following facts:

1. In a series of deposits, which for the individual sections appears geologically continuous, with no evidence of violent changes of conditions of deposition, the details of composition and order, both lithologic and faunal, for a series of strata occupying the same interval, may suffer such degree of modification in the passage of one or two hundred miles as to be beyond recognition. For instance, the list of species occupying the interval between the termination of the Hamilton and the beginning of the genuine Chemung faunas in the Genesee section differs more widely from the fauna occupying the same interval in the Unadilla section than the Hamilton fauna differs from the Chemung in the same area.

2. In a continuous section the most natural and closely related successor to any particular fauna may lie far above it stratigraphically and be separated from it by hundreds of feet of thickness of strata differing in lithologic features and carrying an entirely distinct fauna. This state of things is interpreted for the single section as a recurrence of fauna; but in the comparative study of faunas it is interpreted as the expression of the continuation of the fauna, with geographic shifting of its location and the gradual modification of its contents co-ordinate with the passage of time, as marked by the thickness of the deposits containing the fossils.

The work is of a valuable character, and will afford important data for Professor Williams's monograph on the Devonian faunas.

Mr. Cooper Curtice, assistant paleontologist, began work in July, at Cedar Bluff, Ala., for the purpose of collecting Cambrian fossils and locating their geologic horizon by making geologic sections. After completing that, he continued north, and endeavored to trace the connection between the fauna of the Upper Cambrian of Alabama and Northeastern Georgia and that of Eastern Tennessee. A section taken by him from Cedar Bluff southward shows a remarkable development of Cambrian strata, whose outcrop extends from the Chatooga River on the north to Craig's Mountain on the south, a distance of at least 12 miles. Fossils of Cambrian age were collected near Rome, Adairsville, Spring Place, and Gordon's Spring, Ga.; and at Knoxville, Tenn., fossils were gathered from the Upper Cambrian and Lower Silurian beds. An examination of Cambrian strata near Bull Run Post Office, Tenn., developed the best section that was seen of the uppermost part of the Cambrian in the State. Mr. Curtice returned to Washington on November 20, 1885.

Mr. A. M. Gibson was employed, during the spring, in collecting fos-
sils from the base of the Silurian rocks, in the vicinity of his home, at Chepulitepec, Ala.

Mr. S. W. Ford was employed during the year as a paleontologic assistant. He collected a quantity of fossils from the Middle Cambrian strata in the northeast corner of Columbia County, N. Y., on the shores of the Hudson River; he also obtained additional data on the distribution of the Cambrian strata in Columbia and Rensselaer Counties, N. Y., and traced the great fault separating the latter from the Hudson River Group.

Mr. William P. Rust collected fossils from the Lower Silurian strata of Oneida and Herkimer Counties, N. Y., from April 12 to June 30, 1886, and obtained a large number of specimens that will be of value in establishing a collection for comparison and study.

During the months of August, September, and October I studied the Cambrian strata of the Highland Range in Central Nevada; I also examined the strata of portions of the adjoining Hyko and Pah-ran-a-gat Ranges. On completing this, we (Mr. J. E. Whitfield accompanied me as field assistant) crossed to Southwestern Utah and measured a section of the Permian strata of the "Plateau System" of formations, and then returned north to measure the Cambrian section of Big Cottonwood Cañon, Wasatch Mountains.

The results obtained were—

1. The discovery of a great series of Devonian strata, in the Hyko and Pah-ran-a-gat Ranges of Central Nevada, more than 3,000 feet in thickness, and carrying a characteristic Devonian fauna; also the discovery that this fauna is succeeded by one referred to the Lower Carboniferous. At the base the Devonian passes down to the Upper Silurian and this to the Trenton horizon of the Lower Silurian.

2. In the Highland Range a connection was made, both on stratigraphic succession and paleontologic evidence, with the Silurian of the Eureka District, Nev., and the section carried down through the Upper and Middle Cambrian to the Great Cambrian quartzite. A large collection of fossils was obtained from different portions of the 6,000 feet of strata included in the central portion of the Highland Range west of Pioche, Nev.

3. Crossing from Pioche to Toquerville, Utah, via Hebron and Saint George, the only data obtained was the evidence of the non-presence of the Paleozoic strata of the Great Basin system.

4. Southeast of Toquerville, Utah, a section was measured of the Permian formation and numerous fossils were collected. This completes my study in the field of the Permian formation between House Rock Spring, Arizona, and Toquerville, Utah, and north of the Grand Cañon of the Colorado.

5. The examination of the Wasatch Cambrian section gave nearly the same thickness of strata as that obtained by the Fortieth Parallel Survey (12,000 feet). The paleontologic data, however, is of the great-
est importance, as it locates the horizon of strata which have been re­ferred to the Quebec Group (Geol. Expl. Fortieth Parallel, vol. i, p. 230) as Middle Cambrian.

With the data we now have, most of the Paleozoic fossils heretofore collected in the entire Rocky Mountain region can be referred to their true stratigraphic horizons, but it is desirable that further study should be given to the Cambrian strata of the Uinta, Wasatch, Oquirrh, and Tintic Ranges, as we know nothing of the fauna that preceded the Middle Cambrian fauna in the Rocky Mountain region.

OFFICE WORK.

Prof. H. S. Williams continued his study of the Devonian stratigraphy and faunas, and prepared a paper for publication on the Genesee section and a few new species of fossils.

The work of the office consisted in the special study of the new material collected from the Middle Cambrian strata of Utah and Nevada, and the incorporation of the results into the bulletin already prepared on the Middle Cambrian faunas. This was completed and transmitted for publication February 19, and put in type as Bulletin 30, during March, April, and May.

The collections made by Mr. Bailey Willis in connection with his geologic work in Tennessee were studied and lists of the species furnished to him.

A preliminary examination was made of the collection of Paleozoic fossils obtained by Mr. Arnold Hague and assistants, in the Yellowstone National Park, and a brief report given to Mr. Hague.

A small collection of Carboniferous fossils from California was examined for Mr. J. S. Diller and a list of the genera and species furnished him November 18, 1885.

The collection of Silurian and Devonian fossils made in Central Nevada in September, 1885, has been studied and the species have been identified for the purpose of using the lists of genera and species when reporting on the geologic sections.

A paper was prepared and read before the National Academy of Sciences, April 23, on the Classification of the Cambrian System of North America. Much of the data used in the paper was taken from the introduction to Bulletin 30, but the notice of the pre-Cambrian formations was enlarged.

As honorary curator in charge of the collections of the invertebrate Paleozoic fossils of the United States National Museum, I gave attention at various times during the year to the arrangement of the collections, and a large amount of material collected by the Geological Survey has been labeled and transferred to the Museum. This included the remaining Carboniferous fossils collected in the White Pine District, Nev., 9 genera, 14 species, and 107 specimens; and the rest of the collections
of Carboniferous fossils of the Fortieth Parallel Geological Survey, excluding the corals. The material transferred embraced 31 genera, 48 species, and 351 specimens, and the typical material studied in the preparation of Bulletin 30; the latter collection contained 38 genera, 102 species, and 2,183 specimens, and a full list of the Cambrian collection is given in my report to you for the month of June, 1886.

The Director and the Assistant Director of the U. S. National Museum have continued to provide the facilities for laboratory work enjoyed the past two years; they also added a small work room in the annex, which has been of service, as our available space is too limited for the demands of the work.

Mr. J. W. Gentry remained in charge of the office during my absence in the field. His duties have been of a varied character and connected with the writing out of manuscript notes, proof-reading, preparing index to Bulletin 30, &c.

Mr. Cooper Curtice, on returning from the field, superintended the unpacking of the field collections and prepared for study the larger portion of them, besides writing out notes taken in the field.

Mr. M. T. Burns was detailed from the Division of Geography, for the purpose of continuing the work of labeling and recording collections, from January 15 to June 1, 1886.

The following publications, made on the results of studies carried on in this division, appeared during the year:


Very respectfully, your obedient servant,

CHAS. D. WALCOTT,
Paleontologist in Charge.

Hon. J. W. POWELL,
Director U. S. Geological Survey, Washington, D. C.

REPORT OF DR. C. A. WHITE.

DEPARTMENT OF THE INTERIOR,
U. S. GEOLOGICAL SURVEY,
MESOZOIC DIVISION OF INVERTEBRATE PALEONTOLOGY,
Washington, D. C., July 1, 1886.

SIR: I have the honor to submit the following report of the work which has been performed by the division in my charge during the fiscal year ending June 30, 1886:
In accordance with your instructions I left Washington August 3, 1885, in company with my assistant, Mr. R. T. Hill, and proceeded directly to Utah for the purpose of prosecuting the field work of my division. The work which I had planned for the season was the stratigraphic and paleontologic study of the later Cretaceous and earlier Tertiary formations and their relation to each other. I selected the village of Moroni, in San Pete Valley, Utah, as the most convenient place from which to commence the season's work, and accordingly began operations there. The strata which first demanded my attention were those which are exposed in the range of hills bordering the south side of San Pete Valley, opposite the villages of Moroni and Wales. This series of strata, which is there between 2,000 and 3,000 feet in thickness, contains the coal that for several years past has been mined in the neighborhood of the village of Wales. These strata were found to contain a fauna which plainly indicates their identity with the Wasatch Group, the lowest member of the great fresh-water Eocene series of Utah and Wyoming, although that fauna was found to embrace several species of the fresh-water mollusca which characterize the Laramie Group and which had evidently survived their earlier brackish-water contemporaries.

After examining these strata upon the western side of San Pete Valley, we proceeded down the valley with a field outfit and crossed the main range, or Wasatch Plateau, by way of Salina Canon, into Castle Valley, upon the eastern side of the range. Thence we proceeded northward to the small stream in Emery County known as Cottonwood Creek, which flows eastward from the main Wasatch Range. Following up the canon of this creek we re-entered the range, traversing Joe's Valley, from which we proceeded northward through a series of short, high valleys, and then descended to Pleasant Valley, upon the eastern side of the range. From Pleasant Valley we recrossed the mountains to the northeastern part of San Pete Valley, and from thence returned to Moroni. This trip enabled us to traverse in both descending and ascending order the whole series of strata from the upper portion of the Eocene Wasatch Group to the Colorado Group of the Marine Cretaceous, inclusive. In doing so I was able to confirm the evidence of the superposition of the formation containing the coal beds near the village of Wales upon the Laramie Group, which I had already observed in the character of the fossils. During the trip I was also able to recognize several distinct coal horizons, belonging respectively to the Wasatch, Laramie, and Fox Hills Groups.

From San Pete Valley we proceeded to Evanston, Wyo., and examined the coal-bearing series of strata in that vicinity for the purpose of comparing it with the coal-bearing strata near the village of Wales, Utah. This comparison, together with others which I had previously made, left little or no doubt in my mind that the coal of the well known Almy mines,
near Evanston, Wyo., and that of the Wales locality, in Utah, belong to one and the same horizon; that is, I believe them both to belong to the lower portion of the Wasatch Group. The coal of Pleasant Valley, in Utah, I regard as belonging to the same, or nearly the same, horizon as that of Coalville, Utah, the strata of both localities being of marine origin.

I observed indications of the presence of large deposits of coal in the Laramie strata in Cottonwood Cañon, before referred to, which of course hold an intermediate position between the other coal horizons just mentioned.

Returning eastward from Utah and Wyoming, I visited the locality near Cañon City, Colo., from which Professor Marsh has obtained such large collections of Jurassic vertebrates. Here I obtained an important collection of fresh-water invertebrate remains, which has added much to our previous limited knowledge of the continental invertebrate fauna of the North American Jurassic.

On the 10th of September I left Mr. Hill in the valley of the Republican River, near the boundary between Colorado and Nebraska, with instructions to attempt the tracing of the eastern border of the Laramie Group in that region. From that point I proceeded to Washington, where I was joined two weeks later by Mr. Hill.

The results of the above mentioned studies in the field, together with those of the studies of the fossils then collected, are largely presented in bulletins of the Survey Nos. 29 and 34, now in press. Some of the leading features of those results may be stated as follows:

It is shown that a portion of the fresh-water molluscan species which characterize the Laramie Group survived their brackish-water contemporaries and became a part of the purely fresh-water molluscan fauna of the Wasatch Group. This fact indicates that there was a continuity of congenial aqueous habitat for those mollusks from the Laramie to the Wasatch epoch, and the observed character of the strata also indicates that sedimentation was continuous from the one group to the other.

The observations upon the Jurassic strata and their fossil contents which I was able to make during the past season, together with those which I had previously made, seem to justify the opinion that a large continental area existed upon the site of the present North American continent during the latter part of the Jurassic period.

It will be readily seen that these questions have a very important bearing upon the geological history of the North American continent.

OFFICE WORK.

The office work of the division during the year consisted in the arrangement and care of the Survey and Museum collections of fossils and in the preparation of bibliographic work. Messrs. J. B. Marcou, R. T. Hill, Frank Burns, C. B. Boyle, and J. T. Hendley were engaged upon
this work during the year, Mr. Burns and Mr. Hendley having been transferred to other work after the first four months and Mr. Marcou after the first six months, and Mr. Hill having been absent in the field about two months.

In July last all the fossils belonging to the Survey and in charge of this division were transferred to the newly allotted space in the northeast balcony in the first story of the Smithsonian building, where all the specimens were cleansed, numbered with distinguishing green labels, and stored away in cases for convenient reference and study. The arrangement of all the previously obtained fossils of the Survey and Museum has been completed so far as to make them readily accessible for study and reference.

Besides the above mentioned office work, various collections of fossils have been examined for different parties of the Survey, who needed such determinations of their material to aid them in the prosecution of field work.

During the year the U. S. National Museum published, in the name of Mr. Marcou, the Bibliographical Bulletin No. 30, and in its proceedings a catalogue of the type specimens in the collections of the Museum. In this work, as well as in the preparation of a large amount of yet unpublished bibliographical manuscript, Mr. Marcou had the assistance of the greater part of the force of this division.

The published results of my own labors for the past year are contained in Bulletins of the Survey Nos. 29 and 34, now in press.

Respectfully submitted.

C. A. WHITE,
Geologist in Charge.

Hon. J. W. Powell,
Director U. S. Geological Survey, Washington, D. C.
ance given to private students, from whom requests are frequently received calling for names of fossils or other information in regard to specimens, modes of work, &c.

The intimate way in which the study of the Tertiary invertebrates is linked with that of Quaternary and recent forms has rendered it not only practicable but highly important that the two should not be divorced. Consequently, with your approval, I retained the direction of the department of mollusks of the U. S. National Museum, long confided to me as honorary curator, and to the routine of the paleontological work I added that of the department devoted to the recent forms.

In matters embraced under the fourth head, advice or assistance in writing was furnished to the following gentlemen, among others: Edward Bartlett, esq., England; Dr. Stephen Bowers and Dr. J. G. Cooper, California; M. E. de Boury, France; Dr. D. T. Day, New York; Mr. H. E. Dore, Portland, Oreg.; Mr. N. Grebuzitki, Russia; Lieut. A. W. Greely, U. S. A., Washington; Dr. S. Hertzenstein, Russia; Mr. C. W. Johnson, Florida; Mr. W. G. Mazeyck, South Carolina; Mexican Commission to New Orleans Exhibition; Dr. W. S. Newlon, Kansas; Mr. C. R. Orcutt, California; Dr. Paul Pelseneer, Brussels, Belgium; Mr. Charles T. Simpson, Florida; Mr. L. M. Turner, Washington; Mr. A. G. Wetherby, Florida; Mr. J. F. Whiteaves, Canadian Geological Survey, Ottawa, Can.; Mr. S. Hart Wright, New York.

Under the third head several informal reports have been made, especially on fossils from the Todd quarry, for Mr. John P. Eogan, at the request of Prof. Cyrus Thomas; on fossil land shells and freshwater mollusks from California, for Dr. C. A. White and Mr. J. B. Marcon; on others from the Kansas loess, for Mr. W J McGee, &c.

FIELD WORK.

In regard to field work under the direction of this division, I have to report that about March 15 Mr. Frank Burns, of the Geological Survey, took the field at Orangeburgh C. H., S. C., and continued at work during the greater part of the remaining three months of the year looking up the original localities of Messrs. Tuorney and Holmes, with a view of re-collecting the species described by them in their classic monograph on the fossils of the Charleston Basin, the types of which are lost or at all events not accessible for study. This work was carried on, in spite of very bad weather, until it became useless, in the flooded state of the lowlands, to attempt further collecting. While in the field Mr. Burns obtained about a dozen large boxes and two barrels full of excellent specimens of the Tertiary and Quaternary forms, which prove a great addition to our collection.

Mr. L. C. Johnson, though not under my direction, in the course of his field work sent in a large number of Tertiary fossils from Louisiana and Texas, which promise to be of value. They are mostly Eocene. A
few very interesting forms from the mouth of Saline Bayou, Louisiana, were presented by Dr. D. S. Waddell, through Mr. Johnson.

Mr. James Shepard contributed some very elegant silicified species from Conrad's old locality at Tampa Bay, Florida.

OFFICE WORK.

In administrative work all the new material in regard to which information has been desired was reported upon; but toward the end of the year the Burns and Johnson collections, arriving together, formed such a large mass that it will take some time to classify it and put it in order. Otherwise we have no arrears in regard to Survey work. With the arrears of Museum work we have been reasonably successful, as from July 1, 1885, up to June 30, 1886, 18,638 lots of specimens, including not less than sixty thousand individuals, have been labeled, registered, and put in order; and this notwithstanding the occurrence of sickness more than in any previous year in the division and among my assistants from the Museum. It may be observed that the total registration in this department since 1860 to date, has been about 60,000 entries. During the year, therefore, nearly one-half as much material has been put in order for study, labeled, and registered, as during the whole of the previous twenty-five years since the work was begun.

In a general way it may be said that the land and fresh-water shells, excepting the Unios, have been completed for the American series; and the Unios will be completed also in a few weeks. The forms from marine deposits of the Southeastern United States have been much worked over, and will probably be the next division completed.

I have been assisted by Dr. R. E. C. Stearns and Mr. J. B. Crowe, who, in spite of illness, did a very large amount of work in a satisfactory manner. The National Museum, as usual, furnished all needed cases and material for the work, as well as the services of a clerk, who was chiefly engaged on the labeling and cataloguing.

A number of cases were made ready and put on exhibition in the Smithsonian Hall, showing recent and fossil forms side by side, in sections, &c., as well as illustrations of the formation of pearls and other invertebrate products of economic or geologic interest.

Bulletin No. 24 of the U. S. Geological Survey was put through the press during the same period. It includes 336 pages octavo, of which the proofs were read by the writer.

On the whole the year has seen a very satisfactory amount of work accomplished.

Very respectfully,

WM. H. DALL,
Paleontologist in Charge.

Hon. J. W. POWELL,
Director U. S. Geological Survey, Washington, D. C.
SIR: I have the honor to submit the following report of the operations of the Division of Paleobotany during the past fiscal year:

FIELD WORK.

I have accompanied two expeditions during the year, both of which had for their object the study of the Younger Mesozoic (or Potomac) formation and to collect its fossils, and the results of which will be utilized primarily in the completion of Professor Fontaine's Monograph of the Younger Mesozoic Flora of Virginia, which was in preparation at the beginning of the year.

The first expedition was begun July 27 and concluded August 31, 1885. The party consisted of Prof. William M. Fontaine, Mr. W. J. McGee, and myself, and the expedition took the form of a geological reconnaissance. The carriage and horses used were the property of the Survey and the outfit was very simple. The narrow belt in which this formation is to be found was first traced from Washington southward through the State of Virginia, and its boundaries were determined as accurately as possible. The bluffs of the Potomac and Rappahannock, as well as numerous railroad cuts, afforded good exposures at various points, and fossil plants were found in a number of places. From Richmond an expedition was made in a row-boat down the James River to City Point and up the Appomattox to Petersburg. Younger Mesozoic strata, often plant-bearing, occur from Richmond to Deep Bottom, four miles below the Dutch Gap Canal; they were also seen at corresponding points on the Appomattox. From Petersburg southward they were not visible on the surface, but were found at Bolling's Bridge, on the Nottaway River, in the immediate banks and bed of the stream. The journey was continued southward to the Roanoke, at Weldon, N. C., in the hope of again finding traces of the Mesozoic there, and it is believed to have been found at one point in a very circumscribed area on the left bank of that river.

After the return to Washington the reconnaissance was extended northeastward through the iron mining region in Maryland and in the vicinity of Baltimore, Annapolis, and Marlboro, and the limits of the formation were determined in these directions.

Very few fossils were collected on this expedition, which required too rapid travel for this purpose; but localities were carefully noted, and the best modes of approach for collecting purposes were decided upon.
The second expedition was made in June, 1886, and occupied twenty days. The party consisted of Professor Fontaine and myself, assisted by Mr. F. H. Knowlton, of the National Museum. As the best localities for collecting fossil plants lie in the immediate bluffs of the Potomac and James Rivers, which are inaccessible from the land side, it had been decided that this expedition must be made by water, and as the small boat by which we had explored the banks of the James River was inadequate to transport the party, with its necessary equipage, and to bring away the fossils, it had been thought best to make this expedition in a small steam launch, which would satisfy all these requirements. Such a vessel was accordingly engaged and in fresh water proved admirably adapted to the purpose. It enabled us to make a much better study of the formation in its best exposures along the Potomac from Washington to Acquia Creek and to collect the fossil plants wherever they could be found. The principal collections were made at White House Landing and at Acquia Creek, and much new and valuable material was obtained in this way.

Proceeding from this point to Norfolk by public conveyance, a new outfit similar to the first, but available in salt water, was secured, and we proceeded to complete our labors by ascending the James and spending a week in the vicinity of the Dutch Gap Canal. The collections made in these beds were both interesting and ample, and well repaid the extra efforts required in reaching these difficult points.

The expedition returned, with all the material collected, on June 26.

OFFICE WORK.

The work of the division has been directed toward two distinct ends, which have now both taken definite shape. The first of these is the completion of my Monograph of the Flora of the Laramie Group, a "synopsis" of which was published in the Sixth Annual Report of the Survey. The second is the completion of my "Compendium of Paleobotany," the plan of which has been sufficiently set forth in previous administrative reports.

For the first of these works a large amount of drawing was required, and this has not progressed as rapidly as I had hoped. It was continued by Mr. Everett Hayden, assisted by Miss Annie S. Moorhead, but with many interruptions caused by other kinds of work which they were both called upon to perform, until about the 1st of March, when Mr. Hayden was transferred to another division. On May 1 Mr. Otis E. Pearce was appointed to take Mr. Hayden's place as draughtsman, but he was taken ill very soon after his appointment, and has not yet been able to resume his duties. On June 1 Mr. C. D. White entered upon the work, and has already advanced it considerably.

1 Mr. Pearce died at his home at North Hannibal, N. Y., September 11, 1886.
On my return from the field, at the end of August, I commenced preparing the technical descriptions of the species that were already figured and submitted for publication without descriptions in the Sixth Annual Report. These numbered 139, of which 84 were new to science. The descriptions were concluded before the end of December, and I proceeded to draw them up in the form of a manuscript for a Bulletin of the Geological Survey, entitled "Types of the Laramie Flora," which was submitted for publication February 2.

The remainder of my own time, when not in the field, has been devoted to work bearing upon the other volume above mentioned. The very large slip catalogue of species of fossil plants, which has been accumulating for several years, has been the work almost exclusively of unskilled and untrained assistants, many of whom were unacquainted with the languages in which most of the works catalogued are written, and some parts of the work were done during my absence in the field. This work was therefore necessarily very defective, and the slips written contained many clerical errors. They required careful revision before any further steps could be taken, and this task could only be properly done by myself. I undertook it, in connection with other duties, near the beginning of January, and had only brought it down to date at the end of May. Hereafter all slips will be revised before they are placed in the slip index.

Besides this work I have been obliged to devote much time daily to bibliography in supplying books to be catalogued by Mr. Bruno Müller, who is exclusively employed in writing these index slips. As the works grew more scarce and difficult to find, this part of my duties became very onerous and consumed so much time that I was obliged to ask for an assistant. Mr. F. H. Knowlton, assistant curator of plants at the National Museum, who has been very successful in accumulating a botanical sublibrary, and who has permission to take up the study of the internal structure of fossil and living woods, undertook this work, with the approval of the Assistant Director of the Museum, soon after the middle of February, and has performed it, along with his other duties, with entire satisfaction.

Mr. Leo Lesquereux has undertaken the preparation of a volume of descriptions and illustrations of Cretaceous and Tertiary plants, from new material in his hands and to be supplied to him. The drawings for the plates, thirty in number, of the first part of this volume, have already been completed; these relate to the Dakota Group, and they will greatly extend our knowledge of the flora of that group. In addition to this work Mr. Lesquereux has studied and named or identified a large amount of material sent him for the purpose, most of which has been collected by officers of the Survey and placed in my hands, but which I could not find time to investigate myself.
Professor Fontaine submits the following report of work done by him during the fiscal year 1885-'86:

During the year my work has been in part geological and in part paleontological, all relating to the Younger Mesozoic, or Potomac formation. Field work has been carried on to secure data for a report on the geology of the formation in question and to collect its fossils. When not engaged in field work my time has been occupied in the preparation of the geological report and in paleontological work. The paleontological work consisted in the selection and preparation of the fossil plant material and in the drawing and description of the same. Enough material was illustrated by drawings to make 150 or more plates of monograph size. Most of the plants are new, and all are of great interest, both from a geological and from a botanical point of view, since these plants partly fill a most important gap in the paleontological records. Both the geological and the paleontological reports will soon be ready for the printer.

The field work for the summer of 1885 was carried on, partly in company with Prof. Lester F. Ward and Mr. W J McGee, and partly by myself alone. The Potomac formation was traced by us from Baltimore southward until it disappeared in the southern portion of Virginia. The examination was pushed as far as Weldon, in North Carolina.

At a later date in the same summer I made a detailed examination of points at and north of Fredericksburg, Va., and collected fossil plants from several localities; I also made an examination of points in Hanover County, Virginia.

In the month of June, 1886, in company with Professor Ward, I made an examination of the Potomac formation, as it is shown in the banks of the Potomac below Washington, and in the banks of the James below Richmond. Large collections of the fossil plants were made at the same time. This latter examination was made by boat, as most of the points are not accessible in any other way.

Very respectfully, your obedient servant,

LESTER F. WARD,
Geologist in Charge.

Hon. J. W. POWELL,
Director U. S. Geological Survey, Washington, D. C.
REPORT OF MR. S. H. SCUDDER.

DEPARTMENT OF THE INTERIOR,
U. S. GEOLOGICAL SURVEY,
DIVISION OF FOSSIL INSECTS,
Cambridge, Mass., July 1, 1886.

Sir: During the last six months of the past fiscal year, i.e., from the date of my appointment on the Survey to the close of the year, I have been engaged, first, in the study of a collection of insects from the peat deposits of Nantucket, consisting of about fifty determinable species, probably the largest collection of such insects ever made from a single locality; second, in the determination of insects from the interglacial clays of our northern border; and, third, in the systematic study of the Carabidæ of the Oligocene beds of Florissant, Colo. As a large part of this work has been necessarily introductory, a more definite statement of its results must be left for another report.

Steady progress has also been made in Mr. Blake's work in drawing the Florissant insects, nearly his whole time having been employed upon the Diptera of that locality, and especially on the Empidæ, Mycetophilidæ, Bibionidæ, and Sciarina.

Respectfully yours,

SAM. H. SCUDDER,
Paleontologist in Charge.

Hon. J. W. Powell,
Director U. S. Geological Survey, Washington, D. C.

REPORT OF PROF. F. W. CLARKE.

DEPARTMENT OF THE INTERIOR,
U. S. GEOLOGICAL SURVEY,
DIVISION OF CHEMISTRY AND PHYSICS,
Washington, D. C., July 1, 1886.

Sir: I have the honor to submit the following report of work done in the Division of Chemistry and Physics during the fiscal year 1885-'86:

As regards the force and equipment of the division there have been but slight changes from the preceding year. One additional room was fitted up in enlargement of the laboratory, and there has been a fair increase in the outfit of permanent apparatus. In November, Mr. W. F. Hillebrand was transferred to Washington from the branch laboratory at Denver, leaving the latter, still under Mr. Emmons's division, in charge of Mr. L. G. Eakins. The branch laboratory of Mr. Becker's division, at San Francisco, has remained in operation under Dr. W. H. Melville.
The work done in the Washington laboratory during the year has been very varied in character and has covered a decidedly wide range. Part of it has been analytical and largely in the line of necessary routine; but a fair portion of the time was given to problems requiring independent research. Under the latter heading will fall certain investigations relative to improvements in analytical methods, some experiments having economic significance, and a certain amount of purely mineralogical work. The more important of the various undertakings may be summarized as follows:

For my own part, aside from administrative duties and purely routine analyses, two investigations of interest may be reported. First, an examination of the minerals from the ecoalite-syenite of Litchfield, Me., collected by myself during a field expedition in July. These minerals have long been noted among collectors, especially the cancrinite and sodalite of the locality; but I have been able, by means of careful analyses, to trace the genetic relations of the above named species to the ecoalite from which they have been derived, and to identify as occurring with them a new zeolite, to which the name "hydronephelite" has been given. Secondly, upon the basis of collections made by yourself, I have investigated the turquoise from Los Cerillos, N. Mex., and have placed the composition and nature of that interesting mineral beyond reasonable doubt. In both researches I have been most kindly aided by Mr. J. S. Diller, who studied the more important minerals microscopically, and thereby added much to the certainty of the results. Whatever scientific value the investigations may possess is due fully as much to his labors as to mine.

The fact that in many cases routine work and research must go hand in hand is remarkably illustrated by the elaborate series of analyses made by Messrs. F. A. Gooch and J. E. Whitfield upon the waters of the Yellowstone National Park. Of these nearly forty have been studied, representing geysers, hot and cold springs, streams, and the Yellowstone Lake, and the results have peculiar interest, both from a practical and from a scientific point of view. The fact that all the hot waters of the region contain arsenic in quite appreciable quantities is important from a medical standpoint, and the remarkable complexity of the waters is interesting both to the chemist and to the geologist. As regards completeness, the analyses form a unique series, and in their conduct some difficult problems have arisen. Two of the latter, the accurate estimation of lithia and the accurate estimation of boric acid, hitherto among the greatest difficulties of the analyst, were completely solved by Mr. Gooch; and another, the determination of chlorine and bromine when occurring together, was disposed of by an indirect electrolytic process worked out by Mr. Whitfield. Unfortunately the services of Mr. Gooch will be henceforward lost to the Survey, he having accepted the chair of chemistry in Yale College.

Under Mr. T. M. Chatard an investigation upon the corundums of
North Carolina has been brought to a close, and another upon the saline and alkaline minerals of the United States has been begun. During August he visited the salt wells of Syracuse, the Genesee Valley, and Saginaw, and the salt works at Pomeroy, Ohio; and since his return he has given much time to a study of the waters of Mono Lake. The latter represent a large group of brines, rich in alkaline carbonates, which are found at many points in the Great Basin, and upon them great industries are likely to be based. The question of the practical utilization of such brines is the problem which Mr. Chatard has now in hand, and it can be answered only by work conducted partly in the field and partly in the laboratory.

Although the time of Messrs. W. P. Hillebrand and R. B. Biggs has been mainly occupied by routine, each has been able to contribute something to scientific research. The former has been engaged upon various rare and interesting minerals from Colorado, and the latter has completed a valuable set of fourteen analyses upon the lepidolites of Maine and the curious lithia micas from the Rockport granite. Mr. Biggs has also analyzed two undescribed meteoric irons from the collection of the National Museum.

In addition to the foregoing investigations proper, the following important sets of analyses have been made in the laboratory in the course of the year:

1. Nine rocks and minerals from the trap dike of Elliott County, Ky.
2. Four rocks from the Mount Taylor series.
3. Five rocks from the Leucite Hills, Wyoming.
4. Three rocks from the Penokee series.
5. Three building stones for the Supervising Architect of the Treasury.
6. Five mineral waters from Iowa, Virginia, and Utah.
7. Six clays, collected by the Division of Glacial Geology.
8. Nine iron ores and one limestone from Louisiana.
9. Eight coals from North Carolina, Virginia, West Virginia, and New Mexico.
10. Eight samples of volcanic dust from Montana.
11. A series of fulgurites and sands from Illinois.
12. Forty samples of ink for the Department of the Interior.

Also many assays of ores and identifications of minerals.

Little field work has been done by members of the division during the year, except that which has already been mentioned in the proper connection above. My own expedition in July, in addition to my visit to the mineral locality at Litchfield, Me., took me to the feldspar region near Brunswick and the lepidolite belt near Paris, in the same State, and also to the granite quarries of Rockport, Mass. The material collected on this trip has since been thoroughly worked up in the laboratory, and the results will appear in a forthcoming bulletin.

The physical laboratory of the Survey remained, as heretofore, in charge of Messrs. Carl Barns and William Hallock. Dr. Barns, with the co-operation of Professor Strouhal, of Prague, continued his investigations upon the internal structure of steel, and they have minutely compared the mechanical effect of quenching an iron carbide with the
strain imparted to glass by sudden cooling. Drs. Barus and Hallock jointly investigated the constancy of temperature attainable in metallic vapor baths, and constructed apparatus for the convenient calibration of thermo-electric pyrometers. Dr. Barus also continued his work upon sedimentation, and Dr. Hallock gave some time to the study of seismoscopes. During the summer the latter was stationed at the Watertown Arsenal for the purpose of using the great testing machine of the Ordnance Bureau in experiments upon high pressures. This investigation is not yet finished.

One other item connected with the work of the division remains to be mentioned. On October 10, 1885, the notable explosion of dynamite at Flood Rock, New York, took place. This explosion, the greatest artificial earthquake ever known, offered opportunities for the study of seismic phenomena which could not be neglected. The matter, properly, should have come under the Division of Volcanic Geology, but as Capt. C. E. Dutton was absent in the field the work came partly into my hands. Accordingly, in co-operation with Prof. T. C. Meudenhall, of the Signal Service, and Prof. H. M. Paul, of the Naval Observatory, Dr. Hallock and I went to New York and made such observations as were possible, at short notice, upon the velocity of transmission of explosive waves through the earth's crust. A special bulletin upon the subject is now in course of preparation.

Very respectfully,  

F. W. CLARKE,  
Chief Chemist.

Hon. J. W. Powell,  
Director U. S. Geological Survey, Washington, D. C.

REPORT OF MR. ALBERT WILLIAMS, JR.

DEPARTMENT OF THE INTERIOR,  
U. S. GEOLOGICAL SURVEY,  
DIVISION OF MINING STATISTICS AND TECHNOLOGY,  
Washington, July 1, 1886.

SIR: I have the honor to report that, in addition to a large amount of information furnished to correspondents during the year ending June 30, 1886, the work of this division consisted (1) in the distribution of abstracts and charts of the mineral statistics for 1882, and for 1883 and 1884, of which, including advance proofs, some 4,500 were mailed, and (2) in revising the report on the "Mineral Resources of the United States for 1883 and 1884," which was completed in August. Owing to the delays in the presswork and binding, the report was not issued until December 9, when distribution of copies to agents, correspondents, and the press immediately began. In January, 1886, the work preparatory for the statistical canvass of 1885 was commenced, and by May the bulk
of the manuscript for the report on Mineral Resources for the calendar year 1885 had been written.

From this it appears that the total value of all mineral products of the United States during the calendar year 1885 may be estimated at $428,521,350. This shows an increase of $15,306,608 above the value of the product in 1884. Comparing the totals for the years covered by the reports of this division, a continuous decrease in value is noticed in 1883 and in 1884, being marked in the latter year. The increase in 1885 is due in part, no doubt, to more complete returns and to the increasing facilities for closer estimates. It indicates, however, a more profitable business year, which would be still more apparent if the last half were compared with the corresponding period in 1884, since in many important industries prices increased towards the end of the year.

The following summary shows the changes in each of the more important branches of mineral production during the year:

**Coal.**—The total commercial product of coal of all kinds in 1885, exclusive of that consumed at the mines, known as colliery consumption, was 93,534,705 long tons, valued at $152,915,108. Of this 32,265,421 long tons were Pennsylvania anthracite, valued at $72,274,544, while of other coals, including bituminous, brown coal, lignite, and small lots of anthracite produced outside of Pennsylvania, the production was 63,569,284 long tons, valued at $80,640,564 at the points of production. The total production, including colliery consumption, was: Pennsylvania anthracite, 34,228,548 long tons; all other coals, 64,840,668 long tons, making the total absolute production of the coal mines of the United States 99,069,216 long tons, valued as follows: Anthracite, $76,671,948; bituminous, $82,347,648; total, $159,019,596. The total production of anthracite (including local consumption) in excess of 1884 was 1,052,792 tons and its value $10,320,436. The total production of bituminous coal was 8,889,871 tons less than in 1884, but its value was $4,930,582 greater. The total production of coal of all kinds shows a net loss in tonnage of 7,837,079 long tons, compared with the product of 1884, but a gain in value of $15,251,018, the increase in value being due to an average increase of 25 cents per long ton. The total value is about the same as that of 1883.

**Coke.**—The total production of coke in 1885 was 5,106,696 short tons, valued at the ovens at $7,629,118. Of this Pennsylvania produced over 78 per cent., or 3,991,805 tons, valued at $4,981,656. The remainder was produced in fourteen States and Territories. The maximum production of coke in the United States was reached in 1883, when 5,464,721 tons were made. This declined in 1884 to 4,873,805 tons. The production of 1885 shows a gain upon that of 1884, being within 360,000 tons of the make in 1883.

**Petroleum.**—The total production was 21,842,041 barrels of 42 gallons, of which the Pennsylvania and New York fields produced 20,776,041 barrels. The total value, at an average price of 87½ cents a barrel, was
The production showed a decrease of 2,247,717 barrels and of $1,282,600 in value from 1884.

Natural gas.—No record is kept of the yield in cubic feet. The amount of coal displaced by gas in 1885 was 3,161,600 tons, valued at $4,854,200. In 1884 the coal displaced was valued at $1,460,000. The yield has increased tenfold since 1883.

Iron.—The principal statistics for 1885 were: Domestic iron ore consumed, 7,600,000 long tons, valued at mine at $19,000,000; imported iron ore consumed, 390,786 long tons—total iron ore consumed, 7,990,786 long tons; pig iron made, 4,044,525 long tons, a decrease of 53,343 tons as compared with 1884, valued at furnace at $64,712,400, or $9,049,224 less than in 1884. The total spot value of all iron and steel in the first stage of manufacture, excluding all duplications, was $93,000,000, a decline of $14,000,000 from 1884.

Gold and silver.—The mint authorities estimate the value of the gold produced in 1885 at $31,801,000, an increase of $1,001,000 over 1884. The production of silver is estimated by the same authorities at $51,000,000, an increase of $2,800,000 over the product of 1884.

Copper.—The production in 1885, including 5,086,841 pounds made from imported pyrites, was 170,962,607 pounds, valued in New York at $18,292,999, at the average price of 10.7 cents per pound. The increase in pounds over 1884 was 23,157,200; the increase in value, $186,837.

Lead.—Production, 129,412 short tons; total value, at an average price of $80.90 per short ton at the Atlantic coast, $10,469,431, a decline of 10,485 tons and of $67,611 in value from the product of 1884. The production of white lead is estimated at 60,000 short tons, worth, at 5½ cents per pound, $6,300,000.

Zinc.—The production of metallic zinc in 1885 was 40,688 short tons, worth $3,539,856, at an average value of 4.35 cents per pound, an increase of 2,144 tons and of $117,149 in value over 1884. Zinc was also made from the ore directly into zinc-white (zinc oxide) to the extent of 15,000 short tons, valued at $1,050,000.

Quick silver.—Production, 32,073 flasks (of 7¾ pounds net), or 100 flasks more than in 1884; total value, at an average price of $30.53 a flask at San Francisco, $979,189, an increase of $42,862 over the value in 1884. The production of quicksilver vermilion was about 600,000 pounds, the same as in 1884, but the price advanced to 52 cents a pound, making the total value $312,000.

Nickel.—The production of metallic or "grain" nickel was 245,504 pounds, valued at $169,397. In addition, matte and ore containing 32,400 pounds of nickel were exported. The total value of all nickel was $191,753.

Cobalt.—The amount of cobalt oxide was 8,423 pounds, valued at $19,373. The total value of cobalt in ore, matte, and the above oxide was $65,373.

Manganese.—The production of manganese ores was 23,253 long tons,
valued at $190,281; manganiferous iron ore, 3,257 long tons, valued at $17,318—total value, $207,599.

Chromium.—The production of chrome iron ore was 2,700 long tons, valued at $40,000. The consumption for making potassium and sodium bichromates increased markedly, due to imports of chrome iron ore from Asia Minor.

Tin.—Probably 200 tons of “black tin” ore were made at the concentrating works at the Etta mine in Dakota. No smelting works have yet been erected.

Platinum.—The amount of crude platinum mined in 1885 was about 250 troy ounces, valued at $187. This is exclusive of about 300 ounces of iridosmine, for pointing pens.

Aluminum.—The production of metallic aluminum increased from 1,800 troy ounces in 1884 to 3,400 ounces in 1885, valued at $2,550. Aluminum bronze, containing 10 per cent. aluminum, was made to the amount of about 4,500 pounds, valued at $1,800.

Building stone.—Estimated value, $19,000,000, about the same as in 1884.

Brick and tile.—The demand and consequent production increased to an estimated value of $33,000,000 in 1885.

Lime.—With the price constant at an average of 50 cents a barrel at the kilns, the production increased from 37,000,000, barrels in 1884 to 40,000,000 in 1885.

Cement.—The production of cement from natural rock increased to 4,000,000 barrels of 300 pounds each, but was valued at only $3,200,000. Artificial Portland cement amounted to 150,000 barrels of 400 pounds each, with a total value of $292,500. The total production of cement of all kinds was 4,150,000 barrels, and it was valued at $3,492,500, against $3,720,000, the value of the product in 1884.

Precious stones.—The value of American precious stones produced in 1885 was $69,900. This includes $42,800 for stones sold as specimens and souvenirs and $27,100 for stones to be cut into gems. Besides this, gold quartz, with an estimated value of $140,000, was sold for specimens, and for ornaments and jewelry.

Millstones.—The trade in millstones of all kinds has noticeably decreased from the introduction of roller mills. The total value of the Esopus millstones in New York and Cocalico stone in Pennsylvania did not exceed $100,000 in 1885.

Grindstones.—Estimated value of product for 1885, $500,000.

Phosphates.—With the exception of a local consumption of about 1,000 tons in North Carolina the total production of phosphate rock came from South Carolina, and amounted to 437,856 long tons of washed rock for the calendar year 1885, valued at $2,846,064, at an average value of $6.50 a ton. The occurrence of phosphates is also noted in Alabama, Georgia, Florida, and Mississippi. These States will contribute to the product of 1886.
Gypsum.—The estimated production of land plaster in 1885 was 100,600 short tons; calcined plaster, 72,200 tons; total, 172,800 tons, valued at $859,600. The above includes 75,100 tons from native stone, the remainder being imported from Nova Scotia.

Salt.—The total production, in barrels of 280 pounds, was 7,038,653 barrels, exceeding the yield of 1884 by 523,716 barrels. The total value of all salt produced was $4,825,345, an increase from 1884 of $627,611, which was due partly to the increased value of the Michigan product and partly to the large increase in the production of Western New York.

Bromine.—The production increased slightly, being about 310,000 pounds, against 281,100 in 1884. The total value, at an average of 29 cents a pound, was $89,900, an increase of $22,436.

Borax.—Production, limited to California and Nevada, 8,000,000 pounds; value, at 6 cents per pound for concentrated, $480,000. While the product increased by 1,000,000 pounds, the fall in price lowered the total value by $10,000.

Sulphur.—The production was only 715 tons, worth $17,875.

Pyrites.—About 49,000 long tons were mined, valued at $220,500. In addition, 47,500 tons were imported.

Barytes.—The production was about 15,000 long tons, valued at $75,000 in the unground condition, as taken from the mines.

Mica.—The production decreased in the West owing to the inferior value of the sheets obtained. The whole product, excluding waste, was 92,000 pounds, valued at $161,000.

Feldspar.—Production, 13,600 long tons, valued, before grinding, at $68,000.

Asbestos.—The amount mined was about 300 short tons, valued at $9,000.

Asphaltum.—The production remained constant at about 3,000 short tons, with a spot value of $10,500.

Mineral waters.—The sales amounted to $1,312,845, from 9,148,401 gallons; the value is slightly less than in 1884. The great decrease from the number of gallons given in the last report is due to the exclusion here of the water derived from artesian wells in Madison, Wis., which is used as the regular city supply. A large local consumption is also excluded.

The office force has consisted of Mr. W. A. Raborg and myself, with occasional clerical assistants. The collection of statistics and the preparation of technical and descriptive matter have been carried on in this office, but more largely by agents and correspondents in various parts of the country, to whose public spirit and cordial co-operation I am largely indebted.

Very respectfully, your obedient servant,

ALBERT WILLIAMS, JR.,
Geologist in Charge.

Hon. J. W. Powell,
Director U. S. Geological Survey, Washington, D. C.
SIR: I have the honor to submit a statement in regard to the special duty assigned me as chief of the Forestry Division of the Survey for the year ending June 30, 1886.

My intention was to make during the past fiscal year a personal inspection of the forestry of the Piedmont and tidewater districts of Virginia, and of the mountain districts of the States of North Carolina, Kentucky, and, if possible, Tennessee; but work in the field was necessarily limited by other official duties demanding attention in Washington.

I visited the counties of Rappahannock, Madison, Greene, Albemarle, Prince Edward, Nelson, Buckingham, Cumberland, Nottoway, Dinwiddie, Prince George, Sussex, Southampton, Isle of Wight, Naussemond, and Norfolk, in the State of Virginia, in none of which counties, except to a very limited extent, is the forest an original growth. In a number of these counties, notably Nelson and Buckingham, the change in the system of labor has so crippled farming industries that great areas have lapsed into a wilderness, the growth being principally pine, which, in many instances, is of sufficient size to be ready for the mill.

In the immediate neighborhood of railroads, however, all kinds of valuable commercial woods are substantially exhausted. The important feature is presented of the capacity of a large part of this district for the speedy reproduction of forest. The rapid exhaustion of the forests of the Northern and Northwestern States renders it necessary that districts possessing this valuable feature should be classified.

The lumber product of the United States sold at the mills in 1880 was 18,091,356,000 feet, aggregating $233,268,729 in value. The value of product of 1885 has not yet been published, but the amount of lumber produced was over 28,000,000,000 feet; prices being assumed to remain the same, the value of product for 1885 will be over $360,000,000, exhibiting a great progressive demand for lumber. It is stated, and I think on good authority, that if this demand continues for home consumption, with a steadily increasing foreign demand, the lumber industry in the Northern and Northwestern States will substantially cease within ten years by exhaustion of their forests. It therefore seems to be essential that accurate data in regard to the resources of the South should be secured. With an increasing demand for lumber the use of a greater variety of trees necessarily follows.

In the Northeastern States nearly all the forest growth is utilized; in the South at least two-thirds of the trees composing the forests are
considered worthless. For illustration, in the South, as a rule, the wood of the hemlock is destroyed by stripping the trees for tan-bark; in the North the wood of the tree and the bark are both utilized. In the South the chestnut oak is stripped and left standing, while in the North its wood goes into general utilization, and it has been shown to be as valuable as white oak for many purposes and more valuable than white oak for some. The timber growth of the southern slope of the Blue Ridge Mountains is more diverse in character than that on the western slope of the same range and superior to it in quality. This is true of the Appalachian chain of mountains south of the Pennsylvania line, so far as I have been able to investigate.

Correspondence embracing all the Southern and Southwestern States to secure data in regard to the character of the forests has been carried on, and from information secured in this manner, and such published data as are considered reliable, I am confident that in those localities the lumber value on a moderate stumpage estimate would in the aggregate be more than double the national debt. The plan controlling such correspondence submitted to and accepted by you is still continued, and has been an effective and valuable accessory to my researches.

The General Government is wisely enforcing laws for the protection of the forest growth of the public domain. Would it not be well for the States, especially those of the South, to adopt stringent policies against its destruction, for upon its preservation in a short time will depend the welfare of a large number of our most valuable population?

Very respectfully,

GEO. W. SHUTT,

Hon. J. W. POWELL,
Director U. S. Geological Survey, Washington, D. C.

REPORT OF MR. W. H. HOLMES.

DEPARTMENT OF THE INTERIOR,
U. S. GEOLOGICAL SURVEY,
DIVISION OF ILLUSTRATIONS,
Washington, July 1, 1886.

SIR: During the year the work of preparing illustrations for the various publications of the Survey was conducted according to the scheme presented in the preceding annual report and with uniformly satisfactory results. No change whatever was made in the personnel of the division.

One annual report and seven bulletins have been transmitted through this office. The illustrations for these may be classed as follows:

Twelve plates by chromo-lithography—3 microscopic petrography and 9 maps.
Two plates by lithography—"lettering and conventional signs."
Forty-five plates by wood engraving—42 invertebrate fossils and 3 landscapes.
Fifty-two plates by photo-engraving—17 maps, sections, &c., and 35 fossil leaves.
Forty-six figures by wood engraving—37 landscapes, 8 invertebrate fossils, and 1 model of apparatus.
Thirty-three figures by photo-engraving—sections, diagrams, &c.

Many of the illustrations included in this list were prepared during preceding years. The following table shows approximately the drawings executed since June 30, 1885:

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<td>Fossil vertebrates, 48 plates</td>
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<td>Fossil insects, 84 figures</td>
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<td>Mineralogic specimens, 10 figures</td>
<td></td>
</tr>
<tr>
<td>Microscopic subjects, 4 figures</td>
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<tr>
<td>Geological landscapes, 3 plates</td>
<td></td>
</tr>
<tr>
<td>Sections and diagrams, 38</td>
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</tr>
</tbody>
</table>

The photographic work, conducted by Mr. J. K. Hillers and his assistants, progressed without important change. Field work on a limited scale has been undertaken by a number of persons. Mr. Hillers accompanied the Director to Arizona, and during a short trip to the Grand Cañon made a small series of views. Mr. C. C. Jones spent a few weeks in Virginia, and under the direction of Mr. W J McGee made about sixty studies of geologic subjects.

A number of the geologists carried cameras with them into the field and the office thus secured many views of importance.

A very important feature of the photographic work consists in the copying of unfinished topographic maps and charts for use in the field during succeeding seasons and for the guidance of the engravers.

The photographing of paleontologic subjects has also been carried on with success. The following is a list of the negatives, prints, and transparencies made during the year:

<table>
<thead>
<tr>
<th>Negatives.</th>
<th>Print.</th>
<th>Transparencies.</th>
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<tr>
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</table>

Very respectfully, your obedient servant,

W. H. HOLMES,
Geologist in Charge.

Hon. J. W. POWELL,
Director U. S. Geological Survey, Washington, D.C.
SIR: I have the honor to make you the following statement of work done in this division during the fiscal year ended June 30, 1886:

**LIBRARY.**

The library has already filled its new quarters to such an extent that during the coming year there will be great difficulty in properly administering it unless more room can be provided. During the year a new rack, 27 feet 10 inches by 9 feet 6 inches by 1 foot 4.5 inches, was put in, providing 415 additional feet of shelf-room; and two document rooms were used as annexes. To these two rooms, which are readily accessible, were removed the two subject divisions of the library least frequently consulted, and the room gained thereby, together with the new shelving for 4,500 books, has prevented any serious crowding from the rapid increase in the number of books received during the year.

*Contents of the library June 30, 1886.*

**BOOKS.**

| On hand June 30, 1885:                      | 11,165 |
| Received by exchange                      |        |
| Received by purchase                      | 3,547  |
| **Total received**                        | 14,712 |

| Received during the past year:            |        |
| By exchange                              | 1,553  |
| By purchase                              | 990    |
| **Total received**                        | 2,543  |

| **Total number of books**                 | 17,255 |

**PAMPHLETS.**

| On hand June 30, 1885:                    | 10,400 |
| Received by exchange                     |        |
| Received by purchase                     | 800    |
| **Total received**                       | 11,200 |

| Received during the past year:           |        |
| By exchange                              | 8,000  |
| By purchase                              | 400    |
| **Total received**                       | 8,400  |

| **Total number of pamphlets**            | 19,600 |

**Total number of books and pamphlets**  36,855
The growth of the year has been catalogued by authors, but more than this cannot be attempted by the present force available for the special work of cataloguing. The greater part of the clerical force is occupied by the many other needs of library administration. At all times several thousand volumes are in the work rooms of the different corps of the Survey and an average of 1,000 books are drawn and returned every month. Two thousand volumes have been bound during the year.

**PUBLICATIONS.**

During the year have been published the Fifth Annual Report, Bulletins 14–26, and the second volume of Mineral Resources, making the list of publications of the Survey now issued as follows:

**Annual reports.**

I. First Annual Report to the Hon. Carl Schurz, by Clarence King. 1880. 8°. 79 pp. 1 map.—A preliminary report describing plan of organization and publications.


**Monographs.**


V. Copper-bearing Rocks of Lake Superior, by Roland D. Irving. 1883. 4°. xvi, 464 pp. 15 l. 29 pl. Price $1.85.

VI. Contributions to the Knowledge of the Older Mesozoic Flora of Virginia, by William M. Fouasse. 1883. 4°. xi, 144 pp. 54 l. 54 pl. Price $1.65.


VIII. Paleontology of the Eureka District, by Charles D. Walcott. 1884. 4°. xiii, 298 pp. 24 l. 34 pl. Price $1.10.


**Bulletins.**


2. Gold and Silver Conversion Tables, giving the coining values of troy ounces of fine metal, &c., by Albert Williams, Jr. 1883. 8°. 8 pp. Price 5 cents.


24. List of Marine Mollusca, comprising the Quaternary Fossils and recent forms from American localities between Cape Hatteras and Cape Roque, including the Bermudas, by W. H. Dall. 1885. 8°. 330 pp. Price 25 cents.


THE HEADS OF DIVISIONS.  

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.

Exchange.—The advantage of exchange is becoming apparent to scientific institutions and individuals, and the number of books and pamphlets received every year is rapidly increasing.

A circular having for its purpose the verification of addresses and the acquisition of information as to what has been sent the Survey was distributed during March, 1886. The answers to this now coming in will be the basis of a thorough reconstruction of the exchange list during the coming year.

The Fourth and Fifth Annual Reports have been distributed to the whole exchange list. Bulletins 7–26 and Monographs VII and VIII have been sent to all entitled to complete exchange, making in all 18,424 volumes distributed by exchange alone, as detailed in the following table:

<table>
<thead>
<tr>
<th>Publication</th>
<th>Distributed</th>
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<td>Fourth Annual Report</td>
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<td>Monograph VIII</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>18,424</strong></td>
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</table>

Sale.—The sale of the publications is increasing by natural demand. No effort is made to call attention to this matter, since the most benefit accrues to the library by exchange; but the increasing interest in
the publications of the Survey, as they become known, resulted in the past year in the sale of 2,503 volumes, as shown in the following table:

<table>
<thead>
<tr>
<th>Title of work</th>
<th>Price of work</th>
<th>Third quarter, 1885.</th>
<th>Fourth quarter, 1885.</th>
<th>First quarter, 1886.</th>
<th>Second quarter, 1886.</th>
<th>Whole fiscal year.</th>
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</tbody>
</table>

Whole number of volumes sold, 2,503.
Whole amount received for publications, $767.67.

Free distribution.—A very large number of the Fourth and Fifth Annual Reports and the free edition of Mineral Resources for 1883 and 1884 have been distributed gratuitously, and the supply of all annual reports, from the first to the fifth, and of both volumes of Mineral Resources, save for the immediate needs of the Survey, is exhausted.
The correspondence of this division, including all letters relating in any way to exchanges, distribution of publications, purchase of books, &c., nearly doubled within the past year, 16,526 letters or orders, a daily average of 53+, having been received, and 15,844 letters, a daily average of 51+, having been sent out during the fiscal year. That all these have been indexed and filed so as to permit of ready reference and that the whole work of this division is in such satisfactory shape is largely due to the faithfulness of those upon whom I depend, who, though but few in number, have yet kept pace with the very great increase in work to be performed.

I am, with respect,

CHAS. C. DARWIN,
Librarian.

Hon. J. W. Powell,
Director U. S. Geological Survey, Washington, D. C.
THE ROCK-SCORINGS

OF THE

GREAT ICE INVASIONS.

BY

T. C. CHAMBERLIN.

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<table>
<thead>
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<th>Topic</th>
<th>Page</th>
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</thead>
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<td>171</td>
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<tr>
<td>(3) Ascending</td>
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<td>Striae on overhanging surfaces</td>
<td>173</td>
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<td>Striae on terraced surfaces</td>
<td>174</td>
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<tr>
<td>Striae on rounded angles</td>
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<tr>
<td>Striae on horizontally curved surfaces</td>
<td>177</td>
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<td>Striae on obliquely curved surfaces</td>
<td>177</td>
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<td>Striae on vertically arched surfaces</td>
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<td>Striae on domes</td>
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<tr>
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<td>200</td>
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<tr>
<td>Varying effects of topography in successive stages</td>
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<tr>
<td>Changes of glacial movement during a symmetrical retreat</td>
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<tr>
<td>Changes of movement due to varying topographic influence, producing an unsymmetrical retreat</td>
<td>201</td>
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<tr>
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<td>Changes of movement due to varying rates of ablation</td>
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<td>Changes of movement due to glacial drainage</td>
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<tr>
<td>Changes of movement due to the seasons</td>
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THE ROCK-SCORINGS OF THE GREAT ICE INVASIONS.

BY T. C. CHAMBERLIN.

Under analytical methods of study the phenomena of the Ice Age are found to display such a degree of complexity that a separate treatment of special phases is the only recourse where any approach to thoroughness is attempted within restricted limits. Even within the bounds of a circumscribed subject the phenomena are so rich in variety that some restraint must be laid upon analytical treatment, lest it become wearisome through the very fertility of its distinctions.

Recognizing these restrictions, attention is invited to a single class of work wrought by the ice that invaded the northern United States during the glacial period—the scorings of the rock surface. These have long attracted observation and discussion, but recent investigations have added new data and suggested fresh applications, so that a revised treatment of the whole is desirable.

GEOGRAPHICAL DISTRIBUTION OF STRIAE.

The original distribution of the scorings was doubtless essentially coextensive with the ice invasion, though there are some notable drift mantled tracts in the interior in which, for reasons that will presently be assigned, they have been rarely observed. A brief sketch of the extent of the invasion, therefore, will best lay the foundation for a consideration of the distribution of the scorings left by it.

EXTENT OF THE ICE INVASION.

Through the recent investigations of the U. S. Geological Survey, added to the previous work of States and individuals, the extent of this invasion is now known with sufficient exactness for the purpose of general discussion. The accompanying map (Plate VIII) shows the tract over which is spread transported material borne from the northward and left as a vestige of the invader. It also exhibits, so far as practicable, the position and the direction of the recorded rock scorings. I assume that the reader will prefer the more vivid and precise presentation of the map to the tedium of a verbal statement, and will therefore spare him the latter.
The invasion may be looked upon as embracing two grand divisions. The vaster one came from the eastern British Possessions, and swept at once the whole breadth of our northern border from the Rocky Mountains to the Atlantic Ocean, penetrating to New York harbor on the coast and to the latitude of 38 degrees in the Mississippi basin. The lesser division invaded the western mountainous belt and the Pacific border in several detachments, pushing down the valleys. These reached, however, but limited distances south of the national boundary. They probably had their origin in the mountainous regions of British Columbia and are of a semi-local character.1

Contemporaneous with these invasions of foreign ice, there were unusual developments of local glaciation in the mountains within our borders. These developments of domestic ice only incidentally fall within the restricted limits chosen for this article, which chiefly concerns itself with the scorings of the invasion from the British Dominions.

There was, indeed, a succession of advances and retreats, but it is often convenient to speak of the whole as one great onset of ice, though it now appears that there was at least one very prolonged interval, besides several minor ones.

The most striking fact respecting the limitation of the drift strewn tract of the interior is its approximate coincidence with the Ohio and Missouri rivers. In the former case the coincidence may be held to be largely accidental, since only by regarding the affluent Allegheny as part of the main river can its course be said to have been notably affected by the ice. But in the latter case the relation seems to be in some measure causal, for the course of the present Missouri appears to have been much influenced by the invading ice.

That the great mantle of drift that covers the Northern States down to the limits shown upon the map—save the remarkable driftless area—was the product of ice action, is accepted with practical, if not absolute, unanimity by those geologists who have subjected the question to critical investigation. There has been heretofore, and, indeed, still remains, some divergence of opinion as to whether it was chiefly an invasion of ice by land or by sea, whether by glaciers creeping

1 Along the border of the drift represented on the map (Plate VIII) will be found the names of those whose tracings of the limit have been chiefly followed. In my previous maps for the region west of the Mississippi river I followed in the main the authority of the earlier investigators in preference to the unfinished observations of my associates and myself. The border in this region is attenuated and is locally mingled with river drift from the mountains; it is also in some portions obscured by loess. For these reasons I have heretofore hesitated to reject the positive statements of previous observers until the ground should be carefully re-examined. The chief attention of the U. S. Geological Survey in this region has thus far been directed to the character of the drift and the discrimination of its phases, and only incidentally to the detailed outlining of the border. The limit here given, while subject to minor rectification, will, it is believed, be found essentially correct.
over the face of the country or by icebergs and ice floes sailing over submerging waters. I say chiefly, for all temperate investigators admit some concurrent action of forms of ice agency other than the chief one. Most glacialists admit some associated and accessory iceberg and floe drift, however subordinate they may hold this to be, and all advocates of iceberg origin admit the existence of glaciers as the parents of the bergs, the only question being their location and extent; while the advocates of ice floes at least postulate climatic conditions favorable to glacier development. On this account it is the more important to set forth the specific characters of the environment of the ice markings as a basis for discrimination between these several joint agencies, in the ulterior hope of aiding in the demonstration of the dominant agency and in the measuring of the subordinate agencies. The rock-scorings are the trails left by the invader. Their character should reveal the nature of the icy visitant as tracks reveal the track maker. The glacialist should be able to distinguish with as much certainty the traces of a glacier or of an iceberg or ice floe as the hunter the track of a bear or a moose or a serpent. A glacier may be likened to an ophidian, crawling prone; an iceberg, to a digitigrade, walking on its toes; an ice floe, to a semiplantigrade, setting down the edge of its foot. Where the tracks are plain and un concealed, there is little ground for doubt as to the agent; it is only in the extensive concealment of the glacial markings by drift or in their obliteration and obscuration by postglacial decay that good cause is found for uncertainty; but by assembling numerous examples from the wide domain presented for inspection the deficiencies of local observation may be supplied and overwhelming evidence of the agency may be secured.

There have been recorded about two thousand five hundred observations on drift striation within the United States. These stand accredited to 104 observers. Of these recorded striae, 220 instances are in Maine, 700 in New Hampshire, 307 in Vermont, 135 in Massachusetts, 46 in Rhode Island, 33 in Connecticut, 225 in New York, 104 in New Jersey, 147 in Pennsylvania, 154 in Ohio, 72 in Michigan, 26 in Indiana, 9 in Illinois, 120 in Wisconsin, 98 in Michigan, 8 in Iowa, 6 in Nebraska, and 64 in Dakota, making a total of 2,474. Doubtless not a few have escaped me.

1 Professor Newberry has remarked that the track of a glacier is as unmistakable as that of a man or a bear (Geol. Survey Ohio, vol. 2, Geology, p. 2).

2 I have compiled the records of observation on striæ in the United States with a view to publication for the convenience of geologists; but the demands of other work have thus far prevented the revision of the list and the elimination of manifest errors in the original sources—a work of some labor. I append an alphabetical list of the observers and the States to which their observations relate. It is only a merited recognition of industry to note that the individual observations of Prof. C. H. Hitchcock much exceed in number those of any other observer:

C. B. Adams, Vermont; L. Agassiz, Maine; S. Aughey, Nebraska; H. M. Bannister, Illinois; T. H. Bradley, Illinois; J. C. Branner, Pennsylvania; C. Briggs, New
Of these striæ as many as practicable have been transferred to the accompanying map by Messrs. Merriam and Thompson. In some districts they are too numerous to be platted on so small a scale. The arrowheads indicate the point toward which the motion took place. Where doubt is entertained as to this, a simple line indicates the direction of the scratches. In many instances crossing sets occur, which have been indicated so far as practicable by crossing arrows. In these cases the crossing is at the center of the shaft, and they may thus be distinguished from arrows that cross because of the crowding unavoidable on a map of so small a scale.

DISPARITY OF DISTRIBUTION OF STRIÆ.

the irregularity of distribution would be more striking. The dis-
parity is partly apparent and illusory and partly real and significant.

Illusory irregularity of present mapping.—Some of the apparent
irregularity is merely observational and does not represent the true
relative prevalence of striation. The drift prevails with great per-
sistency and depth over certain regions and obstructs observation,
and hence the striae appear rare; while in other districts access to
the rock surface is more frequent and the record is full, though the
striae may be in reality no more abundant.

Postglacial destruction of striae.—The present prevalence of striae
is also affected by postglacial obliteration. Wherever the rocks
have been exposed at the surface or have been rendered accessible
to air and water by an overlying stratum of gravel, sand, or other
porous material, the surface has suffered decay, and, except where
the rocks are of the most indestructible character, the glacial mark-
ings have generally suffered obliteration. Striae are commonly pre-
served only when the surface has been protected from decay by an
impervious cover. The exceptions to this are to be regarded as phe-
nomenal.

Unequal search for striae.—The apparent unequal distribution is
also partly due to varying closeness of examination, the search in
some districts having been diligent, while in others the subject has
received little attention.

Unequal detection of the striae.—All rocks are not equally well
adapted to receive or to exhibit the results of abrasion. Some by their
softness and plasticity, some by their coarseness and irregularity of
texture, and some by their incoherence and brittleness fail to dis-
tinctly display characteristic marks of the abrasion they have suf-
fereed. While almost all known rocks, under sufficiently favorable
conditions, are observed to have received and retained glacial grooves,
the unequal facility with which they have done this and the unequal
distinctness of the resulting marks have led to corresponding in-
equality of observation.

Original distribution of striae.—But the irregularity of distribution
is not all apparent or illusory; it is in part original and real.
The rock surface was not scored equally in all regions. Making all
possible allowance for the foregoing considerations, the following
general statements seem to be warranted:

(1) Glacial grooves are more abundant in the northern portion of
the drift tract than in the southern; in other words, the abrading
agency acted with more power and persistence remote from the edge
of the drift than near it. The reason of this is obvious.

(2) Glacial scoring is more prevalent and powerful in the area
north of the limiting moraines of the later epochs than south of them.
While such would be the natural result of a recurrent glaciation,
the observed inequality does not seem to be wholly due to this fact,
but to result in part from the more vigorous action of the later glaciation, of which there are other and stronger evidences.1

(3) The markings are more prevalent and pronounced in the hilly regions than in the plain tracts. For evidence of this the crowded striae of New England may be compared with the dispersed lines of the Mississippi plains. That the hills should have stood more obtrusively in the path of the invader, and have thus received a more forceful scoring, is obvious.

(4) Glacial markings are less prevalent in the lee of rock prominences than on the stoss side; so, also, speaking more generally, in the lee of any offset of rock by which a lower surface lies in the wake of a higher one. But the measure of such protection is dependent upon the severity of the glaciation; in the areas of heavy glaciation the striating agency wrapped around eminences and sank down behind offsets with much more promptness than in the districts of lighter glaciation, as will be seen from illustrations given later.

(5) Plains that sloped away from the onset of the ice were less universally scored than those inclined toward it. The southward declining plains of the interior are those least affected by glacial abrasion. This, however, is not wholly attributable to inclination, as other conditions determined, in part, the measure of glaciation.

In the following discussion, to avoid repeated explanation, it will be understood that all statements respecting glacial markings, unless otherwise designated, relate to those associated with the great drift sheet of the northeastern and north central United States or with that of the lowlands of the extreme Northwest. The markings of the local glaciers of the mountains of the West are excluded, since they are local phenomena dependent more upon altitude than upon the exceptional conditions that produced the great visitation of ice from the Northeast.

**TOPOGRAPHICAL RELATIONS OF THE STRIAE.**

**Range of striae in altitude.**—The glacial scorings of the great northeastern drift tract range in altitude from the sea level up to 3,000 feet above tide,2 not to insist upon the marks upon Mount Washington.3 These scorings must therefore either have been inscribed by an agent competent to work at the same time throughout this great range or the agent must have been so favored by oscillation as to have been permitted to act successively upon the surface from the sea level up to the height indicated, which overtops all but

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a few of the extreme peaks of the northeastern part of the United States. It is clear, upon consideration, that, if the striæ are the product of a general glacier, striation throughout the whole range of altitude may have been wrought simultaneously. In this case a general system of southerly movements should disclose itself even in a casual study of the courses of the striæ. Due allowance must indeed be made for deflections of the ice flow consequent upon surface configuration and also for changes of direction incident to the decadence of the ice. The work of successive incursions must also be distinguished. But, dominating all these, a discernible system compatible only with a glacial agency must discover itself.

On the other hand, if the striations are the product of floating ice, they must have been inscribed at successive stages of submergence and with a continually changing distribution of land and water and a continually altering shore line, against which the floating ice must have impinged in diverse directions, according to the changing drift of the winds.

As between these and other alternatives, if there be such, let the record speak for itself.

But more significant than the bare statement of this wide vertical range of the inscriptions are (1) their limitations in altitude along the southern border and (2) their prevalence in all the intricate recesses of the complex topography.

Upper limit of glacial markings.—According to the geologists of New Jersey the summits of the higher hills near the border of the drift in the northern part of that State rise above the limit of the scorings. This limit is relatively low near the border and gradually rises to the northward at the computed rate of 34 feet to the mile. Professor Smock has extended this line of study to the Catskills, where he finds similar limitations, above which the unglaciated mountain tops stand forth. Combining these observations with those in New Jersey he determines the northward rise of the upper limit of scorings to be less than 30 feet per mile. Similar estimates of the rise of the upper limit of glaciation have been made from data furnished by Mount Washington and the higher peaks of Pennsylvania, but the trustworthiness of these has been challenged, apparently with success, yet not in such a way as to invalidate the general conclusion that the striating agent, while competent to score the rocks below a certain upper plane, failed to reach above that, and that this upper plane has a notably rapid rise to the northward.

1 The term "glacial" in such connections as this is uniformly and solely used as the adjective of glacier.
ROCK-SCORINGS OF THE GREAT ICE INVASIONS.

The margin of glaciated area vertically undulatory.—The border line of the glaciated area is not horizontal, as though it marked a limit of submergence or a limit of action of marine or lacustrine ice. Neither are its deviations from horizontality of such a general nature as might be produced by subsequent tilting or warping of the crust. The border line rises and falls over the diversified face of the country almost in neglect of its relief. It is not entirely independent of topographic influence, but it is so far uncontrolled by it that it rises readily over ridges, plateaus, and even mountain ranges, and sinks as promptly into the intervening valleys, thus oscillating through hundreds and occasionally through one or two thousands of feet. In general it retires to the northward in crossing elevations and advances southward in traversing valleys, but even this deflection is often slight where the surface is rough, the hills crowded, and the valleys narrow. The broader basins and the open linear valleys and ridges coinciding with the drift movement seem to have induced greater deflections of the margin, but there is nowhere any approach to horizontality. The most striking deviations and the greatest disregard of surface reliefs are shown in crossing the Appalachian belt, the facts of which have been strongly set forth by Prof. H. C. Lewis, of the Pennsylvania survey. If the border line across the Appalachians were platted in profile it would be almost as undulatory as a line arbitrarily chosen.

North of the border and within the vertical limits of glaciation—save in the driftless region of the Upper Mississippi—striation ranges freely through all altitudes, not only in the general sense of occurring at different heights in different localities, but in the special sense of appearing on hill tops and in valleys, on eminences and in basins alike. Even where deep depressions are engirt by highlands, or where branched, tortuous, and complex valleys insinuate themselves among mountainous elevations, scorings appear on bottoms, sides, and summits alike. From the shores of the ocean to the crests of the Appalachians, from the strong reliefs of New England to the gentle plains of the interior, the scoring agent enwrapped all the diversities of surface and left its record in lithograph on all save certain sheltered or protected spots.

VARYING POSITIONS OF THE STRIATED SURFACES.

Great as is the significance of the vertical range of the glacial scorings, even greater meaning may be found in their specific situations on the diverse slopes which form the elements of the topography.


2 Some of the exceptions are important and will be considered later.
This truth is exemplified in its larger sense in the glaciation of the extensive tracts of level, declining, ascending, and undulatory surfaces that constitute the major features of the landscape. But it is impossible to bring these larger illustrations within the limits of the camera or to reproduce them upon the page in precise detail. At best, illustrations of the grandest examples must involve a large element of ideal reconstruction, since all broad areas are largely covered with drift and vegetation, concealing from direct observation the greater portion of the striated surface; or, if such covering is absent, surface disintegration has largely destroyed the record. While the observer may fully satisfy himself by the correlation of numerous artificially dismantled surfaces, if fortunately distributed, that the scoring agent wrought its effects upon the entire area, he cannot reproduce this evidence in its full force. Recourse for our illustrations, therefore, must be had to the more limited surfaces that have been fully uncovered and that fall within the angle of the camera and the limits of the page.

**Streies on level plains.**—Surfaces of almost absolute horizontality are often found polished and scored in the most complete and beautiful manner. The action at times combined agencies competent to polish, to inscribe the most delicate gravings, to score with strength and firmness, and to gouge with forceful vigor. As an illustration I have chosen a photograph of a surface of Berea grit near Amherst, Ohio (Fig. 1). In this instance the coarser grade of work alone is well exhibited, the texture of the sandstone being unsuitable to receive the more slender lines and finer polishings. Examples of beautiful polishing and delicate striation, however, fall frequently under observation on the flatlying limestones that prevail in the interior. Moderate scorings are indeed more common on horizontal surfaces than deep channelings.

At first thought it might not appear that a level surface of rock presents conditions either specially favorable or specially adverse to striation by any of the agencies thought to have been active in the production of the drift. The horizontal position is manifestly not the most favorable to the grounding of floating ice, nor is it entirely prohibitory of such action. If icebergs always floated in absolute horizontality they would slide over level portions of the sea bottom only when there was a nice adjustment of their submerged base to the depth of water. But icebergs floating in temperate seas are affected by two classes of vertical movements: (1) The first is a slow rise, owing to melting, which in the end brings the bases of the bergs to the water surface. This would at first tend to aid the movement of the icebergs that had previously grounded, but must at length lift their bases above the limit of action upon a level surface. (2)

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1 I desire to acknowledge the guidance and aid of Professors G. F. and A. A. Wright, of Oberlin College, in the examination of this locality.
The vertical movements of the second class are due to changes of the surface level of the water through the agency of winds and tides. If the berg mass be small, ordinary waves might give it a vertical oscillation that would aid forward movement and produce short gouges but would be unfavorable to continuous striation. Under certain conditions continuous wind from a suitable quarter might cause a heaping of the waters that would lift the ice mass, even if it were of the largest dimensions, permitting motion over level surfaces upon which movement was previously impossible. On the reversal of the wind the mass would be depressed and grounded. Tidal oscillations would be effective in a similar way. During the height of the tide the lifting of the ice might enable winds and currents to slide the mass forward, while the ebb would cause its arrest; but all such action of tides, winds, and ablation must be restricted to the narrow limits imposed by the critical working adjustments.

Shore action is obviously limited to a narrow belt, but by a rise of the water surface or a depression of the land the beach belt may advance over an extensive area. If the beach rises against a gentle slope it is manifest that every portion may in turn be brought within reach of the impact of shore ice; but a strictly horizontal area is apparently less suited to such action. Undoubtedly the tidal and other surface oscillations above alluded to would here also render supple-
mental aid, but shore ice seems to me ill fitted to act upon strictly level surfaces. Ice floes, after the land had reached a stage of slight submergence, might be more effective.

Doubtless the advocates of the glacio-natant agencies are more successful than myself in satisfactorily picturing the conditions necessary to satisfy the demands of the phenomena. It is reasonable to assume that the advocates of agencies supposed to be competent to produce the complex phenomena of the drift have a higher appreciation, if not actually a larger and more specific knowledge, of their varied competencies than one who has rejected them as the chief factor in drift deposition and rock striation, and I cannot feel sure of doing entire justice to the capabilities of these agencies. My purpose here, however, is not argument, but a studious consideration of the significance of the phenomena.

To the glacial hypothesis horizontality of surface presents no difficulty, unless it be thought to lie in the want of a manifest cause of motion; but this is illusory, for it is the slope of the upper surface of a flowing body which determines motion, and not the configuration of its base, as long since urged by Dana and others. In all our rivers and brooks the basal currents flow in undulatory courses, rising, falling, or moving horizontally, according to the uneven character of the bed, the general movement being determined by the general slope. So in a glacial stream it is only the special bottom movements that are affected by the basal topography, the general movement being controlled by the surface slope of the mass.

Striae on descending plane surfaces.—Striae occur in numerous instances upon plane tracts which descend in the direction of the motion of the scoring agency. These tracts are not simply nor chiefly the smooth bottoms of valleys connected with heights, down which streams might obviously have poured, but they embrace broad areas unassorted with bounding highlands. The more numerous examples falling in this category occur on the northern slopes of the Great Lake basins and chiefly lie without the limits of our territory; but on the southerly slopes of the interior numerous instances present themselves, and, had the glaciation of that tract been more severe, striation on descending surfaces would apparently be found nearly as prevalent as in any other situation.

Viewed in a comprehensive way, the striation of the Ohio, Mississippi, and Missouri basins belongs to this class. So also does the striation in the upper peninsula of Michigan, on the plain sloping southward toward Green bay and the straits of Mackinaw, and also that in New York upon the plain sloping southwesterly toward the foot of Lake Ontario. The selected illustration is from the latter region, being from Pillar Point, on the east shore of Lake Erie. In a still broader view, the striation on the Atlantic slope of New England may be placed in this category, though, viewed in respect to
their precise situations, the individual examples of striation fall into several categories, according as they lie upon ascending, level, or descending portions of the undulatory surface.

In the illustration given the decline is of a gentle order. But striae upon declivities of much greater slope are frequently observed. It is probable that striae exist on all extensive declivities that lie within the glaciated area, for, although observation is not quite coextensive with such slopes, it is sufficiently wide to justify this general belief. There are, however, numerous instances of the absence of striation on plane declivities when they lie close in the lee of ridges or in similar sheltered spots. These may be best discussed in another connection.

![Fig. 2. Striae on a descending plane surface, on limestone at Pillar Point, on the east shore of Lake Erie, Brownville township, Jefferson county, New York. Course toward the left. The irregular cross gouge bears some evidence of being the work of floating ice. From a photograph by G. K. Gilbert.](image)

Striation upon a descending plane affords a criterion of some value in the discrimination of the agency of production, since it is difficult to believe that icebergs or floating ice in any form can striate extensive areas sloping downward in the line of their motion. Floating ice, under these conditions, must be moving continuously from shallower to deeper water, rendering scoring of the bottom impossible. The difference in altitude between the northern and the southern portions of some of the striated slopes is several hundred feet, or, if we em-
brace the New England slope, the difference in altitude ranges up into the thousands. The only form of glacio-natant action competent to produce strie on declining surfaces is afforded by ice-bearing river floods, and these are entirely excluded from application to the broad phenomena presented by the striaation of the great southerly sloping plains.

Strie on ascending plane surfaces.—Scorings abound on the northward sloping plains of the drift tract, or, in other words, on plains inclined toward the advancing ice. Indeed, it is on these surfaces that the most pronounced evidences of abrasion, planation, and scoring are presented. In the larger view, all the northward slopes toward the Great Lake basins are grand examples, while on the unnumbered minor plains presented by northern declivities glacial groovings abound. Fig. 3 illustrates the essential nature of this class, though the surface here departs somewhat from a typical plain.

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Fig. 3. Striae on an ascending slope, one and one-half miles east of Blend river, north shore of Lake Huron. From a photograph by W. N. Merriam.

On a gently ascending surface, shore ice, icebergs, and glaciers are alike competent scoring agencies. Discrimination does not lie in the general fact of striaition, but in its special character, to which attention will be subsequently invited. Such surfaces seem to me alone, among plane surfaces, well adapted to receive general and effective scoring by floating ice. The greater severity of the abrasive action upon northward slopes harmonizes well enough with the glacio-natant hypotheses; but it likewise falls into consonance with the theory of general terrestrial glaciation. The objection that glaciers cannot

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striate ascending surfaces may now be considered obsolete, since both theoretical considerations and multiplied observations prove it altogether untenable. As above remarked, the flow of a glacier is determined by the upper slope of the ice, and not by its bed. The upper slope may be determined entirely by accumulation and be in no wise dependent upon the elevation of the underlying land. The centers of the Greenlandic and Antarctic ice tracts probably owe their elevation to the accumulation of snow, and not to the height of the land upon which they rest. Mountainous elevations may have been efficient in the initial stages of their formation, and may be important factors in their perpetuation, and may become potential during their final disappearance, should they ever disappear, but the present elevation of these great névés and their efficiency in the determination of outward glacial flow are doubtless dependent upon their own snow-built heights rather than upon topographic eminence.

Given a southward slope of the surface of the ice field which is supposed to have overspread our Northern States, the undulations of the land beneath become only modifying, and not at all controlling, conditions. Given a southward movement, and nothing could be more obvious than that the northward slopes received the more forceful impress from the invading ice, as observed, and hence were more powerfully abraded, more deeply scored, and more effectively polished than the portions that opposed themselves less directly to its advance.

Relations of the striæ to the inclined surfaces.—In the foregoing illustrations of striæ on inclined surfaces the glacial lines coincide in direction with the maximum slope, and the comments were made on that basis; but in a large majority of instances there is a want of correspondence between the direction of striation and the direction of slope. The glacial lines often traverse the plane obliquely and sometimes run horizontally along its slope. These instances embrace striæ both on ascending and on descending slopes. The striæ may rise on an oblique surface at any angle to its maximum inclination and may likewise descend a declivity with like divergence from the maximum slope. These attitudes have their special significances, which, for the most part, are obvious from the considerations above suggested. It is manifest that the phenomena considered in their fullness exclude fluvial agencies, since streams descend along the lines of maximum slope. If they produce scratchings in other directions it is only by incidental deviations from that course. Not infrequent instances of oblique striation might, perhaps, thus be produced, but never a broad, pervading, consistent system, such as our great glaciated tract presents.

Fig. 4 furnishes an illustration of oblique striation on an ascending surface, the illustration being drawn from Kelley's island, in the western end of Lake Erie. It exhibits the action on but a limited
surface. Good examples of a broader kind have been subjects of frequent observation, but photographs, or sketches suitable for accurate illustration, are not at command.

As the best available illustration of horizontal striae upon a sloping surface I have chosen a photograph of strong scoring and fluting upon crystalline rock at Victoria, B. C. (Fig. 5).

Striae on vertical surfaces.—Striation is not limited to level or moderately inclined surfaces. Rock faces that are approximately and even absolutely vertical exhibit polishings and groovings of a character precisely identical with those of horizontal surfaces. The significance of this phase of striae lies, however, not so much in the bare fact of striae upon vertical surfaces as in the three special attitudes of the striae upon such faces.

1) The striae on vertical walls most often consist of approximately horizontal lines stretching along the face of the glaciated cliff. But even in these instances critical observation discovers that the lines are not absolutely horizontal, but incline more or less, and even such

slight variations are significant of the producing agency. Floating ice, shod with débris, drifting along a vertical face should either score it with perfectly horizontal lines or with notably undulatory ones, according as the waters were calm or were affected by waves or swells. The marks made under these conditions could hardly fail to leave characteristic evidences of their origin either in their horizontality or in their definite undulation. Vertically zigzagging strie on the cliff face of a gorge of the Sable River, on the north shore of Lake Huron, have been described and figured by Dr. Edmund Andrews, which, he suggests, may have been produced by ice driven through the flume with a rocking motion, so that the bowlders on its lateral margins were caused to take a zigzag course, scoring the walls in a corresponding form.¹

An illustration of horizontal striation on a vertical face is presented by a cliff near Ithaca, N. Y., a photograph of which, taken under the direction of Prof. H. S. Williams, of Cornell University, furnishes the accompanying Fig. 6. A portion of the horizontal lines shown are obviously bedding seams, but the glacial lines are fairly distinguishable in the figure and amply so in nature. Some of these lines, it will be observed, are not accurately horizontal, nor do they bear among themselves the same relationship to horizontality.

(2) But still more interesting and significant is the observation of Professor Williams that, on certain portions of a vertical glaciated face near Ithaca, the whole group of striæ descends to the south, the angle of declination reaching as high as 25° to 30°. Many of the lines descend curvingly, while some descend in nearly straight courses. The topographic situation in which this peculiar phenomenon occurs deserves attentive consideration, since its elucidation and chief significance are to be sought in the surrounding topography. The descending striæ are inscribed upon a cliff face on the east side of Cayuga valley, about a mile north of the southern extremity of Cayuga lake, and at an elevation of about a hundred feet above its surface (Fig. 7).

When my attention was first directed to this phenomenon by Professor Williams, I submitted three hypotheses as possible explanations of such striation, with the suggestion that the topographic environment would probably decide between them. They may be worthy of statement here, because of their possible applicability to other cases. Under the glacial hypothesis, descending striæ on the

sides of a deep valley may have been formed in one of the following ways:

First, if the valley is widening at the location, the prism of ice flowing through it is being broadened, and hence settles down from above; and any given portion of it — as that which rests against the limiting wall — will pursue a descending course. To give any notable descent, a very marked enlargement would be necessary.

Secondly, if, at the given locality, there is a sudden descent of the valley bottom, the stream of ice must have curved downward correspondingly in some measure.

In the third case it is assumed that the striae were made at the very latest stage of occupancy of the valley by the retreating ice and that the downward curving of the striae was caused by boulders and glacial debris, fixed in the superficial portion of the glacier or lodged between it and the limiting wall, being carried forward and downward along the line of the upper curvature of the terminal portion. The glacial lines would, under this hypothesis, mark approximately the slope of the upper surface of the ice.

In the case in hand the first explanation is entirely eliminated by the fact that there is no enlargement of the visible portion of the valley at that point. The second is rendered extremely improbable, since the present surface of the valley bottom rises instead of descending and there is no indication of a drift filled deepening of the valley. To the third explanation there appears to be no valid objection; but, on the contrary, all considerations lend their combined support to it. Should it be the truth, this interesting phenomenon represents the very closing action of the ice at that point, since such curvature of motion could only obtain in the extreme terminal portion of the ice. It further reveals the approximate surface slope of the extremity of the glacial lobe which occupied Cayuga valley. It is not to be inferred that this high inclination is inconsistent with the surface slope deduced from observations on the upper limit of striation, before alluded to, since the surface curvature of the extreme edge of a glacier is notably greater than that of portions back from the border, where the ice has acquired a thickness that permits something of free flowage. The profile of an ideal glacier is undoubtedly a curve whose elements change rapidly at the extreme edge and more slowly backwards from it until the curve graduates into a horizontal line at the center of dispersion. That this phenomenon could be the result of floating ice it seems impossible for any one to contend.

(3) The only instances within my knowledge of striae ascending on vertical surfaces were produced by movements manifestly forced by topographic environment. They are all of limited extent and have their significance chiefly in illustrating the pliancy of the scoring agency. The best illustration at command is drawn from a portion of the "Whirlpool" on Kelley's island (Fig. 8).
Strive on overhanging surfaces.—As if it were not enough to demonstrate its versatile adaptability by engraving on horizontal, vertical, and sloping planes, the ice further illustrated its pliancy by polishing and scoring actually overhanging faces. These are obviously limited to special situations, but not a few instances in widely separated localities and in different topographic surroundings have come under observation. The illustration here selected shows at once the adaptability of the ice to a curving, fluted, and partially overhanging surface. Another notable instance is shown in Fig. 6, given on page 170, in the horizontal groove traversing the vertical face, which is polished.

and striated on its upper as well as on its lower and interior sides, indicating the ability of the ice to mold itself to a narrow groove so completely as to polish all its sides. I shall have occasion to recur to this instance. Several beautiful illustrations occur in the vicinity of Victoria, B. C. (Fig. 12), where the adaptability of the ice is shown by its molding itself to convex surfaces, whose embossments overhang, and are thus distinguished from the concave and impressed grooves in the above instances. It is beyond all belief that any observer can study these instances upon the ground and become familiar with all their details, which defy illustration, and still believe they are due to floating bergs, floes, or shore ice. Disregarding their topographic relations, they might at first impression be thought to be the product of running water, loaded with debris shed ice or with simple detritus; but a study of the actual surfaces, presenting deep steady grooves, delicate continuous lines, and smooth pressure polished surfaces, together with the less definable indices of a slow motion and high pressure, effectually banishes this hypothesis from the mind of the discriminating observer. While, in a general sense, the motion of a glacier is that of a fluid, the tortuous movement of such a slightly plastic medium, pressing slowly through narrow or tortuous channels or molding itself to an overhanging projection, differs markedly from that of a highly mobile, fast flowing fluid in the special character of its twisting and rotary currents. As every glacialist is aware, the polishings of water and the polishings of glacier ice are clearly distinguishable phenomena.

*Striae on terraced surfaces.*—Striation is not uncommonly observed to coexist upon a series of contiguous planes so related to one another as to constitute a terraced surface, thus exhibiting the ability of the abrading agency to act simultaneously upon several planes in different attitudes. Several of the figures of this article illustrate this adaptability in a minor way, but a suitable illustration on a large scale is not at command.

*Striae on rounded angles.*—When two contiguous planes are striated the intervening angle usually suffers abrasion, often to a very notable degree, presenting a rounded contour, which is glaciated continuously with the adjacent surfaces. In some instances the stria upon the two plane surfaces and upon the intermediate rounded angle are essentially parallel to the trend of the latter; but this is not universally the case. Not infrequently the stria pass obliquely from one of the faces over the rounded angle to the other. Examples of rounded angles of one or the other form are quite common. An excellent one occurs near Ithaca, N. Y., which may be looked upon as the connecting link between the scored vertical faces above described and the horizontal and inclined striated surfaces that are also exhibited in that interesting locality. I am indebted to Prof. H. S. Williams for a photograph of a well rounded angle from this locality.
rounded angles, combined with the striated terraces, occur at Pewaukee, Wis. Among the fertile phenomena of Kelley’s island there are numerous fine exhibitions, from one of which the illustration here produced is taken (Fig. 10).

![Fig. 10. Ledge on the north shore of Kelley's island, western part of Lake Erie, showing the rounding and longitudinal striation of an angle. The lakeward face of the ledge—not shown in the view—is also striated.](image1)

In the above instances the glacial movement was nearly parallel, or, at most, moderately oblique, to the trend of the planes and their included angle; but instances also occur of such rounded angles where the ice movement was transverse to the strike of the striated surfaces. Such illustrations usually occur more frequently on the stoss than on the lee side of the rock mass. An illustration of this is given in another connection (Fig. 23).

![Fig. 11. Striae on two contiguous surfaces, cutting each other at a large angle—one plane and the other curved—indicating that the striae were formed at different times and under different conditions. From southeast shore, Kelley's island.](image2)

In striking contrast to the rounded angles are those instances in which contiguous striated planes are joined by a sharp dividing line
(Fig. 11). The striation of the two planes in these cases was not con­
temporaneous, but successive. The conditions of pressure were such
that the ice, in producing the last planation, did not mold itself to
the surface with sufficient closeness to come in contact with all por­
tions of the previously striated surface. This may have been either
because they were protected by drift, which was not removed at the
points in question by the later glaciation, or because, owing to rela­
tively slight pressure, due to thinness, the ice failed to force itself
completely into the inequalities of the rock surface, but, instead, sup­
ported itself upon the more permanent portions, abrading and polish­
ing them, but leaving the more depressed portions untouched.

Fig. 12. Striae horizontally curved. The figure also illustrates the striation of a curved groove as well
as a vertically convex surface. Photographed at Victoria, B. C.

Under the last head we passed from the phenomena of striation
upon plane surfaces to that impressed upon curved surfaces. This
invites us on to the consideration of the various phases of curvature
which suffered scoring and which exhibit more strikingly even than
the previous illustrations the characteristic accommodation of the
plastic agent to the surface wrought upon.

1An excellent illustration is noted by W. Upham: Geol. Minnesota, vol. 1, 1884,
pp. 505-549.
Striae on horizontally curved surfaces.—Attention is first invited to the least distinctive instance: that in which the striae are curved horizontally. The illustration which I have selected is from Victoria, B. C., and exhibits at the same time other plastic capabilities of the ice (Fig. 12). I go just beyond our borders for the illustration, partly because of its inherent merit and partly because of its value in illustrating the coincidence of the phenomena upon the lowlands of the Pacific Coast with those of the great lowlands of the interior and the Atlantic Coast. The basin of Puget sound and the adjacent straits were invaded by drift from a northerly and northeasterly direction, at a time approximately contemporaneous with that of the great incursions in the East; but the region of the sound is so deeply buried with débris that no illustrations of the bottom abrasion of the ice have yet been observed, and we are left largely to inference from the phenomena of deposit as to the precise method of action, greatly aided, however, by the beautiful glacial engraving upon Vancouver island.

Striae on obliquely curved surfaces.—Pliancy suited to an inclined plane implies different qualities of adaptability from those which are necessarily involved in pliancy adapted to a horizontal plane. A floating body may readily yield to an obstruction and pursue a horizontally curved course, rubbing and, if suitably armed, scratching and polishing the obstacle which causes its course to deviate; but such floating body is not equally well adapted to pass obliquely over and around an obstacle in a plane which has a notable degree of inclination, and hence obliquely curved striae are significant of qualities not necessarily implied by horizontal deviation. A most beautiful and marked instance of a curving course oblique to the horizon is exhibited in the accompanying illustration, taken from the great central groove at the north quarry on Kelley's island (Fig. 13).

Striae on vertically arched surfaces.—The significance which attaches to curved striae lying in an oblique plane is accentuated in some respects, though not in all, by striation on vertically arched surfaces.

Finally, I would make mention of a green magnesian rock, with vertical walls, to the east, along the road leading from the Jackson landing to Teal lake (Marquette region, upper peninsula of Michigan). The walls, although almost semi-cylindrical, are covered with striae, which may be traced along the surface like hoops around a gigantic cask. This is an important instance, since it goes to show that the striae could not possibly have been made by an iceberg or any other body floating in the water, but that the agency must have been such as to conform to the direction of the rocky wall."—E. Desor, Foster and Whitney's Report on the Geology and Topography of the Lake Superior Land District, 1850, pt. 1, p. 307.

"At the Lubec lead mines a series of striae were observed upon the side of a perpendicular wall, following the course of the wall around a corner. The course of the striae ultimately varied at right angles from their original directions."—C. H. Hitchcock: Prelim. Rept. Nat. Hist. and Geol. Maine, 1861, p. 262. Cf., also, Geol. New Hampshire, vol. 3, 1878, p. 185.
surfaces and by vertically arched strie on vertical plane surfaces, both of which are well illustrated in the accompanying figure, likewise from the great central groove of Kelley's island, in which there are at the same time less notable exhibitions of horizontally curved grooves in the right foreground (Fig. 14). 1

**Fig. 13.** Glacial strie on obliquely curved, as well as variously otherwise curved, surfaces. North quarry, Kelley's island, western Lake Erie. From a photograph by A. C. Platt.

**Strie on domes.**—The phenomena of striation upon the special variety of arched surfaces which may be classed under the head of domes have long been familiar and, under the name "roches moutonnées," have received abundant attention and illustration in the literature of glacial geology. Fig. 15 illustrates a group of glaciated domes of granite near Cocolalla, Idaho, in the vicinity of Lake Pend d'Oreille. These appear to have been the work of a glacier descending from British Columbia and penetrating our territory at least as far as the southern extremity of that lake. This, so far as known,

1 The visitor to Kelley's island will find what remains of the most noted striation of that island at the quarry upon the north side of the island. Unfortunately the most remarkable features of that locality have been destroyed or buried in the progress of quarrying, but many features of great interest still remain. In the quarry upon the south side, in the spring of 1886, a great groove was in process of being uncovered, which promised to develop features of interest. Along the southeast shore may also be found several phases of striation of very considerable significance. Fortunately photographs of the more important features that have disappeared were taken by Mr. A. C. Platt and by Messrs. Bishop & Barber, of Sandusky, Ohio.
was the most southerly point attained in the Cordilleran belt by an ice incursion from the north. This does not belong to the distinctive category of mountain glaciation, since the stream, before reaching the locality of these domes, had traversed for at least 60 miles the valley of the Kootenay pass and the Pend d'Oreille basin and was here working at an altitude greater than the bed of its trough through the greater part of this course.

Perhaps the most significant theoretical feature presented by roches moutonnées is the divergence of the strie as they pass over the domes, implying a spreading or quasi-stretching of the ice, due to the wedging force of the embossment, illustrating another of the multitudinous phases of glacial pliancy.\(^1\) This is finely illustrated in the original of Fig. 16, although the cut is defective.

*Striae on warped surfaces.*—The climax of adaptability is reached in the striation of warped and twisted surfaces and of tortuous valleys. One of the most remarkable known instances of this within the limits of photographic illustration is furnished by the great glacial grooves at

\(^1\) Cf. Agassiz: Geol. Sketches, 2d series, p. 44.
Kelley's island (Fig. 17). These exhibit not only the pliancy of the ice, but at the same time its strong hold upon the armature with which it did its work of abrasion, grooving, and striation. For, while these grooves can scarcely be supposed to have been originated de novo by the gouging action of the ice, they are nevertheless plowed with deep furrows, the symmetry, continuity, and peculiar form of some of
which are only intelligible on the supposition that they were cut by
a single graving tool, held with sufficient tenacity by the ice to ex­
cavate by a single movement a deep, sharply defined groove. There
is, perhaps, no finer illustration of the pliancy with which the ice
yielded to its encompassing barriers, the tenacity with which it held
its armature, and withal the pressure that both forced it into com­
pliance with its tortuous channel and pressed it relentlessly forward.

FIG. 17. Striae on warped surfaces, on limestone. North quarry, Kelley’s island. From a photo­
graph by A. C. Platt.

We shall have occasion to return to some of the questions presented
by these extraordinary grooves. In this connection they serve to il­
strate the above properties of the scoring ice and to strengthen—
if the abundant illustrations to which attention has now been directed
leave yet a possibility of strengthening—the demonstration of the
glacial origin of at least all this class of striation.

TOPOGRAPHY AS AFFECTING THE DISTRIBUTION OF STRIÆ.

Distribution and direction of striae.—The general purport of the
foregoing study has been to show the independence of the ice of
topographic control. Allusion has been made, however, to the op­
posite fact, that topography exerted an influence in determining both
the distribution and the course of the striae. These aspects of the Janus-faced phenomena now need amplification.1

In the preceding part of the discussion, emphasis has been laid upon the undulatory course of the glaciated border, rising and falling over hill and dale, in great negligence of the topography, yet not in entire disregard of it. While there are some notable deviations from directness, there is no approach to such a to and fro course as would bring the border into a horizontal plane, on the supposition of any amount of northward depression, without the most incredible distortions of the crust. In other words, there is no rational possibility that the border line could ever have been a shore line. While this had been much urged previously, the specific evidence brought out by Messrs. Cook, Smock, Lewis, and Wright, in the detailed tracing of the border across the hilly and mountainous region of the Middle States, has given special and emphatic force to it, as have also the tracings of the border in Nebraska, Dakota, and Montana by Professors Todd and Salisbury and myself.

But, while the disregard of topography is such as to form demonstrative evidence on this point, the sinuous outline of the ice at its several stages testifies that some important influences on the degree of extension and on the course of movement were exerted by the grander reliefs of the surface.

Distinction between glacial borders.—In a study of the relations of the striae to the margin of the ice, it is necessary to distinguish between the margins of successive stages. General truths respecting glacial movements hold true without such distinctions; but, unless they are duly considered, special errors of some gravity are liable to be entertained. If, however, we attempt to discriminate the successive positions of the ice border by the evidence of striation alone and then proceed to draw generalizations respecting the law of striation based upon these determinations, we shall give ground for the suspicion of reasoning in a circle. We must, therefore, step outside the special class of phenomena under consideration for the evidence upon which to distinguish the separate border lines, and it is manifest that no satisfactory presentation of that evidence is compatible with our present limits.

At certain stages the great ice-sheet pushed up about its edge ridged accumulations which mark its limits in a very definite way. The most notable of these are the great moraines of the later ice advances. These traverse the interior in looped courses, indicating a strong lobation of the margin of the ice. The courses of these are indicated upon the accompanying map, and, as will be seen, they lie in part upon or near the margin of the drift area and in part back from

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it. Owing to the practical difficulties of determination in certain tracts, these lines are not absolutely continuous, but all grounds for legitimate questioning are sufficiently indicated in the delineation itself.

Had the invading ice marked the limits of each of its advances in this effective manner, the tracing out of its successive stages would be relatively definite and demonstrative. But the outer drift sheets of the interior, which represent the earliest invasions thus far identified, are not marked by any such definite ridged accumulations at their borders, but vanish in attenuated edges. There appear to be two or more sheets of drift occupying this outer area, apparently indicating an equal number of stages of glaciation, the extent of each of which yet awaits complete determination. However, that does not seriously concern us here, since the phenomenal courses of striae which require discussion do not lie within that territory; indeed, striae are there relatively rare.

Additional evidence relative to the successive outlines of the ice is furnished by the glacial flood gravels that took their origin on the edge of the ice and stretched away from it. The abrupt and elevated heads of these gravel trains, blending with the moraines, give testimony of the most convincing character.

The great fluvio-lacustrine deposits of silt tell of very different conditions and aid in differentiating the glacial stage. So, also, the drift sheets themselves, their superposition, their degree of erosion, their separation from one another by assorted drift and vegetal deposits, their weathering, ferrugination, and decay, furnish auxiliary evidence. The specific character of these I have endeavored to set forth in previous reports.¹

By reference to the general map (Plate VIII) it will be observed that the southern border of the ice sheet, in both the earlier and the later stages—in fact, in all its determined stages—was lobate. In the earlier stages this lobation was less pronounced than in the later, in which it was phenomenal. By a study of the southward prolongations in connection with the topography of the country, it will be observed that each corresponds to a depression lying to the northward, while the intervening retreats correspond to general topographic elevations. This correspondence is peculiarly marked in the case of the later incursions, where the lobation is conspicuously associated with the great depressions along our northern border.

Considered in this broad sense, the influence of topography upon the distribution of the ice was of the most pronounced character. The law appears to be that a broad depression, reaching well backward along the line of glacial movement, was effective in producing pro-

longations of the ice, while narrow valleys, even if deep, were comparatively ineffectual, if they were associated with rough topography or if their courses were tortuous, or transverse, or oblique to the general ice movement. One is astonished at the apparently great effects of relatively shallow basins when broad and extensive and at the trivial effects of the deep valleys in the rough, hilly tracts.

From a wide survey of the glaciated area within the limits of our domain—that is, within the broad border tract of the great ice field of northeastern North America—the broad indication may be drawn that the elevations were retarding influences, while the valleys, and especially the great prolonged basins, favored glacial flow. This seems clearly to signify that the extension of the ice was due essentially to conditions of flowage and waste; and it follows as a corollary that the heights within our borders were not centers of accumulation and dispersion to any degree that was effective in controlling the general movement of the ice.

Now, to bring these general considerations to bear upon the specific subject of striation it is necessary to emphasize the general law of glacial flow as applied to the marginal portions of the ice, namely, the movement was essentially at right angles to the border. Upon consideration, the reason for this law is obvious. The direction of the movement, as before observed, was controlled by the upper slope of the ice, and this slope was curvingly downward toward the margin, whether that margin were a portion of the extremity of the lobe or one of its lateral faces. In a prolonged lobe this law required that while the movement along the axis coincided essentially with it the movement of the sides must have been divergent toward the lateral border, giving to the current-system, when platted, a bilaterally divergent or axi-radiant form. This was beautifully illustrated in the great ice lobes of the later glacial stages.

When it is considered that the highlands retarded the progress of the ice and increased the relative rate of waste, it will be seen that the surface of the ice over them would be lowered more than that of adjacent regions and that a movement would be established toward them whenever the overlying ice was sufficiently thinned to be subject to such influences. In the closing stages of glaciation these highlands usually became uncovered first. In some mountainous and semi-mountainous regions and in some others in which it was possible for the ice to become stagnant in its closing stages, because of their peculiar situations, this law may be traversed by cross laws and fail of application. But the general fact that the ice movements in the closing stages—which have chiefly left us our striae—were toward highlands, and not from them, is so well established and so important as a working and interpreting basis that it not only merits recognition, but emphasis. Far from expecting to find the striae descending from the highlands to the basins, this general
law, within the limits of its applicability, leads us to expect to find them ascending from the basins to the highlands.\footnote{1Cf. M. C. Read, Geol. Survey Ohio, vol. 1, part 1, Geology, 1873, p. 529; T. C. Chamberlin, Geol. Wisconsin, vol. 2, 1877, p. 200, and Third Ann. Rept. U. S. Geol. Survey, 1883, pp. 320 et seq.}

The applicability and the limitations of this general law may be best appreciated by considering the vital fact which lies back of it, namely, the slope of the upper surface of the ice, which determined the motion, as before stated. Where the highlands and rough reliefs retarded the outflow of the ice, so that the supply failed to compensate for the ablation, there resulted a depression of the surface and a sinus of the margin, which, in turn, developed glacial movement toward them, or, in other words, toward the highlands. On the other hand, where broad valleys, free from retarding asperities, gave open and abundant avenues through which the ice poured freely and promptly supplied and overbalanced the waste, there was a swelling of the surface and a protrusion of the ice.

Obvious exceptions to this law are to be found in those mountains that were sufficiently elevated to give rise to local independent glaciers of their own, as the White, the Catskill, and, probably, the Adirondack Mountains.

So, also, where mountain peaks rose up through great depths of ice, the glacial currents doubtless wrapped around them rather than turned toward them, for the obvious reason that the retardation and melting were trivial factors, in comparison with the deep currents in the midst of which they stood; or, in another view, the ice they displaced was greater than the increase of waste they caused. This finds illustration in recent times among the mountain peaks that rise from the mer de glace of Greenland; but even there the above principle is exemplified in the minor phases of movement.\footnote{2Meddelelser om Grønland, part 1, Copenhagen, 1879, Lieut. J. A. D. Jensen and Mr. A. Kornerup. See, also, Am. Jour. Sci., 3d series, vol. 23, 1882, pp. 363, 364.}

\textit{Influence of deeply overridden topography on glacial currents.---} But if the ice overrides in a deep current all accentuations of the surfaces alike, the striations upon individual hills and valleys conform to different laws, corresponding with the differences in the conditions, for here the upper surface of the overflowing ice is essentially alike over hill and valley, and the problem presented is merely the effect of these hills and valleys upon the basal currents. Surface ablation and surface slope do not enter as differential factors into the dynamics of the problem.

There were two other sources of variation that gave rise to great complexity: (1) There was an almost infinite variety of forms of eminences and depressions, and these were grouped into innumerable combinations. Moreover, mere variations in size introduced varying effects. (2) There were also variations in the degree of
plasticity of the ice and in the rate of its motion, and these introduced not only varying but almost contrasted effects. In the struggle with these complexities we can only hope to gain certain typical concepts and define certain classes of action, not all the intergradations. Certain antecedent conceptions may aid us.

I beg leave to use the term plasticity as the most convenient expression of the moving and molding property of the ice of glaciers, without being held responsible for any theoretical doctrine respecting the precise physical action involved. To the student of geological effects a glacier moves as if it were a plastic solid, but not as a viscous liquid that has the property of stretching. The conditions of this apparent plasticity are thought to have been ascertained in the main and to be important elements in the interpretation of glacial markings. The mobile and molding power of glacial ice appears to be due (a) to pressure, (b) to temperature, and (c) to saturation by water, either from rains or from its own melting.

Temperature and saturation as affecting glacial movement.—It is a well determined fact that the mobility of a glacier is greatly influenced by temperature, though motion is not destroyed by the severest cold of winter. It may be confidently assumed that the temperature of the ancient ice-field was highest on the average at its border and was increasingly lower northward toward the area of origin. So far, then, as this element was concerned, motion was freest near the border, the pliancy of the ice was there greatest, and its hold on embedded debris was least rigid. Seasonal changes introduced alternations of rate and rigidity. These seasonal changes chiefly affected the upper stratum and the border, the basal and inner portions maintaining a measurable uniformity.

In like manner it is known that the mobility of glaciers is facilitated by saturation with water, though not apparently at all dependent on this as a necessary condition. It is safe to conclude that the water, both from melting and from the atmosphere, was most abundant near the border and that it decreased backward to the névé fields, upon which it was scanty. This also was dependent on the seasons, but was not confined to the superficial and marginal portions. The constant issuance of subglacial streams from beneath existing glaciers seems to indicate that the basal ice is more or less bathed in water at all seasons. The penetration of warm water was obviously a means of raising the temperature of the ice, if below the melting point, or, if not, of adding to its own quantity by melting the ice. It is highly probable that in so far as pores and fissures gave access the whole mass of the ancient glacier was penetrated by water during the season of rains and melting and that much of this was long retained for want of ready outlet. In the great basins no outlet for such water as penetrated the lower thousand feet or was generated there by friction, compression, or internal heat was ac-
cessible except over the lips of those deep basins. The ice within these must have been permanently saturated, in the sense that every accessible crevice and pore was filled with water, and this may have been one of the important conditions that determined the great flows through these basins. The superior saturation of the ice in the broad, smooth valleys and on open plains over that of the broken country may have been one important element in facilitating the flowage there, the freedom of which is a source of surprise.

It would be a satisfaction to know demonstrably whether temperature and saturation act directly in promoting motion or merely indirectly by inducing plasticity. So far as geological phenomena are concerned there is probably no essential error in the current assumption that gravitation is the ultimate source of glacial motion and that, in its details, the flowage conforms to the laws of plastic solids. It is probably quite safe to treat temperature and saturation as aids merely, whether we regard them as increasing the plasticity or as sources of pressure, for their agency in either case would become effective only through gravitation and would be dominated and directed by it.

Pressure as affecting plasticity.—Pressure, considered as a source of plasticity in glaciers, may be regarded as having two elements, the one vertical, arising from the weight of the ice, the other lateral, impressed by the flow of the ice. Assuming that the greater the pressure the more plastic the ice, it follows that, other things being equal, the basal portion of the thick glaciers was more plastic than that of the shallow ones. It may accordingly be assumed that the ice of the deeper portions molded itself the more freely and completely to all the inequalities of its floor, wrapping about protuberances, insinuating itself into cracks and crevices, and adjusting itself to minor reliefs, the result being striae conforming closely to the subglacial surface and quite negligent of the general trend of the main glacial movement. On the other hand, where the ice was thin and the downward pressure slighter, the relative rigidity was greater and the ice mass may have moved bodily over the inequalities of bottom with only partial adjustment to them.

That there were great differences in the degree of conformity of the ice at its bottom is abundantly shown by observation of the character of the abrasion and striation. On certain glaciated surfaces we observe that the ice in passing across a crevice or cavity in the rock was depressed so as to cut away the opposite edge, rounding and rasping it forcibly, while in other instances the ice passed over considerable spaces with only very slight action. Fig. 18, rep-

1 The embossment of certain ledges in Pittsburg and Shelburne is peculiar, in that the lower part of the rock below the smooth surface is rough. * * * The Pittsburg examples may be eight or ten feet high, with a roughness of three feet. * * * The Shelburne example is more striking. * * * The ledge is about thirty feet
resenting a piece of very hard, striated hornstone which could only be cut by a forcible abrading agency, illustrates the former fact. Upon examination it will be seen that the ice in passing across a cavity one-half inch in diameter yielded so as to round the edge of the cavity upon the farther side and to cut a shallow groove leading away from it. Even the small shallow cavity, one-eighth of an inch in diameter, illustrates the same phenomenon. In these instances, however, there does not appear to have been an extreme pressure exerted, since the sharp edge of the ice on the upstream side was not crushed by the pressure. Some of the illustrations heretofore and hereafter introduced exhibit the molding of the ice in a high degree and illustrate the adaptability of the ice to grooves, some of which certainly were not originally formed by the ice, but merely occupied and refashioned by it.

Fig. 18. Striated hornstone, about natural size, showing the yielding of the ice in passing over small cavities, the greater erosion of the distal side of the cavities, and the formation of grooves leading away from them. From a photograph of specimen from Buffalo, N. Y.

On the other hand, Prof. W. H. Niles has shown by observation upon the Aletsch glacier of the Alps that the ice may ride over the crests of underlying prominences without being depressed so as to fill the intervening concavities, and he has further shown that when the base becomes fluted by being forced over prominences of rock, or even over boulders, the channels are prolonged far beyond the obstruction without collapsing, indicating a notable lack of plastic adaptation of the glacier’s bottom. Prof. T. G. Bonney has made similar observations upon the terminal portions of the Bois and

high and seventy-five long, and the roughness below the striated part as much as six feet. The irregularities upon the lee side begin at the very top of the eminence. The end struck is forty feet wide, tapering to a blunt point, where the smoothed appearance disappears and the inclination of the stoss slope toward the northwest is about 50°." Geol. New Hampshire, vol. 3, part 3, p. 195.


2 Geol. Mag., London, 1876, p. 196.
Argentière glaciers. I have myself observed the foot of the Rhone glacier passing freely over its own glacial débris without pressing forcibly upon it, much less insinuating itself among the interspaces. In our own glacial field we have numerous instances where the tops of asperities are planed, while the soft products of ancient decay fill all the intervening spaces. All, or nearly all, these observations, however, relate to the marginal portion of the glacier, where vertical pressure was slight, and hence little plasticity arose from that source.  

It would be as erroneous to argue from the one of these extremes as from the other without reference to the special conditions of each individual case. The amount of plastic molding, as well as the amount of abrasive action, was doubtless very largely dependent upon the weight of ice overriding the locality at the time the inscription was wrought; and, as the depth of ice varied at different times in the history of glaciation for any locality that lies well back from the drift edge, striations made at different stages may be expected to vary accordingly. For instance, upon our northern border, at the time the ice reached its maximum extension, there were not less than two or three thousand feet of overriding ice, and may have been much more, while in the last stages of retreat the same surface was acted upon by ice of slight thickness. The striations produced at different stages may, therefore, rationally be presumed to show different degrees and kinds of deflection in connection with identical bottom inequalities. That this is not simply an assumption seems to be demonstrated by Fig. 11, already introduced (p. 175) to illustrate another feature. This example is from the southeast shore of Kelley's Island, a region of phenomenal molding of the ice to bottom inequalities, at one stage at least. The figure shows striation of the lee slope of the rock, indicating that the overriding ice was pressed forcibly down the lee side of the elevation, planing and striating its surface. But at a later stage the upper portion of the prominence was trun-

1 Since the above was given to the printer, Prof. J. W. Spencer has described even more remarkable phenomena of similar import. I cannot agree with him, however, in regarding these as an indication of viscosity, for, if the ice had been viscous in a degree that permitted it to flow around boulders without sliding them along, it would certainly not have been able to bridge the great cavernous spaces which afforded entrance to the explorers and which made these important observations possible. If this be doubted, let the vertical pressure of 50 feet of ice—not to speak of a greater depth—be computed and compared with the lateral resistance of a boulder.

While the cause of this phenomenon remains to be decided by critical observation, I incline to regard it as chiefly due to temperature arising from four sources: (1) solar heat transmitted through the relatively thin edge of the glacier, where alone the phenomena have been observed; (2) terrestrial heat transmitted from below; (3) atmospheric heat borne in by convection currents through the subglacial passages, which afforded entrance to the observers; and (4) heat generated by the resistance of the obstacle itself.
cated by the passage of the ice across the top without suffering depression in its lee. The inference seems unavoidable that the ice in the two stages was acting under widely different conditions, resulting in a ready adaptation to the surface in the earlier stage and a comparatively rigid, inflexible riding upon the crests of the prominences in the later stage. Theory and observation thus seem to justify the general proposition that the basal currents of deep ice adjust themselves to inequalities like stiff, slow-moving fluids and abrade and striate accordingly, while the bases of shallow portions of glaciers manifest little plastic adaptability to the bottom. It may even be true that the pressure in the greatest depths reached such an intensity as to produce too high a degree of quasi-fluidity to effect striation, because the rock fragments could not be held with sufficient firmness to score the bottom. Indeed it has been debated whether complete fluidity might not be generated from the intense pressure of the central portions or of deep basal embayments.

There is a second phase of glacial pressure that needs attention, namely, that which arises from the onward movement of the ice. The distribution of this pressure throughout a glacier is almost the reverse of that of vertical pressure. At the center of dispersion of glaciers of the continental class vertical pressure is at a maximum while flowage pressure is practically zero. Toward the outer edge of the ice the ratio is reversed, in a qualified sense. So, also, it may be said, in a very general way, that in deep currents the flowage pressure against obstacles is less than in shallow currents. These general statements are subject to important qualifications, but it is not essential to dwell upon them here.

The onward motion of the ice induces pressure on the stoss sides of prominences that interpose themselves as obstacles in its path and this develops pressure-plasticity in the ice in contact with them, giving it pliancy and causing it to deviate in the direction of least resistance and to pass around them. On the stoss side of a prominence, therefore, both classes of pressure combine their forces, while on the lee side only the plasticity due to vertical pressure is exerted to close in the ice behind the prominence. The general nature of the result is obvious. Near the edge of the glacier the flowage pressure causes a yielding of the ice on the stoss side of prominences, but, the vertical pressure being slight, the ice does not close in promptly in the lee, as shown by Professors Niles and Bonney and illustrated by the unworn lee faces of many prominences in our glaciated area. On the other hand, under the deeper currents of the ice distant from the edge, where the pressure-plasticity arising from depth is great relatively to the flowage pressure, scoring upon the several sides of prominences is more nearly equal. Obviously, so long as there is any flowage pressure—which is practically equivalent to saying so long as there is any striation—the stoss side must suffer the greater action, because flowage pressure is there added to the vertical pressure.
Rate of flowage as affecting the course of striae about obstacles.—The manner in which the ice deported itself in passing prominences in its path was dependent upon the rate of flow of the ice. This has been already implied, but not indicated with sufficient definiteness. Time is an important element in the yielding of a plastic body. It is well known that viscous substances, like pitch or sealing-wax, may be slowly molded with the greatest facility, but if struck suddenly they deport themselves like very brittle substances. Glacial ice illustrates the same property. If the ice is pushed rapidly over an obstacle which furrows its base, little time is given for the closing in of the ice in the lee, and the furrow is prolonged. If, on the other hand, the current be slow, the plastic yielding of the ice enables it to close up the furrow and hug the lee of the prominence. In this case, the currents that diverge in front flow inward on the rear, following closely the sides of the obstacle. If it be true that, in the deep, capacious currents, movement is slower than in the shallow ones, a greater conformity of the striae to the contours of the underlying surface will be found in such situations, while a greater degree of non-conformity would prevail in the shallow and in the fast flowing portions. It is to be noted throughout that we are dealing with the basal currents, and not with the average ones.

The forms of prominences as affecting the course of flow about them.—In general, currents close in behind a prominence both from the sides and from above; but the relative measure of these two actions depends much on the form of the prominence. If its section transverse to the movement is broad and low, the currents which pass over it can manifestly descend its lee more readily than those that pass around the sides can close in laterally, though both movements may take place. In cases of this type the chief deviation of the currents will consist of a vertical arching over the prominence. On the other hand, if the hill be high and narrow, the currents which pass by on the sides will close in behind at less disadvantage, especially as they are the deeper and more fluent, while those that pass over the crest will take less part in the action. Looked at in another way, if the arch of the furrow which the hill may be conceived to make in the bottom of the ice passing over it be broad and low, it will collapse chiefly from above; if it be high and narrow, it will collapse chiefly from the sides. Now, since striae are ordinarily read only in a horizontal plane, the recorded deflection in this latter case will be much more notable than in the former instance. Our customary notation is somewhat defective in this regard.

The element of magnitude.—It is a recognized fact that arches of the same form and proportions do not possess strength in the simple ratio of their dimensions. Beyond certain limits increase of size is attended by weakness. There is even a limit beyond which an arch will not be self-sustaining. Applying this principle to the arches of
the grooves that we have conceived to be impressed on the under surface of glaciers in passing over obstacles, it becomes apparent that, while a furrow of limited dimensions might be prolonged some distance, a similar furrow of greater dimensions might yield at once to the pressure of the ice above. So a hillock or mere knob of rock might escape all abrasion on its leeward face because of the prolongation of the basal furrow, while the ice would close tightly around massive hills or mountains, scoring them on all sides, though the proportions of hillock and mountain were alike. The simple element of magnitude determines a difference of results.

The foregoing considerations, though not exhaustive, sufficiently bring to attention the complexity of conditions which deserve consideration in reading the significance of the deflection of striae in the vicinity of eminences of the surface. Respecting their results, they may be reduced to two general classes: first, those in which the ice, on encountering an obstacle, is diverted to the right and left and upward and, hugging the sides of the prominence, closes in tightly behind, rubbing front, sides, and rear and producing a system of striae concentric with the surface; and, secondly, those in which the ice, on encountering the obstacle, is forced laterally and upward as before, but does not close in promptly in the rear, and hence striates only the front and sides. The first of these finds illustration on a small scale in typical roche moutonnée domes, polished and striated on all sides; on a large scale it finds illustration in those mountains which are glaciated on all sides.

Of the second class, Figs. 19 and 20 poorly illustrate a beautiful example of the minor grade. The angular, unglaciated faces of the lee side indicate a very slight disposition of the ice to close in behind the
prominences. When in action, the under surface of the glacier probably presented prolonged fluting analogous to that described by Professor Niles. It is probable, however, that in many instances the angular character of the rear side is due to the breaking away and removal of blocks by the ice, the phenomenon of "plucking," as it is graphically termed by Prof. N. S. Shaler. It is clear that when, for any reason, a fragment of the embossment is loosened the whole tendency of the glacial action would be to carry it away, while on the stoss side the flowage pressure would tend to hold it in place, so that the two sides of the prominence present opposite conditions in this regard, the front side suffering the greatest abrasion and the least plucking, while the rear suffers the least abrasion and the most plucking.

Fig. 20. The same glaciated ledges as shown in Fig. 19, seen from the lee side looking northeastward, illustrating the abrupt, unstriated character of that side.

*Miniature ridges behind hard knobs.*—Another phase of the same class of phenomena is found in the development of little ridges of rock in the lee of hard portions which resisted the wear of the ice-rasp and protected the rock behind them. These are usually best developed in limestone containing nodules of chert, which, resisting abrasion better than the surrounding rock, are left standing forth from the surface and are followed by raised trails, which

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stretch out some distance behind them and gradually merge into
the common glaciated surface as they pass beyond the protecting
influence of the little obstacle. This phenomenon is shown in the
accompanying figure (Fig. 21), and still better in Fig. 48, p. 245.

In the discussion thus far we have assumed but one phase of ac­tion on the stoss side of an eminence, namely, that the ice was simply
pressed into forcible contact with it and diverted to the right and
left and upward. There appear to be two departures from this sim­ple system of deflection that deserve attention, and, as is so often the
case in glacial phenomena, they are of precisely opposite character.

**FIG. 21.** Frontal and lateral glacial grooves, caused by a projection of harder rock. From St. Da­
vid's, Ontario. Length of lateral groove, 18 inches; width, outside measurement, 3 inches. From a
photograph.

**Grovewing in front of obstacles.**—In the one case, the obstruction
seems not only to have turned the currents upward, but to have made
an apparent effort to turn them downward also, producing an excep­tional pressure in front of the prominence. This manifested itself
by unusual wear just in front of the obstacle, sometimes tending to
undermine it. Chert nodules embedded in limestone occasionally
show such undercutting in front, and their uprooting is probably
hastened in this way (see Fig. 48). Very commonly, however, the
point of maximum wear is a little in front of the obstacle, leaving a
short space between the point of greatest wear and the edge of the
obstacle. There are instances in which very remarkable grooves are
developed in front and at the sides of hard nodules embedded in
softer rock. The lateral grooves are often prolonged much beyond
the nodule, trailing far out to the rear. An excellent description of
this phenomenon as witnessed on West Sister Island, Lake Erie, has
been given by Mr. G. K. Gilbert. The illustration here given is from
a photograph of a large specimen obtained from the quarries near St.
David’s, Ontario, by Mr. Gilbert. The symmetry of these lateral
grooves, their prolongation, and their smooth and striated surfaces show that they were developed by persistent currents, and not by the accidental agency of a gouging fragment; besides, the phenomenon recurs too often and has too definite and uniform a character to be considered the result of a chance gouge.

In some instances, as in the illustration given (Fig. 21), the groove is developed across the whole front of the nodule and, extending around the sides, is prolonged to the rear, producing a U-like form, not unlike the imprint of a staple, embracing the projecting knob. But in other cases the groove is less developed immediately in front of the knob, or scarcely developed at all, and there appear, rather, to be two lateral grooves, partially joined or approximating each other by incurving in front. Indeed, in the illustration the abrasion immediately in front is somewhat less than at the sides, although the figure feebly illustrates this. In these cases the greatest abrasion is at the sides of the knob and slightly in front of its center, as in the accompanying figure.

Fig. 22. An asymmetrical groove and lee train developed by a silicified coral embedded in limestone. Quarries near St. David's, Ontario. From a photograph.

In an unusually fine and somewhat unique example from St. David's, Ontario, procured for the National Museum by Mr. G. K. Gilbert, there is a large, deep groove on one side, while there is but a bare trace of one on the other. This asymmetry seems to have been determined by the slightly oblique position of the silicified coral that formed the obstruction. It is not this, however, that is remarkable, but that the principal groove starts nearly in front of the obstacle, has a rounded, deeply excavated head, and is developed slightly backward and downward before it begins to curve around the side of the obstacle (Fig. 22). On the outer side of this curve, opposite the knob, and next to the advancing ice, the groove has a sharp edge and almost overhanging wall, as though the current that wore it out

recurved (we might almost say eddied) backward beneath the general overrunning current. This would not be regarded as a strange action in a free-flowing fluid, but is very remarkable if wholly the work of ice. That the ice took this abruptly curving course seems to be proved by the fine strie which line the groove throughout. This does not seem to me, however, to prove that the groove was primarily and wholly cut by the ice or that its form was solely determined by it. The following may possibly be the explanation, though I offer it with limited confidence: It may be supposed with probability that the groove was made at the closing stages of the glaciation at that point and that melting took place at the bottom of the ice with some freedom because of the penetration of solar rays through the ice and from other causes, giving rise to a thin film of water between the ice and the rock. This water, as it found opportunity, flowed forward along any available space between the rock and the ice, but continually under constraint and pressure from the mass resting upon it. On encountering the knob, however, on which the ice pressed heavily, the supposed film of water would be turned aside and flow around the obstruction. Possibly the very pressure of ice on the obstacle may have been a special source of melting. If the obstruction tended to lift the ice in front and at the side of the knob—a supposition contrary to that made at the head of this section—that would determine the course of the water, which, being silt-laden, would cut a groove for itself and determine a permanent little ribbon-like rivulet. Into this little channel the ice would continually tend to mold itself, pressing upon the little ribbon of water and scoring its channel whenever, from change of temperature, discharge of the water, or other circumstance, ice action took the place of water action; and so the two agents may have worked jointly and alternately and have together developed a groove whose form and curvature are clearly not produced by water alone and do not seem to be readily producible by ice alone. The deep, sharply defined cutting and the recurved course seem inconsistent with the usual action of glaciers, while the straight, smooth fluting of the lateral portion of the groove seems equally inconsistent with simple water action, and the strie within the groove are certainly so. It may be that such joint action entered into the production of all these frontal and lateral grooves and of the great grooves of Kelley's Island and elsewhere.

This explanation, as already suggested, does not involve an increase of pressure in front of the obstruction, as implied at the head of this section, but rather the opposite, for the supposed subglacial water would follow the line of least pressure. If this be the true explanation, these grooves belong rather to the following class.

Absence of grooving in front of obstacles.—A phenomenon precisely opposite to the above is observable, namely, an absence or a
feebleness of abrasion immediately in front of an obstacle. This, from its nature, is less likely to arrest attention, though it appears to be not uncommon in the tracts of slighter glaciation. It occurs with the larger class of obstructions and with those of the nature of low, flat ledges rather than those with rounded embossments. It would appear as though, in these instances, the rigidity of the ice, aided by the form of the obstruction, determined a lifting in front of the obstacle, or a relief of pressure rather than an increase. Assuming that the weight of the ice at the time of this action was relatively small and its practical rigidity relatively great, this effect becomes a necessary result. In some cases of frontal and lateral grooving this phenomenon occurs also in association with frontal grooving.

Another expression of the same principle of action appears to be found in the phenomena of pre-crag accumulations of drift. Under certain conditions, which appear to belong to the closing stages of glaciation, subglacial debris accumulated in front of obstacles as well as in their rear, producing both pre-crag and lee-crag lodgments of drift.

Deflection of currents in crossing valleys.—It has been long held by many glacialists that valleys lying oblique to the general movement of the ice developed basal cross-currents conformable to themselves, resulting in striation varying widely from that of the general system, but strictly contemporaneous with it,—indeed, but a divergent element of it. On the other hand, it has been doubted by some whether valleys were competent to develop independent basal currents, the striation supposed to indicate such cross-currents being held to be due to local ice tongues developed on the margin of the general sheet after it had become thinned by melting in the progress of its decadence.¹ There is an intermediate view, to which I incline, which, while admitting both cross-currents and local ice tongues, supposes that a given portion of the basal ice on encountering a valley oblique to its course descends into it and is also deflected by it, crossing it in an oblique course and reaching the opposite heights at a point more or less distant from the projected line of its former course, the amount of offset depending upon the nature of the valley, its angle to the general current, the relative force of the main current compared with the subordinate one, and other conditions.² In this case, in a certain sense, the ice in the valley moves as a cross-current, but not in the sense of being completely differentiated from that above. No given portion of the ice is supposed to follow the valley for any great distance, and so the transportation of drift in the two cases is notably different. In the one the material once in

the valley is borne down it as far as the supposed cross-current reaches; in the other the material is carried obliquely across the valley. I do not know that any advocate of cross-currents would maintain that there was a definite shearing plane separating the overriding general current from the obliquely moving cross-current beneath, and, if not, then the distinction between the two views is rather one of degree than of kind. But there is a practical distinction of some importance in the fact alluded to, viz, the transportation of the débris, and the line of distinction between the two may, perhaps, best be drawn here. If the drift in the bottom of the valley is borne wholly along its course and not lifted out of it, the case may be regarded as belonging properly to the class of well differentiated cross-currents, but if the drift is borne obliquely into and again out of the valley the instance belongs to the other class.

That cross-currents of notable independence are sometimes developed, and on a surprisingly small scale, the foregoing examples of grooves lined with striæ running transverse to the general currents seem to prove beyond cavil. The tortuous grooves of Kelley's Island, already illustrated, are further striking examples. That there were tongues of ice in the closing stages of glaciation, following the valleys in a somewhat similar manner, but capable of being discriminated from the cross-currents by the manner in which they deposited their load of erratics and by other characteristics, seems also to be clearly demonstrated. That there were also currents which descended into and rose again out of the valleys that lay athwart their course with greater or less obliquity seems likewise to be shown by trains of bowlders stretching across them and by the obliquely descending and ascending striæ on their slopes. The truth of this passes beyond discussion when we examine the accompanying photographic illustration (Fig. 23).

This is an example on a small scale, and may not be applicable to all ranges of magnitude, but probably the greater the magnitude of the valley the greater the adaptability to such method of action. The figure fails to show satisfactorily the little valley that lies at the base of the terrace. The course of the movement was from front to rear. On entering the little valley the lines curve downward and are deflected to the left, and in the trough of the valley they run in a direction nearly coincident with it. As they rise along the face of the terrace it will be observed that their course is at first quite oblique and then less so, until they round over the terrace edge, when they assume the general course of striation of the vicinity. This course and that of the foreground are not accurately coincident, because of the slope of the latter, which likewise had a

slight diverting influence; but there is really a nearer approach to coincidence than is indicated by the figure, the perspective of which has suffered some distortion.

As evidence that this illustration, confessedly small in scale, is applicable to valleys of larger magnitude, the diverting influence of the Great Lake basins may be cited. We may pass without insisting upon it the evidence presented by Lake Erie and Lake Ontario, because it may be assumed, with plausibility, that all the observed striation in their basins is the work of the closing stages of occupancy, and therefore not representative of the movement at the time when the whole region was profoundly enveloped in ice reaching far southward. But there seems to me to be conclusive evidence that at all stages of glaciation the great valleys of Lake Superior and Lake Michigan diverted and effectually controlled the glacial currents, and yet the southwesterly movement of the ice through Lake Superior did not prevent portions from flowing southward up over the highlands of northern Wisconsin, in pursuance of the general average course of glaciation of that region.\footnote{For a fuller discussion of the influence of the Lake Superior Valley upon the glacial currents, see paper on the driftless area of the Upper Mississippi Valley, Sixth Ann. Rept. U. S. Geol. Survey, 1883, pp. 199-322; also, Geol. Wisconsin, vol. 1, 1883, pp. 269, 270.}

I anticipate that when the full evidence relating to this problem is gathered and its import carefully discriminated it will be found that the following general propositions will be sustained: (1) Other things being equal, the broader and shallower the valley, so long as it remained a purely local feature, the less the currents were diverted.
in crossing it; and, conversely, the narrower and deeper the valley, the greater was the deflection, except when they became exceedingly small, when they were ignored. It may be that in the deep, narrow, cañon-like valleys the diversion amounted practically to an independent underrunning cross-stream, approximately as held under the first hypothesis. (2) The smaller the angle between the course of the valley and the course of glaciation, the more efficient was its diverting action. (3) When a valley stood at right angles, or nearly so, to the current, the result depended chiefly upon its magnitude; if of any considerable size, the currents flowed down into, across, and up the opposite side of the trough. There was probably a limit below which the ice passed across the valley without descending into it, this limit being dependent upon the relative degree of plasticity and of rigidity of the ice, as indicated in a previous part of the discussion. The limit is unknown, but is presumably determinable by the class of observations which this discussion is intended to invite.

There can be little doubt that, in the case of a deep valley whose course is only moderately divergent from that of the general glacial movement, a control may be exercised over the basal currents sufficient to produce a tortuous course measurably conformable to its own windings; but in this case the deflected current may appear to show a greater independence of the overrunning stream than it really possesses, as shown by the entrance and exit of striæ.

**CROSS-STRIATION.**

**VARYING EFFECTS OF TOPOGRAPHY IN SUCCESSIVE STAGES.**

The foregoing considerations have perhaps made it sufficiently evident that the effects of topography must have varied at successive stages of glaciation, and that as a result the successive systems of striation crossed one another at varying angles. Such a result must have obtained respecting both classes of topographic influence, whether we consider those grander ones that affected the whole contour of the ice and determined the great movements or those lesser ones that merely determined deviations of the basal currents of the ice.

The temptation is strong to regard systems of striæ that cross one another at high angles as evidence of distinct, general ice movements and to draw broad inferences from them (Fig. 24). As these crossing striæ are engraved on the same surface it is an easy conclusion that only the very slightest degree of abrasion took place during the second movement, at least at that point, and a far-reaching inference respecting glacial erosion is liable to be drawn thence. Thus important theoretical structures may be built upon the phenomena of cross-striation. It is imperative, therefore, to consider with some

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care the agencies that were competent to produce local changes of movement during the history of the same epoch of glaciation, for it is manifest that cross-striae become weak evidence of distinct epochs if they are entirely explainable by the changes incident to the history of a single epoch.

Fig. 24. Cross-striae. From photograph of a limestone slab in the educational series of the Survey, procured by E. E. Howells at Rochester, N. Y. It clearly shows the older set by the drag-lines on their lee sides.

Changes of glacial movement during a symmetrical retreat.—Recalling the general law that the glacial movement near the edge of the ice was approximately at right angles to the margin and recalling also the lobate outline of the ice-field, it becomes obvious that the direction of movement at any given locality near the border must have changed at each successive stage of retreat, however symmetrical that retreat may have been. This becomes manifest to the eye by mapping the successive contours of a well developed lobe at its several stages of retreat, as illustrated in the accompanying Fig. 25. If any one is disposed to regard this divergent movement toward the border as overdrawn, let him study the map of the Frederikshaab glacier of Greenland,1 or the striae, bowlder trains, and drumlins of the Green Bay lobe.

Changes of movement due to varying topographic influence, producing an unsymmetrical retreat.—Topographic features that were deeply buried, overridden, and ignored by the ice in the stages of

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maximum glaciation became effective in its declining stages and determined its shrunken outlines, and thus induced new courses of movement which combined their effects with the local changes incident to simple retreat, as illustrated in the last paragraph.

Less important divergences of movement were effected by eminences and depressions whose influence was merely local, not affecting the outline of the glacier. It has been previously shown that the stria inscribed upon a prominence when overflowed by profound ice encircle it and are concordant with its surface, covering front, sides, crest, and rear, but those formed at a later stage, when thinness had supervened and the relative rigidity increased, cover front, sides, and crest, but were not impressed on the rear, while at a still later stage, when drift had perchance accumulated in front, they are confined to the sides and crests or to limited portions that, under the existing conditions, were last to be protected by drift. The lines thus successively imposed, while not radically discordant with one another, fail of complete concordance and are found crossing one another at appreciable angles. Faces even appear to have been cut by the later planation, so that the striae not only take different courses, but occupy distinct planes, joining adjacent ones at notable angles.

Fig. 55. Diagram of the extremity of a glacial lobe, showing ideally the successive courses of movement during three stages of a symmetrical retreat and illustrating the crossing of the courses.

Recalling the influence of valleys, previously discussed, it will be apparent that cross-systems of striation of large divergence may have been developed during the decadence of the ice, since the relative strength of the valley currents and of the main ones varied greatly.

Changes of movement due to inequalities of supply.—It is the opinion of many glacialists that the inequalities of glacial supply depended largely upon the inequalities of snow accumulation in the...
region of glacial growth, and that important changes in the distribution of the ice and in its movements were thus effected. It is evident upon statement that, if the sources of supply of certain portions of the great snow field were copious for a term of years while those of adjacent portions were scanty, the currents springing from the former must have deployed themselves at the expense of the latter. If the more copious supply oscillated from one district to another, continual fluctuation of movement might have resulted.

Changes of movement due to varying rates of ablation.—The rate of waste of the ice about its border was dependent upon a complex combination of influences which presumably were quite varying in their efficiency. Dry or hot winds sweeping over a given tract would facilitate waste, and so, in like manner, would a succession of warm rains, as there is probably no method by which the heat of the atmosphere can be more promptly and effectively transferred to the ice than through the medium of rain (Gilbert). Again, a succession of cold or moist atmospheres, without either rain, on the one hand, or warmth or dryness, on the other, would greatly retard ablation. Such meteorological combinations are apt to follow given tracks with more or less persistency and hence make themselves felt upon the wastage of the ice-field. If a certain portion of the border belt of the ice were more freely melted than adjacent portions these latter would tend to move toward the relatively depressed area and the resulting lines of striation would cross the previous ones.

Changes of movement due to glacial drainage.—Superficial melting gave rise to superficial drainage, and because of the greatness and flatness of the ice-field the result may sometimes have been the formation of canons in the ice, the walls of which would tend to flow toward each other, giving rise, possibly, to striation in courses crossing those immediately antecedent. Subglacial drainage, by developing arches beneath the ice, may have furnished conditions for a similar lateral movement in the effort of the plastic walls to close up the tunnel. This action would be perpetuated so long as the stream was competent by melting or wearing to maintain itself against their encroachment. In so far as the subglacial stream for any reason was forced to change its course, in so far there were developed new possibilities of additional cross-striation.

Changes of movement due to the seasons.—During the summer, wastage of the marginal portion of the ice was active, while during the winter it was suspended. During the summer, heat and moisture were freely imparted to the ice; during the winter, they were withheld. The general effect of the former upon existing Alpine glaciers is a relatively rapid onward flow; the effect of the latter is a

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1 Mr. Warren Upham has maintained that very important changes in glacial movements in Minnesota were induced by unequal accumulations on the two sides of the glacial lobes (Proc. Am. Assoc. Adv. Sci., 1883).
suspension of the motion of the marginal portion of the ice without a suspension, but only a retardation, of the motion of the ice farther back. Precisely how far this is representative of ancient continental glaciation, it may be impossible trustworthily to conjecture; but that some such influence obtained is in the highest degree probable. The reduction of temperature, the absence of saturating waters, and the congealing of the basal waters in the thinner portions of the glacier's edge, all tended to antagonize the movement of the margin of the ice, while such influences could not have been equally effective upon the great body mass. The probable result was a flattening of the glacial lobes in summer and a fattening in winter, the latter due to the suspension or great retardation of the movement of the border ice without a corresponding retardation of the oncoming movement from the rear.

Now, some of the ancient glacial lobes extended throughout several degrees of latitude and the seasonal influences were felt somewhat successively instead of simultaneously. It is probable also that the presence of the great northern body of ice heightened the difference in the time of the seasonal changes. So, after the autumnal freezing had checked the marginal flow on the sides of a lobe in the higher latitudes, the southern apex might still have been subject to active flow and waste, inviting onward flow through the whole axial belt, none of which would have been diverted to supply lateral waste. So also, in the spring-time, warmth at the south end would have invited movement earlier than it did along the more northerly sides, but when these became loosened by the advancing season a lateral draft must have been made on the axial currents.

But, independently of these effects, due to differences of latitude, the alternate flattening and fattening of the marginal tracts and the alternate acceleration and checking of motion, combined with the unequal thickness and sinuous contour of the ice, must apparently have induced divergences in the courses of the currents.

Changes of movement due to solar action.—Mr. W J McGee has called attention to interesting changes in the course of an ancient glacier that descended from the Sierras into the basin of Mono Lake, which he attributes to solar influences. While I have not been able to detect this influence in the successive courses of movement of the ancient glacial lobes, it may have been occluded among the numerous influences that combined to induce changes of course in the successive stages of glaciation.

Changes of movement due to climatic periods.—In the discussion of changes due to inequalities of supply and to varying rates of ablation, attention has been called to local climatic influences such as would naturally arise from the fortuitous distribution of wasting and

contributing climatic combinations. But in the progress of the somewhat prolonged glacial period there was room for climatic epochs of a more important nature, that in a more general and potent way may have affected the course of glacial movement. There was at least the great change from conditions that produced glacial onset to those that induced glacial retreat; and, unless this change was symmetrically apportioned to the whole border tract of the great ice-field, variations in the course of ice movement must have resulted. In an age which was itself an expression of the most extraordinary climatic vicissitudes it is most natural that even the lapse of a subepoch should cover notable variations. Whether due to this or to other causes, it is a matter of observation that the successive marginal morainic lines are not strictly concentric, even where they are thought to mark only minor oscillations. In explanation of certain announced changes of current in eastern Minnesota, Mr. Warren Upham has urged that the increased warmth and moisture of the southwesterly winds in the declining stages of the last glaciation gave the winds increased velocity, whereby the greater precipitation was shifted to the eastern side of the ice lobe, determining a growth of the glacier in that direction. Whether or not this special application of the doctrine be endorsed, the presumption that differential effects would follow the changes of climatic conditions that induced and dissipated the ice seems well grounded.

Changes of movement due to inequalities of débris covering.—The currents near the edge of the ice were doubtless influenced by the débris upon the surface of the ice, whether it was borne there as dust by prevailing winds or brought to the surface from within by ablation or by other agencies. If the distribution of this débris were changeable from any of several supposable causes, corresponding inequality of glacial waste would result, leading to corresponding changes in ice movement.

Changes of course due to possible movements of the earth's crust.—The beach lines and other deposits of the ancient glacial lakes and of the sea show that important changes of level have ensued since the glacial period. The distribution of the loess and of the glacial flood gravels—indeed, the whole fluvial phenomena of the glacial period, as well as certain features in the distribution of the great moraines, indicate changes during the glacial period. While some changes of water level are explicable without postulating changes of the crust, all the phenomena here briefly alluded to seem only intelligible on the supposition of crust changes competent to notably influence fluvial movement. As these changes were apparently progressive, cor-

responding changes of ice movement are probable, and I have elsewhere called attention to the direct evidence of such changes. 1

In the foregoing discussion I have dwelt chiefly upon possible causes of cross-movements in the marginal portion of the ice. The crossed striation does not in itself imply great intervals of time between the formation of successive sets; hence broad inferences respecting great changes of movement are to be drawn with much circumspection. In the greater number of instances it is obvious from their very nature that no very great amount of work was done in the interval, either by decomposition between the glaciations or by glacial erosion during the later invasion, else the earlier lines would have been entirely obliterated, for the very manner in which the lines are engraved indicates the efficiency of the agency. If there were no other demonstration of the efficiency of a glacier as an abrasive agency it could be found in the very obvious fact that the grooves are made in a geologically infinitesimal length of time, and it is quite incredible that a debris-charged glacier, having the abrasive competency which the striae themselves prove it to have had, could have passed over an exposed surface without obliterating the striae as readily as it produced them. It is therefore probable that in the great majority of cases where cross-stripe are found upon a planed surface they are the product of the minor cross-movements that affected the border tract of a given glaciation rather than of widely separated glaciations.

On the other hand, it is to be observed that the presence of subglacial débris may have interposed a protection which preserved the striae of an earlier stage throughout a long period and permitted a later inscription to be imposed without their obliteration. But this supposes somewhat nice conditions of adjustment. It presumes that the second glacier wore away the protecting drift and reached the old glaciated surface so as to impress its lines upon it, but was there arrested in its work before it had filed them away and produced a new surface.

While, as a general proposition, the presumption is that the striations which we observe are those of the latest stage of glaciation, such presumption is subject to very important qualifications, for subglacial accumulations may have protected the striated surface not only during the whole of the declining stage of the glaciation by which it was produced, but during a subsequent one. In some regions 100 and even 200 feet of drift overlie the rock and much of this appears to have been the product of earlier glaciation. If the later glacier in its incursion had plowed up the whole of this before its prow, it would have produced moraines of the most gigantic character, whereas in many regions they are so unimpressive as to have have long escaped detection.

Notwithstanding these conservative considerations, it is quite certain that there are crossing systems of striæ that belong to different epochs and to glaciers of different sources. The most notable instances within my observation occur in northern Indiana. At Moneon there are two systems of striæ, one running S. 34° E. and the other S. 85° W. magnetic. At the quarries some three miles south of Kentland, about forty miles west of the above locality, there are two sets, the one S. 70° E. and the other S. 77° W. In both cases the sets cross each other at nearly right angles. In the latter instance the southward-pointing striæ lie in grooves and furrows in the limestone, while the westward-pointing striæ only affect the crests of these furrows, which have been slightly truncated by the later westward movement. In the same general region there are southward-pointing striæ at Rensselaer, Williamsport, Waynetown, and Darlington, while at Rainsville and opposite Attica there are westward-running striæ. There are also two sets of moraines, which complete the demonstration of a movement from the east that overrode territory previously invaded from the north.

SCORING ACTION AND THE SCORINGS.

As we turn from the distribution, attitudes, and courses of the scorings to the scoring action and the scorings themselves, it may be profitable to dwell a moment on the nature of a glacier as a scoring agent.

A glacier is at once a plow, a file, and a sled, and yet it is not quite any one of these. To act as a plow it must have both rigidity and motion; it must be in effect a moving mass with an inflexible prow. But the mobility of a glacier is obtained at the expense of its rigidity; a certain degree of practical plasticity must take the place of the seeming inflexibility of ice. Now, this very pliancy, which enables it to flow, permits it, in some like measure, to yield to obstructions and relieves it of the necessity of cutting away, uprooting, or overturning obstacles in its path. There is a temptation to play fast and loose with a glacier: to consider it inflexible when we regard its plowings and plastic when we regard its motions. We are apt to generously attribute to it the very accommodating nature of being at once rigid enough to plow and plastic enough to flow. There is, indeed, some slight ground for this. A glacier is something of a paradox. Its mobility or rigidity is dependent on time and pressure, as also on temperature and saturation. It is plastic under slow pressure; it is rigid under sudden impacts. Maximum temperature and complete saturation with water favor plasticity. There are differences of pressure, temperature, and saturation between the ice of a glacier’s prow and that of the interior of its thick body, and to this extent there is a basis for diversity of action. But this has narrow
limits. The prow of a glacier advances with exceeding slowness against obstacles in its path. Its rate is not even the flowing rate of the ice. It falls short of that by the amount of melting of the edge, which varies with times and seasons from nearly nothing to an amount greater than the onward flow of the ice, in which case the glacier does not advance bodily at all. We shall do well, therefore, I think, to treat cautiously the conception of a glacier as a plow with rigid point and share. We need not dismiss the convenient simile, however. Rigidity is a thing of degree. Any plow point will yield to sufficiently obstinate and protracted resistance. It is merely necessary duly to recognize the pliant nature of the ice plow and to limit our conception to those actions consistent with such a nature. Glaciers certainly do plow up earth and overturn obstacles in their path.

But much the larger part of the work of striation and polishing was the result of action more analogous to that of the file.

The ice of a glacier has of itself but little abrading and practically no striating power. It can neither groove nor scratch; it can only very slightly wear indurate rock. The little effect that it may produce is of the nature of polishing, rather than grooving. But when it has armed its under surface with fragments of rock, sand, silt, and clay, it becomes an erosive agency of notable efficiency. It may be likened to a rasp, but not to a rasp simply. The plastic element qualifies the conception here, as in the figure of the plow. Not only is the armed ice flexible and mobile, but its hold upon its armature is yielding. The embedded fragments are held to their work by a matrix that yields under pressure. It may not yield in exact proportion to the friction the fragments beneath encounter, but it yields, and they may at any moment be rotated into a new phase of action or entirely out of action, or be wholly arrested, or be, in various degrees, held back while the ice flows on over them (Fig. 20).

A block of rock that presents a large surface to the embracing ice and but a small area in contact with the rock or earth floor may be held relatively firm and act as a steady graver. On the contrary, a block may have so large and effective a contact with the glacial floor as to overbalance the hold of the ice, and the bottom of the glacier may suffer grooving, instead of the rock floor, as in the instance cited by Professor Niles, previously alluded to.

In a river the bed material at times moves with the current and becomes abrasive, while at other times it lies at rest and suffers abrasion and even aids the lodgment of other débris; so, in an ice current, in less degree, the loose basal material may alternately play its part with the ice or with the ice bed, may at one time score the rock bottom and at another protect it.

Again, a glacier sometimes seems to glide over its floor, after the fashion of a sled. While it pushes or drags some little material be-
neath itself, it chiefly passes over the bottom debris. Unless I misinterpret, there are very numerous and extensive illustrations of this action in the plain drift region of the interior.

![Glacially faceted and scratched pebble](image)

It is clear, then, that there is free scope for variety of action and corresponding complexity in the phenomena of abrasion. Among the results, four classes are worthy of being distinguished: (1) Disruption (2) grooving, (3) striation, and (4) polishing.

I. DISRUPTION BY GLACIAL ACTION.

The consideration of disruptive action in this connection finds its justification in its intimate association with scoring action and in the supplemental evidence which it affords of the nature and direction of the abrasive movements. The evidence derived from disruption is in certain respects more decisive than that afforded by striation, and often supplements it in a most satisfactory manner. Striae often present only obscure evidences of the point from which the ice movement came, and, where the lines have a nearly east and west trend and no safe inference can be drawn from the general fact of a southerly movement, some other proof of direction is most important. It is here that disruption often comes to the support of striation. The data of its evidence are drawn (1) from the truncation which the outliers have suffered, (2) from the peculiar methods of the disruption, and (3) from the course in which the dissevered material has been transported.
(1) That side of the outlier which received the full force of the glacial impact manifestly suffered most severely, and it exhibits this in a denuded, if not truncated, contour. The trained eye readily detects the loss which the exposed extremity has suffered.

(2) This stoss side often also exhibits fractured rocks and disturbed strata that attest the point of attack. A figure is given in the New Hampshire geological report¹ and also one in that of Wisconsin² illustrative of instances of fracture of the beds, apparently from glacial action. Besides indicating the cause, there is in these instances a hint of the time of the action, since it can be quite safely inferred that the fracturing took place at the latest stage of glaciation; otherwise the fractured rocks would have been removed after being loosened.

The value of the evidence of truncation and fracturing is not so much in their simple occurrence as in their distinctive characteristics, since truncation and disruption may originate from other causes.

(3) The material which is broken from the protruding rock is borne onward by the moving ice and either is carried to the limit of glaciation or—which is by far the more frequent case—finds lodgment at distances more or less remote from the parent rock. There results from this action a train of rocks leading away from the parent knob in the direction of glacial movement. When the outlier chances to be of a kind of rock altogether different from that of the surrounding region, the train of erratics derived from it gives the most satisfactory attainable evidence regarding the course of the transporting movement. When it chances that the parent knob is abraded upon its stoss side, is also glaciated, and is furthermore attended by a distinct train of derivative bowlders, the combination presents as decisive evidence as could be demanded. In those instances in which the outlier is of the same class as the surrounding beds, the evidence derived from transported blocks becomes very much weaker, but it is often not without something of strength.

**Inthrusting of drift.**—There is a special form of disruptive action which is sometimes especially significant of the character of the producing agency. The beds of rock are lifted from their natural position and drift is thrust in under them, wedging them apart and producing an enforced interstratification of drift and indurated rock. Prof. James Hall figures an interesting example of this in the New York reports.³ Such inthrusting of drift manifestly cannot take place on the lee side, but must, from the nature of the case, be confined to the exposed edges of the disturbed beds. The direction of attack is thus indicated.

The terms "grooving" and "striation" are often used synonymously, and, within certain limits, properly enough, since it is impossible to draw any sharp line of distinction between them. But they are not quite identical in significance. There are glaciated grooves whose large size and whose method of origin make the term striae inappropriate, and, on the other hand, there are delicate, ice-graven lines to which the name grooves is unfitted. It will be impossible, however, to draw a hard and fast line between the two classes, but the distinction has some value in an analytical study.

Respecting their mode of origin glacial grooves belong to two classes which it is of some importance to distinguish, though it may be difficult in many instances to make the distinction in the field. The one class had an existence as grooves prior to the incursion of the ice and were simply molded and modified by it. The other class owe their origin solely to glacial action.

Pre-existent grooves.—Previous to the incursion of the ice, the surface of the rock had been subjected to various destructive agencies which produced great inequalities in it, among which were surface grooves. Thus the invading ice found furrows already formed. Where these lay coincident with its course its work was merely to rasp them out and polish and striate their sides. In their remolded form they may have the aspect of channels wholly due to glacial action; but critical observation often discovers features which, in their nature, indicate that they could not have arisen solely from glacial abrasion. There must have been a pre-existent channel to guide and mold to itself the abrading ice. Among these indications may be enumerated a curved course through a homogeneous rock. Grooves which were entirely formed by glacial action in homogeneous rock must correspond quite accurately with the prevailing direction of the glacial movement and must have an essentially direct course. It is impossible to conceive of tortuous grooves—such as those of Kelley's Island—as having been originated by a straight, on-flowing current. Such grooves must have been originally due to some other than glacial agency. The ice merely remolded them, while it was itself in turn molded to them (Fig. 27).

(1) Even in the case of straight grooves whose alignment is closely parallel to that of the ice movement, the striae are sometimes seen entering the groove from one side and passing very obliquely across and out upon the opposite side. This is satisfactory evidence that the glaciation which produced the striae did not at the same time produce the groove. It does not, however, prove that the groove may not have been made by an earlier stage of glaciation, when the groove may have been accurately parallel to the main movement of the ice. Nor is the inference safely applicable to cases in which the
groove is associated with a fissure or a softening of the rock, whose weakening effect may have determined the excavation of the groove.

(2) The last consideration leads on to the second source of grooving, viz, inequality in the hardness of rock. This finds its simplest expression where beds of unequal hardness were slightly upturned so as to present their beveled edges to the ice which acted along them like a beading plane. In such cases the soft beds were easily removed, while the harder ones were left standing forth as ridges, the whole assuming a fluted surface. Grooves of this sort are little more than an expression of the unequal hardness of the rock beds. On a large scale this is thought to have been sometimes an important factor in determining the topography that resulted from glaciation.

![Fig. 27. Cross-section of glacial groove, North Quarry, Kelley’s Island, Lake Erie. From a photograph.](image)

But, independent of such stratal variations of hardness, there were incidental soft or weak lines of rock which invited the formation of the shorter grooves and gouges. If the softened portion of rock was entirely removed, the cause of the exceptional abrasion may not be evident, but the form of the excavation and the relation of the courses of strie to it are likely to give some indication of the fact that it is not a simple product of glacial abrasion.

(3) That streams of water flow beneath glaciers has been determined by the most abundant observation, but, excepting in the immediate vicinity of the ice border, where alone observation has penetrated, the precise relations of the ice to the stream are chiefly matters of conjecture. Whether the ice continually tends to press down upon the stream and to force it hither and thither at will or whether the stream maintains itself by melting and wearing back the encroaching ice as fast as it presses upon it, and so retains a constant channel, is unknown. It is quite certain, however, that such subglacial streams have much abrasive power, because they are loaded with fine, rasping, glacial silt, a most effective abrasive agency. That
they cut for themselves rock channels is unquestioned; that into 
these the ice subsequently molds itself and, in turn, molds them 
by its own abrasions is attested by observation. It was probably 
not an uncommon phenomenon beneath the great continental sheet of 
Quaternary times, though observation has not yielded much specific 
evidence of it. The most remarkable example is probably to be found 
in the great striated grooves of Kelley's Island, to which frequent 
allusion has already been made. The sinuous form of these grooves 
suggests their primary excavation by a stream of water, while their 
engravure points to their occupancy by ice which was molded to 
their tortuous courses and which in turn refashioned their walls, 
reducing them to those smooth, striated surfaces and those beautiful 
curves that attest the work of a glacier. Some of the less remarka-
bility tortuous grooves of that famous locality seem to have been pri-
marily determined by irregular decay of the limestone along certain 
winding tracts.

(4) Turning from those grooves which are but partially due to gla-
cial agencies, attention is invited to those which owe their origin 
solely to glacial action. Two classes may be here recognized: First, 
grooves due to special gouging tools and, secondly, grooves due to 
exceptionally long-continued or successive scoring. The former 
are usually limited in size and sharply defined, the latter wider and 
more vaguely delimited. As before remarked, the fragments of 
rock that were embedded in the sole of the ice, as it moved forward 
over the face of the land, were its abrading tools. Some of these 
fragments were of soft material and were readily worn into blunt 
forms or crushed beneath the ice; but others were exceedingly ob-
durate and sometimes sharply angular, as blocks of quartzite, quartz 
porphyry, granite, etc. It is inferred that these were forced along 
over the rock surface in various attitudes, because not only their 
sides but their edges and angles are found to be abraded as if by 
such action. When forced along upon a sharp angle they cut into 
the underlying rock and left their mark in a groove of greater or 
less magnitude, according to the pressure under which they were 
driven and the relative softness of the grooved surface. Such grooves 
have definite and sharp limits and a measurably uniform cross-
section, which corresponds to the form of the grooving tool; but in 
the progress of the action the tool itself was abraded and there was 
a corresponding change in the form of the groove.

Single grooves.—Grooves formed by a single rock fragment are 
characterized by a rigid relation of the several parts of the groove. 
Each inequality of the grooving rock necessarily left its mark in a 
subordinate groovelet, and so long as the tool retained its position 
and integrity the subordinate markings must have maintained an

1See Ancient glacial action, Kelley's Island, Lake Erie, by Charles Whittlesey: 
unvarying relation to one another and to the main groove. It can rarely be the case that such unvarying relations, such perfect and rigid parallelism, were maintained by independent fragments. The larger and more complex the groove the less the probability of imitation by a group or by a succession of graving fragments; and it is only in the larger examples that the discrimination has much significance. In case of a large groove, it is of some value to know whether the scoring power of the glacier was such as to excavate it by a single embedded rock or whether it was cut out by a succession of bowlders following the same track. The dynamic implications of the two cases are quite different.

Single grooves should present sharp margins representing the limit of contact between the bowlder and the bed rock, and they will rarely have more than a moderate length, for the bowlder suffers wear as well as the bed rock and—unless the latter be exceptionally soft—must soon become so far blunted as to be no longer efficient as a graving tool. It is also liable to suffer rotation into a position of inaction. The rotation may, however, only bring a new portion of the bowlder into contact with the rock floor and develop a new groove or a new staff of strie, characterized, like the last, by rigid parallelism and unity of production (Fig. 28).

**Compound grooves.**—To be distinguished from the gouges of a single block or bowlder, are those that resulted from a series of such instruments carried along the same track in succession. As above

"The tendency here illustrated of glacial ice to prolong the existing knob into a ridge and the cavity into a groove seems to afford the better explanation of the law of smooth, even furrows, so frequently seen, than the theory that they have been engraved by large bowlders." (G. K. Gilbert: Geol. Survey Ohio, Geology, vol. 1, 1873, p. 540.)
indicated, the groovelets and strie made by the little asperities of the bowlders must show the variations from a strictly identical course which the successive members of the train followed. The general result is a broader, less regular, and less sharply delimited style of grooving (Fig. 29).

The occurrence of clusters of bowlders in some of the great grooves has suggested that there may be an intermediate class of grooves formed by a group of bowlders packed together and pushed along as a single mass, producing simultaneously a belt of furrows that have somewhat fixed relations to one another. A figure illustrative of this is given subsequently (see Fig. 47).

The simple grooves give some indication of the strength of the glaciating agency; the compound grooves may indicate only a coincidence of gouges, none of which alone may represent very forceful action. The coincidence may be fortuitous or it may have an assignable cause. A protruding knob or cliff face of very hard, brittle rock may, by the successive breaking off of blocks, charge the passing ice with sharp, obdurate fragments, and these, carried forward in a train, may readily fall into coincident lines.

(5) A variety of very broad grooving is thought to have arisen from inequalities of glacial flow and pressure. That the ice followed certain great channels in its invasion of our domain has been abundantly demonstrated. In part—probably in very large part—these great channels were predetermined by antecedent erosion, forming preglacial valleys, but, in part, they were probably due to agencies
inherent in the invasion itself. However this may be, both reason and observation attest that the result of such great currents was an exceptional erosion along their beds and the development by enlargement and modification—and possibly by creation de novo in subordinate instances—of great glacial troughs. The Great Lake basins of the interior furnish the finest examples. In these instances the opinion seems well sustained that, before the incursion of the ice, valleys of some magnitude existed which had sufficient capacity to give controlling direction to the ice currents, and that, as a result, exceptional flows were directed through them, resulting in exceptional abrasion and excavation of their beds. Thus effect was joined to cause in the production of these titanic glaciated, though not strictly glacial, grooves. But I apprehend that neither antecedent erosion nor glacial corrosion nor both combined embrace the complete causation of the great basins. This mooted theme, however, is not germane to our present subject.

III. STRIATION.

Under this term are embraced those fine-cut lines on the surface of the bed rock which were inscribed by the overriding ice. The agencies of striation consisted of bowlders, gravel, sand, and clay inserted in the base of the ice or forced along between it and the rock. The character of the engraved lines differs according to the nature of the inscribing tool, the force and steadiness with which it was impelled, the firmness with which it was held to its work, its endurance, the constancy of movement, the homogeneity of the engraved surface, and many other conditions. Reversing the order of thought, we may infer the character of the cutting tool and the force and method of action of the great graving agency from the character of the lines produced. Thus there spring from a study of the glacial linings certain important inferences as to the character of glacial action, independent of the mere determination of the direction of movement. It may be exceedingly difficult to correctly interpret such indications and to draw safe inferences from them; nevertheless, the study is a matter of interest and will doubtless eventually prove to have adequate importance (Fig. 30).

DEFINITION OF THE LINES.

Striae differ widely in respect to the perfection and the character of their definition. This apparently resulted partly from the form of the cutting tool, partly from the looseness or firmness with which it was held, partly from the smoothness or roughness of the surface on which it was inscribed, partly from the texture and lamination of the rock, both of the tool and the bed, and partly from the rate and the irregularity of the motion of the ice. Where any one of these influences became markedly predominant its agency is capable
of more or less certain determination, but where they commingled their influence in a characterless result the individual effects of each are discernible with difficulty, if at all.

![Fig. 30. Striated block showing differences in the definition of the striae, ranging from fine lines, through rough-edged scratches, to rupture gouges and surface bruising.]

The simplest form of striation consists of fine, hair-like lines, as cleanly cut and as sharply defined as those made by a diamond point. So far as I am able to judge from my attempts to reproduce such lines experimentally they were rarely inscribed by the points of pebbles or boulders, but almost universally by fine particles of sand. I am also led to doubt whether they were generally cut by sand embedded in the base of the ice, since sand particles bury themselves without difficulty in its yielding body. Fine striae are, however, readily producible by sand pushed over rock beneath some less yielding backing, and it seems probable that the deep, fine lines were quite largely engraved by sand and silt caught between the larger erratics and the bed rock over which they were being forced.

Well defined, delicate lines sometimes possess sharp, angular edges and sometimes rounded ones. In the former case the engraving particle must have had a sharply definite and presumably hard point, and the engraving must have been the very latest striating work at that spot, for further motion would have worn the edges by the ever-present dirt and rock flour of the glacial bottom. In the latter case, the rounded margin was apparently due sometimes to the blunt form of the engraving particle and sometimes to the wear of polishing material subsequently pressed over it. But to attempt to distinguish relative age by the angular or the worn character of the
margins of hair-line striae may be drawing distinctions a little too fine.

By far the larger number of striae, when closely examined, are found to present rough borders. Among them are furrows that are well plowed, but whose edges are bruised, torn, or hackly. Among them also are all kinds of rude, ragged scratches and scrapings such as would be caused by coarse, dull rocks dragged over the surface. We need not dwell upon the innumerable ill-defined varieties, but certain specific types deserve attention.

![Fig. 31. A striated surface of limestone bearing a gouge characterized by chatter marks; from Montreal, Canada. One-half natural size. From a photograph.](image)

"Chatter marks."—It is well known to machinists that a vibratory motion is very common whenever a gouging tool is forced over a resistant surface if there is any want of firmness in the fixing of the tool, or any unsteadiness of motion, or any persistent unevenness of the surface or of the texture of the material acted upon. Under any one of several conditions chatter marks are the result. The same phenomenon is exhibited by striae much more frequently than appears to have been commonly noted. A considerable percentage of the deeper gouges exhibit it in some degree. These chatter marks, when well developed, are usually curved and have been thought to present uniformly their convex side toward the point of compass from which the motion springs, and thus to furnish an index of the direction of movement; but observation has not yet been carried sufficiently far to make it certain that this is an infallible guide. If proved trustworthy, it will be a criterion of much value, for examples are sufficiently common to give it wide application.¹ Fig. 31 is the best exact illustration at my command, being taken from a photograph of a finely glaciated slab procured from Montreal by Mr. G. K. Gilbert and myself and now in the office of the Survey.

Prof. L. Vanuxem gave, many years since, a beautiful figure of vibratory striae in which the intervals present almost ideal regularity. The specimen is now in the museum at Albany, N. Y., and Prof. J. C. Smock assures me that its perfection justifies the symmetry of the figure.

**Jagged grooves.**—A similar phenomenon is sometimes exhibited by grooves of large size where cut into a rock whose texture is coarse and whose disposition is to fracture roughly rather than to plow smoothly. Fig. 33, from a photograph of a groove in sandstone at Amherst, Ohio, is an excellent illustration of this. It will be observed, however, that here the convexities point forward and the concavities are toward the point of origin. It is manifest that here the gouge was master of the situation and that the rock gave way before it, whereas in the preceding illustration the gouge appears to have been dull and to have been dragged — reluctantly we might almost say — over the surface of the rock under heavy pressure, instead of plowing it up vigorously before it.

**Crescentic gouges.**—Sometimes the intervals between successive ruptures became distant, as illustrated in Fig. 33. This instance furnishes a connecting link between the phenomena of jagged grooves and the more remarkable phenomena of crescentic cracks, next to be noted. In this figure, between the widely separated deep gouges, may be seen irregular cracks of a rudely curved character crossing the lines of striation. Some of these are associated with the strong groove along which lie the deeper curved gougings, while some are associated with smaller independent striæ. In this instance the convexities of the crescent are turned forward, the concavity being toward the point of origin. As this feature is of great interest I introduce a different view of the same example in which the observer looks southwesterly down the line of motion (Fig. 34). Three of the prominent grooves are shown to terminate abruptly in gouges, indicating unquestionably the direction of the moving force. This

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1 Nat. Hist. New York, Geol. Third Dist., 1842, p. 244.
figure also illustrates one of the forms of vibratory markings, the convexities of which are forward or in a direction opposite to that of the chatter marks above described. These examples throw doubt upon the applicability of the chatter marks as criteria of the point of origin until the significance and limits of these apparent exceptions are determined.
Crescentic cross-fractures — In Fig. 35 we have an illustration of crescentic cross-fractures in which, contrary to the fact illustrated above and concordant with that of the chatter marks, the convexities are opposed to the movement of the ice. Along the lee side of the cross-groove in the figure there may be seen drag-lines which show conclusively the direction of the movement. These crescents are upon limestone, which is not a rock favorable to their development, and they are not so perfect as many examples that have been observed. They especially affect close-textured, brittle rocks, particularly quartzite. The cracks usually are quite superficial and commonly not more than one or two inches long, averaging perhaps less than one inch. They indicate an extremely localized pressure and this localization is undoubtedly accomplished by bowlders, which may concentrate upon a point the greater part of the entire pressure they receive, thus possibly intensifying it many fold. A notable part of the pressure comes also from the onward movement of the ice, as shown by the curvature of the cracks, and the hitching motion concentrates this in some degree, in the form alternately of localized stress and of "striking force," if I interpret correctly the modus operandi. It is doubtful, therefore, whether any satisfactory inferences can be drawn from these respecting the depth of ice at the time of their formation, and hence respecting their date relative to the advance and retreat of the ice.

The phenomena of crescentic cross-fractures have been heretofore observed and described by Prof. N. H. Winchell,1 Dr. Edmund

Andrews, Prof. J. E. Todd, and the writer, and all concur in representing the convexities as being toward the point whence the ice came. This appears to be the prevailing fact. But the illustrations given above seem to indicate that it is not universal, or at least that a phenomenon closely akin presents the opposite aspect. The presumption towards which we all naturally inclined, namely, that this was an additional criterion for the determination of the direction of movement, seems to need more rigorous verification before it is accepted.

It is highly probable that the opposite aspect of the curvature in the above instances is dependent upon some radical difference in the scoring action, but it would seem premature to venture an opinion as to its precise nature. I have not been without the suspicion that the cross-gougings of the Amherst region might be due to floating ice borne by waters fringing the Lake Erie glacier after it had retired partially within its basin, the existence of which waters does not appear to me to be a matter of question. But if this were so it would not solve the difficulty.

Jumping gouges.—Closely allied to the chatter marks, crescentic gouges, crescentic cracks, and the jagged gouges is a phenomenon which may be termed jumping gouges, in which the chiseling instrument only cut at intervals, skipping the intermediate spaces. The tool appears in these cases to have been alternately forced into the face of the rock and lifted above it. The action is very much as though the ice were bobbing up and down as it pushed forward. The action is readily explainable on the supposition that the gouges were made by a bowlder held in floating ice, and they do not seem to accord well with the usual action of a glacier. Fig. 36 is an illustration of such jumping gouges. They are immediately associated with the disruptive, crescentic gouges illustrated in Fig. 34, and partially seen at the right, and they are also but a few rods distant from the deep, jagged gouge illustrated in Fig. 32. This adds somewhat to the doubt whether any of these are the product of glacier action.

Lunoid furrows.—Professors Hitchcock, Packard, and Vose have described, under the above term, a peculiar form of glacial excavation having a lunoid outline with its concave side abrupt and turned toward the course of ice movement, while the opposite or convex side

2 MS. report 1883.
4 In the Sixth Ann. Rept. Geol. and Nat. Hist. Survey Minnesota, 1877, p. 106, Professor Winchell states and figures the concavities as turned to the north, but as the statement and figure are reversed in his quarto report of 1884, p. 548, I assume the former to have been simply a clerical error and that the above statement of coincidence is warranted.
is rounded and faces down stream.\textsuperscript{1} These lie in series transverse to the lines of striation and appear to be disposed along them somewhat as the crescentic gouges are in Fig. 34, given above, to which they appear to bear some analogy. They are represented as presenting the concave sides toward the onset of the ice. I am not familiar with them from observation and can express no opinion as to their precise method of formation, and only offer the suggestion, of doubtful value, that they may be related to the phenomena above described.\textsuperscript{2}

\textbf{VARIATIONS IN THE WIDTH AND DEPTH OF STRIÆ.}

While some striæ are nearly uniform in breadth and depth, the large number present variations in both these respects. Of those that exhibit a systematic change three varieties may be noted: First, those which begin shallow and narrow and steadily increase in width and depth until a maximum is reached and then suddenly


\textsuperscript{2} The explanation given by Dr. Packard and incorporated in the New Hampshire report (vol. 3, part 3, 1878, p. 182) is manifestly based upon a misapprehension of glacial movement, that of the glacier as a body being mistaken for that of the individual portions of the ice, which constantly moved onward at a very appreciable rate and never had the forward and backward oscillation to which the lunoid furrows are attributed.
terminate; secondly, those which, beginning and increasing as in the previous case, reach a maximum size and then steadily decline and terminate as they began; thirdly, those which start abruptly and gradually taper out. In these instances there is usually a correspondence between the increase in width and the increase in depth. In the first class the abrading particle seems to have been pressed gradually into action until it passed the limit of its strength and was suddenly crushed, or was rotated out of place, or was in some other manner removed from action; in the second class the particle or point seems to have been brought gradually into activity and as gradually withdrawn; while in the third class the particle or point appears to have been suddenly forced down upon the surface of the rock and then gradually to have been worn out or withdrawn from action. There are occasional instances of striae which suddenly enlarge and deepen, and then suddenly shallow and contract, only to repeat the process again and again, forming a succession of enlargements along the unequal groove. These bear some analogy to the jumping gouges above figured, and may be another expression of the same mode of action.

![Figure 37](image-url)  
**Figure 37.** Clustered striae illustrating the greater apparent than real continuity of striae. From a photograph of a slab of limestone from Rochester, N. Y., in the educational series of the Survey. Scale, about 4-10 natural.

**VARIATIONS IN LENGTH OF STRIAE.**

Striae are exceedingly variable in length. On the whole, I think an attempt to measure them will demonstrate that their average is shorter than might be supposed from a general inspection. Where the rock floor upon which they are engraved is plane, the finer striae often begin and disappear so unobtrusively that they replace one another unobserved and give an appearance of continuity which is not sustained by close inspection. Nevertheless, the stronger and deeper grooves maintain an existence through many feet, occasionally a score and more rarely a hundred feet or more. Facilities for determining the full lengths are limited, because it is rare that very extensive fresh surfaces are exposed to observation and only fresh surfaces retain the striae in sufficient completeness to furnish satisfactory determinations in length unless the furrows are strong and deep.
It is probably worth while to roughly classify strie into the long, persistent varieties and the short, vanishing ones, since the former seem to abound on surfaces that have been powerfully glaciated, while the latter are more characteristic of surfaces that exhibit only feeble glaciation.

**Interrupted Continuity of Striae.**

Strie are sometimes abruptly terminated, and a little to one side a new groove is commenced that seems to be the representative of the former. The interval is sometimes bridged over by irregular abrasions between the two extremities. This has been remarked by numerous observers who unite in the belief that the phenomenon is due to the lateral rolling of the scoring pebble and the resumption of its work of cutting, with a new angle and in a new line parallel to the one it had previously described.¹

An almost equally interesting example of disrupted continuity may be found in the abrupt termination of a strong furrow and in the commencement immediately beyond the point of its interruption of several smaller lines that thence move onward as a group. The probable explanation in this case is that the striating pebble was crushed at the point of interruption of the deeper strie and that the fragments so produced took up the work and cut the group of lines that extend from that point onward.

**Persistency or Deviation of Direction.**

*Straight strie.*—One of the leading characteristics of glacial strie, as distinguished from other forms of scratching, is the persistency of direction which they usually manifest when uninfluenced by obvious topographic causes. Their predominant habit is rectilinear, and the persistency with which a given course is followed, even in disregard of the slope or undulation of the surface, is sometimes quite surprising and is certainly very suggestive of the massive character of the ice.

*Deflected strie.*—Nevertheless, deviations from a rectilinear course are common. These deviations are often so related to curvature of the rock surface that they find a manifest cause in its diverting influence. Currents of ice are often turned aside by embosments of rock or are drawn away from their former course by capacious valleys, as set forth in a previous portion of this paper.

*Angulated strie.*—But several observers have noted abrupt deflections entirely unassociated with any topographic features competent to produce deflection. In the discussion of cross-strie I enumerated a list of influences that tended to produce changes in the course of the glacial currents. The most of these presumably caused gradual changes, giving only a gentle curvation of the strie, but some may

have been measurably abrupt, producing sudden deflections. To these may perhaps be added the special effects of crevassing, particularly the longitudinal form. Just previous to the fissuring the ice is under strain to which, immediately afterwards, it yields, moving in a course somewhat divergent from that previously pursued by that particular portion of the ice. This involves the assumption that crevasses reach the bottom of the glacier within the zone of striation. They are known to penetrate to the base near the margin of existing glaciers, but to what extent they reach the bottom of deep glaciers is a matter of inference (Fig. 38).

Fig. 38. Curved and angulated striae associated with common straight striae and rough gouges. From a photograph of a slab of limestone, in the educational series of the Survey, from Rochester, N.Y.

Curved striae.—We here take no note of striae on curved surfaces or striae manifestly forced into curvature by topographic influence; their significance is topographic; but striae of gentle curvature are common on plane surfaces. When, in other respects, they possess the same characteristics as the common straight striae, with which they are associated, they may deserve attention only in the fact—not an unimportant one—that they are direct evidence of such changes of course in the ice currents as I have argued above must have been incidental to the vicissitudes of a glacial retreat.¹

Curvature may, however, arise from a very different source, and the short, isolated curves are more plausibly referred to such a cause than to a change in the ice movement. The boulders or blocks that do the scoring either directly or indirectly by dragging fine material between themselves and the ice, are often quite unsymmetrical in form, and the part which is brought into contact with the rock may not lie beneath the center of the mass, but at one side, and, as it is held back by the resistance involved in the scoring, the block or boulder may be turned in the plastic ice, giving a curved course to the groove.

Fig. 33. Supposed iceberg striae seen on paving blocks of sandstone at Bellefontaine, Ohio. Said to have been taken from Berea, Ohio.

Supposed iceberg strie.—There are rough, curved gougings, however, which suggest at once the action of floating ice. In grounding, the point of contact or the point of greatest resistance is quite liable
to fall at one side of the center of the mass and induce a rotation of the whole, producing curved gouges. On some paving blocks at Bellefontaine, Ohio, probably brought from Berea, I observed, three years since, some fine exhibitions of curved, crooked, and intermittent gouges, of irregular width and depth and rough, hackly definition, that fulfilled my conception of typical iceberg striae. Fig. 39 presents fac similes of rough sketches made on the ground. Other blocks showed more irregularity of curving and of varying and crossing directions. I measured the curvature of the deep, curved gouge shown in Fig. 39 (a), which cuts directly across the main set, and found that for a chord of 12 inches the versed sine was 2\(\frac{1}{8}\) inches. As Berea lies in the plane region that slopes toward Lake Erie and as there are good reasons, in the nature of its superficial deposits and in its relations to the retreat of the ice, to believe that it was buried beneath a glacier-fringing lake, the existence of iceberg striae there is entirely compatible with the general glacial hypothesis. The jagged gouges and crescentic ruptures at Amherst, Ohio, are similarly situated, and there is nothing in the general glacial hypothesis at variance with their interpretation also as the work of bowlder-shod icebergs. The case stands purely on inherent evidence.

If we search in the character of the curvature for features distinguishing the work of glaciers from that of floating ice, a distinction may be found in the fact that the curve produced by the rotation of a block or bowlder in a glacier, as above described, is limited both in length and in the degree of curvature. The block will only turn until the point of greatest friction falls into line with the center of the block, and, from the nature of the case, the curve will usually be gentle and short. An iceberg, on the other hand, being free, may ground on a point and rotate through a complete circle—theoretically, at least—and may describe any curve within the limits of its radius. Practically, circles would be described only when the grounding point remained stationary, which could rarely be the case. But curvatures of a higher degree than those likely to be produced beneath a glacier would undoubtedly be formed by grounding bergs and floes, and the curved gouges on the flagging above described seem to me to present such an example.
Zigzag striae.—On a bowlder at Whitewater, Wis., I found the zigzag striae represented in the accompanying figure, which were copied by placing a sheet of paper over them and rubbing with a pencil until a truthful, though rude, impression was taken which was reduced photographically and engraved. I have never observed anything precisely like this on bed rock, but the counterpart of this was probably zigzag also. The cause of such a motion I will not venture to conjecture.

ORIGIN AND END OF STRIÆ.

Discriminating characters of some value are found in the way striae begin and end, though in the multitude of cases no satisfactory conclusion can be drawn from these indices: (1) Striae sometimes originate very gradually, the iceward extremity being delicately attenuated, indicating that the abrading point was brought into play by slow degrees. This may imply that the embracing ice was moving in almost perfect parallelism with the rock surface and that the graving particle was little by little extruded from the bottom of the ice and pressed upon the rock, as might have happened from the slow wasting of the contact ice or by its internal motion or by the motion of the particle in the ice. A similar effect might be produced where an attenuating sheet of clay lies under the ice and lets the engraving particle gradually down into action at its vanishing edge, or, where the graving particle was embraced in the subglacial clay, the yielding and attenuation of the latter may have brought it gradually into the control of the ice. There are doubtless other conceivable ways, and, while they may not all be peculiar functions of glacier action, they foster the general impression made on the observer that the aspect of these attenuated anterior ends is more consonant with glacial action than with the fitful pounding of grounding ice. (2) There are other striae that begin more bluntly and widen and deepen rapidly, indicating that the gouging rock was pressed into action more promptly. (3) In still other instances they originate quite abruptly, the head being blunt and unheralded by any premonitory line. Striae do not, however, unless very rarely, begin, as they often terminate, in a deep gouge with an abrupt fractured end, and therein lies a useful means of discriminating between the anterior and the posterior extremities.

Striae terminate somewhat more diversely: (1) In some instances they disappear by gradually narrowing to a fine, tapering, well cut line. (2) In other instances the grooves shallow rapidly and disappear in a blunt, ill defined point. (3) In other cases, without much narrowing, the groove grades out in depth and vanishes by progressive shallowing without lateral contraction, as though the abrading point wore off or was lifted out of action. (4) Still again, the vanishing end is formed by a gradual broadening of the simple groove and its transition into finer and shallower lines, fading out in a brush-like,
cometic termination (Fig. 41). This is not identical with the case above described, where the line ends abruptly and seems to find its continuation in several new lines that appear to arise out of its destruction. In this case the point seems to be worn off and the broadening, blunt point gradually gives place to a surface that ceases to striate.

(5) Still again, as described above, the groove terminates abruptly and may be replaced laterally by a new line or lines or may have no evident representation beyond. (6) In some instances the groove splits into subordinate striae, as though the scoring particles were fractured, but not at once crushed (Fig. 42). (7) The most significant termination is perhaps that in which the groove suddenly enlarges to a broad, deep gouge which is broken off abruptly by a fracture face, showing that the gouging stone first plowed deeply into the face of the rock and was then arrested and turned over or pushed up into the ice (see Fig. 42).

Besides these various forms of true termination, there are many instances of false or secondary termination, caused by the wearing down of the surface after the striae were inscribed. In these instances we see not the original ends of the grooves, but those produced by subsequent filing.

Notwithstanding the distinctions between the heads and the tails of strie, it is impossible, in the great majority of cases, to identify them with sufficient confidence to base conclusions upon them alone respecting the direction of glacial movement. The terminal disruptive gouge affords the most satisfactory criterion and is often entirely conclusive.

THE PROCESS OF STRIATION.

The foregoing phenomena of the definition, continuity, curvature, origin, and disappearance of strie invite a brief consideration of the methods by which striation was accomplished, especially of the methods by which the graving tools were brought into and taken out of action.
It is but repetition to say that the material by which the scoring was accomplished consisted of rock fragments of larger and smaller sizes, pebbles, sand, silt, and clay. It has been indicated that the function of the silt and clay was mainly that of polishing—yet to be considered—and they need mention here only as agencies which modify the definition of the striae. It has also been indicated that erratics may have acted either directly, by scoring the rocks themselves, or indirectly, by catching smaller particles between themselves and the bed rock and thus forcing them to score as neither could do independently (Fig. 43).

(1) If we lose sight of the weakness of the grasp of the ice and conceive it to clasp boulders firmly in its base, the process of striation...
becomes the simplest of conceptions. But the strength of the ice is
limited in its best estate; in the base of a glacier it is pressure-plas­
tic to a varying and undetermined degree and is, withal, subject to
melting in contact with the bowlder from heat derived from com­
pression, basal friction, and conduction from below. If the shearing
resistance of ice under all the conditions of the case were known,
a cross-section of the bowlder being ascertained, the cross-section of
the maximum gouge that it could make might be computed, and it
might be ascertained under what conditions the bowlder would cut the
rock bed, under what conditions it would furrow the base of the ice,
and under what conditions it would divide its cutting between the
two, or would rotate, or would be itself crushed. But, the melting
and plasticity of the ice being variable and undeterminate elements,
precise computation and rigid discussion are impracticable. We know,
however, from observation and specific evidence, that the bowlders
sometimes rode with the ice over its bed and at other times lay on
the bed and were themselves overridden by the ice, while there is every
reason to believe that in many cases the bowlder dragged through
the ice and at the same time moved on its bed, while in many other
instances it rotated in the ice. From a wide and cautious study of
the striation of the bed rock, and, not less, of the drift, under the
light shed by existing glaciers and the necessary conditions of glacial
action, rational conceptions, doubtless approximate to the truth, may
be formed and will certainly be serviceable, but they remain intel­
lectual substitutes for the real action, and mental estimates thereon,
rather than strict inductions from ascertained facts or deductions
from determined mechanical data.

As it is certain that the amplitude of glacial conditions was such
that bowlders sometimes moved and sometimes lodged, sometimes
gouged deeply and sometimes slid lightly over the surface, the
special conditions that determined different modes of action are
those most important to consider. Those conditions that relate to
the different states and actions of the ice itself have already been
considered in another connection; those that relate to the different
positions and functions of the debris in the ice remain to be noted.

If the bowlder was large and presented a very considerable surface
to the embrace of the ice and only a relatively small surface in con­
tact with the bed rock, this contact point may have been pressed
upon the bed with considerable force without loosing the hold of
the ice, so that steady and persistent grooving may have been effected.
If, on the contrary, the block embraced in the ice presented to the
bed rock a broad, rasping face and was not deeply inserted in the
ice above it, so that its hold was small relative to the friction upon
the base, the ice may have flowed over the block instead of forcing
the block over the bed rock (Fig. 44). But if the block had
a broad, smooth face, it may have moved, but rather as a polishing
than as a scoring agency. If the boulder was rounded or nearly equidimensional, its form was favorable to rotation when the friction of contact became strong. From the fact that the great majority of glaciated pebbles and boulders are striated on their several sides and in discordant directions there can be little doubt that rotation was an exceedingly common mode of action; indeed, their glacially rounded condition is evidence that they habitually changed their position. In some instances there is direct proof of rotation in the concentric curving of the markings on them, as illustrated in the spiral lines of the accompanying figure (Fig. 45).

The fact that so large a majority of glacial grooves are short is probably partly due to the turning of the scoring rock and is a further indication of the frequency of rotation.
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With conditions favorable to rotation spheroidal erratics could have readily turned upon themselves, while irregular blocks and flat slabs would have held their positions with greater persistency. This accords in a general way with observation, but so various were the conditions at different stages and in different situations, that flat fragments are sometimes found to have been well rubbed on all sides and angles, while spheroidal pebbles were sometimes held firmly and planed and striated on a single face.

In view of all the probable conditions, it seems doubtful whether boulders simply embedded in ice and acting alone accomplish so much of the deep, prolonged striation as is commonly attributed to them. Considered independently of their relations to one another and to fine débris they probably produced prolonged striation chiefly when they presented relatively large surfaces to the ice grasp and relatively small, angular, or rough portions to the rock; otherwise they were probably either rotated, after making short gouges, or were soon smoothed to polishers.

![Diagram illustrating the supposed overriding of small débris by larger.](image)

(3) The mutual relations of the débris as it came into action clearly gave rise to special results, and I think that some notable measure of the finer striation, as distinguished from the rough gouging and scraping on the one hand and the light scratching and polishing on the other, was due to the joint action of large and small débris. A study of glaciated pebbles and boulders makes it evident that a large part of their striation was not inscribed by rubbing on the rock bed, but by interaction upon one another or upon the drift bed (Fig. 46). Much of this appears to have been due to the latter, but this part is measurably distinguishable by the evidence of the pliancy of the drift matrix, which the scratches and polishings of the pebbles exhibit. But there is another class of striation on boulders and pebbles that seems to indicate that they were forced over sand and small bits of rock caught between them and some firm bottom, presumably the bed rock (see Fig. 43). Such entrapped sand must have been dragged forward on the bed rock, as well as backward relative to the boulders, and so must have striated both at the same time, if they offered about equal resistance. Where the particles thus forced to pass between the upper and nether glacial millstones were enduring, as quartzose
sand, fine, firmly cut lines doubtless resulted. Where larger, obdurate particles were entrapped, deeper scorings were made. Under this view the abrupt origin and disappearance of some of the strie are quite readily accounted for. When a particle was overtaken by a slab or a flat-bottomed boulder embedded in the ice, it was forced strongly into the under surface and kept in action as a graver until the boulder passed over it—unless sooner worn out or crushed—when it was abruptly freed from the exceptional pressure. It is probable that the particle was not carried along at an equal pace with the overriding mass, but rather lagged behind, because of the exceptional friction upon the bottom. If the two rocks offered equal resistance to scoring it may be roughly assumed that the length of the line upon the bed rock was equal to the diameter of the overriding boulder; in other words, that the under side of the boulder was scored equally with the bed rock. But whatever may have been the proportion of scoring suffered by the boulder and by the bed rock, respectively, there must have been a limit to the time the particle remained between the upper and the under millstones, and the moment it escaped at the rear edge it ceased to be a graving tool and the stride abruptly terminated.

OTHER MODES BY WHICH SCORING DEBRIS WAS BROUGHT INTO ACTION.

In the last paragraph one of the methods by which a particle is brought into scoring action was indicated. Some others have been implied before. Others require brief statement here. Among them are the following:

(1) By melting.—There can be little doubt that the friction of the moving ice upon the bed rock generated a sufficient amount of heat to melt a portion—possibly quite small—of the contact ice, and thus the glacier was slowly reduced at its base. It is also probable that the interior heat of the earth was sufficient to melt a certain, but very small, additional quantity of ice. Every observer of such matters is familiar with the thawing of the earth during winter under deep snow and that the thawing is from below upward. The great depths of glacial ice were probably quite sufficient to cut off external atmospheric temperature, in the main, and to give free activity to so much of internal heat as the conductivity of the rocks was able to bring to bear. In thinner portions, not so protected, the direct penetration of solar heat, arrested at the base, may have added a greater or less contribution. We know, at least, that considerable streams continue to issue from most existing glaciers during the severities of winter, in both Arctic and Alpine regions, and, whatever may be the source of the water, even if it be due to springs, a certain amount of wastage of the glacier below must be assumed. Now, this wastage tends to bring down ice from above and with it the embedded rock débris, which thus comes into scoring action.
(2) By precipitation through crevasses.—The familiar phenomena of Alpine glaciers have taught us that the breaking open of a glacier not only permits rock fragments that may have lain over the fracture, or so close to the brink as to be thrown down by subsequent melting, to be precipitated to the bottom, or at least into the interior of the ice, but that it furnishes an open passage by which superficial streams plunge to the base and carry down such fragments of rock as they may have been able to transport along their courses. In continental glaciers, if we may judge from that of Greenland, the crevassing is impressive, but very little material is transferred from the surface to the base, because of the comparative absence of superficial débris. To some extent débris near the base might be carried to the bottom, if crevassing there attains any considerable development, which is doubtful. Superficial streams, however, traverse this portion in their descent and must carry down some material. The material thus borne down is perhaps largely retained within the channels of the subglacial streams below, and may not, in any very large measure, become entrapped between the ice and the bed rock, and so become a striating agency. But, as such streams are doubtless disturbed in their courses, a portion of their débris is probably overridden and becomes a part of the basal armature of the ice. It is doubtful, however, whether crevassing played any important part in bringing the débris of the ancient glaciers into the plane of action.

(3) By quasi-fluidal movement.—It is an old demonstration that the movements of glacial currents are closely analogous to those of any stream and that, to all general intents and purposes, the motions of glacial ice may be viewed as those of a stiff liquid. If this holds strictly true as to the interior and basal currents of the ice stream—which, I think, has only been approximately demonstrated—there must have been something of the rolling and gyrating currents that characterize rivers. If developed at all, these would probably affect chiefly the basal portions, which, by virtue of their pressure, were the most plastic and also the most affected by bottom inequalities. Since, however, such rolling and gyrating movements are largely dependent on rapidity of motion, there is ground for hesitation in assuming that there was any very free interchange between the basal and the juxtabasal currents. Nevertheless it is probable that rock débris in the juxtabasal strata of the glacier may have been brought to the base in greater or less degree by such quasi-fluidal movements.

(4) By gravitation.—While ice is competent transiently to support masses of rock of much greater specific gravity than itself, yet abundant experimentation has shown that, when at or near the melting point, continued pressure brought to bear by a body of greater specific gravity causes yielding, and the body very slowly descends.
In the plastic interior of a glacier, where movement is continually in progress, with every shift of the particles some opportunity is afforded for the superior gravity of the heavier mass to pull it to a lower position. This seems theoretically irrefutable, but existing glaciers do not appear to have offered much direct evidence of its practical effectiveness. Still it cannot be doubted that a certain measure of influence was exerted by gravity tending to carry embedded masses of rock to the base of the ice.

(5) By derivation from the bottom.—The foregoing considerations relate to the bringing of masses down to the rock surface from some position in the ice above. It is natural to consider the striating débris as coming from above, because each groove gives evidence that a point descended upon the surface undergoing striation, as the necessary condition of its origin. So, starting from a study of striae, we naturally approach the subject in this aspect. But the chief ultimate source of the débris was the bottom itself. In part, it was only necessary that pre-existing débris should be embraced in the ice and moved along beneath it, perhaps to some extent only pushed along, without even being embedded. In part, the ice shed itself by detaching rock from its bed. The method of picking up slabs from their stratified position and bringing them into action is sometimes indicated by the positions in which series of them are left. The ice-ward edge appears to have been lifted and forced up into the ice until a high angle was attained, when the whole was carried out of its place and pushed forward on its edge, a position which, however, it probably soon lost.

(6) By rotation.—It has been observed that a block or flat-bottomed boulder may be moved along the surface of the bed rock with very little scoring effect, because smooth, flat surfaces are in contact. Such blocks, however, may be made to present a graving angle by being rotated in their positions in the ice. This rotation may be brought about by the edge of the block encountering some obstruction on the surface of the bed rock, a projecting layer or obsturate knob of rock, or by the forward side becoming depressed in crossing a gaping fissure and catching on the opposite side, or by other agencies readily conceived. The block thus tilted upon a rough edge or point becomes an efficient scoring agent until by further rotation it is carried into a new position.

(7) By mutual action of subglacial débris.—It has been remarked previously that the striae of the boulders and pebbles appear to show that the interaction of subglacial débris was an important agency in striation. It is idle to attempt to picture all the possible conditions of action. Glacial rubbish forced other rubbish into action or out of action in innumerable phases. Subglacial till protected certain surfaces and left others exposed, and perhaps suffered fluxion itself, with incidental striation. The consideration of these activities is more
germane to a discussion of the abrasion of the débris itself and of the deposition and structure of the till than to that of the striation of the rock surface. It may be helpful, however, to contemplate the possible agency of a bunching of boulders in hollows and troughs in the rock surface until they are forced to move as a mass, when they may produce those grand channelings and compound flutings of which Kelley's Island furnishes such fine examples. This possibility was suggested by the cluster of boulders in the groove represented in the following figure. This suggestion did not, however, arise while I was on the ground and was not tested by observation. The trough extends beyond the group of boulders and was not originated by them (Fig. 47).

![Fig. 47. Erratics clustered in a glaciated groove, illustrating a possible method of joint action in producing compound furrows.](image_url)

**REMOVAL OF SCORING DÉBRIS FROM ACTIVITY.**

It is as important intellectually to understand the methods by which strie were terminated as to understand those by which they originated, or, in other terms, to understand how particles were taken out of action, as well as the methods by which they were brought into it. Several of these methods have been either stated or implied.

1. **By rotation.**—If the rotation of an erratic embedded in the ice may bring it to bear on the bed rock it may also throw it off. Indeed, the very resistance encountered in the process of scoring necessarily tends to this end. The rotation that brings it into play is incidental, but that which carries it out is inherent in the action itself.
By quasi-fluidal movements.—So, also, if the fluidal movements of the plastic ice tend to bring boulders into contact with the bed rock they may tend to remove them from such contact. It has been remarked by numerous observers that boulders have been carried from a lower to a higher altitude. This has been thought by many glacialists to imply an upward movement through the body of the glacier. While it is not certain that such transportation may not have been accomplished in many cases by following the basal currents of the ice up the slope of the eminence on which the boulders are found deposited, still there are grounds for belief in internal upward movements, as, for instance, in the winter fattening of a glacier and in the sinuous and changing currents before alluded to.

By removal of the rider.—As indicated above, a particle that has been brought into scoring action by being overridden by a block or boulder is relieved of such action when the mass has passed over it.

By crushing.—In the statement of the character of the terminations of stria it was noted that a strong furrow sometimes ends abruptly and roughly and that there passes onward from its extremity a series of finer lines. This was interpreted as signifying the crushing of the particle into fragments, which then severally started new striae and thus moved onward. If, however, the fragment was nearly homogeneous, the crushing may have so far reduced it to powder that it ceased to be a scoring agent and became merely polishing powder.

By wearing out.—The competency of a particle, large or small, to score a rock surface may have been destroyed by wearing. When the mass was large, the angular portion in contact with the bed rock, which at first was competent to furrow, gradually became worn by the process until too dull to visibly abrade the surface. It was degraded to a polishing agency, except so far as scoring particles were caught beneath it. Small grooving particles were doubtless often entirely worn out, especially when caught beneath larger ones. We are apt to fasten our attention upon the abrasion of the bed rock and overlook the fact that a corresponding abrasion must have been suffered by the scoring tools. A limestone fragment forced over a limestone bed must have suffered not only equal but more abrasion than the limestone bed, because its form was less resistant. It presented an angle, or a convex surface, held by cohesion only upon one side, while the bed rock presented a surface held by cohesion on all sides but one. A particle removed from the furrow was held by greater cohesion than a particle removed from the furrowing stone. So in general, with like rocks, the gouge suffered more wear than the gouged surface. Even where a harder rock acted upon a softer one

1 See Note on the occurrence of erratics at higher levels than the rock-masses from which they have been derived, by James Geikie: Trans. Geol. Soc. Glasgow, vol. 4, p. 235.
the amount of reduction of the graving particle, because of its form, was large in proportion to their relative hardness. The cumulative effect of this wearing process was to substitute polishing powder for scoring points, and hence the great preponderance of the phenomena of polishing as compared with the phenomena of scoring. Polished surfaces, especially of hard rocks, are often found of considerable extent, over which distinct grooves are very rare.

IV. POLISHING.

The preceding remarks have opened the way for the consideration of the subject of polishing in distinction from striation. Indeed, they have largely anticipated what might otherwise need to be remarked under this head. The distinction between striation and polishing has been here drawn as a classification not simply of bare facts, but of factors significant in the study of glacia tating processes. Striation and polishing imply not only different agents, but different conditions — conditions not separated indeed by hard and fast lines, but by differences of manner and of meaning.

Polishing of two orders may be distinguished: (1) polishing by wear and (2) polishing by pressure. To illustrate, two pieces of wood may be made to polish each other by being lightly rubbed together until the attrition has removed all roughness or by being forcibly rubbed together until all roughness has been subdued by pressure. The dominant element in the one case is wear, in the other compression. The resulting surfaces are not identical. In like manner there are polished rock surfaces in which attrition was the chief agency and others in which great pressure produced its distinctive effects, unless I have misinterpreted the phenomena.

Attrition polishing.—Polishing as the result of light abrasion may have been due to material either too fine or too smooth to abrade coarsely or too lightly pressed upon the surface. Of fine material there were (1) the preglacial clays, soils, and silts and (2) the rock flour produced by the glacial grinding. Two great stages of polishing may be theoretically recognized, based on this seemingly unessential distinction of material, the one pertaining to the first invasion of ice, when nearly the whole surface was mantled by residuary earths, interposing a polishing, anti-striating sheet, and the other pertaining to the closing stage, when the production and subglacial accumulation of rock flour reached its maximum. (3) The flat, smooth surfaces of erratics also appear to have been polishing agents under light pressure, both by their direct action and by giving effect to the fine material under them in the manner so familiar to our marble workers.

Under light pressure, material otherwise competent to scratch and score may only polish. It is a familiar fact that if sand be moved very gently over a rock surface it will polish rather than scratch it.
The same is measurably true of rock surfaces. So far as this element is concerned, polishing was coincident with light glacial pressure, which chiefly pertained to the border tract and the closing stages.

Pressure polishing. — I do not know how better to indicate the distinction between attrition-polished and pressure-polished surfaces than by recalling the well known distinction between the surface texture of wood treated by the two methods, the smooth but porous character of the one, the compact, glazed texture of the other. The surfaces of slickensides furnish the best known natural example of the latter. A hard, compact surface glazing, associated with deep, strong grooving, affords the best criterion for identification. This form of polishing seems to be by far the least prevalent on existing surfaces. Obviously it was liable to obliteration as fast as formed, and it is not strange that it should have been widely replaced by lighter-pressure polishing as the glacier withdrew.

Taking limestone surfaces, which are about equally well adapted to receive polishing and to receive striation, as a basis of judgment, I estimate that the area of the polished portions of the surface is greater than the area of the striae. It does not, I think, follow, however, that the corrosion of the lighter attrition was greater than that of the scoring abrasion. It certainly would be unsafe to make that inference for the whole period of glaciation, since that is not fairly represented by the surfaces left for our study, which in every case mark the cessation of the work on that surface. The prevalence of polishing seems, in some general sense, to indicate relatively light pressure and relative abundance of clayey material beneath the ice, conditions which, there are other reasons for believing, prevailed in the closing stages of glaciation. Inferences are to be drawn from the prevalence of polishing only with great caution. There are many qualifying conditions. For instance, a glacier passing from a granitic region into one of limestone would be armed with abundant sharp, cutting material, while polishing powder would be largely absent, as may be seen by an examination of the glacial debris of the Chamouni region. On the other hand, a glacier passing from a region of shale, as that of the Cretaceous districts of the interior, would be armed mainly with soft material competent to polish, but incompetent, in the main, to striate.

Without dwelling at unnecessary length upon the complex conditions that determined the prevalence and character of glacial polishing, increased attention may be invited to it as the counterpart of striation, bearing its own peculiar testimony respecting glacial material, motion, and pressure.

Glacial polishing distinguishable from that of wind or of water. — There is little difficulty in distinguishing glacial polishing from that of wind or of water. With the former there are almost constantly associated characteristic strie and planed surfaces. With the latter
there may be impact marks, but rarely true striae, and the surfaces they develop are undulatory, of a style quite different from glaciated faces and quite well known.

V. PLANATION.

Each of the foregoing processes contributed toward planation. The disruption and overthrow of rock prominences by the massive action of the ice produced that major leveling of the surface that may be most strikingly realized by comparison of the topographies of adjacent glaciated and non-glaciated regions. The scoring was most strongly impressed on rock prominences and tended to reduce them. The finer furrowings and striation aided in the same direction, as did also the polishing and the more gentle forms of abrasion. For obvious reasons the general effect of all kinds of abrasion was planative.

This general law, however, is not without its exceptions. A glacial stream, like other streams, has its own differential habits of action, and under a general disposition to subdue the surface to a plane aspect there was a subordinate tendency to develop inequalities suited to facilitate its own flowage, just as the general effect of surface waters is to reduce the entire drainage area to a common base level; but, as a step toward it, inequalities are developed often more pronounced than before; so, to a less degree, glacial action developed inequalities as a feature of its general work of planation.

The same law which differentiates the erosion of the great aqueous streams differentiated that of the ancient ice currents.

This differential action is of some importance in estimating the amount of corrasion which the glaciated surface has suffered. If the glaciers had been absolutely rigid, so as to have filed down the summits of the hills only until the whole surface was reduced to a plane, it would have been comparatively easy to estimate the amount of reduction which the surface suffered by computing the truncation of the summits. But in most situations there was an adaptation of the glacial rasp to the surface and a more or less common reduction suffered, as set forth in a previous part of this discussion. Moreover, in the great valleys that became the chief glacial avenues, the abrasion was greater than upon the hills and uplands and the inequalities of topography were increased. This constitutes a great reversal of the law. No competent observer will question that the Hudson River Valley suffered more abrasion than the adjacent heights of the Catskills, nor will any discerning student of the region doubt that the highlands of Michigan and Wisconsin suffered less severely than the lowlands on the adjacent lake borders, nor will he probably hesitate to carry the inference to the lake bottoms themselves.

The whole of the problem of glacial abrasion does not fall within our present province. There are lines of approach other and more
important than that through the testimony of scoring. But, there are two valuable considerations immediately connected with it that deserve our thoughtful consideration.

The aid of striation in estimating glacial erosion.—By collating the courses of the strie it is found that the great glacial movements lay through certain great avenues and that from these there diverged laterally subordinate currents. It is a matter of sound inference, supported by observation, that the great channels were the tracts of great abrasion, while the lateral currents produced comparatively feeble effects upon the adjacent country. The determination of the great courses of glacial movement is an essential preliminary to a rational estimate of the effects produced by the glacial wear. It is as illegitimate to infer from the slight abrasion of the marginal areas that the ancient glacier did but a feeble work as it would be to infer from the slight corrasion accomplished by the lateral overflow of a swollen river that the great river itself was an incompetent eroding agent. Before any trustworthy conclusions can be drawn as to glacial abrasion, account must be taken, definitely and specifically, of the distinction between the work in the main channels of glacial movement and that in the tracts merely overspread by peripheral dispersion. The work in the one was as impressive as it was insignificant in the other.

Observations on the character of the striated surface.—Within certain limits the amount of abrasion which the surface has suffered may be approximately determined by the character of the scored surface. It is well known that the natural face of rock which has been long exposed to weathering is more or less deeply affected by disintegration and changes of coloration. Limestones are usually much corroded, crumbled, and dissevered, and the original bluish or grayish colors, due to ferrous compounds, are changed to yellowish and reddish hues by oxidation to the ferric state. This is only a type of what is more or less true of other classes of rock. The depth to which this superficial modification extends is quite various. It is perhaps more dependent upon the depth of the common underground-water level than upon any other single condition. The superficial changes usually extend downward to the permanent water level along the crevices and other accessible portions, even where the changes do not penetrate to the cores of the more solid masses of rock, so that an entire absence of visible oxidation and disintegration is not usually found above the water level. On the other hand, below the common water level general oxidation seems not to be prevalent, though disintegration of a less striking kind deeply permeates the rock.

Where the amount of glacial reduction is slight the strie are inscribed upon oxidized and disintegrated rock, which testifies to the fact of slight erosion. Abundant examples are presented in which
the rough, etched surface of the rock has not been entirely cut away, but only some of the more protuberant knobs here and there have been truncated by the planing agency. In other instances the striated surface shows a further step, the rough projections resulting from disintegration having been cut away to a common plane, while the disintegrated faces of the fissures and the deeply corroded spots still remain to signify the limited extent to which abrasion has extended. Still, again, the more notably disintegrated portions have been cut away and the unoxidized fresh cores exposed, bordered only along the fissures by disintegrated and oxidized surfaces, indicating that the reduction has reached a plane below the horizon of complete disintegration and oxidation, but not below the reach of surface agencies where favored by fissures.

Still, again, instances may be found in which the whole planed surface is as fresh as any known ancient rock. Indications of oxidation and disintegration of the kind characterizing this action are wholly wanting; the ferrous compounds show no indications of higher oxidation; the decomposable portions are not disintegrated; the crystalline facets are as clean and fresh as if the rock had been taken from any known depth; in short, every trace of ancient superficial disintegration has been planed away and a perfectly fresh surface has been presented.

In such a series as this we find a measure of the amount of glacial reduction. To transpose such observations into exact terms of measurement is only approximately possible because of the uncertain elements which have been above indicated. Nevertheless they furnish valuable data and serve as a check against extravagant estimates of glacial reduction on the one hand and against a too narrow conception of erosive action on the other.

It is, therefore, very desirable that in the notation of glacial polishing and striation the degree of disintegration and oxidation of the planed surface should be carefully noted. The limestones present the best field for such observations, since, in general, the effects of oxidation are more remarkable and more distinctly recognizable in them than in most other rocks.

METHODS OF DETERMINING THE POINT OF MOTION.

Incidentally in the foregoing discussion the methods of determining the direction of the glacial movement have been indicated, but the importance of such determinations in instances where the striation deviates much from the general southerly course, and even in a few instances of nearly meridional directions, is such that it may be helpful to group together the indices of direction. It will be largely a recapitulation.

Knobs and trails.—In the attrition to which the rocks were subjected, hard, resistant particles were caused to stand forth as knobs
on the planed surface. These protected the softer rock immediately in their lees and thus gradually developed a raised trail following the embossment, showing in the most convincing manner the direction of movement (Fig. 48). In some instances a frontal groove was developed, attended by lateral grooves sometimes prolonged to the rear on each side and fading out at some distance (see Fig. 21, p. 194).

Advance cones.—In rare instances the phenomenon represented in the accompanying illustration (Fig. 49) is found, consisting of a half cone in bas-relief on the face of the glaciated rock, the apex of which is directed toward the point of origin of motion and the base of which is unworn, as is also a limited space in the rear. The origin of such a structure is not obvious.

Abrasion of the distal side of cavities.—In passing across a crack or cavity in the planed face of rock the ice was pressed downward and by its plastic yielding was made to impinge upon the farther edge of the cavity or crevice, rounding its edge and perhaps even developing shallow fluting in the wake of the cavity, as illustrated in
Fig. 18. This phenomenon is so common as to have wide applicability as a criterion of direction (see Fig. 18, p. 188).

**Drag-lines.**—Attention has already been called to a series of short, feeble lines originating on the lee side of an older glacial groove where crossed by younger ones. It is but a narrow fringe of friction lines, but is quite distinctive (see Fig. 24, p. 201). They are best shown on dark limestone.

**Stoss and lee phenomena.**—If from the common surface of the rock a ledge rises higher than its fellow rock, presenting a miniature plateau or terrace or forming a prominence of any kind, whether of the major or minor order, whether a small knob or a massive hill, the course of movement may be indicated by the inequality of the scoring action suffered. The iceward or stoss side may alone appear striated, while the lee is found rough, un-scored, and unpolished. The nature of this action has been abundantly pressed upon attention in the previous discussion.¹

**Truncation of prominences.**—When both stoss and lee sides have been striated, the superior degree of truncation of the stoss side may be such as to indicate that it has received the brunt of the abrasive action. The value of this criterion depends upon the confidence that can be reposed in the discrimination of the observer.

**The phenomena of “plucking.”**—On the iceward side of prominences loosened rocks were pressed against the surface and not easily dislodged, but on the opposite side the force of the ice was exerted in a manner favorable to the removal of blocks as fast as disrupted. The freedom of the lee sides of prominences from striation is probably in part due to this, and not wholly to failure of the ice to close in behind them. As criteria of direction of glacial movement it is unessential to distinguish between the two cases (Fig. 50).

**Fluted hills.**—Some valuable hints and some approximate demonstrations of the direction of advance are occasionally offered by hills whose sides have been fluted on a scale too large to be denominated groovings and yet partaking of that general nature. These great grooves originate on the stoss ends, but do not follow the contours of the hills around into the lee.

All the foregoing are fundamentally phenomena of the same class.

**Character of the ends of scratches.**—Attention has already been directed to the method of origin and termination of the striae and to something of their significance. Though the discrimination is often quite difficult and unsatisfactory in any given case, yet the number of scratches on a given surface is usually so great that a careful study of many examples may furnish a sufficient basis for a confident opinion, though the observer might not choose to trust to the indications of a single instance. Striae rarely originate with extreme abruptness; the grooving tool may have been brought down

into action with some promptness and force, but it leaves a gradu-
ated mark at that extremity. On the other hand, the pebble is fre-
quently taken out of action with great suddenness and the terminal
extremity of the scratch may be an abruptly ended gouge. So, also,
the groove may break up and terminate in several minor lines, which
may be the manifest work of fragments of a crushed pebble. The
opposite phenomenon, that of several small lines joining and forming
a single groove, must, from the nature of the case, be rare and not
precisely analogous, even when it closely simulates it. So, likewise,
the several methods by which strie fade out are more or less indica-
tive.

![Figure 50](image-url)

**Figure 50.** A fluted and striated surface showing the influence of position on the stoss or lee sides in relation to "plucking." In the right lower portion will be seen a fissure passing down to the right, largely or wholly dissevering a block, but being on the leeward side it has retained its position, only suffering a little breaking at its edge. But on the left side, both in the lower and upper corners, will be seen faces from which similar blocks have been manifestly removed, they being upon the lee side. Besides this phenomenon the illustration shows fine glacial fluting and striation. From a photograph of granitic rock, Victoria, B. C., seen looking westward.

**The roll of a pebble.**—When a pebble is rolled out of the track it has been grooving and begins a new scratch, the termination of the one and the beginning of the other are apt to furnish features that deter-
mine the course of movement, though the discrimination may be
often unsatisfactory.

**Chatter marks.**—As previously explained, a fragment of rock act-
ing as a gouging tool often produces "chatter marks," little trans-
verse lines of breakage due to the unsteady action of the tool in gouging the rock. These are quite common phenomena, though they seem to have generally escaped observation, because they are far from being obtrusive and often require close inspection for their detection. The convexity of these markings is usually turned toward the direction whence the movement came.

*Disrupted gouges.*—Of the same nature as the chatter marks, but of much more striking character, are the occasional disrupted gouges that mark the action of a manifestly large mass of rock carried forcibly over a rock surface whose nature favors a coarse, rough breakage rather than a smooth gouge. As previously stated, the examples of this, illustrated by Figs. 33, 34, and 36 present their concavities toward the point of advance of the ice.

*Crescentic cracks.*—On extremely hard and brittle rocks a series of short, curved, concentric cracks are sometimes observed to mark the course of striation. These cracks, although very closely allied in nature to chatter marks and disrupted gouges, yet appear to be a somewhat different phenomenon. The convexities of the cracks, so far as yet observed, are turned toward the point of origin of movement.

Aside from and supplementary to the foregoing indications of direction of movement are those evidences that are derivable from transportation of the drift, the position of boulders or tilted blocks, the inthrusting of drift between the exposed layers of ledges, and other phenomena that lie outside of my present province.
OBSIDIAN CLIFF,
YELLOWSTONE NATIONAL PARK.

BY

JOSEPH P. IDDINGS.
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OBSIDIAN CLIFF YELLOWSTONE NATIONAL PARK.

BY JOSEPH P. IDDINGS.

INTRODUCTION.

The tourist who, in his wanderings in search of entertainment, adventure, or health, has been so fortunate as to visit the great National Park vividly recalls how, on the first day's ride from the Mammoth Hot Springs to the geyser basins, after traveling up the picturesque road along Glen Creek, at the northern base of Mount Bunsen, to Rustic Falls, he came upon Swan Lake Valley and beheld for the first time the grand and imposing peaks of the Gallatin Mountains, which extend from Electric Peak, 11,000 feet in height, southward to Mount Holmes, with an altitude of 10,300 feet. After driving over open country to the crossing of the Gardiner River and through the flat-bottomed valley known as Willow Park, he entered the timber and rode along the west bank of a narrow stream, which fights its way through grass and fallen trees, until he reached the northern end and outlet of Beaver Lake. On his left, to the east, stretches a long, low cliff, the southern end of which is formed of nearly vertical columns of black obsidian, or volcanic glass, which has resulted from the rapid cooling of a perfectly fused, igneous rock. From this great blocks have fallen and accumulated at its base in a talus slope, over which has been built what is popularly known as the glass road, the material of which it is made being as true a glass as any artificially produced. The colors and structure of this natural glass not only make it the most interesting rock the visitor will find, but the phenomena of its occurrence in this locality are of special scientific importance, and the present paper has been prepared with the view of describing and explaining it.

GEOLOGICAL OCCURRENCE.

Obsidian Cliff is at the northern end of Beaver Lake, in the Yellowstone National Park, about eleven miles south of Mammoth Hot Springs. It forms the eastern wall of a narrow cut in the plateau country through which Obsidian Creek flows at an elevation of 7,400 feet. The cliff extends for half a mile, rising from one hundred
and fifty to two hundred feet above the creek and falling away gradually to the north; the upper half is a vertical face of rock, the lower portion a talus slope of the same material. Back of the cliff to the east the country rises in a series of rude benches to about four hundred feet above Beaver Lake; at this level, a little south of Obsidian Cliff, the edge of the plateau forms a small cliff fifty feet high, above a long, steep slope east of the lake. From here the top of the plateau rises in hillocks and basins eastward to an altitude of about eight thousand feet above sea-level. On the opposite side of Beaver Lake and Obsidian Creek abrupt hills slope up to the plateau country west. The whole region in this vicinity is thickly timbered with a small growth of pines.

The cliff presents a partial section of a surface flow of obsidian which poured down an ancient slope of rhyolite from the plateau lying to the east. The underlying rhyolite has a purplish-gray color and is readily distinguished from the black obsidian, as well as from the lithoidal portions of the obsidian flow, by the abundance of porphyritic crystals of quartz and feldspar which fill the older rock, the later flow being entirely free from them. The older rhyolite is not exposed beneath the obsidian along the creek, but is first met with in the edge of the timber south of the end of the cliff, where a narrow drainage channel has cut into the slope. This rhyolite rises higher to the south and forms the long slope east of Beaver Lake, above which is the low cliff already mentioned. This cliff is of obsidian, which is exposed in a vertical section of more than fifty feet. Following the obsidian back from the face of this cliff up the hummocky surface it becomes filled with gas cavities and passes into banded, pumiceous rock and finally into light-gray pumice. This covers the surface of the plateau for two and a half miles eastward to the valley of Solfatara Creek, which drains into the Gibbon River; here, again, the lava flow is exposed in a cliff the lower portion of which is black and red obsidian. Toward the south the obsidian flow extends for a mile beyond the Lake of the Woods, and northward across the east and west drainage, which cuts off the higher portion of the plateau, a distance of some five miles.

What was the original thickness of this lava sheet it is not possible to say. The dense glass, or obsidian, forming the lower portion is from seventy-five to one hundred feet thick; the porous and pumiceous upper portion has suffered more or less erosion, which was in part the result of ice action, the evidence of glaciation being more marked along the lower western slope of the plateau than on the top of it. The surface of the plateau is mostly pumice, with little if any glacial debris scattered over it, but along the western slope the rock has been worn down to the massive obsidian, and the top of the cliff is covered with planed and striated glacial drift from a great variety of sources.
Half a mile southeast of Obsidian Cliff, on the plateau, about five hundred feet above the level of Beaver Lake, is a circular pit 100 feet deep, the mouth of it being 300 feet wide by 350 feet long; its sides stand at an angle of 35° and appear to be formed of pumiceous obsidian, the angular masses in the bottom being pumice. The rim of the pit does not rise above the level of the surrounding surface, and one comes upon it quite unexpectedly in the timber. The general appearance is that of a small crater which has been but slightly affected by glaciation.

Near by to the south is a short, narrow ridge of porous obsidian, rising two or three feet above the general surface. The ridge curves considerably and is cracked along its center. The only other surface features characteristic of a lava flow which are found in this vicinity are several small basins with obsidian rims; one is 30 feet long by 10 feet wide and about two feet deep, and within it at one end is a smaller basin, six by three feet.

The exact point at which this obsidian broke through the older rocks and reached the surface has not yet been discovered; but that forming Obsidian Cliff has evidently flowed down from the high plateau in a northwest direction into a pre-existing valley, the planes of flow in the lava clearly indicating that it has crept down the slope back of Obsidian Cliff and accumulated in the bottom of a channel between rhyolite hills. This old channel was just east of that occupied by Obsidian Creek, which has cut its way along the contact between the rhyolite to the west and the obsidian. This is shown by the fact that the general bedding or flow structure of the columnar portion along the face of the cliff dips slightly to the east away from the western body of rhyolite.

**LITHOLOGICAL STRUCTURE.**

**COLUMNAR CRACKING.**

Obsidian Cliff is especially remarkable for the development of prismatic columns, which form the southern end of the mass. Such columns are of common occurrence in basalt the world over, the most familiar localities being the Giant's Causeway and Fingal's Cave, on the coast of Ireland. There are others in central France and Germany and throughout the great volcanic area in western North America, especially along the Columbia River and in the Yellowstone Park; they are in almost every basalt flow in fact, so that columnar structure is often erroneously termed basaltic structure. But columnar structure is by no means confined to such rocks, being found in all varieties, from the basic to the acidic, though less frequently in the latter. Columnar structure is well developed in the rhyolites of the Yellowstone Park. Instances of its occurrence in obsidian, however, are exceedingly rare, and in the obsidian flow under considera-
tion it is confined to a small area, several hundred feet in extent, in that portion which poured into the old channel and acquired a greater thickness than that of the main flow.

A view of the west face of the southern end of the cliff is given in Pl. IX. The shining black columns rise from a talus slope which reaches some fifty feet up the cliff. These prisms are fifty or sixty feet high and vary in width from two to four feet near the end of the cliff, the width of each column being quite constant throughout its length. On the south face of this end of the cliff the columns are the same, but grow less clearly defined toward the east, where a sharp bend in the lava sheet has formed gaps in the rock and destroyed the continuity of the mass; beyond this the columns incline considerably toward the west, as though the underlying surface of contact sloped toward the west also. Farther up the slope to the east they disappear. The columns in the main face of the cliff are tilted 10° to the eastward, and the planes of flow which cross them have an average dip of 10° east, indicating that the underlying surface at this place slopes toward the east. Along the cliff to the north the columns become gradually broader, the largest being 20 feet in width.

The prisms have no uniform number of sides, four, five, and six being those most frequently observed; the sides are unequally developed, but at a distance the general effect is quite regular. Toward the north, with the change in the nature of the rock, to be described later on, the broad columns grade into massive blocks formed by vertical cracks much farther apart.

The rock forming the lower part of the columns is dense, black obsidian, with thin, lithoidal bands or layers of small spherulites, which are round, stony bodies, resembling hazel-nuts, or sometimes clay concretions. They have a radially fibrous internal structure and will be fully described (see p. 14). In this part of the columns there are almost no cavities or lithophysae, as the hollow forms of spherulites are called, and but little contortion of the layers. Higher up, the rock is less massive and contains large lithophysae flattened in the plane of flow. The tops of the columns pass into massive obsidian, which for 10 feet is quite dense, but above is full of large cavities which fairly honeycomb the mass. This may be seen on Pl. X, engraved from a photograph taken near the base of the columns, which, though nearly vertical, appear considerably inclined and distorted in the picture.

This upper portion, about fifty feet thick, is divided by vertical cracks into broad, quadrangular blocks having no resemblance to columns. The sides of the columns are comparatively straight and are independent of the flow structure within the mass, which is indicated by the microscopic banding of the obsidian and by the layers of spherulites which traverse the rock in parallel planes. The
OBSIDIAN COLUMNS.
bending and twisting of these show the contortion of the viscous lava just before it came to rest. These layers pass through the columns at all angles, often showing abrupt folds and curves, which have been cut across sharply by the prismatic cracks. The crystalline layers formed planes of weakness through the rock, which has parted along them, producing transverse cracks that bear no fixed relation to the direction of the prisms, but follow the deviations of the flow. The contortion of the lava is particularly noticeable along the south face of the cliff, where the nearly horizontal layers in the most westerly columns curve upward and pass nearly vertically out of the present top of the cliff. Still farther to the east the layers are greatly twisted. At one place vertical rents and gaps between the layers show that the molten glass was so viscous and stiff before it finally came to rest that it pulled apart where the layers were vertical and did not close up again before the lava solidified.

The columnar portion on the west face extends for only a few hundred feet, the nature also of the rock changing in this direction. The lithoidal and spherulitic layers become more frequent until the black glass appears only in thin bands between light-gray layers, finally being represented by dark-gray lines between those of lighter color. This transition takes place in ascending the face of the cliff toward the northern end of the columnar portion, and also horizontally, the great bulk of the lava farther north, where the cliff is 200 feet high, being a light-gray, lithoidal rock, thinly fissile parallel to the planes of flow and bearing no resemblance to obsidian. In places through it black and red glass occurs in considerable quantity, mostly near the upper part of the cliff. The lithoidal form of the rock is not found in other parts of the sheet where it is one hundred feet and less in thickness, but only where it reached a much greater depth by filling up the old valley already mentioned. Unfortunately there is no indication of the original thickness of the lava at this place, as the top has been planed down by ice action and very considerably lowered. It is divided by two systems of vertical cracks into great quadrangular blocks which form a bold cliff rising 100 feet above the debris slope, a view of which is shown in Pl. XI.

As previously noticed, the columnar obsidian is only found in a small portion of that part of the lava that poured into a depression and acquired a greater depth than that of the flow in general, which is often 100 feet thick. The columnar portion was something over one hundred and sixty feet deep, but probably less than that of the lithoidal part farther north, where the mass cooled slowly enough to permit crystallization. The exceedingly rare occurrence of columnar structure in obsidian is probably owing to the fact that the conditions favorable for the production of prismatic structure and also for the solidification of the lava as amorphous glass are seldom coincident, the cause of columnar structure being unquestionably the shrinkage of a homogeneous
rock which is cooling at a moderate rate from its surface. The very rapid surface cooling of a molten rock tends to produce cracks parallel to the surface, and cracks normal to the surface appear only in that portion of the mass which cools more slowly, the rate of cooling and the nature of the rock affecting the size of the columns, which are larger as the cooling is slower. The internal micro-structure of this obsidian and the fact that the spherulites and lithophysae are cut sharply across by the planes of the cracks prove that the glass was rigid before the columns were developed. In general the obsidian shows but little tendency to crack, even where it has cooled rapidly, and in many parts of the flow no particular system of cracks is observed.

LAMINATION.

If the cooling rock is not homogeneous in composition or texture the results of contraction will be altogether different. This is illustrated at the northern end of the cliff, where the lithoidal rock is traversed by widely distant, vertical cracks and a multitude of nearly horizontal ones which follow the planes of flow through all their complexities. The latter have resulted from differences in texture of the alternating layers, the most probable cause of which differences will be suggested later.

The origin of lamination or layer-structure frequently observed in many lava flows and so strikingly developed in the lithoidal portion of Obsidian Cliff is readily understood from the following: In a fluid free to flow over a horizontal surface the movement of the molecules will meet with least resistance in directions parallel to the plane of that surface; the fluid will therefore spread horizontally in all directions, producing a movement of its molecules in planes parallel to the underlying surface. Particles suspended in the fluid will be carried along these planes and portions differing in the amount or character of the suspended matter will be drawn out into layers along these planes of flow. In the case of lavas, the production of such layers will depend on the viscosity and lack of homogeneity of the mass at the moment of eruption and on the distance it flows. In the more liquid and homogeneous lavas, such as basalt, evidence of internal flow or lamination is less marked than in the more viscous and less homogeneous acid lavas, as rhyolite, where slight variations in the consistency of the mass find expression in bands and streaks of color or in layers of differing micro-structure and degree of crystallization. The greater the distance over which a viscous lava has spread, the thinner will be the layers of different consistency, which, near the source, may have been lenticular or quite irregularly shaped portions.

Petrographical Character.

Obsidian.

Approaching nearer the cliff and climbing over the masses of rock which lie at its base we shall find our interest increasing as the great beauty and variety of the lava are disclosed. At the southern end, where the road passes beneath the columns, the greater part of the rock is black, lustrous glass, or obsidian, so named after Obsidius or Opsius, its discoverer, in Ethiopia, according to Pliny, who says that when inlaid in chamber walls in the form of mirrors it reflects shadows instead of images. He also states that the ancients made signet stones of it.\(^1\)

King, in the work just cited, calls attention to the fact that the Peruvians also used the same stone for mirrors.

When broken it flies into sharp, angular fragments, with razor-like edges which are quite transparent and colorless in the thinnest places. It is this quality of the stone, together with its hardness, very nearly that of quartz, which makes it a favorite material for use as knives, spearheads, and arrowpoints by semi-civilized people. It was in common use among the Aztecs at the time of the conquest of Mexico by the Spaniards, as we learn from Prescott,\(^2\) who, in describing the various implements used by these people, says:

> They employed another tool, made of itztli, or obsidian, a dark, transparent mineral, exceedingly hard, found in abundance in their hills. They made it into knives, razors, and their serrated swords. It took a keen edge, though soon blunted. With this they wrought the various stones and alabasters employed in the construction of their public works and principal dwellings (p. 143).

Their weapons were slings, bows and arrows, javelins, and darts. * * * These various weapons were pointed with bone or the mineral itztli (obsidian), the hard, vitreous substance already noticed as capable of taking an edge like a razor, though easily blunted. * * * Instead of a sword they bore a two-handed staff, about three feet and a half long, in which, at regular distances, were inserted, transversely, sharp blades of itztli — a formidable weapon, which an eye-witness assures us he had seen fell a horse at a blow (p. 433).

Another character of obsidian, which it shares with other homogeneous glasses, is the shelly or conchoidal fracture which is developed when it is broken by the blow of a hammer; the undulations of the surface of fracture spreading in arcs of concentric circles around the point of concussion. Occasionally the fracture takes the form of a cone, whose apex is at the point struck. Still more rarely a natural spherical sundering is observed, where thin layers like those of an onion encase a solid nucleus.

The color of this obsidian for the most part is jet black, but much of it is mottled and streaked with bright brownish red and various shades of brown, from dark to light yellowish brown, purplish brown,

---

and olive green. The brilliant luster of the rock and the strong contrast of these colors with the black are very striking. In places the glass has been broken into small, angular pieces and cemented together, producing a many-colored and beautiful breccia. Some of the obsidian shows a fine, satin luster in certain positions. This is produced by the reflection of light from the walls of long, slender gas cavities which fill that portion of the glass that approaches the surface pumice. Another luster is occasionally exhibited in deeper-seated obsidian; it is a golden sheen which under a lens resolves itself into thin beams of red and yellow light, apparently reflected from minute cracks along the surface of microscopic shreds of brown and yellow glass.

SPHERULITES.

Through the black and red glass are scattered dull, bluish-gray patches and bands and round, gray and pink masses, looking like concretions, some of them being hollow or porous. The effect of these spherulitic forms is still further to vary the appearance and beauty of the rock and to make it the most conspicuous and characteristic variety of volcanic lava known. Similar spherulitic obsidian occurs in many parts of the world, notably in the Lipari Islands in the Mediterranean, in New Zealand, Mexico, and the western United States. The last-named occurrence will be more particularly noticed at the end of this paper. Owing to the great variety and the freshness of the spherulites and the perfection and beauty of the lithophysae occurring at Obsidian Cliff, as well as to the interesting results derived from a careful study of them, they will be described with considerable detail, in order to give a clear idea of their structure and composition.

The simplest forms of the macroscopic spherulites—that is, those visible to the unaided eye—are small, dark-blue spherules about the size of a mustard seed, embedded in the black obsidian. When broken they appear lighter gray within, have a dense, porcelain-like texture, and show slight indications of a radially fibrous structure. They are mostly located along fine lines of minute punctures on the surface of the obsidian. The small, blue spherules are generally crowded together along these lines, or more properly along the planes of which these lines are the traces, the layers of spherules agreeing in all their bending and contortions with the fundamental planes of internal flow in the glass. A number of layers will sometimes lie close together, with the thinnest possible sheet of black glass between, or they will unite in a band a quarter of an inch or more thick, whose surface is covered with protruding hemispherules. Isolated clusters of blue spherules occur, making compound spheres, and more rarely these groups are prolonged in one direction, forming parallel ropes through the black glass.
The surfaces of the spherules are often brown or red and constitute planes of weakness between the spherules and inclosing glass, along which the two frequently separate with ease, leaving a dull, pitted surface on the obsidian. The arrangement of the spherules in the plane of flow is then seen to be quite irregular, though occasionally in arborescent figures.

Spherules about the size of peas have an agate-like banding in concentric shells, combined with a radially fibrous structure. Their form is more or less spherical, sometimes being depressed on one side and looking like miniature tomatoes or else prolonged into oblong gourd shapes. More frequently they are aggregated in botryoidal and kidney-shaped forms. Their surface, when relieved of the obsidian, has a delicate, velvety bloom like a peach, which in rich shades of brown and terra-cotta contrasts finely with their black, glassy matrix.

The larger spherules, an inch or more in diameter, are mostly lighter colored, in various shades of reddish gray, sometimes with a blue center. They appear of a more earthy texture than the small ones, but have a fine, radially fibrous structure, with a satin luster; in some cases there is a granular, spotted appearance toward the outer portion, and frequently a distinctly concentric structure is present, the shells being either broad and dense or of the most delicate thinness. The surfaces of these spherules are often ribbed with rings running parallel to the flow planes of the rock, closely resembling the surface of concretions in sedimentary rocks. Their shapes vary from spheroidal to flattened disks and hemispheres, and are also in irregular sectors and plume-like forms produced by the interference of spherules growing close together.

Through all these spherules, large and small, run delicate lines of banding parallel to and in continuation of the planes of flow inherent in the rock; sometimes they are only recognizable with the aid of a lens. This indicates that the spherules were developed in the glass in the same relative positions they now occupy; that is, they must have been formed after the lava came to rest. Frequently the largest spherules were formed earlier than the smaller ones, but this is by no means a fixed rule, for large, red hemispherules have often developed on a layer of small, blue ones, and discoidal ones between such layers.

Hollow spherulites.—Finally, the spherules are not all solid, the larger ones not at all so. Those looking earthy and densest have microscopic spaces between the fibers and grains composing them. Others have a fine granular appearance and glisten from the crystals of which they are made up. Most of them have porous or open cavities within their mass, the periphery often forming a solid shell or crust like the rind of a cantaloupe. These cavities ramify through the heart of the spherule and are coated with brilliant crystals. The porous spherules resemble pithy berries, while the central mass of
the more open ones appears to have shrunken and cracked apart like
the heart of an overripe watermelon. This is shown to a certain ex-
tent in Pl. XII, Figs. 1 and 5. The fibers and nodules of the mass
are often very distinct and course and its color is nearly white. In
many cases the cavity is confined to the limits of a single spherule, de-
tached ones with perfectly solid exteriors being often hollow within.
The isolated spherules in dense, black obsidian without the micro-
scopical trace of cracking are sometimes half hollow, presenting the
purest white skeleton of fibers and nodules, or consist of concentric,
crystalline shells dotted with minute pellets. This form is repre-
sented in Pl. XII, Fig. 3. The shells are usually so delicate that
parts of them are loosened and fall out when the obsidian is broken.
On the white and beautifully frosted substance of these hollow
spherulites rest the honey-yellow crystals of fayalite, as yet unat-
tacked by atmospheric agencies. Cavities are less frequent in the
small, blue spherules, though occasionally the smallest are white and
porous, and along the spherulitic layers or through the black glass-
run crinkled bands of small cavities, or porous layers, with a white,
gray, or pink coating.

LITHOIDITE.

Besides the thin, blue layers with spherulitic structure, occurring
in the obsidian, there are light-gray ones of a more crystalline or
porcelain-like nature. As these become more frequent the rock as-
sumes a lithoidal or stony appearance and grades into purplish-gray
rock, finely banded with blue, having occasional layers of black ob-
sidian running through it. At the northern end of the cliff, as
already noticed, there is very little black glass left and the rock is an
excellent lithoidal rhyolite or lithoidite. This lithoidite is a light-
 purplish-gray rock, which shows, on cross-fracture, delicate bands of
light and dark colored layers. The former are crystalline, with small
cavities scattered along them, which form planes of weakness and
permit the rock to split into thin plates often one-sixteenth of an
inch in thickness. The dark layers are microspherulitic and dense,
showing in many cases a system of fine parallel cracks, all of them
running in one direction and perpendicular to the plane of the layer.
These cracks are at quite uniform distances apart in any one layer,
usually half an inch and less, being closer together the thinner the
layer. Upon examination it is seen that the direction of the cracks
is at right angles to the streaks of color in the rock, which mark the
direction of flow. From this position of the cracks, which are the
result of the shrinkage of the rock upon cooling and which must
lie at right angles to the direction of maximum strain, we see that
along the line of flow at the time of consolidation the tension was
greater than in other directions, which was probably due to a pull-
ing stress exerted in that part of the lava sheet that stretched down.
the slope from the plateau above. In places the rock breaks into blocks which bear so striking a resemblance to silicified wood that one is easily deceived at a little distance.

**LITHOPHYSÆ.**

The lithoidal rock is as full of spherulitic forms as the obsidian, but it appears more porous and contains a multitude of hollow spherules of the utmost delicacy and beauty. An idea of their great abundance is given by Pl. XIII, Fig. 2, which was drawn from a slab of lithoidite and is the natural size. Most of them are hemispherical and consist of a group of concentric shells which curve one over another like the petals of a rose (Pl. XII, Fig. 4, and Pl. XIII, Fig. 1). The shallower ones present small, rose-like centers surrounded by thin, circular shells (Pl. XIII, Fig. 2). The disks are sometimes oval and sometimes composed of several sets of shells which have started from centers near together and developed in sectors, giving a scalloped form to the curves (Pl. XIII, Fig. 2). Others are eccentric or send out long, curving arms, cross-walled like a chambered ammonite (Pl. XII, Fig. 2).

The partition walls are generally very thin and often close together, in one instance fifty occurring within a radius of two inches. They are very fragile and crumble under the touch, being made up of small and slightly adhering crystals with brilliant, glistening faces.

A fine example of a lithophysa is shown on a natural scale in Pl. XIII, Fig. 1. The rose-like center is surrounded by delicate shells. Those outer portions to the right and left which still remain are somewhat massive, though finely porous and crystalline, and are traversed by well marked shrinkage cracks. The contraction of the massive portions is clearly indicated by these cracks, which gape open from the base to which the substance of the lithophysa adhered. The largest forms are a foot or more in diameter and are very suggestive of wasps' nests.

These hollow structures have been called Lithophysen by von Richthofen, because the rock appears to have been inflated or expanded like bubbles. He described those found in the rhyolites of Hungary and considered that the viscous rock had been expanded by steam. A review of his observations on their nature and origin will be given in its proper connection.

But these lithophysae cannot be considered as having been actually expanded by gas or steam, however much they resemble the bursting bubbles which rise to the top of boiling mud, a sight familiar to all who visit the Yellowstone region. They bear an intimate relation

to spherulites, as the stone spherules are called, which becomes evi-
dent upon comparing the various structures exhibited by each.

Corresponding to the complete spherulite with simple, radially fibrous structure and no concentric banding, there are similar spher-
ulites partly hollow at the center or irregularly so through their mass, as in Pl. XIV, Fig. 1. The simple spherulite which is traversed by parallel bands, in continuation of the planes of lamination in the rock, has a corresponding porous form, in which these bands become partition walls between the porous or hollow portions (Pl. XIV, Fig. 2). Spherulites with concentric banded structure have more or less hollow varieties where the denser bands remain as thin shells coated with crystals (Pl. XIV, Fig. 3), and among these are some crossed by the parallel bands of flow structure, which are clearly recognized in the hollow forms (Pl. XIV, Fig. 4). The hemispher-
ulite with concentric bands, when developed in a narrow layer of glass, spreads out in the shape of a flattened disk, the bands farthest from the center being only short arcs of circles. The hollow form corresponding to this is the most characteristic lithophysa found in the lithoidite of Obsidian Cliff, which has already been described and is shown in cross-section in Pl. XIV, Fig. 5. Lithophysae inter-
sected by the bands of lamination of the matrix also occur (Pl. XIV, Fig. 6), the two systems of delicate walls being distinctly independ­
ent of each other. Finally, partial spherulites in the shape of sect­ors and plume-like forms are represented among the irregularly de­
veloped lithophysae.

From the foregoing it is evident that lithophysae differ from spher­ulites neither in outward form nor general structure, but in the nature and continuity of the material composing them. At first sight it would appear as though the substance of the spherulites had been attacked by some corrosive agent which had partially reduced it and deposited in the resulting cavities the crystals already alluded to. How far this may have been the case will appear in the sequel.

MINERALS COMPOSING LITHOPHYSA.

The minerals which coat the walls of the lithophysae and make up the material which is found in the perfectly fresh ones are quartz, tridymite, feldspar, fayalite, and magnetite. The size of the crystals bears a direct relation to the size of the cavity in which they have been developed when the lithophysa is isolated in a glassy matrix. The crystals are very minute in small lithophysae and larger in the large ones, the character of the minerals remaining the same. Where several lithophysae are connected or where a system of cavities traverses the rock a separation of the minerals takes place, certain varieties being deposited in particular localities, producing larger crys­
tals whose size bears no relation to that of the cavity in which they occur.
Quartz is in prismatic crystals characteristic of this mineral when freely developed in cavities. The crystals are often doubly terminated with two sets of rhombohedrons, the ordinary set, \( \pm R \), and a steeper one, and occasionally a scalenohedron. The prism faces are strongly striated transversely. The substance of the quartz is very pure and transparent, with numerous gas cavities inclosed in it.

Tridymite, the second form of silica found in lithophysse, is in delicate, six-sided plates. The larger crystals, which may be recognized by the unaided eye, are \( 0.5 \text{ mm} \) (one-fiftieth of an inch) broad and have rather stout, tabular forms with a very simple combination of faces. They are easily confounded with the feldspars, on account of their form as well as of their substance, which is transparent and colorless, with scattered gas inclusions. Between crossed nicols they show the optical anomalies characteristic of tridymite. The crystals are frequently single or grouped in clusters, which latter, when composed of microscopic individuals, appear as minute pellets. The tridymite is deposited along with prismatic quartz in varying proportions, sometimes one occurring to the exclusion of the other.

Two forms of feldspar have so far been recognized. One is in almost microscopic crystals, which make up the coarser fibers in the lithophysse. They are short and stout, with the form characteristic of adular, that is, in rhombic prisms bounded by the unit prism faces and terminated by a striated, compound face formed of the basal plane and an orthodome. These short prisms are attached to one another end to end, making crooked and forking branches of feldspar.

Another form is found in the lithophysse of the lithoidal rock and the cavities connected with them, where the largest crystals occur. They are thin, tabular crystals about \( 1 \text{ mm} \) broad, flattened in the plane of the base, and bounded by the clinopinacoid, prism, and two orthodomes. Such a development of the basal plane is quite uncommon for orthoclase, of which species these feldspars prove to be a somewhat doubtful variety.

Mr. S. L. Penfield, of the Sheffield Scientific School, has measured and figured the crystals, besides making a chemical analysis of them.

The simple and usual form is represented in Fig. 51, though many of the crystals are much thinner than this. They are frequently twinned according to the Manebacher law, as in Fig. 52, and very rarely according to the Baveno law.
The axial ratio of the crystals was found from the following measurements:

\[ a : b : c = 0.6466 : 1 : 0.5522 \]

\[ \beta = 63° 41' 50'' \]

Additional angles measured and calculated were as follows:

<table>
<thead>
<tr>
<th>Angle</th>
<th>Measured</th>
<th>Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>( c \wedge x )</td>
<td>50° 53'</td>
<td>50° 55' 30''</td>
</tr>
<tr>
<td>( c \wedge b )</td>
<td>90°</td>
<td>( \beta = 63° 41' 50'' )</td>
</tr>
</tbody>
</table>

Angle \( c \wedge b \) could not be measured very accurately, owing to poor reflections from the faces. The reflections from \( x \) also were very faint. These measurements show that the crystals belong to the monoclinic system, and their habit is that of orthoclase feldspar, but their optical character is not that of a monosymmetric mineral. The thin, tabular crystals furnish plates parallel to the basal plane and readily permit of optical investigation in this position, which is a fundamental one for a monosymmetric crystal. The edge made by the base and clinopinacoid is sharply defined, and the edge between the orthodome and base is seen to be exactly at right angles to it, as closely as can be measured by the cross-wires of the microscope. But between crossed nicols these basal plates do not extinguish the light parallel to the trace of the clinopinacoid, as they should do if the crystals were monosymmetric, and in convergent polarized light it is found that the plane of the optic axes makes a small angle with the clinopinacoid, which in the first eleven feldspars examined ranged from 1° to 4°. In fifteen more feldspars examined with the wide-angle, immersion, Bertrand lens of Nachet et Fils, the inclination ranged from 1° 30' to 5° 12', in no case being 0°.

The inclination of the bisectrix to the edge \( c \wedge b \) measured on the clinopinacoidal face of cleavage pieces varied from +6° to +10°.

Optically the crystals are asymmetric and approach the recently described anorthoclase of Klein¹ and Förstner.² It is to be hoped that better material may be found which will furnish larger crystals for a thorough determination of the optical properties of these abnormal feldspars.

The substance of the feldspars is perfectly transparent, with minute gas inclusions. The crystals exhibit a brilliant, blue opalescence that appears to be reflected from planes of microscopic parting parallel to an orthodome, indicated by delicate lines, which, on the basal

---

plane, lie parallel to the axis \( b \), and, on the clinopinacoid, make an angle of about 71° 42' with the axis \( a \). This corresponds closely to the observations of Mr. Whitman Cross\(^1\) on the sanidine in the rhyolite of Chalk Mountain, Colorado, and still further confirms the deductions of E. Reusch,\(^2\) who ascribed the iridescent colors noticed in many labradorites and other feldspars to the effect of thin plates due to delicate parting in certain directions through the mineral.

The chemical composition of these feldspars is shown by the following analysis made on less than a gram of material, which was obtained by means of Thoulet's solution of iodide of potassium and iodide of mercury—a solution which may be prepared with a specific gravity of about 3, when it will float many of the rock-making minerals, the heavier ones falling to the bottom. By gradually diluting the solution with water its density may be lowered to that of the suspended minerals, which one by one will settle to the bottom, as the specific gravity of each is passed. In this way the feldspars were separated from portions of the rock mixed with them and fell between the specific gravities of 2.589 and 2.541.

Partial analysis, I, was made on 0.6002 gram, and, II, on 0.3581 gram.

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
<th>Mean</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica, SiO(_2)</td>
<td>67.78</td>
<td>67.39</td>
<td>67.53</td>
<td>1.125</td>
</tr>
<tr>
<td>Alumina, Al(_2)O(_3)</td>
<td>17.85</td>
<td>17.18</td>
<td>17.52</td>
<td>.774</td>
</tr>
<tr>
<td>Ferric oxide, Fe(_2)O(_3)</td>
<td>.94</td>
<td>.66</td>
<td>.80</td>
<td>.882</td>
</tr>
<tr>
<td>Lime, CaO</td>
<td>5.08</td>
<td>5.08</td>
<td>5.08</td>
<td>.688</td>
</tr>
<tr>
<td>Soda, Na(_2)O</td>
<td>8.96</td>
<td>8.96</td>
<td>8.96</td>
<td>.984</td>
</tr>
<tr>
<td>Potash, K(_2)O</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ign.</td>
<td>0.30</td>
<td>0.30</td>
<td>0.30</td>
<td>.30</td>
</tr>
</tbody>
</table>

\(a\) Determined by difference.  
\(b\) Determined by uniting both portions.

The ferric oxide was derived from a little yellow oxide of iron which coated some of the crystals and may be omitted in discussing the analysis.

The ratio

\[
\text{SiO}_2 : \text{Al}_2\text{O}_3 : \text{R}_2\text{O} \\
1.125 : .774 : .882 \\
6.54 : 1.01 : 1.00
\]

indicates a slight excess of silica, probably due to a small amount of quartz or tridymite which adhered to the feldspar crystals. Eliminating this excess of silica, which, when calculated to bring the ratio


of \( \text{SiO}_2 : \text{Al}_2\text{O}_3 : \text{R}_2\text{O} = 6 : 1 : 1 \), would be 5.25 per cent., the analysis becomes

<table>
<thead>
<tr>
<th>Substance</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free silica, ( \text{SiO}_2 )</td>
<td>5.25</td>
</tr>
<tr>
<td>Silica, ( \text{SiO}_2 )</td>
<td>62.28</td>
</tr>
<tr>
<td>Alumina, ( \text{Al}_2\text{O}_3 )</td>
<td>17.99</td>
</tr>
<tr>
<td>Ferric oxide, ( \text{Fe}_3\text{O}_4 )</td>
<td>6.00</td>
</tr>
<tr>
<td>Lime, ( \text{CaO} )</td>
<td>0.09</td>
</tr>
<tr>
<td>Soda, ( \text{Na}_2\text{O} )</td>
<td>5.08</td>
</tr>
<tr>
<td>Potash, ( \text{K}_2\text{O} )</td>
<td>3.36</td>
</tr>
<tr>
<td>Ignition</td>
<td>0.30</td>
</tr>
</tbody>
</table>

which will reduce to

<table>
<thead>
<tr>
<th>Substance</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica, ( \text{SiO}_2 )</td>
<td>66.40</td>
</tr>
<tr>
<td>Alumina, ( \text{Al}_2\text{O}_3 )</td>
<td>19.18</td>
</tr>
<tr>
<td>Lime, ( \text{CaO} )</td>
<td>0.90</td>
</tr>
<tr>
<td>Soda, ( \text{Na}_2\text{O} )</td>
<td>5.41</td>
</tr>
<tr>
<td>Potash, ( \text{K}_2\text{O} )</td>
<td>3.91</td>
</tr>
</tbody>
</table>

From the ratio of the alkalis in this analysis, the feldspar may be considered as an isomorphic mixture of orthoclase and albite in nearly equal proportions, its formula will then be \( \text{Or}, \text{Ab} \). It is the middle member of the orthoclase-albite series, with apparently the crystallographic characters of orthoclase, though somewhat exceptionally developed, but with the optical characters of a trichinic feldspar—an anomalous combination of characters which requires further investigation.

*Fayalite* is in small, tabular crystals scattered through the lithophysse, usually projecting from the walls of the cavities, its crystals being larger than those of the associated minerals. In most instances they appear as opaque, black crystals about 2\( \text{cm} \) and less in length; their form is flattened, or tabular, with orthorhombic symmetry. They frequently have a metallic luster, occasionally with brilliant, iridescent colors, mostly reds. Examination shows that these crystals are coated with ferric oxide, the interior of the crystals being transparent and of a light-yellow color. Perfectly fresh, unaltered crystals are found in the small lithophysse isolated in the obsidian, where they have been preserved from the action of the atmosphere. The best crystals of this sort were found in compact, black obsidian, about half a mile north of Lake of the Woods, near the southern end of this obsidian sheet. They are in thin, square or rectangular plates, of a light honey-yellow color, perfectly transparent and free from inclusions of other minerals, but occasionally containing gas cavities. They show very slight pleochroism, pale greenish yellow parallel to the \( b \) axis and golden yellow parallel to the \( c \) axis. The cleavage parallel to the brachypnacoid is good, but a second at right angles to the first is less distinct and is probably in the plane of the macro-pnacoid, as in olivine.
Mr. S. L. Penfield has kindly determined and figured the crystallographic forms presented by the rectangular, tabular crystals from the locality north of the Lake of the Woods and the more elongated and pointed crystals from Obsidian Cliff. The measurements were made on a thin, tabular crystal 0.1 mm thick and 0.8 mm broad, which was broken across the prismatic zone. The observed forms were a (100, i-i), b (010, i-i), s (120, i-2), e (111, 1), d (101, 1-i), k (021, 2-i).

Arrangement of planes is quite constant, as in Fig. 53. For fundamental angles the best two reflections were chosen:

\[
\begin{align*}
\alpha \wedge s, & \quad 100 \wedge 120 = 43° 31' \\
\delta \wedge d, & \quad 101 \wedge 101 = 103° 17'
\end{align*}
\]

giving \( \alpha : \delta : \epsilon = 0.4584 : 1 : 0.5791 \)

The angles measured and calculated were:

<table>
<thead>
<tr>
<th>Measured.</th>
<th>Calculated.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a \wedge b )</td>
<td>90°</td>
</tr>
<tr>
<td>( s \wedge s )</td>
<td>95° 8'</td>
</tr>
<tr>
<td>( a \wedge d )</td>
<td>38° 20'</td>
</tr>
<tr>
<td>( d \wedge e )</td>
<td>19° 52'</td>
</tr>
<tr>
<td>( e \wedge e )</td>
<td>95° 5'</td>
</tr>
<tr>
<td>( a \wedge e )</td>
<td>42° 35'</td>
</tr>
<tr>
<td>( b \wedge k )</td>
<td>40° 45'</td>
</tr>
</tbody>
</table>

The plane of the optic axes is parallel to the base, one of the bisectrices being normal to the macropinacoid, as shown by a polarizing microscope. Owing to the minuteness of the crystal examined, the divergence of the optic axes was not determined.

The opaque crystals from Obsidian Cliff show the same forms, with the additional basal plane, c, but are mostly developed as in Fig. 54. With the exception of the macropinacoid, the faces were too dull to give good reflections and the forms were identified by approximate measurements only.

This mineral is the same as that described in 1827 by Gustav Rose, who measured the small crystals found in the lithophysae in 1827.  

OBSIDIAN CLIFF, YELLOWSTONE NATIONAL PARK.

obsidian from Cerro de las Navajas, Mexico, which von Humboldt had collected.

"The crystals," he says, "are very small, the largest half a line long and broad, and very thin, of a greenish and reddish-yellow color, transparent, but with a strong, vitreous luster." The forms of the crystals figured by him are exactly the same as those found at Obsidian Cliff, and the angles measured are almost identical. They are as follows:

<table>
<thead>
<tr>
<th></th>
<th>Complementary angles</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>By G. Rose.</td>
<td></td>
<td>By S. L. Penfield.</td>
</tr>
<tr>
<td>$M \wedge d$</td>
<td>141° 37' and 38'</td>
<td>38° 33' and 22'</td>
</tr>
<tr>
<td>$k \wedge k$</td>
<td>80° 58' and 81° 30'</td>
<td>38° 30'</td>
</tr>
<tr>
<td>$d \wedge e$</td>
<td>160° 8' and 20'</td>
<td>19° 52' and 40'</td>
</tr>
<tr>
<td>$M \wedge s$</td>
<td>137° 17' and 34'</td>
<td>43° 43' and 36'</td>
</tr>
</tbody>
</table>

From the similarity in crystallographic form and in manner of occurrence, it is probable that the crystals which Rose determined as olivine belong to the purely ferruginous variety, fayalite.

A chemical analysis of the coated crystals from Obsidian Cliff was made by Prof. F. A. Gooch, at that time in the chemical laboratory of the U. S. Geological Survey. All the material available was 0.24 gram.

Under the microscope the crystals were seen to carry a small amount of adhering quartz and to be coated with iron oxide. They were readily decomposed in hot hydrochloric acid with the separation of silica and yielded the following results:

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica, $SiO_2$</td>
<td>25.61</td>
<td>32.41</td>
<td>17.375</td>
</tr>
<tr>
<td>Alumina, $Al_2O_3$</td>
<td>Trace</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ferric oxide, $Fe_2O_3$</td>
<td>14.92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ferrous oxide, $FeO$</td>
<td>51.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnesia, $MgO$</td>
<td>1.66</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lime, $CaO$</td>
<td>None</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ignition</td>
<td>None</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insoluble silica</td>
<td>7.62</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

100.96

Considering the ferric oxide as the opaque coating of alteration and the insoluble silica as the adhering quartz, the composition of the unaltered mineral will be:

<table>
<thead>
<tr>
<th></th>
<th>Oxygen ratio.</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica, $SiO_2$</td>
<td>25.61</td>
<td>32.41</td>
</tr>
<tr>
<td>Ferrous oxide, $FeO$</td>
<td>51.75</td>
<td>65.49</td>
</tr>
<tr>
<td>Magnesia, $MgO$</td>
<td>1.66</td>
<td>2.10</td>
</tr>
</tbody>
</table>

79.02 100.00

which is essentially the composition of the unisilicate fayalite.

In the case of the unaltered crystals from near Lake of the Woods, a very careful qualitative test by Mr. Penfield showed that these crystals were an iron silicate containing no magnesia.

The magnetite in the lithophysae is in microscopic grains which under the microscope appear to be octahedral crystals.
CLIFF OF LITHOIDAL RHYOLITE.
LITHOPHYSE
LITHOPHYSE IN THE LITHOIDITE OF OSSIDIAN CLIFF, NATURAL SIZE.
VARIEITES OF LITHOPHYSÆ.
SECTIONS OF SPHERULITES AND GRANOPHYRE GROUPS.
MICROSCOPICAL CHARACTERS.

Having familiarized ourselves with the general outward appearance of the rock forming Obsidian Cliff, let us look deeper into the subject and by means of the microscope penetrate to the very heart of the matter. To this end thin sections of the rock were prepared by grinding one side of small fragments about the size of a 25-cent silver piece and polishing it smooth, cementing this to glass by means of heated Canada balsam, and then grinding away the other side of the rock until it became thin enough to be transparent, when by very skillful polishing the section was reduced to a thinness almost imaginary, 0.001 of an inch and thinner. With such sections magnifying powers as high as 1,500 diameters may be employed if necessary, permitting very little to escape notice. For most purposes, however, a power of 100 diameters is all sufficient.

TRICHITES AND MICROLITES.

The black obsidian in thin section becomes perfectly transparent and of a gray color. Under the microscope it is seen to be a colorless glass crowded with minute, transparent, pale-green crystals and short, black, hair-like bodies called trichites. The crystals are in thin rhombic tablets or irregular grains, 0.005 mm (0.0002 inch) in diameter, either scattered about or strung on the short, opaque threads like conserved cherries on a straw (Pl. XV, Fig. 6). The larger of these transparent microlites, or microscopic crystals, prove to be a variety of augite, which only appears in microscopic forms in this rock. The trichites are about 0.0008 mm (0.000032 inch) wide and may be traced through different gradations to grains of magnetite, which in larger form are recognized in the glass intimately associated with the augite, usually inclosed in a grain or crystal of the latter mineral. These trichites give the obsidian its black color. Such microlites and trichites are found in nearly all volcanic glasses and differ in shape and character according to the condition and composition of the lavas in which they occur. They are rudimentary crystals of minerals which develop in rapidly solidifying glasses, where a larger and more perfect crystallization is hindered by the viscosity of the glass.

The strings of microlites and trichites often have a distinctly parallel arrangement and are in layers of greater or less abundance, which mark the planes of flow within the glass.

Occasionally the trichites are in curved groups, radiating from a central grain and looking like the downy seed of a thistle. One variety of red obsidian derives its color from bright-red trichites and grains, due probably to the higher oxidation of the iron. Most of the brownish-red varieties are composed of colorless glass through which run orange and yellow, microscopic streaks and ribbons in the greatest complex of contortions and streams (Pl. XVI, Fig. 1), often
producing very grotesque and curious shapes, among which one rec­
ognizes the forms of flowers, toad-stools, sea-anemones, jelly-fish,
spearheads, and the like, a list only limited by the size of the thin
section and the imagination of the observer.

These colored bands, when highly magnified, appear to be composed
of the minutest yellow or orange granules. In places there is a
shading through brown into black, which is accompanied by a shrink­
age of the bands, and in their stead is clear glass streaked with clouds
and lines of opaque grains and trichites, apparently magnetite. Some
of the clouds of minute grains look blue in transmitted light.

The various shades of color in the obsidian arise from the differ­
ent proportions in which these yellow, orange, brown, and black part­
icles are mingled. In some the colored streaks are in broad, thin
bands, either straight or twisted, according to the last movements of
the viscous glass. In others they are in the most delicate threads, al­
ternating with streaks of black grains running continuously through
the rock, though sometimes interrupted by streaked patches of other character or appearing as though the rock had been broken
into fragments and welded together again (Pl. XVI, Fig. 2). The
transition of the yellow and orange bands into black grains, the-
larger of which are recognizable as magnetite, indicates that the
former are made up of finely divided particles of iron more highly
oxidized, which is confirmed by the chemical analyses of the red and
black obsidian. The iron in the red variety is almost wholly ses­
quioxide, while in the black obsidian there is a slight excess of pro­
toxide over that required to form magnetite in combination with the
sesquioxide.

The only other minerals crystallized out of this obsidian are a few
microscopic crystals, suggesting feldspar, and the various spherulitic
bodies. We shall consider the different forms of crystallization in
the order of their production or growth, having already started with
the first, namely, the trichites and microlites of magnetite and augite.

GRANOPHYRE GROUPS.

Following these come the microscopic crystals of what at first ap­
pears to be feldspar. They are not, however, simple feldspar, but an
intergrowth of this mineral with another in groups of small crystals
with the nearly rectangular outlines of feldspar, averaging 0.2 mm
(0.008 inch) in diameter. Close inspection with a high magnifying
power reveals the fact that each group is composed of several indi­
viduals of feldspar intersecting one another and that each indi­
vidual has a fibrous structure in several directions through it and is
granular in places. This is represented in Pl. XV, Fig. 3, where a
section has been cut through two individuals, one end of one not
having been developed. The fibers run nearly perpendicularly to the
sides of each rectangle. The margin of what appeared to be a straight-
edged crystal section is found to be serrated with the projecting ends of minute crystals. The component minerals are too finely divided to be determined optically; all that can be observed is the general structure, that they are colorless, and that between crossed nicols they extinguish light at various angles to the direction of the fibers. They inclose trichites and microlites, and have therefore crystallized after these.

Their structure recalls that of other groups of colorless minerals noticed in rocks of similar composition which occur in the neighboring regions, namely, the rhyolites of the Great Basin of Utah and Nevada, where we find similar groups of larger size, and in a rock from Eureka, Nev., there is one large enough to allow of the optical determination of the component minerals. This is represented in Pl. XV, Fig. 5, as it appears between crossed nicols when magnified 37 diameters. It is a section through three orthoclase feldspars that have crystallized about a grain of plagioclase, part of which has fallen out in grinding. The section has been so placed between crossed nicols that one orthoclase is dark and the others are light gray. Inclosed in the feldspar substance are strips of another mineral which appear white in two feldspars, but white, gray, and black in the third. This mineral is quartz, which has formed at the same time as the feldspar and has been inclosed in its mass. It is in shreds, which are long and thin or short and irregularly shaped. Many of them are bounded by crystallographic faces, which in cross-section give triangular and polygonal figures characteristic of pegmatite. All the quartz shreds in the largest two feldspars have the same crystallographic orientation, as though they belonged to one continuous crystal, but in the smallest feldspar the quartz shreds are in three sets, with different orientations. Thus, in one instance, quartz in one position is combined with feldspar in two positions, and, in another, quartz in three positions is combined with feldspar in one. In the largest individual, while the clear margin of feldspar extinguishes light at one angle and the quartz at another, in that portion where the thin shreds of quartz alternate with those of feldspar the maximum extinction of light takes place in various positions, according to the relative thickness of the two minerals through which the light passes. Hence we find in this fibrous portion different extinctions, none of which corresponds to that of either of the component minerals.

From some cause the quartz ceased to crystallize before the feldspar, as is seen by the clear border and sharp, straight outline of the latter mineral, pierced, however, in several places by shreds of quartz which protrude from the surface. If the feldspar had stopped forming a little before the quartz the outline would have been serrated like that of the groups formed in the obsidian. We have, then, strong evidence that these microscopic groups are composed of feldspar and
quartz intergrown in the manner so frequently observed on a larger scale in many granites, porphyries, and rhyolites.

From the simple intersection of two feldspars the groups grow more complex with the increasing number of feldspars, the outline in cross-section becoming oval or circular. An extreme case is represented in Pl. XV, Fig. 4; in this the feldspars wedge out toward the center, their outer ends making an almost continuous outline and the crystal form being no longer recognizable. The fibration, however, is in wedge-shaped sets and does not radiate uniformly from the center. The extinction of light between crossed nicols is quite irregular, as shown in the drawing, and, as we observed in the rock from Eureka, Nev., the orientation of the quartz may vary greatly throughout this group, being quite independent of that of the feldspar. The inclosed trichites are crowded in a ring about the center.

These microscopic pegmatoid or granophyre groups, together with the trichites and microlites, crystallized before the lava came to rest and have been more or less twisted or turned about and arranged in layers along the planes of flow.

**Spherulites.**

The next order of crystallization in the obsidian is the spherulitic. The simplest and smallest as well as the first formed spherulites appear as minute, colorless spheres about 0.2 to 0.05 mm in diameter, scarcely noticeable in ordinary light. Highly converging light makes evident a finely fibrous structure, and between crossed nicols a more or less well defined, dark cross is observed. The arms of these crosses do not remain of constant width during the rotation of the section, but alternately contract and spread, and split into branches near their ends, as represented in Pl. XV, Fig. 2, and Pl. XVII, Fig. 1. The latter figure is from a photomicrograph taken by Mr. Clifford Richardson, of the chemical laboratory of the Agricultural Department, to whom the writer is greatly indebted for a number of beautiful photographs of rock sections taken with the aid of a solar microscope. Some of these photomicrographs are reproduced on Pls. XVII and XVIII.

A fibrous margin surrounds many of the granophyre groups; its character and length of fiber correspond to those of the smallest spherulites and from its optical behavior between crossed nicols it appears to be a continuation of the material of the inclosed kernel. The spherulites are often in rows and layers (Pl. XVII, Fig. 1) and sometimes their centers are along straight lines and so close together that they produce transparent, fibrous bands (Pl. XVIII, Fig. 1). These minute spherulites correspond to the dots observed in lines on the surface of the obsidian. After the microscopic spherulites those appearing blue in the hand specimen were formed. In thin section
SPHERULITIC STRUCTURES IN THIN SECTION.
SPHERULITES IN THIN SECTION.
they are light gray in incident light, but brown by transmitted light. They range from less than one millimeter to five and rarely ten millimeters in diameter. Under the microscope they show a finely fibrous structure, radiating from a center at which there is frequently, though not always, a granophyre group or colorless spherulite. The fibers are so delicate that many are superimposed one on another within the thin section, preventing a determination of their optical characters. Most of these larger spherulites are traversed by the streams of microlites and minute colorless spherulites which pass through them and the surrounding matrix without change of direction; but in some cases the microlites and trichites have been pushed out or crowded into radial lines (Pl. XVIII, Figs. 1 and 2). Between crossed nicols the rays of shadow seldom form a perfect cross, but are scattered and broken into many arms, some branches lying at an angle of 45° to the principal plane of the nicols. One of these spherulites is represented in Pl. XV, Fig. 1, the scattered nature of the dark rays corresponding to that exhibited by the granophyre groups (Pl. XV, Fig. 4). The fibers are in sectors and do not radiate from a single point. The smallest colorless spherulites appear to be somewhat more regular forms.

The similarity in structure and optical behavior between these spherulites and the fibrous, granophyre groups indicates a correspondence in their mineral composition which would lead us to conclude that the spherulites are composed of feldspar and quartz that have crystallized from the molten glass at one and the same time and have intergrown with each other, the fibers not necessarily being individuals of these minerals elongated in the direction of their principal crystallographic axis. This view we shall see is confirmed by their chemical composition.

The striping and banding of these spherulites in different colors arises from the crowding together of minute brown or black particles into radial or circular bands. These particles, which appear opaque by transmitted light, are often white by incident light and are probably in part gas cavities, as these are recognized in large numbers in the coarser-grained spherulites to be described. The red surface of many spherulites is produced by the higher oxidation of the trichites and opaque grains which are inclosed in them; and it is quite noticeable that the black trichites and nearly colorless microlites of the surrounding glass as they pass into the spherulites become red, as though they had encountered an oxidizing agent not active in the surrounding glass.

The forms of these radially fibrous growths are not confined to spheres, but through unequal development in different directions take the shape of hemispheres, disks, and sectors, at times spreading out like plumes (Pl. XVIII, Fig. 3), others in section resembling a fox’s tail.
Porous spherulites.—The large gray and red spherulites, which have an earthy and rather porous appearance in hand specimens, are seen in thin section to be quite coarsely fibrous, which permits their structure to be clearly made out. They frequently have a dense, dark spherulite at their center and appear under the microscope to be simply the continuation of its fibers under somewhat different conditions. The fibers consist of slender needles of feldspar, often twinned and generally showing low extinction angles. The needles are not straight-edged, are frequently jointed, and branch at low angles, in some cases having short, curved needles attached like those of a pine twig. Cross-sections of the needles show them to be polygonal, but the shapes are not uniform. Between the feldspar needles are rows of tridymite scales and scattered grains of magnetite, together with abundant gas pores. The tridymite is often aggregated in spherical masses surrounding a number of feldspar needles, leaving spaces between. The presence of tridymite instead of quartz (the latter being probably the form of free silica occurring in the smaller spherulites) suggests a difference in the conditions governing the formation of the two varieties of spherulites.

Similar feldspar growths are found starting in the clear glass from a stout stem, like the limb of a tree, from which branch smaller rods that continue to fork until a radiating bunch of thin needles results, forming a partial spherulite. This is illustrated in Pl. XVII, Fig. 2. The needles are all twinned, apparently according to the Mauebach law. Their form becomes still more arborescent when the feldspar crystals are somewhat tabular and assume foliate shapes which strongly resemble oak leaves. All these structures arise from the combination of small crystals attached to one another in such a way as to produce apparently curved forms. When viewed between crossed nicols their effect is very striking and beautiful, the delicate feldspar crystals standing out in brilliant white against the black background of isotropic glass.

The light-gray bands or lithoidal layers of the rock unite two or more of the structures already described, together with coarser forms of crystallization of quartz and feldspar too numerous to describe, except to note, as another freak of mimicry, a structure resembling most excellent examples of microscopic eozoön. The microstructure of the lithoidal portion of this lava flow is the same as that of many other lithoidal rhyolites in various parts of the world.

FAYALITE.

In the porous portions of the larger spherulites, intimately crystallized with the feldspar and tridymite and generally surrounding the feldspar, as of later growth, are occasional crystals of fayalite, irregularly outlined, evidently one of the last minerals formed. They
are sometimes noticed among the coarser crystals of feldspar, quartz, and tridymite, near the cavities of the more porous layers.

It is most unusual to see so basic and ferruginous a mineral as this iron olivine intimately associated with abundant quartz and acid feldspars in a highly siliceous, volcanic rock containing less than 2 per cent. of iron oxide. It is contrary to almost universal observation, and therefore to the laws which are supposed to govern the mineral composition of igneous rocks. It is formed especially within the lithophysae, and an explanation of its occurrence may throw some light upon the origin of these interesting structures.

ORIGIN OF FAYALITE AND LITHOPHYSEÆ.

The probable origin of fayalite in so siliceous a rock as obsidian will appear from the following considerations:

MINERAL ASSOCIATION.

First. Its association with abundant quartz and tridymite and acid feldspars, with a small amount of magnetite, is not according to the laws which appear to govern the production of minerals by purely igneous fusion; for olivine is only found in igneous rocks low in silica and rich in iron and magnesia, and it is doubtful whether a purely iron olivine, like fayalite, has ever been found as an essential constituent of such rocks. At Fayal, where it has been found associated with trachyte, it would seem, from the description of Gmelin, to occur as inclosed masses in the lava, for it is said to be full of bubbles in places, with the appearance of having been fused, and in the Mourne Mountains, Ireland, according to Delesse and Haughton, it occurs in drusy cavities in muscovite granite accompanied by beryl, chrysoberyl, fluorite, and topaz. The minerals accompanying olivine are usually lime-soda-feldspars, augite, and magnetite. Its occurrence in an obsidian with 75 per cent. of silica and less than 2 per cent. of iron oxide is so contrary to common experience that the observations of Gustav Rose, in 1827, on an occurrence of olivine in the obsidian of the Cerro de las Navajas, Mexico—which, as already pointed out, is similar to that at Obsidian Cliff—have been generally discredited by the most eminent petrographers.

Secondly. The chief minerals which accompany the fayalite are those which have not been reproduced artificially under the ordinary conditions of purely igneous fusion. The experiments of Messrs. Fouqué and Michel-Lévy and others have demonstrated the failure of the purely igneous fusion of the chemical constituents of quartz and the acid feldspars, orthoclase and albite, to produce crystals of these minerals similar to those found in acid rocks, though the more basic minerals have been so produced.

Thirdly. Quartz, tridymite, orthoclase, and albite have all been reproduced artificially by heating their component elements in the presence of superheated water in a closed tube; that is, by a form of aqueo-igneous fusion. The experiments bearing most directly on the case in hand are those of Messrs. Friedel and Sarasin, who heated in a closed tube basic silicate of potassium and silicate of aluminium and obtained along with hydrous silicate of potassium crystals of orthoclase and quartz and, at higher temperatures, tridymite. The orthoclase crystals were in great variety of forms, some of which correspond to those accompanying fayalite in the lithophysse. A similar treatment of silicates of sodium and aluminium gave rise to crystals of albite; but it is remarked that these were never accompanied by either quartz or tridymite and that a mixture of the alkalis produced orthoclase alongside of albite, although never in isomorphic combinations. Here, again, we see that the artificial methods of aqueo-igneous fusion, like those of purely igneous, or dry, fusion, have failed to reproduce intermediate varieties of feldspars corresponding to the isomorphic mixtures of distinct species, which are everywhere produced in nature, and of which the feldspar already described and figured from Obsidian Cliff is an example, and it seems probable that while all the conditions attending the natural processes of crystallization may not be comprehended in the artificial methods, still the far more gradual and less violent action of the same forces, which in particular instances in nature act feebly through long periods of time, may be an essential factor in the production of the infinite gradations in the composition of the minerals formed.

The experiments of K. von Crustschoff show that under the influence of superheated water tridymite is produced at a higher temperature than quartz. Other experiments have given both quartz and tridymite in the same closed tube.

Magnesian olivine has been produced by the action of steam and chloride of silicon on magnesium at a red heat under the pressure of the atmosphere, but as yet there seems to have been no attempt to reproduce iron olivine, which, however, occurs accidentally in many furnace slags. And finally magnetite has been reproduced by the action of aqueous vapor upon iron wire at high temperatures. From the foregoing we see that the minerals occurring in the lithophysse at Obsidian Cliff are such as may be formed from a mixture of silicates under the influence of superheated water or steam.

Fourthly. The experiments of Mr. Daubrée upon the effect of super-
heated water on glass are of special interest in this connection. A sealed glass tube which contained only water was inclosed in an iron case also containing water, which was sealed and heated to redness for different lengths of time with differing results. Under certain conditions, part of the glass, a silicate of lime and soda, with 5 per cent. of alumina, was converted into a hydrous silicate, accompanied by a considerable increase of volume; part was reduced to a white, opaque mass distinctly fibrous, with a delicate banding parallel to the surface of the glass tube and resembling agate.

The surface of the tube in places was warped, blistered, and excoriated and frequently full of cracks, besides which a delicate foliation parallel to the surface of the glass was developed. In some instances the whole mass was reduced to powder. Examined under the microscope the altered glass showed minute nearly opaque spherulites, acicular microlites, small crystals and grains of pyroxene (diopside), and larger spherulites of a material like chalcedony. The surface of the glass was covered with prismatic crystals of quartz.

The correspondence of many of these characters with those observed in the obsidian of Obsidian Cliff is very striking and suggestive. The fibrous and delicately banded structure is similar to that of the smaller spherulites in the obsidian; the thin foliation, the gaping cracks, and encrusting quartzes are features characteristic of the lithophysae. The microscopic forms of crystallization, though of different mineral nature, bear a great similarity, considering the difference in the chemical composition of the two glasses. Mr. Daubrée calls attention to the large amount of alteration produced in the glass by a small amount of water, scarcely one-third of the weight of the glass.

The question then arises whether water was present in the molten obsidian during the crystallization of the spherulites, and, if so, to what extent.

As already pointed out, the larger spherulites composed of rays of feldspar and a cement of tridymite are filled with gas cavities, easily recognized by their spherical shape and behavior toward light. The smaller spherulites are often clouded with minute particles, which it was suggested were partly gas cavities. That this is the case is shown by the following experiment: A fragment of a small blue spherulite was heated in the flame of an oxyhydrogen blow-pipe till it melted, when portions of it puffed up into a pumiceous glass by the expansion of the inclosed gas. The same experiment was repeated on the compact, black obsidian itself. When melted it also puffed up to a light-gray glass full of comparatively large gas cavities, quite identical with the pumice which is found on the top of this obsidian flow. This shows that the vapor which escaped from that portion of the lava that was on the surface and only subjected
OBSIDIAN CLIFF, YELLOWSTONE NATIONAL PARK.

to the pressure of the atmosphere was imprisoned in the deeper portions of the obsidian, probably combined with the glass, since the microscope fails to detect it.

The chemical analysis of the black obsidian and that of the dark-blue spherulites show almost identical losses on ignition, in the former 0.66 per cent. and in the latter 0.33 per cent. The greater part of this is water, which has been determined directly as such, and careful analyses of the disengaged gases from other similar obsidians, made by Boussingault and Damour, have shown its widespread occurrence, frequently accompanied by chlorine. It is to be noticed that a small amount of sulphur is present in the rock of Obsidian Cliff.

That the vapors existing in this obsidian were absorbed by the magma before its eruption is rendered highly probable by the experiments of Mr. Daubre on the penetration of water through rock by capillary attraction against a counteracting pressure of steam and on the hydration of glass by superheated water. From the observations of Mr. Fouqué at Santorin it is likely that at extremely high temperatures the elements of these vapors are dissociated.

CHEMICAL EVIDENCE.

That the absorbed vapors in the rock were the sole agents affecting the crystallization of the denser spherulites and the production of the lithophysae will appear from a consideration of the following chemical analyses, which were made of the rock of Obsidian Cliff for Mr. Arnold Hague, in charge of the Yellowstone National Park division of the U. S. Geological Survey. No. I is a black obsidian free from spherulites; No. II, red obsidian; No. III, small, dark-blue spherulites; and No. IV, white material forming small lithophysae in solid, black obsidian.

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Analyses I and II were made by Mr. Edward Whitfield, of the chemical laboratory of the U. S. Geological Survey, and III and IV were made by Mr. S. L. Penfield, of the Sheffield Scientific School. Nos. I and II are almost identical, with less than 1 per cent difference in silica. The chief point of interest lies in the relative amounts of ferric oxide and ferrous oxide present, the red obsidian having nearly all the iron in the form of ferric oxide, as already noticed.

Analyses III and IV are enough alike to be duplicates. They differ from those of the rock by being a little higher in silica and the alkalis and a little lower in the other bases. They are as close as could be expected, since the materials analyzed are from different parts of the lava flow. Other analyses might lessen this slight difference.

The main facts brought out by the analyses are that the chemical composition of the spherulite is essentially the same as that of the surrounding rock; it is then nothing more than a small portion of the magma which has crystallized with a particular structure; and, further, that the lithophysae have the same composition as the dense spherulites, which shows that the transformation of a spherulite to a lithophysa can only be a modification of its structure, a rearrangement of its minerals, without any chemical addition or loss.

This rearrangement took place through agencies within the limits of the spherule affected and disconnected from other possible sources, for perfect lithophysae occur isolated and hermetically sealed in dense, black obsidian. But where many such spherulites adjoined one another the cavities formed sometimes connected and spread irregularly, permitting the segregation of particular minerals in different places, which has been the case in the laminated, lithoidal portion of the lava flow.

Moreover, the hollow lithophysae were formed prior to the consolidation of the surrounding matrix, for they are occasionally found with the outer shell crushed and the viscous matrix forced part way in, showing that the mass was at a very high temperature and still viscous when the modification of the spherulites took place.

CONCLUSION.

We may fairly conclude that the lithophysae in the obsidian of Obsidian Cliff, with their contents of prismatic quartz, tridymite, adular-like and tabular soda-orthoclase, magnetite, and well crystallized fayalite, are of aqueo-igneous origin and result from the action of absorbed vapors upon the molten glass from which they were liberated during the process of crystallization consequent upon cooling.

Apparent exceptions.—Cavities and lithophysae occur, over which a distinct arching of the lamellae of the lithoidal rock is observed, the layers apparently accommodating themselves to the swelling of the hollows beneath; some appear simply as cavities coated with crystals...
of quartz, feldspar, and associated minerals; others have the concentric chambered structure of lithophysae (Pl. XIV, Fig. 7). The same phenomena have been described by Prof. F. Zirkel in the lithoidite from the southeast shore of Taupo Lake, New Zealand. The hollow spaces in that rock are intersected by partition walls coated with crystals of quartz, feldspar, hornblende, and mica and in many ways correspond to the lithophysae of Obsidian Cliff. At first sight it would seem that the expansion of a bubble of gas within the lava had occasioned the distention or displacement of its layers, but a careful study of portions of the rock which exhibit great contortion and plication of the layers makes it evident that in these cases the hollows occur beneath arches in the folds where there has been a local relief or diminution of pressure, which might allow the absorbed vapors to disengage themselves and bring about the conditions which produce hollow lithophysae in connection with spherulitic development. In other words, the arching of the layers appears to have been the cause of the liberation of gases and the production of the cavity beneath, and not the result of expanding gases.

That such local inequalities of the layers could have existed within the plastic mass is evident from the fact that the moving lava was so viscous and stiff before its final halting that, as already noticed, in one place where the layers of flow reached a vertical position they pulled apart and solidified with gaping crevices between, the surfaces of the separate slabs consisting of stony fragments on aropy, corrugated glass.

DEVELOPMENT OF VARIOUS STRUCTURES IN OBSIDIAN.

The development of the various forms of structure exhibited in this obsidian flow may be summed up as follows:

The molten mass when it reached the surface at the time of eruption was a viscous glass, highly siliceous and slightly hydrated or holding certain gases absorbed in it. Those in the glass at the top of the mass immediately expanded, being relieved of the pressure to which they had been subjected, and the glass chilled quickly into pumice. A little lower in the mass the expansion of the gas was but slight, filling the glass with small bubbles. In the compacter glass, which cooled more slowly than the pumice, trichites and microlites formed. After these the microscopic groups of feldspar and quartz with pegmatoid and fibrous structure crystallized; this must have been under the influence of the absorbed vapors at a high temperature, since they have not as yet been produced artificially by dry fusion.

Undoubtedly particular conditions of temperature, pressure, and consequent rate of cooling obtained in different parts of the flow at different stages of its progress, but about the time it came to rest in the region of Obsidian Cliff small colorless spherulites and fibrous
coatings around the granophyre groups were formed under conditions differing from those attending the production of the granophyre groups by the influence of a slightly lower temperature. In these the free silica would still seem to be quartz. In the next stage small colored spherulites crystallized with a fibrous structure in sectors of various orientation, which also appear to be composed of feldspar and quartz inclosing trichites and microlites.

With progressive cooling the nature of the spherulites passed to those whose centers are similar to the small ones just described, but the outer portion of which is formed of rays of short, attached feldspar crystals cemented with tridymite, the whole imprisoning multitudes of minute gas cavities. The absorbed vapors now began to assume the rôle of superheated water in their action on the surrounding silicates, which is more evident in the hollower forms, where the process appears to have been somewhat as follows: In the still viscous glass, from a center of crystallization the first frail beginnings of feldspar spread in innumerable rays, pre-empting, as it were, a sphere of the magma. The enlargement of these anhydrous microlites by crystal growth from their matrix of hydrated glass not only altered its chemical constitution by eliminating the alumina and the alkalies, but rendered it relatively more hydrous, so that, with decreasing temperature, it may no longer have been able to retain the vapors in combination.

The vapors separated from the glass were probably disseminated in minute particles through it, in some cases being able to coalesce into larger bubbles or to accumulate in certain parts of the spherule. A prolonged action of this sort permitted the separation of the original paste into feldspar, iron silicates and oxides, and residual silica, which at high temperatures would take the form of tridymite, but at lower temperatures would crystallize as pyramidal and prismatic quartz; a change of temperature or an intermediate one would cause both tridymite and quartz to crystallize.

The first crystallized feldspars were suspended in a plastic, hydrous silicate, which, from the observations of Mr. Daubrée, would occupy considerably greater volume than the same siliceous glass if anhydrous, and therefore still more than its component elements when crystallized. Upon the change of the hydrous paste to a crystalline aggregate through the process above indicated there would be considerable shrinkage, the extent of which is indicated by the gaping cracks and parted segments characteristic of lithophysae. This shrinkage was prior to the ultimate crystallization of the cementing paste, for the surfaces of the disrupted portions are coated with well developed crystals of fayalite, tridymite, and quartz. The tendency observed in spherulitic crystallization to produce concentric layers of different texture, which in the compact spherulites results in bands of greater or less density and of various colors, in the hollow
varieties gives rise to the concentric shells of typical lithophysae, by producing layers which act as nuclei about which the later-formed minerals, tridymite, quartz, and fayalite, crystallize, leaving cavities in place of the porous layers of the more solid spherulites.

CONDITIONS MODIFYING THE DEVELOPMENT OF LITHOPHYSÆ.

Finally, the occurrence of lithophysae in a rock, the nature of their contents, and the extent to which the cavities are developed (that is, their relative size) will depend on a number of conditions, first among which are unquestionably the character and chemical composition of the molten lava, the degree of hydration, and nature of the absorbed gases, and, second, the rate of cooling and the pressure under which consolidation takes place, for it is evident that under the same physical conditions glasses of different chemical composition will be affected differently by the same amount of absorbed gases. So far observations indicate that only the acid glasses produce these hollow spherulites. The amount of water vapor and the nature of the gases associated with it will alter both the extent of the action and the character of the minerals formed. With a given combination of these primary conditions, the results will vary with the rate of cooling and with the pressure, too rapid cooling not giving time enough for any crystallization to take place, too low a pressure permitting the gases to escape suddenly, and too high a pressure preventing their liberation in the proper state to produce the effects observed in lithophysae, and bringing about with the consequent slower cooling a granular; crystalline structure, the grains of which inclose the imprisoned gases condensed to a liquid form.

THE CAUSE OF DIFFERENT LAYERS IN LAMINATION.

In an earlier part of this paper attention was called to the parallel lamination of the rock, specially noticeable in the lithoidal portion. It was referred to slight local differences in the consistency or composition of the lava, which in flowing over the surface in a viscous condition spread these differing portions out in layers parallel to the plane of flow. A cause for such-local differences is suggested by the following observations: In the lithoidite the layers vary in their degree of crystallization, some being glassy, others finely spherulitic, others more coarsely spherulitic and porous, while still others are quite granular and full of cavities; some glassy layers have the crystallization localized in spherulites and lithophysae. These alternate and repeat themselves in endless succession and variety. In the obsidian the differences find expression in layers of spherulites, large and small, and bands of lithophysae, and in layers varying in the abundance of granophyre feldspars, microscopic spherulites, mi-
Croscites, and trichites; that is, in the different phases and amount of crystallization developed. Approaching the surface of the flow the same laminated condition of the rock appears in still more striking differences between the amount of microlites present and in layers of gas cavities which produce alternating bands of vesicular and dense-glass and pumice, until at the surface the whole mass is thoroughly pumiceous.

It is evident that there is a difference in the amount of vapor absorbed in layers of the rock, which is shown by the varying extent to which the layers are inflated when the pressure is removed and the confined gases are allowed to expand.

From the part which superheated water has undoubtedly played in the development of lithophysae and the larger spherulites, from the aqueo-igneous conditions deemed necessary for the production of the granophyre groups of quartz and feldspar, and, finally, from the observed changes of plasticity produced in a siliceous glass by hydration, it seems highly probable that the differences in consistency and in the phases of crystallization here developed are directly due to the amount of vapors absorbed in the various layers and to their mineralizing influence.

Besides the lamination of the pumiceous portion of the rock, which proves that the absorbed vapors were distributed unequally in alternating layers, there are highly pumiceous or inflated spots scattered through the mass, which show that the vapors were more abundant also in certain spots than in others. The distribution of these inflated spots corresponds to that of the isolated lithophysae and spherulites throughout the rock.

**HISTORICAL REVIEW.**

Having attempted an explanation of the nature and origin of lithophysae which seems to accord most closely with the phenomena of their occurrence at Obsidian Cliff, it will be of interest to review the opinions of those who have studied the question in other fields and upon different material.

**Ferdinand von Richthofen.**—The first notice of these curious rock structures is the very full and graphic description of those found in the rhyolites of Hungary, given by von Richthofen more than twenty-five years ago, at which time he proposed the name of Lithophysen, because the rock appeared to have been inflated by the expanding of gas. He considered them quite distinct from spherulites and said that only through the most careful chemical analysis could positive conclusions as to the process of their formation be reached. He thought that a gas had been evolved, for the oft-repeated, lam-

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OBSIDIAN CLIFF, YELLOWSTONE NATIONAL PARK.

collar banding of the surrounding rock showed that it had been forced apart, not violently but gradually, since the separate layers of the rock bent themselves exactly to the curvature of the hollows. Moreover the gas had been evolved from the inclosed substance for the hollow spaces are found only in connection with this and do not occur by themselves in the groundmass. Further, they have come into existence after the laminated arrangement of the rock; consequently the gas must have been connected with the inclosed substance in either a solid or fluid condition. From the form of the repeated shells within the lithophysae it would appear that their substance was exceedingly viscous at the time the gas was set free. The question then suggests itself how and for what reason was the substance of the inclusion separated out of the rock and what sort of gas was evolved. He thought that the experiments of Daubrè threw some light on the process. They showed, he said, that water at a temperature of 400° C. under high pressure dissolves all the constituents of glass and upon cooling deposits them as different crystals, in part anhydrous. He referred to the effect of hydration in increasing the fluidity of lavas and added that, if in consequence of this any hydrate had been developed in particular parts of the rock, then the process already suggested would easily take place, for a part of the water could no longer remain in combination, because of the lessening of pressure upon the eruption of the rock, and would disengage itself as gas. It would force the viscous rock mass apart, but could not escape, and thus the forms in question must have been produced.

With this view, expressed by von Richthofen in the early days of the science of microscopical petrography, that of the present paper is in accord at many essential points; but the earlier view represents bubbles of gas expanding from their point of liberation within the viscous lava and forcing back the surrounding matrix; they carry up successive films of the plastic glass and thus produce concentric shells. The objections to this are the physical difficulty of expansion under the circumstances and the radially fibrous structure observed in connection with the often incomplete shells, which correlate them with the concentric layers of spherulites.

Dr. Joseph Szabó, in a paper on the trachytes and rhyolites in the vicinity of Tokay, Hungary, expresses the opinion that lithophysae are only a stage in the mechanical and chemical alteration of spherulites, which through chemical alteration first lose their luster and then their coherence. He thinks the bases are removed chemically, the insoluble particles mechanically, and that the silica is concentrated in the cavity.

1Die Trachyte und Rhyolite der Umgebung von Tokaj: Jahrbuch k. k. geol. Reichsanstalt, vol. 10, 1866, p. 89.
Karl Ritter von Hauer published in the same year the results of the chemical analyses of four rhyolites which carry lithophysae, and also of the substance of the lithophysae. They are given further on, in the table of chemical analyses (p. 43). They show that the lithophysae do not differ chemically from the groundmass which contains them and give some idea, he said, of their mode of origin. He thought that the lithophysae were separated out from the groundmass only in a mechanical way through the development of gas, and not as the product of metamorphosing influences on the groundmass; that the gases (in this case water vapor), upon being evolved in the still viscous mass, were able to find exit only slowly and occasionally not at all; in this way pores, larger hollows, and bladder-like inflations were produced.

Justus Roth in 1869 adopted Szabo's views that lithophysae are only mechanical and chemical alterations of spherulites and repeats them in his Allgemeine und chemische Geologie, 1883, vol. 2, p. 216.

Ferdinand Zirkel, in describing the rhyolites in the collection of the Geological Exploration of the Fortieth Parallel, calls attention to spherulites in the rock from Shoshone Mesa, which "develop, by decomposition, a concentric layer-structure." These he considers to be the same as the lithophysae of von Richthofen and that they in like manner were only the result of chemical alteration.

Ch. E. Weiss considers the cavity of a hollow spherulite as playing the same rôle as a solid body around which the spherulite forms. He thinks hollow spherulites and hollow spheres are only larger and smaller spherulites which have formed around gas bubbles; where several bubbles were near together and touched one another there arose the chambered, hollow spherulites, or lithophysae. The coarser-grained spherulites, he says, show they are composed of two minerals, quartz and feldspar.

Grenville A. J. Cole reviews the previous opinions on the subject and concludes that the hollows are due to the decomposition of solid spherulites by chemical agents, the material having been carried out through cracks in the rock.

C. A. Tenne describes the lithophysae in the obsidian from Cerro de las Navajas, Mexico, collected by von Humboldt, to which von

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1 Die Gesteine mit Lithophysenbildungen von Telki-Banya in Ungarn: Verhandl. k. k. Reichsanstalt, 1866, p. 98.
2 Beiträge zur Petrographie der plutonischen Gesteine, 1869, p. 168.
3 U. S. Geol. Ex. Fortieth Par., vol. 6, Microscopical Petrography, 1876, p. 212.
Richthofen calls attention in the paper already cited and from which Rose obtained the olivine crystals. He says that the substance of the lithophysae must be devitrified obsidian, which a microscopical investigation makes probable. He gives chemical analyses (see analyses VII and VIII, next page) which show that the obsidian and lithophysae have the same chemical composition.

Whitman Cross, in a paper "On the occurrence of topaz and garnet in lithophyses of rhyolite," points out the fact that these minerals are not of secondary formation in the cavities, but primary, "produced by sublimation or crystallization from presumably heated solutions, contemporaneous or nearly so with the final consolidation of the rock. The lithophysal cavities seem plainly caused by the expansive tendency of confined gases or vapors, while the shrinkage cracks in the walls and white masses of the Nathrop rock suggest the former presence of moisture. Certainly the history of the lithophysae themselves embraces that of both topaz and garnet."

From this it is seen that two distinct views of the origin of cavities within the lithophysae have been taken: One, that the hollows were of primary origin, formed while the lava was still plastic, and were due to inclosed gases or vapors. Among those who held this opinion some considered the lithophysae as wholly distinct from spherulites, while others thought them simply hollow varieties of spherulites. The second view was that the hollows had been produced in solid spherulites by chemical decomposition and alteration, and were subsequent to the solidification of the lavas in which they occur.

GEOGRAPHICAL DISTRIBUTION OF OBSIDIAN.

As the thoroughly glassy forms of many varieties of rocks present much the same general appearance and are with difficulty distinguished from one another, they have all been classed together as obsidian. Thus the term has come to signify any volcanic glass which has a small percentage of water and is almost if not wholly free from porphyritic crystals. But since the more siliceous rocks have a greater tendency to cool as glasses than the basic ones, most of the volcanic glasses belong to acid rocks. They may range from less than 60 per cent. to 78 per cent. of silica, including a few basalts with some andesites and trachytes and all dacites and rhyolites. The rock forming Obsidian Cliff is a rhyolitic obsidian, and on the next page is given a table of chemical analyses of similar rhyolitic obsidian from widely distant parts of the world, together with the analyses of spherulites and lithophysae found in some of them. The analyses of rhyolite and lithophysae made by Karl von Hauer are placed side by side for comparison.

I. Black obsidian free from spherulites, Obsidian Cliff, Yellowstone National Park.

II. Red obsidian free from spherulites, Obsidian Cliff, Yellowstone National Park.

III. Small, dark-blue spherulites, Obsidian Cliff, Yellowstone National Park.

IV. White lithophysse from black obsidian near Lake of the Woods, Yellowstone National Park.

V. Black obsidian with numerous gas cavities (Russell), Mono Lake, California.

VI. Black obsidian, Obsidian Hill, Tewan Mountains, New Mexico.

VII. Black obsidian (Tenne), Cerro de las Navajas, Mexico.

VIII. Lithophysse from the same (Tenne), Cerro de las Navajas, Mexico.

IX. Obsidian (Abich), Lipari Islands.

X. Rhyolite (K. von Hauer), Grenczer Pass, Hungary.

XI. Rhyolite (K. von Hauer), Telki-Banya, Hungary.

XII. Rhyolite (K. von Hauer), south of the Neue Massamühle, Telki-Banya, Hungary.

XIII. Rhyolite (K. von Hauer), south of the Alte Massamühle, Telki-Banya, Hungary.

XIV. Contents of the lithophysse in the last-mentioned rhyolite.

<table>
<thead>
<tr>
<th>Constituents</th>
<th>I.</th>
<th>II.</th>
<th>III.</th>
<th>IV.</th>
<th>V.</th>
<th>VI.</th>
<th>VII.</th>
<th>VIII.</th>
<th>IX.</th>
<th>XI.</th>
<th>XII.</th>
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<tr>
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<td>1.74</td>
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<td>1.45</td>
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<td>.96</td>
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<td>1.92</td>
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<td>.06</td>
<td>.73</td>
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<tr>
<td>MnO</td>
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<td>Sp. gr.</td>
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<td>2.342</td>
<td>2.385</td>
<td>2.392</td>
<td>2.370</td>
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<td>2.420</td>
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<td>2.420</td>
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Obsidian with more or less porphyritic crystals occurs over large areas in the Yellowstone Park; it abounds in spherulites and lithophysse, which are also found in the pearlitic and rhyolites of the same region. Lithophysse also occur in the dark, pearlitic rhyolite from the base of the cliff of Shoshone Mesa, near Rock Creek, Idaho, where they were collected by Mr. S. F. Emmons, who says they "are generally hollow and look like a clayey mass formerly filled with gaseous matter which has burst forth leaving a hollow interior. * * * The centers of some of the lithophysse are still filled with crystals of quartz and feldspar."
A well known locality for obsidian is Mono Lake, California, where a chain of extinct volcanic cones stretches southward from the lake. They are mainly composed of rhyolitic pumice in vast flows, with which are associated large outbursts of obsidian. This obsidian is a black glass without porphyritic crystals. Thin sections of the obsidian from the first and second large craters south of Mono Lake, which were collected by Mr. Arnold Hague, show it to be a clear glass, free from microlites and trichites. Its chemical composition, given in analysis V of the table, which was made for Mr. I. C. Russell, is almost identical with that of the black obsidian of Obsidian Cliff, except that there is only a trace of iron and over 2 per cent. loss by ignition. The obsidian passes into vesicular and bubbly glass and pumice; in places multitudes of minute bubbles produce gray bands through the black glass, which in certain lights show a beautiful luster and heliotrope color. From the highest volcanic cone at the south end of Mono Lake Mr. George M. Wright collected obsidian full of small, blue spherulites, among which are scattered larger ones about an inch in diameter.

Very beautiful, black obsidian, with small lithophysse and occasional spherulites, occurs at Obsidian Hill and on the Rio San Diego and in other localities in the Tewan Mountains, New Mexico, where it has been collected by Maj. J. W. Powell, Director of the U. S. Geological Survey, and by Mr. William H. Holmes. This obsidian is remarkably transparent in thin fragments, but is intensely black in larger pieces; it is almost free from microscopic secretions, there being only a small amount of black grains, probably magnetite, and a few microscopic feldspars. Chemical analysis, No. VI, of the obsidian, from Obsidian Hill, N. Mex., shows that it has very nearly the same chemical composition as the obsidian of Obsidian Cliff, with slightly more silica and less iron oxide, which may account for the absence of fayalite from the lithophysse of the former.

Near Coyote Spring, 30 miles north of Milford, Utah, Mr. G. K. Gilbert found obsidian closely resembling that at Obsidian Cliff. It is black, variegated with red and brown, some of it being very transparent in comparatively thick pieces. It is spherulitic and free from porphyritic crystals. Associated with it are pumice, lithoidite, and porphyritic rhyolite. Through the kindness of Mr. George P. Merrill, of the National Museum, the writer has been able to look over the collections of obsidian from the Western States and Territories and some foreign localities and make such notes as he desired.

From Beaver Valley, Utah, Mr. I. C. Russell has collected spherulitic, black obsidian, the spherulites having a curious, ragged form, probably consisting of a cluster of smaller ones. At White Mountain, Utah, a black obsidian occurs which is full of light-gray lithophysse. Black obsidian without porphyritic crystals has also been brought in from High Rock Cañon, Nevada, and a black pearlite from
Trout Creek Point, on the crest of Quinn River Mountains, Nevada. This rock is crowded with dark red and brown spherulites of considerable size; it contains 75.50 per cent. of silica.

Black obsidian more or less spherulitic has been found at White Sulphur Springs, Napa County, and in the Pitt River district, California, the latter locality furnishing beautifully banded and mottled varieties.

Glass Butte, Oregon, is formed of a fine, red, brown, and black obsidian, specimens of which were collected by Mr. I. C. Russell. Some of the black is very transparent and clear, with a smoke-brown tinge in thin pieces; through it are scattered small white spherulites.

One of the purest obsidians known, according to Professor Zirkel,\(^1\) occurs in the form of kernels and balls in the pearlite of Grass Cañon, Nevada, which has been described by Mr. Arnold Hague.\(^2\) The obsidian balls are from half an inch to an inch in diameter and are associated with a white, pumiceous tufa inclosing fragments of pearlite. They are intensely black in color and in thin section are gray with few black, trichitic lines. The obsidian from Cerro de las Navajas, Mexico, as already mentioned, corresponds in many ways to that of Obsidian Cliff (compare analyses VII and I). It is associated with liparite and bluish-gray, spherulitic lithoidite and carries occasional crystals of sanidine and lithophysae. Red and black obsidian is found at the same place. At Cerro Pelado, southwest of Cerro de las Navajas, spherulitic obsidian with lithophysae is associated with lithoidal and spherulitic rhyolite and pearlite. Similar obsidian is found at San Juan de los Llanos, Puebla.

In Ecuador, near Guamani, occur spherulitic obsidian flows. The glass is banded with dark layers which are older than the spherulites. It contains a few porphyritic crystals of sanidine and biotite and is associated with lithoidite and pumice.\(^3\)

An obsidian lava rich in spherulites is described by G. vom Rath\(^4\) from Antisana in the Andes. The microscopic characters of the spherulites correspond closely to those of Obsidian Cliff.

The Lipari Islands, north of Sicily, are famous for the abundance of obsidian found there. It is partly spherulitic, with lithophysae, and is intimately associated with pumice. Analysis IX, published by Abich, is of obsidian from this locality. At Monte Guardia a gray, porous, and pumiceous rock contains exceedingly numerous, thin strips of black obsidian, which are parallel to the direction of the lava flow.

Another celebrated locality is Iceland, where the obsidian, judg-

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ing from its chemical composition, belongs rather to dacite. The flow at Hrafntinnuhryggr is banded by alternating layers of crystalline and glassy rock.

It is not very abundant in Hungary, but occurs in the Caucasus, on Teneriffe, Ascension, and Guadeloupe, in Java, and Japan.

In New Zealand, on the southeast shore of Rotorua Lake, spherulitic obsidian is found which is dark-grayish brown in thick masses; in thin splinters it is as clear as water or has a light tinge of smoky gray. In it lie sharply defined, small spherulites with a bluish-gray, waxy luster. The obsidian has 75.03 per cent. silica and the spherulites have 74.55 per cent.

Black obsidian is very abundant on Tuhua Island, Bay of Plenty, tuhua being the South Sea Islander's word for obsidian. Pieces often have a silvery or iridescent coating like that produced on artificial glass by the decomposing action of the atmosphere. Its silica percentage is 74.91.

Behind the village of Totara, on the southeast shore of Taupo Lake, stands a vertical wall of lithoidite with most remarkable lamellar structure and regular columnar parting. The lamellae are of almost microscopic thinness, principally in two colors, a grayish-black and purplish-gray, of which there are many lighter and darker shades, alternating with one another like the banding of an agate. Occasionally bubble-like distensions are observed, in the neighborhood of which the lamellae of the rock thin out. The cavities are mostly flattened in the plane of the lamellae. The interior is often interrupted by partition walls, which are coated with minute crystals, probably of quartz and feldspar, with hornblende and thin flakes of mica. The rock corresponds very closely to the lithoidite at Obsidian Cliff, except for a few porphyritic crystals of quartz and feldspar and a slightly lower percentage of silica, 70.67.

CONCLUSION.

In conclusion, we see that obsidian of nearly the same chemical composition and microstructure occurs in all parts of the world; that it is generally accompanied by like modifications, passing into pumice on the one hand and into lithoidal or porphyritic rhyolite on the other; and that in most instances it is more or less spherulitic. But the obsidian flow a part of which forms Obsidian Cliff is especially remarkable for its extent and thickness, which exceed those of any other described locality, unless surpassed by some occurrences in Mexico. It is, so far as we are able to learn, the only occurrence of rhyolitic obsidian in which a distinctly columnar structure has been developed. It is entirely free from porphyritic crystals and abounds in spherulitic structures and lithophysae of great beauty.

1 F. Zirkel: Petrographische Untersuchungen über rhyolitische Gesteine der Taupo-Zone; F. v. Hochstetter: Geologie von Neu-Seeland, 1884.
and perfection. The absolute freshness of the rock and absence of secondary alteration permit the study of these forms of crystallization without confusion with decomposition-products or subsequent metamorphism, common in older and more crystalline rocks, or even in recent lavas which have been attacked by solfataric or hot-spring agencies, as those in many parts of the Yellowstone Park have been, where the effects of secondary alteration are easily recognized. They leave no doubt that the spherulites and lithophysae, in all their complexity of form and structure, are of primary crystallization out of a molten glass, which was gradually cooling and consolidating, and that, since its solidification, no alteration, chemical or mechanical, has taken place.
REPORT

ON THE

GEOL OGY OF MARTHA'S VINEYARD.

BY

NATHANIEL S. SHALER.
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REPORT ON THE GEOLOGY OF MARTHA'S VINEYARD.

BY NATHANIEL S. SHALER.

INTRODUCTION.

The following report on the geology of Martha's Vineyard is one of three separate studies which I have devoted to the interesting field of southeastern Massachusetts; the second, that on Nantucket, it is hoped may be soon issued; and the third, on Cape Cod and the Elizabeth Islands, is now in preparation. The special aim of these reports is to furnish a basis for the geological history of this part of the shore line of North America.

As the larger part of this district shows only deposits of the glacial age, the material of these inquiries principally concerns the work of the ice sheet of that epoch. On Martha's Vineyard, however, there are, as is well known, considerable deposits of the Tertiary age, which are the northernmost deposits of that geological horizon on the eastern coast of the United States. As will be seen in the following pages, these Tertiary beds of the Martha's Vineyard series present certain important peculiarities from which we shall be able to make many inferences as to the physical conditions in this district during that time. The literature concerning the geology of Martha's Vineyard is limited. Incidental references to the geological structure of this district are numerous. The following are some of the more important papers concerning the geology of Martha's Vineyard: A letter concerning Gay Head, Rev. Sam. West, Mem. Am. Acad., vol. 2, 1798; Description of Gay Head, Dr. William Baylie, ibid.; Observations on the geology of the United States, explanatory of a geological map, William McClure, Trans. Am. Phil. Soc., vol. 6, 1809; Notices of the geology of Martha's Vineyard and the Elizabeth Islands, Rev. Ed. Hitchcock, Am. Jour. Sci., vol. 7, 1824; Geological essay on the Tertiary formation in America, John Finch, ibid.; Review of "Outlines of the geology of England and Wales, with an introductory compendium of the general principles of that science," Rev. W. D. Conybeare and William Phillips, ibid.; Report on the geology of Massachusetts, Ed. Hitchcock, ibid., vol. 22, 1882; Review of Chas. Lyell's On the Tertiary Strata on the Island of Martha's Vineyard, of Massachusetts, ibid., vol. 46, 1844; Address delivered at the meeting of the Association of American Geologists and Naturalists held in Washington, Henry D. Rogers, ibid., vol. 47, 1844; On the physical geology of the United States east of the Rocky Mountains, and some causes affecting the sedimentary formations of the earth, W. W. Mather, ibid., vol. 49, 1845; On the fossil crab of Gay Head, Dr. Wm. Stimpson, Boston Jour. Nat. Hist., vol. 7, 1863.
when we reflect that Gay Head presents by far the most striking geological features on our eastern shore.

The party-colored Tertiary sands exposed in the section near Gay Head light-house make this part of the shore extremely conspicuous. These beds contain a greater variety of fossils than can be obtained in any other part of the coast region of New England.

As will be seen in the subsequent pages which treat of the economic resources of the Gay Head series, this rock yields some clays and sands useful in the arts. Certain of the beds may also prove valuable for fertilizing materials, while the lignite deposits which abound in this section may possibly have a certain value as sources whence iron pyrites may be obtained. The considerable economic possibilities afforded by this series of beds, together with the purely scientific interest which attaches to them, are sufficient warrant for the extended consideration which they have here received.

It will be observed that this report contains no discussion of the fossils found in the Tertiary deposits of Martha's Vineyard. A chapter on this subject was prepared, but it became evident to me that it would be necessary to procure by systematic excavations far more material than is now accessible before the work could be suitably done. I hope to undertake this task in a separate memoir.

**GENERAL GEOLOGICAL RELATIONS OF THIS AREA.**

The island of Martha's Vineyard, as will be seen from the inspection of any good map, is a part of an extensive fringe of low land, mainly composed of glacial drift, which extends from New York City to Cape Cod. These beds are represented beneath the surface of the sea by the great fringe of sandy reefs known as Nantucket Shoals and by the extensive submerged deposits of apparently similar nature which exist in the shoal water to the north of Cape Cod known as George's Shoal, Cultivator Shoal, etc.

The part of this belt of glacial deposits which is above water is composed of an outer series of drift ridges which form Long Island, the island of Martha's Vineyard, Nantucket, and a number of lesser islands, and a similar inner ridge evident in Cape Cod, the Elizabeth Islands, and several smaller islands. It is possible that this inner line of drift deposits is continued westward in the northern half of Long Island, which may thus combine the two drift belts in one mass.

The eastern portion of this double coast fringe is separated from the western portion by a considerable gap, i.e., that which divides Martha's Vineyard from Block Island and Long Island. The cause of this break is not perfectly clear, but it is probably due, not to any failure of the glacial deposits to be formed in this space or in any considerable degree to their erosion, but rather, it is likely, to the fact that the floor on which they rest was originally lower in this part of the coast than elsewhere. This is indicated by the circum-
stance that from the western end of Martha's Vineyard there is a shoal that extends to Block Island and thence to Long Island. This shoal seems to be a continuation under water of the glacial mass to which Long Island and Martha's Vineyard belong.

On the east, Martha's Vineyard is divided from Muskeget Island, which is essentially a part of Nantucket, by a shallow strait known as Muskeget channel. This channel, though about seven miles wide, is not over fifty feet deep at any point and does not average half that depth. These two islands may therefore be regarded as essentially one mass of land.

The general form of the island of Martha's Vineyard is triangular, with the apex of the triangle turned to the north. The island has a length of about twenty miles and a width on a north and south line of about nine and a half miles. The base of this triangle, i.e., the southern shore of the island, is a nearly straight east and west line from its easternmost point to near its western extremity; at that point it is somewhat abruptly deflected to the south. This deflection, as we shall hereafter see, is due to the geological structure of this extremity of the island. On the eastern end there is a peculiar tangle of sand beaches wrapped round the island of Chappaquiddick, which is barely separated from Martha's Vineyard by an impermanent, narrow, and shoal channel. This channel has been closed during a large part of the present century; it is at present open, as is indicated on the map.

The northern shore of the island is much more irregular than the southern. At the eastern end of the island, Cape Poge, with the very extensive barrier of sand beaches which are attached to it, forms a great salient, within which lies Edgartown harbor. On this northeastern face of the island lies also the extensive inlet known as Sengokon-tacket Pond. This pond was originally a broad bay which has been barred from the sea by a wall beach of sand. At the very apex of the northern shore is a deep re-entrant
known as Holmes’s Hole or Vineyard Haven, which is prolonged to the southward by a narrow, fjord-like inlet known as Lagoon Pond. These two areas of water form an indentation extending about three and a half miles in a north and south direction. At the western extremity of the island there is another extensive bay which resembles the indentation of Edgartown harbor and is known as Menemsha Bight. Besides these bays, there are two large ponds on the north shore, Chappaquonsett, or Tashmu, and Menemsha, which were originally arms of the sea, but have recently been barred from the open water by walled beaches.

Although the periphery of the island is simple, this simplicity is in good part due to the action of the sea, which by a system of barriers has masked the irregularities of the shore line. This uniforming action of the sea is most conspicuous on the southern face of the island, where the shore is exposed to the assaults of the ocean waves; on the northern shore, which faces Vineyard Sound, this effect of the waves is of course much less pronounced.

**SURFACE CONTOUR OF MARTHA’S VINEYARD.**

The surface contour of this island is closely connected with its geological structure; it will therefore be well to describe it before entering on its geological history. The surface of Martha’s Vineyard is distinctly divided into three parts. On the north side, extending from the western horn of Vineyard Haven to Gay Head, there is a belt of hills composed of sand and gravel interspersed with many large bowlders. This belt of hilly land is on the average about a mile and a half wide. Its ridges have a height of about fifty feet on the eastern extremity of the belt and of about three hundred feet at Prospect Hill, near the western half of the line.

South of this hilly belt, on the eastern half of the island, the surface passes rather suddenly into a plain, which occupies nearly the whole of the area south and east of a line drawn from the village of Vineyard Haven to Chilmark Pond. This plain is at the altitude of about fifty feet above the sea, at least on its northern edge, where it comes in contact with the bowldery hills before mentioned, but it slopes gradually to the south, until, at the southern shore of the island, it rises only about ten feet above the sea level.

West of this plain region we have in West Tisbury, Chilmark, and Gay Head a district where the general surface is much higher than in the other parts of the island, it having an average height of about one hundred and fifty feet above the sea. This district is hilly, but the hills are mainly composed of drift materials, while the deeper part of the mass on which the hills rest is of Tertiary age. Generally the surface of the Tertiary deposits rises to about one hundred feet above the sea.
NASHAQUITSHA AND MENEMSHA PONDS, MARTHA'S VINEYARD, LOOKING NORTH, SHOWING MORAINES CROSSING WATER.
The difference between these three districts is marked not only in their larger features, but in the details of their surfaces as well. The belt of detrital elevations has the usual aspect belonging to deposits of this nature in southeastern New England. They consist of a confused assemblage of hills composed in the main of more or less irregularly stratified sands and gravels mingled with bowlders that are often extremely numerous and of large size. At first sight there appears to be no distinct order of arrangement in these drift hills, but on closer study we see that there is a certain order of distribution in the eminences, their alignment being parallel to the direction of the belt which they occupy. In Pl. XIX these parallel ridges of drift are shown, though in an imperfect manner, forming projections from the shores.

The plain country to the southward is on the whole remarkably level, but on closely examining the surface we find that it is intersected by broad, shallow, and slightly defined channels, which at present are not occupied by streams. These channels widen and deepen southwardly and terminate in the numerous ponds or lagoons which exist on the southern border of the island. These ponds are separated from the sea by the continuous barrier beach which extends from Cape Poge, along the eastern and southern shores of the island, to Nashaquitsa Cliffs, near Gay Head.

The surface of the bed rocks west of Tisbury Brook is to a great extent hidden by the glacial deposits; it is, however, clear that the foundations on which these drift heaps lie is molded into broad elevations, which have a fairly defined north and south axis. On Gay Head one of the troughs between these elevations is so low that the waters of the sea almost cross the island. In this trough lie the basins of Squipnocket, Menemsha, and some lesser contiguous ponds. On the surface of this district the drift materials are accumulated in a very irregular way. Here we find the glacial deposits in such a position that we may see them from top to bottom. This is the most southerly point on the New England shore where it is possible to trace the contact of the drift deposits with the underlying rock. It therefore merits a careful study.

It is worth while to note that on the plain district of the island there is nothing which deserves the name of a brook and on the gravel hills east of this Tertiary district there is not a single stream that is large or constant enough to have received a name. The western part of the island has a number of large and constantly flowing streams, two of which afford good mill power. This difference is clearly due to the presence in the Chilmark district of impervious layers of clay belonging to the Tertiary deposits, which arrest the downward movement of the rainwater and compel it to find its way to the surface before it attains the level of the sea. On the sandy southeastern part of the island the rainwater sinks at once into the
ground and enters the ocean in the form of a broad, subterranean sheet which creeps through the interstices of the sand and escapes unnoticed between high and low tide.

The general character of the eastern surface of Martha's Vineyard is essentially like that of the greater part of Cape Cod and almost exactly the same as that of Nantucket, which island, as before remarked, is a part of the same drift deposits. The only important difference to be observed is in the direction of the ridges of drift hills which occupy the northern face of both islands. On Martha's Vineyard these ridges extend in a northeast and southwest direction (or, more accurately, from N. 55° E. to S. 55° W.), a course essentially parallel to the similar ridge which forms the Elizabeth Islands and a considerable part of Cape Cod. On Nantucket, however, the morainal ridges extend in an east and west direction, the difference in azimuth being about 40°. The meaning of this difference will be considered in the report on the island of Nantucket.

The aspect of the two islands differs greatly on account of the peculiarity of the vegetation. Nantucket is essentially treeless, while the greater part of Martha's Vineyard is forest-clad. This difference is probably owing to the greater exposure to the sea winds suffered by Nantucket, which is due to its smaller size and greater distance from the shore. In part the deforested condition of Nantucket may be attributable to the fact that for nearly two centuries its fields were used as open sheep pastures and the young trees were constantly browsed down by the flocks. Martha's Vineyard, on the contrary, has held its woods; only a small strip on the southern shore shows any tendency to become sterilized in respect to forest growth by the action of the sea winds. On the sand plains the woods are of stunted oaks and other dwarf varieties of trees, but the growth is vigorous enough to give a wooded aspect to the surface and thereby to distinguish it in a very marked way from the neighboring and otherwise similar island of Nantucket.

For further considerations on this subject the reader is referred to a forthcoming report on Nantucket.

GLACIAL DEPOSITS OF MARTHA'S VINEYARD.

We have already noted the fact that there is a considerable diversity in the drift materials of this island. The careful examination of the structure of the island shows that there are upon it the following groups of glacial deposits:

1. Ordinary ground moraines or till, such as is left by the melting of a glacial sheet.
2. Frontal moraine deposits, formed where the materials have been pushed before the glacier.
3. Kame deposits, where the materials have been brought to their
GEOLOGIC MAP OF MARTHA'S VINEYARD SHOWING SUB-STRUCTURE BY N. S. SHALER

Scale 1:160,000 = 1/2 mile.

Vineyard Series [Above sea level]
Weyquoque Series [Probably above sea level]
Naushon [below "]
Indian Hill ["]

Soundings (approximate) in feet.
MAP OF MARTHA'S VINEYARD
SHOWING THE SURFACE GEOLOGY
BY N.S. SHAIKH

Scale 1:160,000 = 2\text{\textfrac{1}{4}} \text{in.} = 1 \text{km}

- Recently transported sands
- Terraces without kames
- Kames and rolling terraces
- Till and frontal moraine
- Advancing shores \rightarrow (pointing seaward)
- Retreating shores \leftarrow (pointing landward)
position by the action of violent currents of water operating near the ice front of the glacier.

4. Terrace deposits, formed by tidal action or by the action of the waves at some distance from the ice front.

It may be noted here that there are no lenticular hills or drumlins on the island and that the group of Indian ridges, or long, wall-like varieties of the kames, is represented by a single deposit of that nature.

We will now consider each of these groups in the order in which they are named:

**ORDINARY GROUND MORAINES.**

(1) Ordinary moraines and frontal moraine deposits are seen only on that part of the island where they rest upon Tertiary clays which rise much above the sea-level. In the greater part of this district the till is found as a thin sheet in no way differing from the deposits of a similar kind exhibited on the surface of the mainland to the northward. Its average thickness does not probably exceed ten feet, but it is so irregular in this regard that it is not easy to assign it an average depth; considerable portions of the surface are almost bare of it, having only two or three feet of pebbles mingled with the clay derived from the subjacent Tertiary beds. Probably as much as one-tenth of the surface of this district is to this degree wanting in the covering of till. The maps given in this report (Pls. XX and XXI), together with Fig. 56, will give an approximate idea of its distribution.

In its composition the till of the Gay Head and Chilmark districts is much more clayey than that on the mainland. This may readily be explained by the fact that it is in good part derived from the Tertiary beds which it overlies.

This sheet-like till often passes gradually, or at least without distinct demarkation, into steep-sided ridges and hillocks of a somewhat similar nature which are irregularly scattered over the surface of this Tertiary district (Pl. XXII). These drift elevations are generally till-like in their nature, but the materials have evidently been shoved before the glacier and so have the form of frontal moraines. They exhibit obscure traces of stratification; therefore, presumably, they must have been affected by the movements of water. We can most readily account for all their peculiarities of structure by the supposition that they were formed on the sea floor at the front of the glacier during its
period of retreat and shoved forward during the slight and temporary readvances which accompanied that retreat.

A remarkable fact regarding the glacial accumulations which lie on the Tertiary beds is that a good deal less than one-half of their mass was derived from these Tertiary clays and sands. The larger part is from the granitic rocks of the mainland. From an a priori point of view it would seem as if these relatively soft beds should have worn away very rapidly beneath the moving ice, but apparently they have worn but little. In the region of the Narragansett coal-fields, for instance, about Taunton, Mass., in any place which we may choose for examination, more than half the waste composing the till is from points within two miles of the place of deposition. But in these Chilmark deposits, especially along the southern part of that field, we are often able to prove that the till is mainly composed of débris derived from rocks which certainly do not occur within four miles to the north and which were probably not touched by the glacier for more than twice that distance. The failure of the glacial sheet to erode these soft Tertiary beds is probably due in part to the fact that they have no joint planes and also in part to the embedding of the granitic boulders in the tough clay. In this position the boulders would in a measure protect the clay from the erosion as by a pavement. Some evidence of this action, it seems to me, may be seen in the section at Gay Head.

The small amount of this erosion is very well shown in the sections at the west end of the island, where the drift is seen in contact with the subjacent Tertiary beds along the marine escarpment for a length of over one-half a mile. It is evident from the small proportion of Tertiary waste in this drift, which does not exceed 10 per cent. of the mass, that the ice took less from these clays than it did from the syenite of the mainland. It is possible that this diminution of the erosion may be due in part to the diminished thickness of the ice near its border. Too much, however, must not be attributed to this cause. The vast amount of coarse débris which was shoved to this point indicates a power of erosion which, though perhaps less than on the mainland, must still have been very considerable.

A peculiarity of the drift deposits which lie on the elevated surface of the Tertiary beds is the small amount of ordinary kame drift which exists there. Enough of this kame drift exists to show that the surface was subjected in a slight degree to the forces which dis
posed glacial débris in that form. It seems likely, however, that the elevation of this Tertiary plateau caused the subglacial streams which formed these kames to be diverted to the lower ground on the east and west, so that they existed slightly if at all in the western part of the island (Fig. 57).

FRONTAL MORaine DRIFT.

(3) We turn now to the frontal and till-like drift which exists in the northern part of the island between Menemsha Pond and Chappaquiddock or Tashmu Pond. The greater part of this section evidently lies on top of the Tertiary beds; only that part which lies west of Indian Hill is unsupported by this pedestal. Even the portion of this line of drift hills which lies west of Indian Hill probably rests on a basement of Tertiary beds, though the surface of that formation is so far hidden that its position cannot well be determined.

This northern moraine drift is essentially like that which is scattered over the northern part of Chilmark and the central part of Gay Head. We may indeed regard it as only a more concentrated form of the same class of drift, and consider it as extending from the seashore about midway between Gay Head light-house and Squipnocket beach northeastwardly to Tashmu Pond, with a considerable interruption at the valley of Menemsha and Squipnocket Ponds.

The essential peculiarities of this district are that in it the distinct sheet till disappears in the crowded hills and that the proportion of stratified or kame-like drift greatly increases. The admixture of clay in the unstratified drift is greatly diminished. From Prospect Hill, which rises to a height of about three hundred feet above the sea, northeastward to Indian Hill this frontal moraine is singularly massive. The general character of the deposit is essentially like that of similar moraines found elsewhere in southern New England. There is a gentle decline in the height of these ridges from Prospect Hill northeastward to Tashmu Pond. East of Tashmu Pond the hills rapidly decline in height and become more kame-like in character, until at Vineyard Haven they are on the whole unlike frontal moraines. This eastward decline in the height of the frontal moraine is probably due to the fact that the surface of the Tertiary beds on which they rest declines in the same direction.

The evidence which serves to establish the hypothesis that these deposits are frontal moraines pushed forward by an ice sheet is as follows: First, the ridges are steep on the iceward and seaward faces; secondly, there is a distinct alignment in these numerous detached ridges; thirdly, this alignment is at right angles to the course of the glacial stream; fourthly, these ridges are in great part composed of large blocks of syenite and other rocks derived from the mainland, which could only have been brought to their present position on the top of the Tertiary beds by the shoving action of an ice sheet. These
evidences are sufficient to establish the conclusion that the accumula-
tion of drift on the northwestern face of the island marks the place
occupied by the ice front for a considerable period.

The evidence derived from the large fragments of crystalline rocks
which make up more than half the mass of many of these ridges
would of itself be sufficient to prove that at one time the ice front
lay against these hills. In the central part of this northern belt,
where the covering of sands deposited from water is somewhat less
thick than elsewhere, the massive blocks of syenite are so numerous
that on the steeper parts of the hills the bare masses of angular frag-
ments remind the observer of ruined Cyclopean masonry. Over
scores of acres in the central portion of this district the large frag-
ments are so thickly packed together that there is hardly any place
for soil (Pis. XXIII, XXIV).

The total amount of detrital material in this belt of moraines be-
tween Gay Head and Tashmu Pond is greater than in any other de-
posit of this nature known to me in New England. On an area about
ten miles in length and about one and one-half miles in width the
drift cannot be on the average less than one hundred and fifty feet
thick. This sheet is therefore equal to a mass of about one-half a
cubic mile or about as much material as is contained in the mass
of Monadnock Mountain.

As the total mineral matter discharged by the Mississippi River in
one year, that in perfect solution as well as that which is in the shape
of sand and mud, amounts to only about one-fiftieth of a cubic mile,
it follows that this accumulation of drift in the northern part of
Martha's Vineyard represents more than the total waste of the Mis-
sissippi Valley during a period of twenty-five years. But the field
from which this glacial waste of the Vineyard was derived cannot
be estimated as having an area of more than one thousand square
miles; none of the large blocks is from a point more than fifty miles
away, and, while it is probable that some of the small fragments may
have been brought from a much greater distance, we may be sure
that their mass is much more than counterbalanced by the fine sedi-
ments which have been washed away from this morainal belt.

It is a fair inference, from all that we know of glacial carriage,
that by far the greater part of the glacially conveyed materials are
ground up before they travel any great distance from the point where
they were detached from their bed. It is furthermore clear from an
examination of any glaciated surface that the greater part of the
waste goes away in the form of fine mud; if it were otherwise we
should not have all the glaciated hard rock surfaces in the striated or
polished shape in which they occur. It therefore seems to me an
excessive estimate to say that this mass represents the erosion of a
strip ten miles wide, extending one hundred miles to the northward
in the direction from which the ice came, during the period while the-
ice front lay at this point; yet, by making this assumption we may secure a valuable basis on which to institute some comparisons of the erosive work done by rivers and glaciers.

To those who have studied the rate of erosion in glaciated districts it will be evident that the detrital matter accumulated immediately in front of the glacier can be but a small part of the material transported by the ice. The material removed from the rocks in a finely divided form, as clay or sand, greatly exceeds that which is removed as pebbles or boulders. It seems pretty certain that the greater part of this fine detritus does not find a lodgment in the frontal moraine, but is carried out to sea. Proof that this is the case will be afforded by a study of the terrace deposits which lie to the southward of the frontal moraine of Martha's Vineyard.

On the supposition that the erosion rate of the ice was the same as that of the Mississippi River, that the area of the erosion was 1,000 miles, and that the whole of the eroded material remains in this frontal moraine, it would appear that the ice front remained at this position for from twelve thousand to twenty-four thousand years. If we conclude that the material gathered in this moraine does not represent the total erosion of 1,000 square miles which took place while it was forming, then we must proportionally extend this term of years. It seems likely that we should then allow from fifty thousand to one hundred thousand years for the time occupied in its formation.

It is not at all likely that the ice front retained its position in the line of this deposit for any such period as that named in the least of these estimates; for, although this is one of the greatest of the lines of morainal matter formed on its front, it is in itself but a small portion of the deposits of this nature which lie on the surface of New England. The neighboring moraine of the Elizabeth Islands is larger than that of Martha's Vineyard. On the mainland south of Canada there is certainly twenty times as much moraine material as is contained within the Martha's Vineyard district.

These approximate computations serve to show that the rate of erosion on a surface exposed to a glacial sheet is many times greater than on a sheet exposed to water action. As I expect to make the subject of glacial wearing in New England the matter of a special essay I shall not deal further with it in this connection.

While considering this moraine we may note the fact that it has no distinct extension beyond the limits of the island on which it lies. It is not in any way indicated on the floor of the sea southwest of Gay Head for more than a mile beyond the present line of the cliffs nor on the bottom of the inclosed waters which separate Martha's Vineyard from the mainland. It cannot be doubted that this frontal moraine once extended far beyond its present limits. Any reason-
able period of its formation requires us to assume that it at one time formed a part of a fringe which extended from a point where the ice front crossed the sea border a little south of the mouth of the Hudson, along the shore, to the far north. Its complete interruption by the sea at either extremity can best be explained by the hypothesis that this shore has been higher than at present since the close of the glacial period, and that during this period of elevation the seaward extension of the moraines was worn away. This problem is one of particular interest, but too general in its nature and demanding too much consideration to be treated in this report. In another memoir I hope to give it careful attention.

It should be noted that there has been a considerable subsidence of this shore since the completion of the great elevation which took place after the glacial period. The precise amount of this subsidence has not been determined and may be indeterminable. It is also evident that we cannot well account for the presence of the extensive moraines on Nantucket, which were clearly formed when the line of the ice projected far beyond the line of Martha's Vineyard, without supposing that they once existed to the south of the latter island and have been worn away by the action of the sea. A careful inspection of the soundings shows that there is no trace of frontal moraines on the bottom of the sea south of Martha's Vineyard (see Fig. 55).

KAME AND TERRACE DRIFT.

On the southern border of the frontal moraine already described the surface descends first to a series of kame deposits, which in part overlie the southern and lower ridge of the moraine, and then to the wide field of terrace drift, which is better shown on this island than on any other part of New England.

(3) The kames are separated from the frontal moraine by very distinct features due to the circumstances of their formation. They contain only sands and small pebbles which are arranged in distinct, cross-bedded layers, showing that they were formed by the movement of swift currents, which currents were subject to frequent variations in direction and energy. These kames are extremely irregular in their shape; in this particular field they have three types of form, namely: First, those which consist of irregular mounds closely huddled together, which mounds, in some cases, appear to have been subjected to a certain amount of deformation apparently arising from the shoving action of the ice; secondly, we have certain rather continuous ridges which may be principally composed of till or of frontal moraine material coated with kame deposits; thirdly, we have the type, elsewhere commoner than on this island, in which the kames appear as kettle-like depressions on the surface of the drift terraces. These basins often contain smaller irregularities on their floors.
The distribution of these kame deposits is exceedingly irregular. Where the frontal moraine is high and continuous they are generally wanting. This is the case in the part of the deposit which lies upon the elevated Tertiary beds of Gay Head and Chilmark as well as in that part of Tisbury which lies west of Indian Hill. East of Indian Hill, where the frontal moraine rapidly diminishes in height, the kames are very extensive. They are especially abundant near the southern shore of Chappaquiddick Pond and about the valley occupied by Vineyard Haven and Lagoon Pond. Their abundance in these districts and their rarity in the west part of the island are readily explained provided we accept the theory of their formation which I have elsewhere set forth, which is in effect that they were formed by the irregular, whirling movement of waters that were discharged into the sea from the subglacial streams at a time when the base of the ice drift lay below the level of the ocean. The subglacial streams were always strongest in the lowlands. It is doubtful whether they flowed at all on other parts of the surface, as the kames are limited to the valleys of New England.

When the stream was strong it could cut out considerable channels, such as those now occupied by Chappaquiddick Pond and Lagoon Pond, or the channels between the islands of the Elizabeth Islands moraine; but such cutting action would be most common where the drift barriers were least extensive and the least lofty. It seems extremely probable that these channels which crossed the frontal moraine were the paths of streams escaping from beneath the ice. At first sight it may seem unlikely that these streams, when poured into the sea, should be able to scour out channels for a mile or more beyond the ice front, but a similar work is performed where surface rivers enter the sea over the front of an extensive delta, though their currents are probably less rapid than those of the subglacial stream, urged as those streams were to their point of escape by the pressure of the ice as well as by the gravitative force given by their descent from the inland district.

Although the kame deposits are most abundant in the region near the foot of the frontal moraine and in the valleys in which lie Lagoon Pond and Chappaquonnsett Pond, there are two other districts on this island in which they are found, though in less abundance and of less characteristic form. One of these is on the western side of Sengekontacket Pond, between Vineyard Haven and Edgartown harbor, another is about Edgartown village, and a third is on the neighboring island of Chappaquiddick. In these outlying fields there is a small though certain admixture of bowlders with the kame material, making it appear as if the ice front of the glacier, during its period of retreat, had remained at these points for a brief period,  

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during which the subglacial stream whirled the sands into the shape of kames.

As will be seen when we come to consider the shape of the underlying Tertiary deposits, the clays of Tertiary age, after sinking to a considerable depth beneath the level of the sea in the central district of the island, probably rose again to near the level of the tide in the central part of the island of Chappaquiddick as well as in the section adjacent to Lagoon Pond. This would tend to preserve traces of the frontal moraines and the accompanying kames on this part of the island, while these ridges would be effaced in the central part of its area by the deep sheet of stratified drift.

I have been unable to determine whether these last-mentioned kames and moraines were deposited anterior to the time when the principal frontal moraine was formed or at the same time with it. The former supposition requires us to assume that the delicate structure of these outlying kames survived unharmed beneath the sea for a considerable period while the other belts of frontal moraine and kame were forming. This is a somewhat unsatisfactory hypothesis. The other view, namely, that they were formed at the same time with the principal moraine, requires us to suppose that the glacier in this district had a very irregular front, with a deep bay extending up to where is now Vineyard Haven. I am inclined to consider the latter to be the more reasonable of the two suppositions, especially as we should expect a re-entrant angle in the ice front where a large subglacial stream, such as that which passed through the depression of Vineyard Haven, found its way to the sea.

The terrace drift is intimately connected with the kames; they are both composed of stratified sands and gravels, with occasionally large fragments of stone, such as may have been borne out of the glacial front on floating ice. In the kame, beds of gravel are found lying at steep angles, and the direction of the inclination often suddenly changes. In the terrace drift there is an alternation of pebbles and sand, but the changes are much less sudden than in the case of the kames, the beds are more nearly horizontal, and the materials are of finer grain. Moreover, we notice a progressive diminution in the size of the pebbles and sand grains as we proceed southward. On the southern shore, at a distance of three or four miles from the moraine, a small amount of clay appears in the terrace deposits, which accounts for the fact that this portion of the island terrace is more arable than the northern part.

(4) The passage from the form of a kame to that of a terrace is sometimes gradual; again, it is sudden; but, when we proceed far enough away from the kame belt to attain the nearly flat surface of the terrace, it maintains that character southward to the sea. In the distinctly terraced district the surface of the ground is cast in gentle undulations which decline southwardly toward the sea and
also slope eastwardly and westwardly toward the shallow valleys that extend from the base of the kames in a nearly southerly direction to the shore line. These troughs generally terminate in the various ponds or coves which indent the southern shore of the island. In fact, these inlets are formed in the southerly extremity of the depressions where they deepen toward the sea and have been widened by its action. Owing to the fact that the surface of this plain, which occupies the central part of Martha’s Vineyard, is covered with a dense growth of scrubby woods, these depressions in good part escape the eye, but if they are closely examined they are seen to have a continuity not indicated on the excellent chart of the Coast Survey, which is the basis of the maps contained in this report. These depressions are best studied on the similar southern plain of Nantucket, where the treeless character of the surface clearly reveals their form. The striking peculiarity of these troughs consists in the fact that though in form much like ordinary stream beds they are not now and never have been the seats of subaerial rivers. Their valleys, often several hundred yards in width, do not present the smooth downward grade so characteristic of ordinary valleys; their floors are generally more irregular than those of any ordinary stream could be. Nor do they have the distinct banks common to all land streams. The only explanation which can be given of these troughs is that they were the channels through which the subglacial streams found their way seaward. It is not necessary to assume that all the streams which formed the several valleys were flowing at the same time; on the contrary, it is most likely that they were excavated in succession by one or two subglacial streams which frequently varied their point of discharge. Observation on existing glaciers shows that such variations would be likely to occur. In fact the difference in the sharpness of outline of the several troughs found on Martha’s Vineyard itself suggests the view that they were successively formed. Some of them appear to have been greatly suffused by the mass of sand which has been deposited on them since their formation, while others retain their delicate outlines unimpaired.

There are only two ways in which a long, sloping terrace of sands, declining gently toward the sea, can be produced: one is by the rather rapid rising of the sandy coast from the sea and the other is by the deposition of sands on a sea or lake floor in front of a coast line whence came the sands which form the shelf. In the former case there will certainly remain a number of slight benches marking the successive lines of the coast and there will be no such troughs as those we are now considering. If any such were in existence the first action of the sea would be to erect barriers across them, such as we now find it has formed across the line of every one of these channels where it comes to the shore.
The formation of this inclined plain of sand beneath the level of the sea fully accounts for its general features; for in all respects, except in the presence of the channels before described, it essentially resembles the bottom of the sea as it exists south of this shore. The angle of the slope seaward is the same and, so far as we can judge by the soundings, the character of the materials in the two terraces does not differ in any important respect. The only difference is that on the existing sea floor there appear to be no such channels as we are endeavoring to explain. We are therefore fairly driven to seek the origin of these channels in some forces which were at work during the glacial period, and there are no others which seem available save the subglacial streams, the existence of which is proven to us in many ways.

It has already been observed that these troughs terminate in considerable coves, or fjord-like inlets, which generally debouch into large ponds; for instance, eight of these channels open into Great Tisbury Pond and about as many into Herring Pond, while yet others empty into the smaller ponds of the shore line. Where these channels decline into the coves we find that they have been greatly enlarged and changed in their form by the action of the waves and tides of those water areas; in this way they have been widened and deepened out of all semblance to their original shape. This cutting action of the waves and scouring action of the tides is not shown in these valleys above the present level of the sea, though the steep benches which indicate such work undoubtedly would have remained to this day if they had ever existed.

It is not unlikely that when once instituted by the subglacial stream these valleys would have been somewhat further developed by the to-and-fro movement of the tides along the shore. The out-running streams from the glacial face would have tended to determine the outflow of the tide into their channels, thus increasing their scouring action.

The question naturally arises, How could the subglacial fresh-water streams have kept their place on the bottom of the salt-water area so as to scour that bottom for some miles from the points where the streams escaped from beneath the ice? To this question we can make the following answer: First, that existing streams along our coast do scour their bottoms and excavate for an equal distance out to sea channels similar to those we are now considering; secondly, that the subglacial stream is always so heavily charged with sediment that it might well be heavier than the water of ordinary rivers. The following table showing the proportion of sediment in some of the subglacial streams of Greenland will make this point clearer:
Solid matter in the glacial streams of Greenland according to Helland

<table>
<thead>
<tr>
<th>Name of glacier</th>
<th>Quantity of sediment in cubic meter. Grams.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aalangordeck</td>
<td>2,374</td>
</tr>
<tr>
<td>Hartdeck</td>
<td>728</td>
</tr>
<tr>
<td>Tunapursuit</td>
<td>678</td>
</tr>
<tr>
<td>Assakak</td>
<td>596</td>
</tr>
<tr>
<td>Kangerdagsuak</td>
<td>278</td>
</tr>
</tbody>
</table>

As the discharge of mud from the great continental glacier of this continent must have been enormous, we may fairly assume that it was equivalent to that of the glacier first named in the above table, or about two thousand grams to the cubic meter. Although the mineral content of ordinary sea water is much greater than this, it is to be remembered that the shore waters near the seat of the discharge of subglacial rivers would probably be much less saline than those which are now found along this part of the Atlantic Coast. In this regard they would resemble the waters near the mouths of our ordinary rivers. It thus appears to be possible that the weight of the subglacial water may have been great enough to enable it to flow upon the bottom for some distance from the glacial sheet. It should also be noted that a stream of water, even if it be lighter than the superincumbent mass, will, if it have a swift movement, force its way along the bottom for some distance before it is displaced by the heavier fluid.

In studying the form of these old channels, especially on Nantucket, where they are best shown, we observe that they gradually widen as they depart from the front of the moraine until at a distance of from three to six miles from their origin they are from five to twenty times as wide as at their source. We also note that the streams which form these channels apparently diminished their energy of movement in proportion to the distance traveled from the glacier. This is shown by the much finer sediment which they laid down in their outer parts. Near their sources they were able to move considerable pebbles, while at their southern extremities they were able to transport fine sand alone.

I desire to say that while these peculiar channels may not in the end appear to be due to the cause above suggested, this cause is the only one out of many considered which appears reconcilable with the facts. They are clearly due to localized streams of some sort which originated at the ice front. They were evidently formed while the surface on which they lie was depressed below the level of the sea, for their troughs do not have the shape of those excavated by subaerial streams.

1 Handbuch der Gletscherkunde, by Dr. Albert Heim, Stuttgart, 1895, p. 363.
The depth beneath the sea at which this terrace deposit was built cannot be determined. It seems, however, tolerably clear that all the drift on the island was deposited at some depth below the level of the ocean. The frontal moraine, including the highest of the ridges about Prospect Hill, is composed of materials which would have been much eroded if they had been long exposed to the action of the sea. There is no trace of morainal erosion on their surfaces. It therefore seems necessary to suppose that this shore was depressed considerably more than three hundred feet during the time when these deposits were formed. As this terrace of drift which extends in a gentle decline from the base of the great Vineyard moraine was certainly formed at the same time as the moraine itself, it follows that it was constructed in tolerably deep water.

Besides the before-mentioned deposits of the glacial age there is a series of clays in this district the relations of which are not well determined, but which may have been deposited during the first stages of the glacial period, though they may belong to an age between that of the Vineyard series and the glacial epoch. These clays are particularly well shown in the western part of Chilmark or Weyquosque Cliffs, where they appear commingled with occasional beds of sands and gravels in the manner indicated in the diagram (Fig. 58).

At first I was disposed to regard this Weyquosque series as belonging to the same age as the Vineyard series, but the sections exposed by the storms of the winter of 1885-'86 furnish evidence that they differ entirely in physical characters and that the Weyquosque series appears to overlie unconformably that of the Vineyard.

As shown in the Weyquosque Cliffs, these beds exhibit many remarkable small contortions and plications which may possibly be due to the sliding of the faces or to the pressure of the advancing glacial sheet; it may be, however, that they are due to the more general conditions of pressure which have flexed the Vineyard series. The great amount of slipping which has occurred on this escarpment makes it extremely difficult to determine any other point save that the general succession is much like that represented in the diagram.

The inclination of these clays, which rises to as much as 15°, is much greater than we should expect to find in a considerable section of such materials. I am therefore inclined to think that they were brought to their present attitude by mountain-building forces, in which case we should have to refer them to the Tertiary series. Un-
Fortunately they seem to be quite wanting in organic remains, so that the positive determination of their age is very difficult.

The emergence of the drift deposits of this district from the sea must have taken place with singular rapidity, for there is no sign of wear on the surface of the moraines or the lower-lying kames such as would inevitably have occurred if their surfaces had been exposed to the action of the waves for any length of time. Nothing save an exceedingly sudden uplift could have secured their escape in the process of elevation; their extremely delicate outlines could not endure the action of the sea for a single month. 1

It is quite evident that this problem of the sudden elevation of the coast line is one of great consequence to the theory of the general movements of the shore as well as to the history of the glacial period. It merits ample discussion with reference to the whole of the facts which may be gathered on the coast line of New England. These facts will receive attention in a memoir on the recent changes of level of this coast, now in preparation.

In closing this description of these several classes of drift deposits occurring on Martha’s Vineyard we may note the fact that there are certain groups of glacial waste which do not appear on this island. Of these the most important are the drumlins or lenticular hills. A careful search of this island has failed to show any forms which could be placed in this class of drift deposits. Several of the hillocks on the elevated Tertiary beds in Chilmark have at first sight a general resemblance to the drumlins of the mainland; but on careful inspection I have been unable to class any of these deposits with that peculiar group of glacially formed hills.

So, too, the group of serpent kames which present a modification of the kame structure, in which the material is more stony, compact, and till-like than the ordinary kames, is scantily represented on Martha’s Vineyard. 2 A single rather obscure specimen of this class of morainal deposits is found on the west side of the road from North Tisbury to Cedar Tree Neck, near the Wood school-house.

The reason of the failure of these drumlins to appear on Martha’s Vineyard seems to me tolerably clear. The drumlins appear to be masses of till or sometimes, though rarely, of kame or terrace drift which have been formed during a period of glacial retreat and during a subsequent extension of the ice have been eroded by the readvancing glacier in the manner in which any other rock is eroded by glacial

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1 This feature of the kame and frontal moraine deposits of New England is also noticed in the report on the island of Nantucket, as well as in the memoir on the origin of kames published in the Proceedings of the Boston Society of Natural History, vol. 33, 1885, pp. 36-44.

2 In this class of deposits the pebbles are not scratched as they are in the till, the clay element is generally wanting, and the outline of the mass is that of a continuous, rather serpent-like ridge.
action. They have taken the lenticular form because they are homogenous in composition, that being the form which a uniform mass of syenite, clay slate, or other rock which presents a uniform resistance to erosion assumes when worn down by a glacier. The conditions which favor the formation of these drumlins were absent from Martha's Vineyard because there was no deep mass of till on its surface to be shaped by the readvancing ice in the latter part of the glacial age.

The serpent-like kames appear to have been formed beneath the glacier near the mouths of the subglacial streams. The only field on Martha's Vineyard on which we can trace the successive retreats of the glacier is on the elevated ground underlaid by the Tertiary beds in the western part of the island, a region in which, as before remarked, there appear to have been no subglacial streams. In the imperfect belt of frontal moraine lying to the east of this Tertiary district the surface is so crowded with the material shoved forward by the ice and with the kame deposits that any serpent kames which may have been formed would have been buried beneath these accumulations. Serpent kames are always among the rarest types of glacial deposits. From their rarity, not more than one or two specimens of this type would be likely, under the most favorable circumstances, to exist on an area like that of Martha's Vineyard.

On the island of Nantucket there are many trustworthy evidences which serve to show that the level of the coast has been somewhat lowered since, at the close of the glacial period, it underwent a swift elevation. On Martha's Vineyard there are no such distinct evidences of recent subsidence, though at Vineyard Haven there are some cases in which dead trees in a marine marsh lie below the level of high tide. On Nantucket the principal evidences are derived from the peat bogs which were originally formed in fresh-water swamps and have recently been depressed below the level of the sea. This difference is probably due to the fact that while on the more eastern island peat bogs are tolerably plenty they are and doubtless always have been less abundant on the island we are now considering. It is not likely that there has been any considerable difference in the amount of subsidence to which these two islands have been subjected.

ORIGIN OF GLACIALLY TRANSPORTED MATERIALS.

The origin of the glacially transported materials found on Martha's Vineyard has been carefully sought for in the hope that it would furnish information as to the direction of the ice movement in this district and perhaps afford some clew as to the deposits which lie buried beneath the drift or under the sea between this island and the mainland.

It is necessary to state at this point that the materials transported by the subglacial streams and accumulated in the kame and terrace deposits were generally transported for a greater distance than the
débris which was carried in the body of the ice. A careful inquiry as to the transportation of glacial waste, especially in the valley of the Taunton River, has shown that the average carriage of the till material from its point of origin to the place where it now lies is less than one-fifth the distance to which the kame and terrace material was conveyed. This difference might be attributed to the fact that the kame as well as the terrace drift contains smaller pebbles than are found in the till. In drift of all kinds the size of pebbles diminishes with the distance to which they are carried. Making allowance for this, however, it is still clear that the kame drift of any district has been transported for a much greater distance than the till drift of the same district. This is a result which would have been expected on a priori considerations; the subglacial streams must have moved with much greater speed than the ice beneath which they flowed; they would transport the fragments which they bore along to a greater distance than that to which the ice would convey its waste. Moreover, it is easily seen that the pebbles in these flowing streams would be less exposed to destruction than those contained in the lower part of the ice, which, as is shown by their scratched and faceted surfaces, were in succession held down upon the bed rock and ground away as the ice bore them on.

These considerations will make it necessary to study the materials of kames and till apart from each other. In this work the till and the frontal moraine may be regarded as of one nature. The pebbles in the kame and stratified drift are so small that it is difficult, if not impossible, to determine their place of origin in the rocks of the mainland with sufficient accuracy. It is, however, evident, from my inspection, that in large measure these materials were derived from points lying beyond a line drawn from Boston to Providence; that is to say, from more than fifty miles to the northwest of Martha's Vineyard. This is shown by the fact that the crystalline rocks represented by the pebbles in this kame and terrace drift are in good part of the classes of rocks which are only known north of that line. The principal part of our attention must be given to the frontal moraine and till represented on this island.

Beginning on the western extremity of the island, we find the bowlders composed in large part of syenitic rock; the larger and more angular blocks are altogether of this material. Many of these erratics are very angular and of considerable size; the largest contain about one hundred cubic feet of rock each. There can be little doubt that these masses are altogether from the syenite which lies along the south shore of the mainland from near Newport to the head of Buzzard's Bay, which probably in large part constitutes the foundation rocks beneath the sea and under the islands which lie to the

1 The term syenite as here used designates the familiar combination of quartz, feldspar, and hornblende now known by petrographers as hornblende granitite.
GEOLOGY OF MARTHA'S VINEYARD.

north of Martha's Vineyard. The generally angular form of the fragments is good evidence that they have not been carried from a distance; moreover, the syenite has the porphyritic character peculiar to that rock in this district. Mingled with these are fragments of sandstone, generally not exceeding twenty cubic feet in mass, which are doubtless from the Carboniferous district of the Taunton Valley that lies to the north of the before-mentioned syenite.

The Coal Measures of the Taunton district contain numerous beds of conglomerate representing the millstone grit. These conglomerates are especially well developed in the part of the Narragansett coal-fields which is south of Dighton. They exist on both sides of the Taunton River and extend from Seekonk and Somerset to near Lakeville, Mass. We note the fact that these conglomerate bowlders are relatively abundant on Martha's Vineyard. The black slates and shales, which are much the more abundant materials in the Carboniferous series whence these bowlders were derived, are not represented in the glacial drift of Martha's Vineyard. This shows us how far the transportation of materials by glacial action depends upon the resistance which they offer to the strain incident to this method of carrying. Such wearing out is probably due not only to the friction of pebbles against one another and against the bed rock, but probably also to the shearing movement which pervades every part of the ice. This movement tends to break into bits every fragment which is penetrated by numerous fissure planes, as are these slates and shales of the Coal Measures. It is only the little-jointed rocks which stand this shearing movement. We may remark, in passing, that this shearing movement is proved by the way in which the ice is turned around every prominence, even the slightest, that interferes with its motion.

There are many other rare varieties of rock found in the region near Gay Head, but they are all fairly recognizable as dike or vein stones, such as are known to occur in the before-mentioned Carboniferous rocks or syenites. A few infrequently represented varieties, certainly not forming more than a thousandth part of the whole, are derived from the district northwest of the line of the Boston and Providence Railroad.

One of these rare erratics from beyond the before-mentioned line, as yet represented in my field-notes by a single bowlder, is from the ilmenite, or titaniferous magnetic iron ore, which occurs in a solitary, very circumscribed locality in the town of Cumberland, about four miles east of Woonsocket, R. I. This very remarkable mineral is not known to occur in place in any other locality in this part of New England, and in this locality it is limited to a single hill which has a length of not more than one thousand feet, a width of not more than six hundred feet, and a height of not over sixty feet. The bowlder trail from this hill has been traced to the south from its point.
of origin to the southern part of Narragansett Bay, where it appears to occupy the whole width of the bay from the eastern shore of Aquidneck Island to the mainland on the western side of that bay. The prolongation of its course would carry the line of this trail much to the west of Martha’s Vineyard; but here, as elsewhere along the New England coast, the path of the ice appears to have deflected slightly to the east after it escaped from the land. This deviation has brought the trail over the southwestern border of Martha’s Vineyard. This specimen was found on the south side of the island, one-half mile west of the western end of Squipocket Pond. The fragment weighed about ten pounds; it was not much rounded; all of it except a small point was buried in the till; the small projecting portion was decidedly decayed; the peculiar feldspar crystals which are dotted through the magnetite were worn into deep pits; the buried portion was undecayed. There can be no doubt that the specimen had been carried by the ice, for it was actually embedded in the drift. It can therefore be assumed that a line from this place to the point whence the fragment came will give us a close approximation to the direction in which the ice moved in its course from what is now Cumberland, R. I., to this part of Martha’s Vineyard. The direction thus obtained is northwest to southeast. The special studies made upon this bowlder trail in my forthcoming report entitled “On the glacial trail extending from Iron Hill, Cumberland, R. I.,” will show that this is only an approximate determination of the direction in which the ice moved, for the reason that there is a certain fanning out or divergence of the trail as we go southward from its source; i.e., though at its source it is only 600 feet wide, it becomes as much as 30,000 feet wide at a point only 25 miles south of its origin. Still this divergence could not lead us to an error of more than five degrees in our estimation of the direction of the glacial movement. It thus gives us much more definite evidence as to the course of the ice in this part of New England than can be obtained from any other source.

The pebbles on the eastern side of the island are more varied in their mineral constitution, closely resembling those of Nantucket. They are generally of hypogene rocks.

**CRETACEOUS ROCKS OF MARTHA’S VINEYARD.**

Rocks of Cretaceous age occur under peculiar conditions at two points on this island. In both places the material occurs mingled with the glacial drift, but under conditions which make it certain that the waste is from a position very near the place where it is now found. The most interesting and instructive of these localities is nearly south of Indian Hill, in immediate proximity to the serpent-like moraine before described and a few hundred feet east of a ruined building known as the Wood school house. At this
point the sandy till, or frontal moraine, is plentifully commingled with small, angular fragments of a reddish sandstone, which contain six or eight well marked species of Cretaceous mollusca. These fragments, which are so numerous that it would be easy to accumulate many tons in weight of the material, are limited to a superficial area of less than an acre. They constitute nearly the whole of the coarser matter contained in the deposit. Their distribution, their friable nature, and the fact that a very careful though fruitless search has been made in order to discover any extension of the deposit satisfy me that the Cretaceous beds whence these fragments were derived are in place at some little depth beneath the surface, within a few hundred feet of the locality where the Cretaceous waste now lies.

At one other point, namely, on the eastern shore of Lagoon Pond, the drift deposits for a north and south distance of two or three hundred feet contain occasional, though rather rare, fragments of the same or similar Cretaceous beds. At this last-named point the material seems to have been transported for a greater distance than that found near Indian Hill. Nevertheless the angular structure, as well as the frail nature of the waste, makes it clear that the transportation has not been for any considerable distance.

On the island of Chappaquiddick and in the region near Edgartown, occasional fragments of a ferruginous sandstone are found which closely resemble in their general character the materials containing the Cretaceous fossils, but as they afford no organic remains I hesitate to consider them of that age.

In the present imperfect state of our knowledge of these interesting beds we can say but little concerning them. It seems to me, however, tolerably clear that there must be at least two patches of rocks of Cretaceous age on the island of Martha's Vineyard, and that the deposits consist, in part at least, of thin-bedded ferruginous sandstone containing abundant marine fossils. My assistant, Mr. Aug. F. Foerste, has made a detailed search of the whole surface of the island for other deposits of the same nature, with negative results.

**TERTIARY ROCKS OF MARTHA'S VINEYARD.**

We are now to consider the Tertiary deposits of this island. These deposits, limited in extent and imperfectly exposed as they are, deserve a very careful study. They are the most northern of all the known Tertiary beds on the eastern versant of North America; they thus afford us information concerning a portion of the continent during that time which cannot be had elsewhere.

The Tertiary deposits of Martha's Vineyard are distinctly exposed to view in a small part of the island. They lie above the level of the sea only in the district west of the meridian drawn through the village of West Tisbury and in a small area near the head of Lagoon Pond. In the greater part of the Chilmark district the surface of these beds lies above the sea level, but along the whole shore
line (except near Gay Head and at Chilmark Cliffs, called on the Coast Survey map Nashaquitsa Cliffs) these Tertiary beds sink below the level of the ocean. They are also below that level in the belt of lowlands occupied by Menemsha and Squipnocket Ponds. It is quite possible that these Tertiary deposits rise above the level of the sea at several points on the eastern half of the island, but, if so, they are, except in the southern part of Lagoon Pond, hidden by the thick coating of drift. It is indeed probable that on the island of Chappaquiddick they lie above the level of the sea, as appears from the fact that numerous fragments of the Tertiary waste are contained in the drift at that point. It is also very probable that they lie above the level of the sea in the region about Tashmu Pond.

Having determined that the Tertiary deposits exist at both extremities of Martha's Vineyard, we may fairly assume that they extend between these two points, and indeed that the portion of the beds exposed on this island is only a part of a much more extensive but imperfectly disclosed area. I am inclined to believe that they exist under a greater part of the Elizabeth Islands district and a portion of Cape Cod. There is also evidence, derived from some chance bits of Tertiary rock which have been brought from the sea bottom by the dredge, that deposits of Tertiary age are extensively developed along the Atlantic Coast.

The apparent occurrence of Tertiary beds in the submarine area bordering New England makes it important that we should search the shore land of this region for localities, as yet unknown, where these beds are exposed above the level of the sea.

Although there is an area of about thirty square miles of Tertiary beds on Martha's Vineyard, and although these rocks in places rise to the height of 200 feet above the sea level, there are only two points where the beds are shown in clear section or where their presence would be remarked by any one not a geologist. Over the surface of Gay Head and Chilmark the glacial drift, though often very thin, is generally so continuous that the underlying Tertiary deposits are very rarely disclosed. At certain stages of the erosion of the Nashaquitsa Cliffs the beds of Tertiary age are imperfectly disclosed near the base of that section (Fig. 59).

The Tertiary beds of Martha's Vineyard have evidently been somewhat eroded by the glaciers of the last ice period; it is, however,
equally evident that they have not been more worn than the hard, crystalline rocks of the mainland. The section at Gay Head shows that the soft Tertiary clays have not rapidly yielded to the rubbing action of the ice, but, as before remarked, they have probably been protected by the adhering glacial waste from such wearing. The amount of the Tertiary waste which is contained in the drift is small, not over one-tenth of the till material in the southern part of the Gay Head section being composed of it, though we are compelled to believe that the ice which deposited this drift had journeyed over the surface of these Tertiary beds for at least a mile, and probably for a much greater distance.

The form of the surface of the Tertiary beds compels me to believe that they retain in good part the shape which they had before the beginning of the last glacial period. If we could remove all the glacial waste from this surface we should find that it had a contour closely resembling that of the chalk downs in southern England. We should see broad, rolling hills sloping gently to infrequent valleys, a topography characteristic of a land surface where the rain, frost, and stream had long and steadily acted upon beds of the uniform nature which characterizes the Vineyard series. I cannot believe that this topography could have been formed by the abrading action of the ice or could have been to any considerable degree affected by such action. If this view be accepted it is clear that this ground was near the southern edge of the ice sheet.

**STRATIGRAPHY OF THE VINEYARD SERIES.**

We shall begin the study of the stratigraphy of the Tertiary deposits of Martha’s Vineyard with the section at Gay Head.

The Gay Head section consists of three divisions: The central part (i.e., that part which faces nearly west) has a length of about thirty-five hundred and an average height above the sea of about eighty feet. At the southern end of this section there is an exposure of about two thousand feet in length, which trends toward the southeast. At the northern end of the principal section there is another short and incomplete section which trends nearly east and west. These three divisions constitute one great and nearly continuous sea cliff having a length of over six thousand feet. The cliffs of this section are from ten to eighty feet in height. Throughout nearly its whole length the escarpment is rapidly wearing away, so that with trifling exceptions it exposes fresh surfaces to view from decade to decade.

The aspect of this section varies much from year to year. The delineation given in the plates represents the results of studies made between 1883 and 1887.

The face of this cliff shows us a great number of thick, steeply inclined beds of sand, clay, and lignitic matter, of extremely vivid and contrasted colors. The colors range from the dazzling white of the
SHARP CONE ON FRONTAL MORaine, SOUTH SIDE OF GAY HEAD PROVINCE.
FRONTAL MORAINE AT INDIAN HILL, LOOKING NORTHWEST.
SURFACE ON SOUTH SLOPE OF FRONTAL MORaine, CHILMARK.
SOUTH END OF LAGOON POND. LOOKING EAST, SHOWING OUTLINE OF KAME AND TERRACE DRIFT.
Approximate section of the beds exposed in the cliffs at Gay Head, Martha's Vineyard.
sandy beds to the nearly pure black of the Carbonaceous layers, with intermediate hues of brown, green, yellow, and red. When the observer has become accustomed to the singular nature of the scene, he perceives that these colors are closely related to the mineral composition of the beds and that the hues are repeated several times in the length of the section (see Pls. XXVI, XXVII, and XXVIII).

The orderly arrangement of the beds in the section is greatly masked by the continued slipping of large wedges of the deposits down the steep incline of the talus. When we apply a correction for this slipping the beds are seen to lie in a tolerably regular order, dipping usually to the northeast, with inclinations varying in general from twenty to sixty degrees of declivity, but rising in one place to ninety degrees. The following distinct varieties are observed in these beds:

First, a whitish sand, which is the most abundant element in the section. This sand is generally composed of coarsely powdered quartz, feldspar, and mica, the last being the least abundant element in the mass; it contains also, though rarely, decayed, hornblende crystals. Occasionally small masses are found where the quartz, feldspar, and mica are still united, but these bits are always much altered. At certain points in the section the white sand is composed almost entirely of finely divided quartz; in other beds feldspar or mica greatly predominates. The material composing this white sand seems to be essentially a powdered, granitic rock. None of the beds shows any admixture of materials other than those which might have been derived from the destruction of granite.

The next most conspicuous beds are those of red clay. These beds are not so continuous as the preceding; they commonly contain layers of the whitish sand and they always lie in immediate relation to those sands, occurring either immediately above or immediately below them. These reddish clays often contain masses of sandstone, generally of a reddish color and angular form; the largest of these fragments does not exceed ten cubic feet in mass. In their lithological character these fragments have a general resemblance to the red sandstones of the Connecticut Valley, though they are not exactly like any of those deposits which are known to me.

The third group of these deposits comprises the brown and greenish clays and sands which have commonly been termed "greensand." This group of deposits is limited to the northern end of the section and has much less thickness than the red clays or the white sand. They consist, in fact, of a single set of beds, the layers of which are separated from one another by partitions of lighter-colored deposits. This section is much more ferruginous than the preceding. It is also noteworthy from the fact that in certain parts it contains numerous fossils, vertebrae of whales, sharks' teeth, etc., and many nodules of
lime phosphate. These nodules have not been recognized in any other part of the Gay Head section.

We have now to notice the most remarkable deposits which occur in this section. These are the lignites, of which there are more than a dozen distinct beds, some of which are divided by narrow partitions of clay and sand, so that the total number of the lignitic layers exceeds thirty. Their thickness varies from forty feet or more down to an inch. Their position and their approximate thickness are indicated in the general section (Pl. XXVI). All these beds are of a dark-brown or black color. The proportion of vegetable matter varies from 15 per cent. to 80 per cent. of the mass, the inorganic matter being in part the ash of the plants, but in larger part clay and sand. In places the mass is composed almost entirely of finely divided woody matter, commingled with stratified clay, in which, here and there, are found fragments of trunks and branches of trees. These fragments appear to have been subjected to much attrition before they were deposited in their beds.

In the greater part of these lignites we find a large amount of iron pyrites in the form of nodules, as well as frequent crystals of selenite. Two or three small fragments of a fossil resin have been found in the uppermost beds of this lignite. This resin is indistinguishable by ordinary tests from amber. Although the lignites are found in every part of the Gay Head section it is only in the upper half of the series that they attain to any considerable thickness. It seems to me pretty certain that these beds are characteristic of the upper portion of the Vineyard series and that when they begin to appear in the section the coarse-pebbly beds as well as the whitish sands begin to disappear.

It will be seen that the history of these lignites, which are distributed throughout the whole of this great section, has a most important bearing on the determination of the origin of the series to which they belong.

Considered in a general way this section may be said to give us a somewhat rhythmical succession of clays and sands alternating with lignite beds which are scattered through the series.

**ANALYSES OF DIPS IN VINEYARD SERIES.**

The following table gives the dips and strikes of the several beds, beginning at the southern or lowermost part of the section and proceeding northwardly. The numbers in the second column give the distance in yards from the point of beginning; those in the third column, the direction of the section plane or general face of the cliff; the fourth column gives the thickness of the bed, determined as carefully as the slipped condition of the escarpment will admit; the fifth column, the direction of strike; the sixth, the angle and
direction of dip. Only a few of the whole number of beds are rep­
resented in this list:

Analysis of the dips etc. of the section.

<table>
<thead>
<tr>
<th>Nature of bed</th>
<th>Distance</th>
<th>Face of cliff</th>
<th>Thickness in feet</th>
<th>Strike</th>
<th>Dip</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conglomerate</td>
<td>60</td>
<td>N. 31° W.</td>
<td>2</td>
<td>N. 40° E.</td>
<td>38° E.</td>
<td>Very local deposit</td>
</tr>
<tr>
<td>Red and yellow sand</td>
<td>180</td>
<td>...do...</td>
<td>40</td>
<td>N. 40° E.</td>
<td>N. 40° E.</td>
<td></td>
</tr>
<tr>
<td>White sand</td>
<td>210</td>
<td>...do...</td>
<td>20</td>
<td>N. 40° E.</td>
<td>N. 40° E.</td>
<td></td>
</tr>
<tr>
<td>Lignite</td>
<td>300</td>
<td>...do...</td>
<td>2</td>
<td>N. 40° E.</td>
<td>N. 40° E.</td>
<td></td>
</tr>
<tr>
<td>Conglomerate</td>
<td>350</td>
<td>...do...</td>
<td>3</td>
<td>N. 50° E.</td>
<td>N. 50° E.</td>
<td></td>
</tr>
<tr>
<td>Lignite</td>
<td>390</td>
<td>...do...</td>
<td>4</td>
<td>N. 100° E.</td>
<td>40° E.</td>
<td></td>
</tr>
<tr>
<td>Yellow sand etc.</td>
<td>500</td>
<td>...do...</td>
<td>30</td>
<td>N. 50° W.</td>
<td>40° E.</td>
<td></td>
</tr>
<tr>
<td>Gray white sands</td>
<td>600</td>
<td>N. 25° W.</td>
<td>20</td>
<td>N. 30° W.</td>
<td>40° E.</td>
<td></td>
</tr>
<tr>
<td>White sand</td>
<td>650</td>
<td>...do...</td>
<td>15</td>
<td>N. 50° E.</td>
<td>30° E.</td>
<td></td>
</tr>
<tr>
<td>White, sandy clay</td>
<td>750</td>
<td>...do...</td>
<td>30</td>
<td>N. 40° W.</td>
<td>30° E.</td>
<td></td>
</tr>
<tr>
<td>White sands, clays,</td>
<td>900</td>
<td>N. 15° E.</td>
<td>25</td>
<td>N. 45° E.</td>
<td>15° E.</td>
<td>Sudden dislocation of this part.</td>
</tr>
<tr>
<td>and lignites</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Whiter sands</td>
<td>1,150</td>
<td>...do...</td>
<td>20</td>
<td>N. and S.</td>
<td>20° E.</td>
<td></td>
</tr>
<tr>
<td>Ferruginous sands</td>
<td>1,200</td>
<td>N. 10° W.</td>
<td>12</td>
<td>N. 30° W.</td>
<td>30° to 40° E.</td>
<td></td>
</tr>
<tr>
<td>Lignite</td>
<td>1,400</td>
<td>...do...</td>
<td>20</td>
<td>...do...</td>
<td>40° E.</td>
<td></td>
</tr>
<tr>
<td>&quot;Green sand&quot;</td>
<td>1,700</td>
<td>...do...</td>
<td>50</td>
<td>N. 40° E.</td>
<td>50° to 90° E.</td>
<td>The strike is local</td>
</tr>
</tbody>
</table>

It is evident that the prevailing dip of these deposits is to the northeast and that the angles of the slopes are generally below 40° of declivity; the only exceptions are two or three points where they rise to 50° and at one point on the northern part of the western face where the beds rise to a vertical position. At many points the observer will find steeper dips than those indicated, but on close inspection he will note that the beds have been tilted by irregular slipping. The total thickness of the deposits shown in the Gay Head section cannot be exactly determined, because of the considerable differences in the amount of the dip and the direction of the strike at different points. Making a rough allowance for these variations we find that the total thickness exposed in the section at Gay Head may be estimated at two thousand feet, with a probable error of two hundred feet.

It will be observed, however, that the escarpment at Gay Head exposes only a very small part of the total section of these deposits on Martha’s Vineyard. We observe at Gay Head and elsewhere that the prevailing strike of these beds is from northwest to southeast; therefore, as the dip is northeasterly, we rise in the series as we go from Gay Head toward Indian Hill. Between these two points the Tertiary beds are very imperfectly exhibited; enough of them is seen, however, to make it clear that the whole of this district is composed of strata essentially like those shown at Gay Head. In this section, which is about eight miles in length, the dip and the strike
are somewhat variable in amount and direction, but hardly more so than in the Gay Head section. If, therefore, there are no repetitions from faults or folds, the total thickness of this series between Gay Head and Indian Hill would amount to at least fifteen thousand feet.

There is no good reason to believe that there is any considerable repetition of these beds by faulting or folding. The very extended exposure at Gay Head, where nearly a mile of section is exhibited, shows no trace of such dislocations. Moreover, as will be seen hereafter, this part of the Tertiary series is certainly of later Miocene or Pliocene age, and there is no reason to believe that the rocks of eastern New England have been subjected to any very great faulting or folding since that time.¹

The only clearly observed case of folding which is shown in these beds is that which appears in the deposits exposed in the section at Weyquosque or Chilmark Cliffs. At that point we have much the same association of materials as is exhibited at Gay Head. In the latter, as in the former exposure, white sands, yellowish and red clays, and lignites are commingled. The lignites are thinner than they are at Gay Head and the brown, phosphatic deposits are wanting; otherwise the series are essentially alike. As is shown in the diagram (see Fig. 59), the Weyquosque section exhibits a slight but distinct anticlinal axis. I do not think it possible that this disposition of the beds can be the result of any process of deposition. I am, therefore, compelled to believe that the development of this axis is due to mountain-building processes. As the axis is low it does not bring about any considerable repetition of the beds. It is therefore reasonable to suppose that this Tertiary section is tolerably continuous and that

¹When I first began to study the Gay Head section it seemed likely that the repetition which is evident in the beds there exhibited might be explained by the supposition that they had been faulted or repeated by folding, the faults or the seats of the folds being hidden in the concealed portions of the section or by the numerous slidings which have occurred on the escarpment. However, on careful study of the section I have been driven to abandon these hypotheses and to regard the repetitions in the succession of the strata as indicating a recurrence of similar conditions in the process of deposition.

At a point about seven hundred feet south of the lighthouse there is reason to suspect the existence of a small fold in the strata. One of the osseous breccias which occur at this point appears, from time to time, as the erosion of the surface favors its exhibition, in the form of a rude, somewhat quadrangular fold. This fold was first observed by Dr. F. J. H. Merrill, of Columbia College. It was very obscurely shown when the section which accompanies this report was made. At the present time, June, 1887, it is again distinctly exhibited. Although it is barely possible that this accident of the strata may be due to some complication of the sliding dislocations which are continually in progress on this escarpment, I am disposed to agree with Dr. Merrill in regarding it as a true fold, though it probably does not lead to any considerable duplication of the strata, for its effects appear to be lost in a certain crushing of the beds on either side of it. It appears to be one of those local accidents which are common in the dislocations of extensive series of beds.
it contains beds in something like the order in which they are disposed at Gay Head.

It is not easy matter to account for the remarkable thickness of this series. The difficulty is increased by the fact that neither the summit nor the base of this great section is visible, so that there may be several thousand feet of the series unknown to us. It is moreover clear from the general physical constitution of the beds that the whole series must be considered as belonging to one great division of the Tertiary deposits. It is manifestly impossible to suppose that we have here 15,000 feet of strata belonging to one section of the Tertiary when all the beds on the eastern shore of the continent belonging to this age do not aggregate more than one-third of that thickness.

**ORIGIN AND NATURE OF THE ROCKS OF THE VINEYARD SERIES.**

The only hypothesis which affords any satisfactory way out of the above-described perplexity is the following: We must suppose that the Vineyard section is not a normal, stratified deposit at all, but that it belongs to the important class of cross-bedded deposits, such as are formed by continuously acting and strong currents. In this particular case the deposits were formed at the mouth of a great river. The beds seen in the great section at Gay Head, and probably all those in Chilmark and Tisbury as well, were deposited in succession upon the advancing border of the delta of that stream.

![Diagram showing delta structure.](image)

So little attention has been paid to the phenomena of cross-bedding that it may be as well to explain more clearly what is meant by the term as it is now used. Ordinary beds of stratified rock are commonly deposited in horizontal layers on the bottom of water-covered basins. Such beds may have an indefinitely wide extension: a single layer may often be traced for scores of miles. Such ordinary beds do not begin or end suddenly except with the shore lines. They may change their character, but they may be traced, theoretically at least, as continuous, equivalent sheets, varying only in thickness and in composition across the floor of the seas. Where, however, sedimentary matter is pushed out to sea by a river current, it builds strata in the form of inclined layers on the outer verge of a shelf, as is shown in the diagram (Fig. 60). These layers have a very limited extension in any direction, and therefore they may be accumulated with great rapidity.

During the time required to form 10 feet of normal strata on the bottom of the Gulf of Mexico, for instance, the Mississippi River may
project its delta, composed of cross-bedded layers, into that gulf for the distance of several thousand feet. Cross-bedded strata often pass by insensible gradations of slope into normal strata. This is the case as we pass from the marginal portion of the delta toward the deep sea. It is also in part the case within the delta itself, where coarse sediments give place to fine mud. But within the portion of the delta which is covered with salt water even the finest muds are precipitated with such rapidity that they become cross-bedded strata. This rapid precipitation, as is well known, is due to the action of the salt in the sea water.

These considerations make it obvious that if we can prove the Vineyard series to have been deposited at the mouth of a great river we shall thereby avoid all theoretical difficulties arising from the very great thickness of the deposits. Assuming, then, for our hypothesis, that these beds were formed in a delta, we will now proceed to examine into their structure to see how far it is consistent with this view.

The first point to determine in this effort to verify our hypothesis is whether the Vineyard series was deposited on a coast line, for it is evident that unless this can be proved the hypothesis of their delta nature cannot be valid. As far as the Gay Head section is concerned there can be no doubt that all the beds were formed along the coast. This is tolerably well shown by the occurrence of lignite beds in every part of the section, there being no part of it where the beds are quite without vegetable matter for more than five hundred feet. Moreover, the character of these lignite beds makes it necessary to suppose that they were accumulated at the mouth of a river. The thicker beds of this nature are almost altogether composed of woody matter, the only admixture being a little sand and clay. Such deposits are never accumulated on the sea floor. The entire absence of marine fossils from the mass corroborates this conclusion. It cannot be doubted that a small amount of lignitic matter may find its way to the bottom of the sea, but it seems impossible that tolerably thick beds of purely woody matter derived from the land could ever have been formed on the floor of the open sea. It is also impossible to believe that such beds of lignite could have been accumulated in the alluvial terraces at any considerable distance from the shore line. The only place where lignitic deposits, such as we find here, can be formed, is in the swamps at the very mouth of a considerable river, that is, in a delta.

There is other evidence to prove that these beds were laid down in a delta deposit. In the southern part of the section there are several thin layers of coarse conglomerate. The pebbles of these beds are mostly composed of quartz, but there are some fragments of syenite and other hypogene rocks among them; at some points these pebbles form an irregular bed lying nearly horizontally on the surface of
the steeply inclined strata; a little farther on they may be observed forming a bed between the two adjacent members of the cross-bedded deposits (Fig. 61). This peculiar arrangement can only be explained by the supposition that we have in the horizontal portion of the conglomerate the part laid down by the stream on its bed; in the inclined part, the portion which was laid down on the advancing front of the delta.

Still further evidence as to the delta nature of these deposits is afforded by the wedge-like shape of certain beds. They run out within a short distance, often within a few feet, of their origin, as is shown in the general section of Gay Head (see Pl. XXVI). This is thoroughly consistent with the nature of delta deposits, but not so with that of those formed in any other way. We also remark the fact that the beds vary much in their inclinations, the coarser materials forming steep frontal slopes, and the finer, slopes of less inclination. Still further we note that the beds of coarse materials often have within themselves a slight cross-bedding. This is observable only in the whitish sands and is not at any point very distinct or continuous. This structure, probably arising from whirling currents, is consistent with the processes which form shore deposits by the aid of tidal currents alone, but it is also quite reconcilable with the theory that this deposit was formed in the delta district of a large river.

The foregoing considerations lead us to the conclusion that the hypothesis of the delta origin of the Vineyard series is essentially verified. We may thus feel satisfied that we have here deposits formed with great rapidity by a large river of the Tertiary age. We will now endeavor to determine something about this stream, as to the direction of its flow and the origin of its peculiar sediments.

The general slope of the beds of the Vineyard series is toward the northeast. This is clearly the case in the district about Gay Head, but less clearly so in the Chilmark district, where the strike is somewhat variable and obscurely shown. There can be little doubt that the general course of the stream, which I shall hereafter call the Vineyard River, was from the westward. It should be noticed that the direction of the dip of the beds formed in a delta does not afford any precise indication as to the course of the stream even at its mouth; the successive débouchures may point in directions which vary greatly from that of the main stream. An inspection of the present delta of the Mississippi or of that of any other great river will make this point clear.
It is evident that this delta must have been formed by a river of large size or by a number of streams debouching in a common delta. The area occupied by the beds on Martha’s Vineyard, provided we assume that they underlie the whole of the island, is larger than the delta of any existing river on the Atlantic Coast. The extent of the beds of coarse sediment on the front of the delta is a proof that the stream was one of much power. No such accumulations are making on the front of our rivers on this part of the Atlantic Coast.

We have now to consider the origin of the sediments which compose the Vineyard series. Our principal point will be, if possible, to determine the portion of the land area whence they came. It may be well to say that the existing surface of New England has retained its present lithological character from a very early time. The pebbles of the Roxbury conglomerate, a deposit of Cambrian age extensively developed near Boston, Mass., closely resemble those of the glacial till in the same region, so little has the general mineral character of the district changed during this vast time. In the Narragansett basin the millstone grit and in the Connecticut Valley the Triassic conglomerates exhibit the same likeness to the beds of pebbles formed during the last ice age. It is therefore evident that we may expect in this search to find no great difficulty arising from changes in the geology which have taken place since Tertiary time unless it arise from the stripping away from this surface of beds of relatively modern formation.

Taking the beds of the Vineyard series in the order of their importance, we shall first consider the deposits of white sand. As before stated, these beds are composed of materials which were derived from the breaking down of granitic rocks. All we know of the structure of this part of New England leads us to suppose that the prevailing rock in the immediate vicinity of the delta is of this nature. The nearest bed rock on the mainland, if comminuted, would yield a material similar to this white sand. The difficulty is to see how such a vast quantity of this granitic material could have been rapidly eroded and brought into the channels of a river unmingled with other forms of detritus. The only way in which we can hope to throw any light on this problem is by comparing these deposits with similar ones whose history is better known to us.

There is a parallel case in which large amounts of detritus derived from crystalline rocks have suddenly been precipitated into the sea, i.e., the millstone grit. The beds of this deposit, especially in the region west of the Blue Ridge, in Kentucky and Tennessee, closely resemble those we are now considering. I have elsewhere endeavored to show that this deposit may be explained by supposing that the crystalline rocks of the Blue Ridge, having long been subjected to atmospheric decay, were suddenly exposed to powerful erosion such
as would come from the action of a glacial sheet and the decayed rock matter was thus given to the sea.  

I venture to suppose that such accumulations of detritus may have been formed at other periods along our New England shore whenever, after long-continued decay, the rocks were exposed to powerful erosion either by glacial action or by the waves of the sea during a period when the surface of the land was sinking. The great difficulty is to account for the exclusion of other sediments from these white sands during the process of erosion and deposition. This exclusion of other sediments may be explained by the supposition that the deposits were formed during a period of subsidence near the line of a shore presenting cliffs of extensively decayed, granitic rocks. At first I was disposed to take this view of the origin of these deposits, but the frequent occurrence of lignites and clay beds with them seems to demand the delta theory. We may reasonably suppose that the Vineyard River had several branches, or rather that there were several rivers terminating in one delta, and that one of these branches drained a district underlain altogether by rocks which yielded these whitish sands. Furthermore, whenever the changes in the outlets brought the detritus from this valley to a particular part of the delta to the exclusion of materials from other adjacent streams these white sands were formed. It should be said that the extreme whiteness of these sands is superficial and arises from the decay of the material, especially feldspar, which they contain. A few feet below the surface they have the hue of ordinary granitic rock.

The deposits of reddish sand and clay next deserve attention. These are necessarily to be explained by the same hypothesis as that by which we account for the white sands, i.e., by the supposition that they were derived from a region where reddish sandstones and shales were exposed to decay. We naturally turn to the Connecticut Valley as the probable source of materials of this nature. As is well known, the Triassic rocks of that valley have a prevailing red hue, and if they furnished the detrital materials for the Gay Head deposits their color and composition would be sufficiently accounted for. It would be obviously impossible to have these bright red clays and sands derived from the Connecticut Valley as it is at present constituted, for the reason that the red beds occupy only a small part of its surface and the detritus borne out from it is a mixture of materials from many different kinds and colors of rocks. But it is evident that the Triassic rocks of this valley have been very much diminished in area in recent geological times. These deposits occur in thin sheets over a large part of the field now occupied by them and they were very extensively worn away during the last glacial period.

1 See Glaciers, by Shaler and Davis, p. 97; also, Reports of Kentucky Survey, new series, vol. 3, pp. 186-188.

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It is reasonable to suppose that they may have covered the whole surface of the valley during the middle Tertiary period.

Thus on a priori grounds it seems not impossible that the detritus composing these red beds of Martha’s Vineyard may have been derived from the region of the Connecticut Valley. When we examine the sediments themselves we find that they afford what may be taken as confirmation of this hypothesis. They contain numerous fragments which appear to be essentially like the red sandstone of that valley and infrequent small fragments of reddish slate which may also have been derived from that district.

There are, however, some objections to this hypothesis. In the first place, it requires us to suppose an extensive area of Triassic deposits in the upper Connecticut Valley or else a narrower limitation of its basin in former times than we may be justified in supposing. Moreover, from Gay Head to the existing deposits of Triassic age above the level of the sea there is a distance of over eighty miles and we have no evidence that the beds of that age exist in the intervening district. Manifestly the alternative is to suppose that during the time when these deposits were forming there were extensive areas of Triassic rocks nearer this district than the Connecticut Valley. It is by no means improbable that the Narragansett basin—i.e., the region now occupied by the valleys of the Taunton and Providence Rivers and their tributaries—may have been covered with Triassic deposits down to a recent time and that the red materials of the Miocene deposits came from that district.

This hypothesis finds some confirmation in the existing conditions of the region about the head of the Bay of Fundy. In that part of the shore there are extensive escarpments of Triassic sandstones and shales essentially like those of the Connecticut Valley. These beds are now yielding sediments which have much the color of the red clays and sands of Gay Head. If we had had a large river in that district which in its times of flood brought down great quantities of reddish mud and another stream, whose sediments were derived altogether from granitic rocks, discharging into the same delta, the changes in the points of discharge of these two streams might produce a distribution of sediments such as we find in the Vineyard series.

It will be observed that in the highest part of the Gay Head section the characteristic red clays and white sands are to a great extent replaced by ferruginous, brownish-colored sands, as before described. These beds appear to be more nearly in the nature of the ordinary delta accumulations such as are forming at the mouths of our southern rivers than the lower lying strata of this section. They not only contain a considerable variety of nodules and broken bones, but the general constitution of the beds has a more familiar aspect than the red and white sands in the lower part of the section.

One of the most remarkable features connected with the Gay Head section is the distribution of the beds of bowlders which are
found in certain of its strata. These layers of boulders are irregularly distributed; they are in the main confined to parts of the section where the white sands are found, but they occasionally occur also in the form of isolated boulders scattered through the red clays. By far the greater part of the pebbles are of quartz and the fragments are much rounded; the other hypogene rocks of the mainland are represented by pebbles which are generally much decayed. At two or three points in the lower part of the Gay Head section these pebbles form thin sheets of conglomerate disposed as shown in Fig. 61. In these pebbly beds the mass commonly has a beach-like structure and in two of these conglomerates there are occasionally sharks' teeth. It is not certain whether these teeth have been transported from some pre-existing bed or not, but their delicate structure makes it appear most likely that they are indigenous to the deposit.

The quartz pebbles of these conglomerates are probably remnants of veins which existed in the granitic rock whence these white sands were derived. As is well known, such quartz veins resist decay much longer than the rocks in which they are found and when the decayed mass is broken up by erosive agents they form pebbles, while the remainder of the mass is reduced to the state of sand or clay. There can be no doubt that the quartz pebbles of the millstone grit of eastern Tennessee and Kentucky had this origin.

Besides these layers of quartz pebbles there are occasionally large masses of sandstone, generally of a dark-red hue, which occur as isolated blocks and so far as observed only in the red clays and sands. These fragments are generally subangular in form. The largest I have seen contained about ten cubic feet. It seems necessary to believe that they have been borne to their places by floating ice. As there are no traces of vegetable matter in these clays it seems unreasonable to suppose that these great erratics have been transported to their place in the roots of trees; moreover, the size of the largest fragments would make it improbable that they should be so carried.

It will be noted that the numerous beds of lignite indicate that the neighboring land was, from time to time at least, the seat of an abundant vegetation while these beds were depositing. The entire absence of vegetable matter in the intermediate portions of the section is a very singular feature. It appears as if these beds had been formed at a time when the land was alternately the seat of an abundant vegetation and quite destitute of such a covering. This sharp contrast in conditions is paralleled in the period of the Coal Measures and less distinctly in the time of the last glacial period. In those stages of the earth's history we have like sudden alternations from organic to inorganic conditions.

This absence of organic life characterizes at least nineteen-twentieths of the total section of the Gay Head series. The red clays
and the white sands are quite without fossils except where a thin bed of lignite occurs. The lignites in these beds are always definitely limited; in no case are the fragmentary vegetal remains scattered through the section. The limitation of the fossil animals is almost equally definite. They are found only in the layers indicated in the diagrammatic section or in half a dozen beds having a total thickness of less than two hundred feet.

In the usual conditions of any land surface it could not yield sediments such as those we find in the white sands or the red clays of the Vineyard series. These beds would inevitably have been discolored by the soil waste which in a normal river would have constituted a large part of the sediments it bore to its delta. The only way in which I have been able to conceive the formation of deposits so entirely free from admixture of soil is as follows, viz: Let us suppose in the first place that the rocks of the region from which these sediments came had been deeply decayed, as we now find them decayed in the southern part of the Appalachian district, where the ice of the last glacial period did not operate as it did in the northern parts of the continent. If, after a long period of exemption from ice action, we should have a glacial sheet imposed upon the surface, the result would be that the decayed rock, without admixture with any solid material, would rapidly be conveyed to the streams and by them borne to the delta. In the temporary retreats of the glacier we should have the surface of the land recovered by forests which would yield the abundant vegetal detritus composing the lignite beds.

In Europe we have some evidence of the existence of a wide-reaching glaciation in the Miocene period. It is therefore not unreasonable to suppose that such conditions may have existed on this continent in the same age.

DEPOSITS OF DOUBTFUL AGE.

There are two sets of deposits on Martha's Vineyard, the relations of which are not as yet determined. One of these is the Weyquosque series before mentioned; the other, the hidden series, which is only certainly known from the drift in the district about Indian Hill and on the shores of Cotamy Bay.

The Weyquosque series, as before remarked, is of doubtful age, with the probabilities inclining towards the conclusion that it overlies the Vineyard series and is of later Tertiary age. If it be of this period and if, as is likely, it shared in the disturbances which have dislocated these beds, it is to be taken as evidence that the mountain-building movements continued to a later time than would be indicated by the Vineyard series alone.1

1 At the southern end of Sengekontacket Pond, immediately south of Cottage City, there is a small area in which occur beds which probably belong to the same age as those at Weyquosque. The exposure is quite superficial, and, though the physical resemblance to the materials composing the deposits is great, I hesitate as yet to class them as of identical age.
It is clear that the Weyquosque series represents erosion from another district than that which furnished the sediments of the lower-lying beds. In it we find no trace of the red and white sands or of the lignites which characterize the Vineyard series in such a remarkable manner. The section, though exceeding fifteen hundred feet in thickness and possibly over two thousand feet thick, is composed of gray and blue clays and whitish sands, the latter sometimes containing a few rounded pebbles of hypogene rocks. For the present its position must be left undetermined. There are reasons to suspect that it may be of the same age as the lower clays on Nantucket and on No Man's Land, and possibly certain others in Duxbury and at other points in the Cape Cod district.

The other and less known series is shown only by the abundant fragments of its beds contained in the glacial drift in the region about Indian Hill and the rarer fragments which are found on Chappaquiddick Island and the neighboring shores of Cotamy Bay. These fragments, which on certain fields about Indian Hill constitute a large part of the glacial detritus, are the waste from deposits of highly ferruginous sandstone, often taking on the form of an impure, siliceous hematite. The strata whence they were derived were thin-bedded and abounded in obscure fossils. The angular form of the fragments and their relatively large size, notwithstanding the fact that the rock is quite friable, shows that they cannot have been transported more than a few hundred feet from their original position.

Although the fossils of this hidden section are very abundant, they are extremely altered by the introduction of the iron oxide which evidently replaced the lime of the fossils. These fossils, so far as determinable, are all of molluscan types, except a few fragments which may be those of crustaceaens, and it is doubtful whether any of them are of the same species as those from Gay Head. They include an oyster of exogyron aspect, a pecten of the costata type, as well as several other forms. The general aspect of these fossils (in all, about a dozen species) leads me to believe that they are of a decidedly older age than those found in the Gay Head section; that they are at least as old as the Lower Cretaceous and may be yet older.

It is a difficult matter to determine with accuracy the areal distribution of the Weyquosque series on the surface of Martha's Vineyard. The materials of which it is composed are of a very yielding nature, and where scarfed by the sea they are apt to be covered by the glacial materials which fall from the upper part of the section. Besides the localities already noted, this deposit, as is shown upon the map, is more or less clearly exhibited at three other localities on the shore of the island. One of these is at the mouth of the brook on which are situated the old brick kilns which are a conspicuous feature on the northern shore of the island. One other lies at a point on the north
shore about half a mile west of that brook. Between the last-named locality and the mouth of the brook there is a considerable exposure of the Gay Head series. About three hundred yards east of the brickyard is another considerable exposure of the Weyquosque deposits. All three of the localities on the north shore have the same essential character as the great section at Nashaquitsa. The clays have an earthy or soil-colored look, though they contain no evident plant remains. The bedding is very indistinct and it appears to have been to a considerable degree affected in a local way by the pressure of the glacial sheet against this part of the shore. The beds, so far as their position can be determined, strike in a general northeast and southwest direction and lie at very high angles.

As is indicated by the map and the foregoing conditions, the Weyquosque series is evidently distributed in such a manner as to make its relation to the Gay Head series tolerably plain. Except in the trifling exposure just south of Cottage City the beds of this age have not been found far away from exposures of the Gay Head series, and even in the locality last referred to it seems likely from the waste of the Gay Head series contained in the glacial deposits that the beds of that age lie near the locality in question. This feature in the distribution of the Weyquosque beds seems clearly to establish the fact that they are related in age to the Gay Head deposits rather than to those of the glacial period.

It is a remarkable fact that the deposits of this last-named series, though very thick and apparently well suited for preserving fossils, have afforded no organic remains of any description. In their non-fossiliferous character they closely resemble the Gay Head series. We have already noted the fact that the pervading lack of fossils in the deposits at Gay Head may most easily be explained on the supposition that they were formed during the glacial period. It may well be that the non-fossiliferous character of the Nashaquitsa deposits can be accounted for in the same manner.

The recent examination which I have made of the island of Naushon, one of the Elizabeth Islands immediately northwest of the island of Martha's Vineyard, has shown me that the greater portion of that island is composed of a mass of yellowish and reddish, stratified sands containing occasionally water-rounded pebbles. The surface of these great arenaceous deposits has been worn into the form characteristic of glacial erosion. On this surface lies an irregularly disposed sheet of till and kame deposited during the last ice age. It is evident on even a casual inspection that these sands of the Naushon series are not in a strict sense of glacial origin. They appear to antedate the time when the ice sheet was first imposed upon this surface, though they may perhaps represent the deposits made in some one of the interglacial periods. After becoming familiar with the aspects of these deposits on Naushon I searched for them on the
island of Martha's Vineyard. I found that although they are not abundantly developed on the last-named island they are noticeable in several of its coast sections. They appear with variable thickness above the level of the Nashaquitsa series in the cliffs which bear that name. They are also imperfectly shown at various points on top of the Gay Head series within a few hundred feet to the north and south of the light-house on that promontory. They are also imperfectly shown in the sections along the north shore. I am inclined to believe that the deposits of this series will be found on Cape Cod, but it is clear that they are generally wanting beneath the glacial deposits on the other portions of the mainland.

Although for the present I must leave the precise age of these deposits undetermined—and, indeed, it must remain doubtful whether or not they belong to the glacial period—there are several reasons which lead me to suppose that they altogether antedate the coming of the ice sheet of the last glacial period to this part of the shore. I am also of the opinion that they are not in any way related in age to the beds of the Gay Head or the Nashaquitsa series. They clearly lie in unconformable attitudes on the eroded surface of both those series of deposits. The circumstances of their distribution point to the conclusion that they are in age most nearly related to the deposits of glacial age. On the island of Naushon I have observed that while the deposits which unquestionably belong to the glacial age abound in grains of magnetic iron ore such magnetic material is entirely wanting in the underlying orange-colored sands, though these beds contain a noticeable quantity of ferruginous matter in a highly oxidized form. As I propose to make these deposits of yellow sands the subject of a special memoir I shall not give them further consideration in this report.

DISLOCATIONS OF THE VINEYARD SERIES.

We turn now to the consideration of the disturbances which have affected this series of beds since the time of their formation. At first it seemed to me that the inclination of the beds might be merely the original inclination of the deposits as they were formed on the advancing front of the delta. A further study of the facts has shown that this hypothesis is untenable for the reasons given below.

The deposits formed on the frontal apron of a delta, though they incline toward the sea, are never placed at anything like the angle in which these Gay Head beds lie. The steepest slopes on the front of existing marine deltas where the tides operate do not exceed 5° of declivity, though in the case of debris formed in great lakes they may have considerably greater slopes. The average inclination of these Gay Head beds exceeds 25°; at several points it amounts to as much as 45°, and at one point the beds are vertical (see Pl. XXVI). These steep dips are sufficient to prove that the beds have undergone
a considerable dislocation from their original condition. They also indicate that the amount of this dislocation has varied very much in different parts of the section.

As the occurrence of considerable dislocations in this district since Miocene time is a fact which goes against the prevailing opinion of the history of this part of the continent, it has seemed to me necessary to consider whether any other cause than mountain-building forces could have brought about this tilting of the rocks.

There appeared to be but two causes, other than the action of mountain-building forces, which could by any chance have brought about the dislocation of the beds. One of these is the slipping of the beds from the undermining action of the sea. Though this cause is doubtless effective in producing many small crumplings and tiltings of the large wedges of detached material which are on their way downward toward the sea, it cannot be held to have operated in the evidently firm-set face of the cliff. Moreover, despite the imperfect nature of the exposures in the inland district of the island, these beds are seen to have steep dips everywhere, and at the Weyquosque section they form a distinct anticline. This suggestion may therefore be dismissed without further consideration.

It has often been noticed that where a glacier has pressed against stratified clays and sands these strata are much flexed, having been crumpled by the great pressure which the ice has brought to bear upon them. Nor is this action of the ice altogether limited to yielding strata. Where slates stand in a vertical position with the strata at right angles to the direction of the glacial path, their beds are sometimes bent or broken and the ruptured fragments turned southward. An excellent example of this action is shown in the slate quarries in the Massachusetts field, at Quincy. In other countries geologists have observed similar instances of dislocated strata which they have ascribed to the action of glacial ice.¹

¹ Since the pages of this report have been in press I have had an opportunity of conferring on the ground with Dr. F. J. H. Merrill, whose paper in the Annals of the New York Academy of Sciences, vol. 3, Nov. 7, 1884, p. 341, entitled "On the geology of Long Island," has called attention to the effect of glacial action in dislocating pre-existing, incoherent, stratified deposits. The result of this conference has been to convince me yet more firmly that the beds exhibited at Gay Head and at Nasketucket cannot have owed their dislocation to the action of the glacial thrust, for the following reasons: First, the pressure exercised by the glacial movement can operate only upon the superficial portion of the ground over which it slopes; it is impossible to conceive that the thrust can be propagated in an effective manner through great thicknesses of deposits which have the incoherent nature characteristic of all the stratified materials found on Martha's Vineyard; secondly, the peculiar position of the axes of the anticlines exhibited by the Tertiary section on Martha's Vineyard requires us to suppose, in case we adopt Dr. Merrill's hypothesis, that the thrust which produced the dislocation was brought about by peculiar converging tongues of ice, and not by the direct thrust of the main glacier operating in the general axis of its motion.

While rejecting the hypothesis of ice thrust as the source of the principal disloca-
On careful examination it becomes clear that the glacial ice had no influence in producing the dislocations of the Vineyard series. This is shown by the fact that these beds have a dip toward the northeast, a direction which is at right angles to the course of the glacial stream. Even were the dip of these beds coincident with the course of the glacier we should be compelled to reject the hypothesis that they were flexed by its pressure, for the reason that a tolerably uniform inclination in a section of such great thickness could not be brought about by such action. It is equally impossible that it could have produced the Wayquesque anticline. On this account I shall omit further discussion of the hypothesis.

We therefore turn, with the assurance that no other cause will suffice, to the ordinary cause of such dislocation, i.e., the mountain-building forces. I confess it is with some surprise that I find it necessary to assume the occurrence of considerable disturbances in this district in a time which we must place later than the close of the Miocene period. But the evidence is clearly sufficient to prove that in this region important movements have taken place since the close of that period. It would be of the utmost importance to determine the precise time at which these dislocations took place. This seems to be impossible. The only point which we can make clear is that, after the deposition of beds which certainly were laid down as late as the Middle Miocene and before the close of the glacial period, a series of disturbances took place which greatly dislocated them. That the disturbances occurred before the close of the glacial period is shown by the fact that the upturned edges of these beds were worn off by the glacier. That the dislocation occurred some time before the last ice period began is rendered probable by the fact that this mass of beds which underlies the townships of Gay Head and Chilmark appears to be the eroded remnant of a much larger area, and this erosion, from the nature of its effects on the contour of the surface, could not well have been brought about by ice action, though it perhaps may have occurred during the recessions of the ice which we know to have taken place.

The direction of the compressive movement which produced these dislocations next deserves our attention. This is hard to determine. When beds originally horizontal have been dislocated by a single movement the direction of this movement is easily ascertained, but, where beds have an inclination before the movement takes place, the resulting attitude depends on the direction in which they originally
sloped, as well as upon that of their last movement. This point is commonly neglected in geological inquiries which concern the attitudes of dislocated strata; from this neglect many serious misapprehensions have arisen. We must therefore state the conditions of the problem.

If the compressive forces act so as to dislocate the beds in a direction at right angles to the strike it is easily seen that the effect will be to diminish or to increase the dip of the beds. If, on the other hand, it act in other azimuths, it will tend to change the direction of the strike to an amount determined by the ratio of the original to the succeeding dip of the beds. Thus, beds originally striking north and south at an angle of 10° to the horizon, and subsequently tilted by a force which in horizontal beds would produce an east and west strike of 10° of declivity, would have the resulting strike line in a northeast and southwest direction. It is evident that the direction of the strike will depend upon the amount of the dip in the first and second states of the position.¹

The sections obtained on the island, except those at Gay Head and Weyquosque Cliffs, are extremely imperfect. So far as they go they appear to indicate that these deposits of the Vineyard series are generally arranged in a continuous, monoclinal form, much as they are at Gay Head, the Weyquosque anticline, though of great theoretical interest, being of small structural value. It is manifestly probable that these dislocations were cast in the form of anticlines and synclines rather than in the form of a monocline, as the last would require either a profound fault or an inconceivable tilting of this portion of the continent.

The pressure which produced these dislocations probably operated so as to produce folds extending in a northwest and southeast direction. This is fairly proved by the anticline of the Weyquosque section.

Before we leave this part of our subject it is worth while to notice the fact that the recognition of a system of mountain axes involving the Tertiary beds of Martha’s Vineyard and vicinity may aid us to explain the general geology of this district. It may, for instance, ac-

¹ Unfortunately there is no certainty as to the original direction of the dip after it has been compounded with the second dislocation. It may be said, however, that the less in amount the original inclination the less it will account for in determining the final attitude of the beds. There is thus a chance of determining the original strike of the beds by ascertaining the variations existing in the azimuth of the same bed at points where it has great differences in inclination; for it is manifest from the foregoing consideration that where the original dip was 5° and the secondary dip at some points 20° and at other points 80° it may be possible by comparing the azimuths to determine the original dip. I have tried to apply this principle to the Gay Head section, but I find that at this point the strikes are gradually turned from a nearly east and west direction in the southern end to a nearly north and south direction at the northern end of the cliff, and that this change takes place in an irregular manner, making it quite impossible to use the method above suggested.
count for the existence of an isolated mass of drift in the island of No Man’s Land. It is hardly possible to account for this solitary mass of kame and terrace drift by the supposition that it owes the whole of its relief to the morainal matter which is exhibited on its surface; for it is not continued even by shallows to the east and to the west beneath the level of the sea. If we may suppose that it is a fragment of a Tertiary axis upholding a portion of the drift sheet, its isolated character would be sufficiently accounted for. So, too, the island of Nantucket, which is not easily explained as a drift-heap alone, may rest upon the remains of an anticline which was formed during its period of dislocation. This theory will also aid in explaining certain peculiarities of Cape Cod which cannot be accounted for on the supposition that they are mere accumulations of drift.

It would be interesting to inquire whether there are elsewhere indications of mountain-building movements which may be referred to this geological period, but such an inquiry cannot properly be undertaken in this memoir. So, too, the detailed discussion of the orographic features of these deposits must be postponed for the reason that they should be considered in connection with the general geological history of the district in which they lie.

**POSTGLACIAL EROSION OF MARTHA’S VINEYARD.**

The general surface of Martha’s Vineyard has been exempt from any considerable erosion since the close of the glacial period, as is shown by the unchanged condition of the moraines and delicately molded kames, as well as by the preservation of the faint channels excavated in the terrace drift or plain region in the southern part of the island. The shores of the island, on the other hand, have been greatly eroded by the action of the sea waves and the tidal currents which sweep by its coast (see Pls. XXV, XXVII, XXVIII, and XXIX). The amount of this erosion is very different on the northern and on the southern shores. The southern coast is exposed to the wide ocean, the northern meets only the waves of Vineyard Sound and Nantucket Bay.

The rate of erosion on the southern coast of the island varies much in different places. From Gay Head to Squipnocket Point there seems at present to be little erosion going on, nor is there any evidence that much wearing has occurred in this section of the shore since the close of the glacial period. This is doubtless due to the fact that, owing to the regimen of the currents, the sands accumulate on this shore. From Squipnocket Cliff to the eastern end of Nashaquitsa Cliffs the erosion is exceedingly rapid (see Pl. XXVIII). From Nashaquitsa Cliffs to the eastern extremity of the island the inward movement of the shore may on the average be less rapid than in the last-mentioned section, but it is still tolerably speedy.
Prof. H. L. Whiting, of the U. S. Coast Survey, has ascertained that in forty years, i.e., from 1846 to 1886, the shore in the central part of Nashaquitsa Cliffs moved into the land 220 feet, or at the average rate of about five and one-half feet per annum—perhaps the most rapid gain of the sea on the land where the shore is considerably elevated which has been observed on any part of the New England coast. This swift invasion of the sea is the more remarkable from the fact that these cliffs of drift material contain large bowlders which we might suppose would have accumulated on the beach in front of the cliff and thus have restrained the action of the waves; but, though quantities of these great bowlders are annually precipitated upon the shore, they quickly sink into the sands, leaving the face of the cliff open to the assault of the waves. The detritus from these cliffs travels to the eastward and finally finds its way to the eastern face of the island, forming the extensive shoals and beaches in that district. This rapid movement of sands is particularly well shown on the beach south of Cotamy Bay. As before noticed, this bay has from time to time a southern outlet. This outlet appears always to open just south of that part of Cotamy bay known as Mattakeset Bay. As soon as an opening is formed the sands from the west encroach on its westward side, causing the tidal current to wear away the eastern boundary of the channel. In this way the opening is crowded to the east toward Chappaquiddick Island. Finally it is driven against the southern part of that island, where it can no longer move eastward, and is finally attacked by some heavy storm, so that at a time of low tide it is entirely closed (Fig. 62). This eastward movement of the sands affords a tolerably good measure of the rate of erosion on this coast.

The recession of the southern coast east of Nashaquitsa Cliffs is as clearly proved as that of the cliffs themselves. There is a well founded tradition that one hundred years ago it was possible to skate from Tisbury Pond to Edgartown village along the line of connected bays which are now separated from one another. From the existing contour of the shore it would seem as if this would indicate a recession of the coast amounting to at least one-fourth of a mile within that time.

The beach at Cotamy Bay separating its waters from the sea has of late years moved swiftly to the north. Prof. H. L. Whiting found that in twenty-five years, or between 1846 and 1872, it retreated a distance of 450 feet, or at the rate of 18 feet per annum. About the same rate of retreat was observed for a mile or more to the east of Mattakeset Bay.1 It should be observed, however, that this retreat has been complicated by the movement of a barrier reef of sand encroaching in areas of shallow water, and not by the erosion of an actual shore line. In the retreat of such a beach the

GAY HEAD CLIFFS, SOUTH END.
WEYQUOSQUE OR CHILMARK CLIFFS, LOOKING SOUTHWEST; NO MAN'S LAND IN THE DISTANCE.
Fig. 62. Map showing the recent changes in a part of the southern shore of Martha's Vineyard.
movement is in greater part caused by the sand being impelled from the front of the beach over its crest, the movement resembling the motion of a sand dune. It is therefore quite different from the erosion of a sand cliff, where the debris has to be removed from the point where it was formed either laterally along the shore to some place of deposit or outward into the deep sea. Either of these last-named movements may require the transportation of the sand to very many times the distance it travels when it is simply thrown over the beach. It seems to me, therefore, that, from these irregularly shifting sands, we cannot form any conclusions as to the rate of actual erosion on this part of the coast.

If we protract the gradual surface slope of the southern drift terrace seaward we find that it cuts the sea-level at a point about three miles to the south of the present shore. It is therefore difficult to believe that since the island had its present attitude as regards the sea-level the shore could have a greater extension in that direction, unless, indeed, there was another line of moraines to the south of this island. At the present rate of erosion, assuming it to be as much as one-fourth of a mile in a century, this would allow but 1,300 years for the erosion from the original shore to the present line of the coast.

On the eastern side of the East Chop, facing the rather broad waters of Nantucket Sound, the process of erosion is rapid. Professor Whiting found that this bluff, which has a height of about forty feet and a length of about forty-five hundred feet, retreated 75 feet between 1845 and 1871, or at the rate of about three feet per annum. In these years about thirteen million cubic feet of matter has been removed from this section. A portion of it—how large a portion the distinguished observer hesitates to say—has been borne into Vineyard Haven. The West Chop, or western horn of Vineyard Haven, has also wasted in a similar manner, though not to so great an extent. The debris from this part of the shore passes westward and is deposited on the beaches between the West Chop and Tashmu Pond.

On the northern shore west of the West Chop of Vineyard Haven the rate of erosion cannot be anything like as great as it is on the southern coast. It cannot well exceed a few feet in a century. It is doubtful if on the average it amounts to five feet in a century. On this coast the bowlders plentifully accumulate along the beach and defend it from the relatively slight waves of the inland waters which it faces.

The question naturally arises, Has this channel between Martha's Vineyard and the mainland been excavated by the action of the sea since the glacial deposits were formed? There can be little doubt that the island of Martha's Vineyard has been connected with the mainland

1 Seventh Ann. Rept. Harbor Commissioners Boston, 1873, p. 112.
2 See appendix (p. 361), containing a report of the results of Professor Whiting's recent surveys, which was received as this memoir was going to press.
since the close of the glacial period. The animals and plants of the island are in no way peculiar. There are a few species existing on the mainland which are not found on the island and none on the island which are altogether limited to it. We can hardly believe that several large-seeded plants and many of the land animals have found their way across the five miles of water which separates the Vineyard from the continent.

As we cannot well explain the formation of Vineyard Sound by the action of waves and currents alone, I am disposed to believe that the original connection of the island with the mainland was due to the fact that at the close of the glacial period this region was considerably higher than it is at present. It is true that we can only prove a subsidence of about ten feet since this postglacial elevation, but as will be seen from the report on the island of Nantucket there is reason to suspect a much greater subsidence of this region. It is to be observed that the channel between Martha's Vineyard and the mainland does not exceed seventy-five feet in depth.

On the western end of the island at Gay Head there is evidence of extensive erosion since the close of the last glacial period. This evidence consists in the waste of the eroded cliff which lies as a platform just below the level of high tide, extending for a distance of a mile from the present escarpment. As will be observed by the soundings on the Coast Survey maps, this terrace plunges abruptly into tolerably deep water. This shelf forms a rude triangle, the base resting on the front of the existing cliff and the sides protruding the line of the shore. There can be no doubt that it affords an approximate horizontal plan of the original outline of these Tertiary deposits as they were left at the close of the last glacial period. The bowlders that constitute this apron have, by the support afforded by the platform of Tertiary beds on which they lie, been kept from the submergence in the sand which has overtaken those that have fallen to the foot of Nashaquitsa Cliffs.

It seems clear from the evidence that the recession of this part of the shore which has taken place since the glacial period amounts to a distance of about one mile. At the present time the rate of recession at the Gay Head Cliffs is on the average not more than one foot per annum. It is probably at the present time less rapid than in the past, for the reason that ever since the erosion began it has been operating on the face which has been constantly increasing in height and width and has thus required year by year more time for the removal of the material. I am inclined to believe that the erosion on the average must have amounted to at least two feet per annum.

It is not quite safe to consider these various evidences of erosion as indicating the long-continued wearing of the lands in this district at anything like the rate at which it is now going on. The present
activity of the destructive agents is principally due to the energy of the tidal currents, which bear away the sediments. If these sediments are not borne away they effectually prevent the waves from doing their work by protecting the cliffs from the assaults of the sea, as is now the case along the Squimnocket shore. The course of these tidal currents alters with every considerable change of the geography of the coast. It is likely that down to a very recent time a part of the sea south of Nantucket, known as Nantucket Shoals, was occupied by many islands. While these islands existed it is probable that the currents about Martha's Vineyard were far less strong than they are at present. It is also probable that Muskeget channel is of recent origin; before it existed the tidal currents about the east end of the island must have had a very different regimen from that which they have under the existing conditions. In other words, in a region where recent changes of the shore line have taken place it is not safe to assume that the existing rates of erosion have continued for a great period of time.

**POSTGLACIAL, FOSSILIFEROUS DEPOSITS OF MARTHA'S VINEYARD.**

Dr. F. J. H. Merrill informs me that in 1884 he found in the upper portion of the cliff, nearly in front of the light-house at Gay Head, at the depth of about six feet below the surface, a small deposit of postglacial fossils having the general character of the beds exhibited at Sankoty Head, on Nantucket. On revisiting this locality with Dr. Merrill, in June, 1887, no trace of this stratum could be found. Dr. Merrill's ample experience in the study of deposits of this general nature in the region about New York leads me unquestionably to trust the accuracy of his observations. I am the more disposed to credit them for the reason that in 1860 I found in the immediate neighborhood of the place noted by Dr. Merrill a similar bed of shells which I then assumed to be of Post-Tertiary age. Although my notes on this observation have been lost, my memory of the fact is sufficiently clear to have a value in substantiating Dr. Merrill's observations.

The importance of these observations with reference to our general hypothesis as to the interglacial history of this island is manifest. Notwithstanding the small area occupied by this deposit it seems sufficient to make it clear that after the first advance of the ice of the last glacial period the surface of this region was lowered to the depth of not less than one hundred and twenty feet below its present level. Following the formation of this bed of shells, which took place during the period of subsidence, the ice again advanced, and on its subsequent retreat deposited a thin sheet of ground moraine above the level of stratified material. Thus the succession of events appears to have been the same as that indicated at Sankoty Head.¹

The island of No Man's Land has a length of a mile and a half and a width of one mile; it lies about three miles to the south of Gay Head Peninsula. Although this island has no distinct physical connection with Martha's Vineyard it throws a certain amount of light on the geological structure of the whole district, especially on the history of the deposits formed during the postglacial period. It seems therefore necessary to consider it in this memoir.

The mass of No Man's Land, at least all the beds which are above the level of the sea, consists of glacial drift. The superficial deposits, everywhere bowldery, are disposed in the form of very stony kames, the materials of which are distinctly stratified. Much of this kame material seems to have been shoved about in the forward movement of the ice in front of which it was formed. This kame drift at certain points lies upon a deposit of fine-grained, stratified sand which in turn rests upon the eroded surface of a slightly stratified, blue clay containing a few pebbles of angular form (Fig. 63).

This clay closely resembles that which apparently underlies the whole island of Nantucket and it is in general character like that which is so well exposed in the western portion of the Chilmark or Weyquosque Cliffs, on the southern side of Martha's Vineyard. On No Man's Land, as at the other points above mentioned, this clay was evidently much eroded, as if by ice action, though possibly by water, before the sands were deposited, as is shown in the section. On top of the clay is a deposit of stratified sand of variable thickness; above that, a bed of true till capped by kame gravel.

We thus have evidence of at least five distinct conditions in these beds: First, the period of the lower or bowldery clays, which have the general aspect of a very clayey till; secondly, slightly stratified clays, which were probably deposited during a period in which the ice had retreated to some distance from this point; thirdly, the fine, stratified
sands, which probably represent the readvance of the ice; fourthly, the upper till, which represents the completion of the readvance; fifthly, the kame gravels of the surface, which were formed in the early stages of the last retreat.

It is evident that the shores of this island, except on the central part of its northern side, are rapidly wearing away. This is well shown by the fact that the cliffs of friable material are almost everywhere steep, and also by the fact that the turf overhangs the edge, often to the extent of a foot or more. It is in this connection a remarkable fact that the island is not prolonged under water by shoals; except on the northern and northeastern faces, we find from thirty to sixty feet of water within a mile of the shore. We cannot well believe that the tidal currents can scour the bottom to this depth, covered as it is with large boulders.

The central part of the northern shore of the island here, as is shown on the map, consists of a V-shaped sand spit which incloses a small pond. Such spits represent a tolerably balanced condition of the shore currents produced by the beating of the waves against the land. Between No Man's Land and Martha's Vineyard the water is shoal. The accumulation of boulders at Dove Rock and Old Man's Rocks seems to indicate that we have at those points the remains of morainal accumulations.

ECONOMIC RESOURCES OF MARTHA'S VINEYARD

The economic resources of Martha's Vineyard are limited to its soils and to the clays, sands, and other products already described, which may be had from the deposits of Tertiary age.

The soils of the island are divisible into three groups: those formed of the terrace deposits, those which lie on the moraines that occupy the northern part of the island, and those which lie on the Tertiary beds that occur in the western part of the island, which, though in part morainal in their nature, are somewhat mixed with the subjacent Tertiary deposits.

The soils of the terrace deposits occupy in the main the district extending from the valley of Tisbury Brook eastward to and including Chappaquiddick Island; they extend also as a narrow fringe along the southern shore to the west of Tisbury Brook up to the eastern end of Nasketucket Cliffs. But in this limited part of the island the terrace deposits have been enriched by a share of the clay derived from the Tertiary series. A slight enrichment has also taken place from the same source in the region about Edgartown village. Elsewhere these terrace soils are composed in the main of siliceous sand, there being very little clay in their composition. The result is that the rain penetrates quickly through the superficial layer and so washes away a large part of the materials which have
been brought into solution by the action of vegetation. The same porosity tends to prevent these soils from retaining sufficient moisture to enable plants to meet the ordinary droughts of the summer season. The result is that these terraces and sandy kames afford soils which are in their natural state rather sterile, except perhaps in the extreme southern part of the island, where, owing to the distance from the old ice front, the sand is of a finer texture and contains a small portion of clay. In time, when the demand for land becomes much greater than it is at present, these soils may have a value sufficient to warrant their improvement by the addition of clay and the marls which abound on the western part of the island, but at present their best use is for timber culture. For this use they are in many respects well fitted. As soon as a forest bed is formed on soils of this nature its spongy quality serves to retain moisture and to prevent the excessive downward penetration of the rainfall and the soluble mineral elements. In plowing, this protecting covering is broken up and destroyed; hence very thin soils frequently do well in timber when they will make no return to tillage.

This generally un tillable area of Martha's Vineyard has an extent of about thirty-three thousand acres. At present about twenty-five thousand acres of this area is covered by low, scrubby woods, principally composed of varieties of small oaks; the remainder consists of abandoned fields which are slowly returning to the condition of forest. Frequent fires sweep over the district, destroying the parts of trees which are above ground, but not injuring the roots, from which a tangle of stems quickly springs up. Originally this region was heavily wooded, mainly with coniferous trees, the present prevalence of the deciduous species being due to the peculiar endurance of their roots in the fires, a capacity which does not exist in the conifers.

The greater part of this land is not at present valued at more than \$2 per acre and much of it could probably be bought for a less price. It is all near the sea, and therefore its timber product would be readily accessible to the market. The timber trees best suited to this soil have yet to be determined, but it seems to me from an inspection of the existing trees on the island that, in the several parts of this field, suitable localities can be found for larches, catalpas, ailantus, white ash, white oak, hickory, and black locust, all, excepting the white oak, trees of tolerably rapid growth and all of much commercial value. Some of the swampy districts of small total area would probably be found suited to the swamp cedar.

Another much more limited class of lands, now neglected, are the swamps of both salt and fresh water origin which exist on this island. The total area of these inundated lands does not exceed fifteen hundred acres and the separate patches are very small. The area of these swamps is less than the average on equally extensive surfaces of the Atlantic Coast line. Excepting an area of about three hundred acres
these swamps were originally of marine origin, though in many cases they have been changed to fresh-water swamps by the recent barring out of the sea from the bays in which they lie. The rapid growth of these barriers of sand, especially along the southern shore, has so far excluded the tide that the marine marshes have ceased to grow with their usual speed; at the same time these ponds are too frequently inundated by the sea to permit the growth of the fresh-water swamp plants.

Along the southern and eastern shores of Martha's Vineyard there are considerable areas of these swamp lands which are tolerably well fitted for improvement. It is doubtful, however, whether any of these semi-marine swamps will prove as suitable for agriculture as the salt-water marshes of the mainland, owing to the variable level and the saltiness of the water about them.

The fresh-water swamps of this island are very small in area and inconsiderable in number. They are essentially limited to the western end of the island, i.e., to the region which lies on the surface of the Tertiary deposits. The only considerable areas are those along the borders of Tisbury Brook. The other swamps of this nature lie in the depressions between the rolling hills of drift; a few hundred acres of fertile land may be won from them.

MINERAL RESOURCES OF MARTHA'S VINEYARD.

CLAYS.

The Tertiary beds of this island have a considerable economic interest for the reason that they contain a number of substances which are of use in the arts. First among these are the clays, which, with their connected sands, exist in great variety and in inexhaustible quantities. As is shown on the map accompanying this report (see Plate XX) these beds underlie the whole district from Tisbury Brook westward to the cliffs of Gay Head, except where the area is occupied by the lignite or the sand deposit. Probably more than one-half this area is underlaid by deposits of some economic value. Unfortunately the greater part of this area is covered by a thick covering of drift, which makes access to the clays, in an economic sense, impossible. Still, over an area of at least six square miles, they are sufficiently near the surface to be worked without excessive cost, and at Gay Head they are well exposed in the cliff. Thus, excluding the sands and lignites, we may reasonably reckon that these argillaceous deposits may be worked over an area of at least two thousand acres.

These clays are well adapted to a considerable range of pottery uses. They are now, with difficulty, mined from the Gay Head Cliffs. Ships anchor off that harborless shore at a distance of half a mile from the coast, and the material is then carried in small boats, at great expense of time and labor, and loaded into the vessels.
The fact that for many years this costly process of securing the clays has been continuously carried on is proof that it has been of considerable commercial value. A royalty is paid to the town of Gay Head for the privilege of mining these deposits. At present all the clay exported from this district is taken by Messrs. Fiske & Coleman, a firm of Boston potters. The following statements, which have been kindly made to me by Mr. Fiske, give all that I have been able to ascertain concerning the economic history of these beds:

The use of these clays began about twenty-five years ago, but, owing to the difficulties of shipment and the lack of demand, the industry was unprofitable. The first to be employed were the ligniticiferous layers, which were sent to Salem, Mass., for use in the manufacture of alum. The results were satisfactory so far as the quantity and nature of the product were concerned, but the European alum was cheaper than that made from materials transported at such cost as it was necessary to incur in taking the clays of Gay Head to Salem. The use of the pottery clays, which began about twenty years ago, was likewise unsuccessful, for the reason that it was carried on under the same difficulties as to shipment. The first systematic work in the development of these clays has been done by the above-named gentlemen. So far their work, though extended over some years, has been experimental, the largest amount of clay exported in any one year being about six hundred tons in 1885. Their experiments show that the red clays serve very well in making the finer sorts of terra-cotta ware. Certain of the white clays are fitted for the production of fire-brick, but not those of the best quality. The finer sorts of the white clay appear to be suitable for the commoner uses to which kaolin is put. So far they have only been used for tile work. It is probable, but not certain, that they would answer for making porcelain. A large number of borings have been made by Messrs. Fiske & Coleman in the towns of Chilmark and Tisbury. It appears from these trials that the clays, especially those of a white color, are of rather better quality in that part of the island which lies directly east of Menemsha Pond than in the Gay Head Peninsula. The work of exploiting the clays of Gay Head is rendered difficult by the constant slipping of the cliffs, which, though naturally slow, becomes rapid when any excavations are made at their base. This slipping tends to commingling the several strata, thus making it impossible to keep the product of the requisite purity. It is therefore important to develop the clay beds in the region away from the seashore.

So far only the argillaceous materials of this series of beds have been commercially used. It is likely, however, that there are several other substances contained in these beds which will have a considerable value in the arts. The sands of the Tertiary series are remarkably pure. Some of the beds can probably be used for glass making; other beds appear to be well suited for making certain varieties of
fire-brick. A portion of the sands where the quantity of feldspar is considerable may possibly serve as a source of kaolin for use in making porcelain, the coarse-grained silica being removed by washing.

LIGNITES.

The lignites which abound in this series, and which in the aggregate have a thickness of several hundred feet, are very impure, as is the case with all such deposits as are composed of driftwood accumulated at the mouth of a river. It is therefore not probable that they can ever be used for purposes of fuel unless for some manufacturing process carried on upon the ground. Some of these beds, however, contain nodular iron pyrites which in certain parts of particular beds probably amount to as much as 10 per cent. of the weight of the mass. It may be that this pyrite can be extracted by washing at a cost which would make its production profitable. The cost of excavating the soft lignite will be small, at least so long as the work is done in open cuts, or it could be effected by steam shovels.

These lignites and their associated clays contain a large proportion of alum, which could readily be extracted by a leaching process. The quantity of alum in the superficial parts of these deposits appears to be so large as to deserve commercial inquiry. Whether this proportion of alum will be found in the beds where they are under cover and also whether the salt is too much contaminated with iron to be useful in the arts are questions which can only be decided by actual trial.

PHOSPHATES.

From the commercial point of view the most interesting portion of these Tertiary beds is found in certain strata which may be valuable for agricultural fertilizers. There are several layers in the Gay Head section which may be valuable for this purpose. Of these the most important are the several beds indicated in the general section (see Pl. XXVI) which contain bones, principally those of whales. These fragments of bones are generally so admixed with quartz pebbles that I doubt if they are likely to have any economic value.

One of the most promising portions of this section lies at the northern end of that part of the Gay Head escarpment which faces about west. It is about one hundred feet in thickness and consists of dark greenish-gray sands and clay, which in part are somewhat oolitic in structure. These beds contain a considerable quantity of cetacean bones. They also contain a certain amount of phosphatic nodules which vary in size from a tenth of an inch in diameter up to five or six inches. An analysis of these nodules will be found in the subjoined tables of analyses. Both the nodules and the fragments of bone, as remarked by Dr. Hitchcock, have probably been derived from pre-existing strata, the débris of which makes up this part of the section. At some points in this bed the quantity of phosphatic nodules and fos-
sil bones seems to me sufficiently great to make the deposit worth examining with a view of determining if it has commercial value. The analyses of certain of the clay beds, as shown in the tables, appear to indicate that certain of the clays may have a value for fertilizing purposes.

IRON ORES.

The late Professor Hitchcock, in his report on the geology of Massachusetts, has noted the occurrence of iron ores in and upon these Tertiary rocks. These ores appear in the form of bog ores, which have recently been deposited in the existing swamps, and also in the form of thin, irregular beds of limonite in the Tertiary series. After a careful inspection of these deposits I am satisfied that they are not likely to prove of any commercial value.

On the sea beaches of this island we find the sand more or less mingled with magnetic-iron oxide. Although a test by the magnet reveals the presence of this material in all the beach sands, it is only beneath the cliffs which are rapidly wearing away that it exists in considerable quantity. On the beach below Nashaquitsa Cliffs and on that which extends from the village of Vineyard Haven to the West Chop light-house these magnetic sands are more abundant than elsewhere. On either of these beaches it would be easy to gather many thousand tons of sand which would be found to contain from 10 to 20 per cent. of magnetite. It seems to me probable that these deposits may prove of economic importance. As appears from the analysis (see table of analyses, next page) the magnet effects a perfect separation of the iron from the sand in which it is contained. This magnetite contains a certain portion of titanium and is therefore to be classed as an ilmenite.

Examination has shown that the magnetite exists as disseminated grains in the glacial deposits of this island and that, the lighter sands being washed away, it remains in a concentrated form at the foot of the ocean cliffs.

MINERAL WATERS.

The only remaining mineral resource of the island, one which has remained as unnoticed as the fertilizing deposits before referred to, is the mineral waters derived from the Tertiary beds. So far I have been able to observe these waters only on the escarpment of Gay Head, where they appear as small and uncared-for springs.

Some of these waters contain considerable quantities of iron; others are charged with alum; others are weakly charged with sulphured hydrogen.

As this is the only part of our northern seacoast where, so far as my information extends, mineral waters are found in any variety, they may have some value commercially because of their therapeutic qualities. It is not probable that the sulphurous waters can be found in sufficient quantities or sufficiently charged with the gas to make...
them useful, but the chalybeate waters and those containing alum
can readily be secured by ordinary wells in many parts of the area
which is underlaid by the Tertiary beds. At Gay Head the quantity
of these waters which could readily be gathered by a little care of
the existing springs amounts to several thousand gallons per diem.
Ordinary wells sunk in the earth at the base of the cliffs would sup­
ply any amount likely to be required for medicinal purposes or for
baths.

For the proper development of the resources of the Tertiary dis­
trict of Gay Head it will be necessary to have a harbor at this end of
the island. Apparently the most satisfactory way of securing such
a port, and probably the cheapest as well, would be by means of a
dredged channel giving access to Menemsha Pond. This channel
would require two short jetties for its protection at its seaward end.
Access to such a harbor would possibly be of value to the coasting
vessels as well as to the mining interests of the island. The local
interests would be well served by a smaller one formed by a break­
water projecting from the shore at Menemsha Bight.

**ANALYSES.**

*Analyses of clays and sands from various parts of Vineyard and Weyquosque series.*

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Loss on ignition</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>CaO</th>
<th>MgO</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>SO₃</th>
<th>P₂O₅</th>
<th>Total</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red clay, southernmost end of Gay Head</td>
<td>9.88</td>
<td>57.50</td>
<td>31.21</td>
<td>0.19</td>
<td>0.20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>99.33</td>
<td>Alkalis, 40%</td>
</tr>
<tr>
<td>White, sandy clay, south end of Gay Head</td>
<td>10.76</td>
<td>56.10</td>
<td>30.60</td>
<td>None</td>
<td></td>
<td></td>
<td>Trace</td>
<td></td>
<td></td>
<td></td>
<td>100.06</td>
<td></td>
</tr>
<tr>
<td>Fine, white clay, south end of Gay Head</td>
<td>6.30</td>
<td>73.40</td>
<td>19.60</td>
<td>Trace</td>
<td>0.70</td>
<td>0.70</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100.31</td>
<td>Frits slightly on ignition</td>
</tr>
<tr>
<td>Average sample white clay, north end of Gay Head</td>
<td>11.47</td>
<td>49.10</td>
<td>39.77</td>
<td>Trace</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100.43</td>
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</tr>
<tr>
<td>Average sample white clay, east end of Chilmark Cliffs</td>
<td>3.47</td>
<td>39.30</td>
<td>18.45</td>
<td>Trace</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>99.87</td>
<td></td>
</tr>
<tr>
<td>Average sample pyrite clay, west end of Chilmark Cliffs</td>
<td>47.76</td>
<td>30.50</td>
<td>None</td>
<td>0.00</td>
<td>1.17</td>
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<td>Trace</td>
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<td></td>
<td></td>
<td>Fe₂O₃ 7.57; SO₃ 0.43</td>
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<tr>
<td>Clay, east end of Weyquosque Cliffs</td>
<td>3.38</td>
<td>70.80</td>
<td>30.67</td>
<td>Trace</td>
<td>1.98</td>
<td>1.23</td>
<td>1.67</td>
<td></td>
<td></td>
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<td>Clay, middle of Weyquosque Cliffs</td>
<td>5.70</td>
<td>61.70</td>
<td>35.35</td>
<td>0.01</td>
<td>1.05</td>
<td>1.83</td>
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<td>100.17</td>
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<tr>
<td>White sand, Gay Head</td>
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<td>1.09</td>
<td></td>
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<td>MgO and H₂O undetermined</td>
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<td>Pyritiferous clay, central part of Gay Head section</td>
<td>5.49</td>
<td>72.74</td>
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<td></td>
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<td>Brown clay, south of Gay Head light-house</td>
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<td>1.97</td>
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<td>2.78</td>
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<td>None 100.56</td>
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GEOLOGY OF MARTHA'S VINEYARD.

Analyses of material resembling greensand from northern end of Gay Head section.

[The two samples are from the same locality and both are intended for averages of the beds.]

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<th>No. 2</th>
</tr>
</thead>
<tbody>
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<td>Phosphoric acid, $P_2O_5$</td>
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<td>0.45</td>
</tr>
<tr>
<td>Carbonic acid, $CO_2$</td>
<td>0.4</td>
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<td>Lime, $CaO$</td>
<td>0.62</td>
<td>1.49</td>
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<tr>
<td>Soda, $Na_2O$</td>
<td>0.33</td>
<td>0.38</td>
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<tr>
<td>Potash, $K_2O$</td>
<td>4.16</td>
<td>3.67</td>
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Analyses of average samples of fossil bones (cetacean) and phosphatic nodules from the above-mentioned greensand.

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<th>Nodules</th>
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<td>Phosphoric acid, $P_2O_5$</td>
<td>27.80</td>
<td>28.88</td>
</tr>
<tr>
<td>Carbonic acid, $CO_2$</td>
<td>3.28</td>
<td>2.00</td>
</tr>
<tr>
<td>Lime, $CaO$</td>
<td>25.21</td>
<td>25.73</td>
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<tr>
<td>Potash, $K_2O$</td>
<td>0.97</td>
<td>0.15</td>
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<tr>
<td>Soda, $Na_2O$</td>
<td>0.56</td>
<td>17.82</td>
</tr>
<tr>
<td>Silica, $SiO_2$</td>
<td></td>
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</tr>
</tbody>
</table>

Analysis of magnetite separated by the magnet from sand of Chilmark beach (material dried at 104°).

Per cent.
- Iron (Fe) ........... 69.87
- Titanium (TiO$_2$) ... 3.64

All the above-named analyses were made in the laboratory of the U.S. Geological Survey and reported to me by F. W. Clarke, chief chemist. Though incomplete, they are in the form requested. It did not seem to me necessary for the end in view to have ultimate analyses of any of these materials.
APPENDIX.

Since the foregoing paper was written I have received the following report of the results of Professor Whiting's successive surveys in Martha's Vineyard. As his statements are of much geological interest it seems well to give them in the form of an appendix.

U. S. COAST AND GEODETIC SURVEY OFFICE, Washington, September 15, 1886.

MY DEAR SIR: By permission of the Superintendent I am glad to give such statements of the results of my late resurveys on Martha's Vineyard as I am able to make at this time. I hope they may contain some of the facts and data you desire in regard to the changes which have occurred.

My first mapping of the topography of the island was in the latter part of the summer of 1845 and the first part of 1846. Later, in 1846, I made the survey of Nantucket. In 1856, ten years subsequent, I made a resurvey of the then new opening from the south into Cotany Bay, and in 1871 a second resurvey, showing the closing, much to the eastward of its original position, of the inlet of 1856. My present or last resurvey shows the second new opening into Cotany Bay of January, 1886, nearly in the site of the artificial cut attempted by General G. K. Warren in 1871.

The changes which have occurred during forty years along the south shore of the island give an interesting illustration of the movement which you yourself have termed a "rolling beach" and of the power of the sea-dash upon a sandy shore to drive this material before it. The geographical position of this beach, so far beyond the trend of the main land and its straight alignment, presents an unobstructed front to the wave action, and, although in occasional storms the breakers come upon the shore in oblique directions, the prevailing action of the sea-dash is normal to it. Even in gales from the southeast and southwest, after the force of the wind has subsided the breakers roll in more directly from the south.

Where the beaches have been low, particularly in front of the several ponds, the overshot (so to speak) of the sands has made a greater encroachment upon the waters of the ponds and the marshes inside of the beach than the sea-dash has effected in the outer shore line opposite. The general recession of the shore along the central part of the main island I should estimate at about one hundred and seventy-five to two hundred feet. At the crest of the summit of the bluff at Nushaquitoes Cliff, which is about one hundred and fifty feet high, the maximum waste is about two hundred and twenty feet. Opposite Chilmark Pond the maximum waste is about one hundred and eighty feet, and the overshot of the sands into the former waters of the pond, near the present opening, is about five hundred and twenty-five feet. At Great Tisbury Pond the outside wastes east and west of the present opening are, respectively, about one hundred and eighty and one hundred and forty feet, while the corresponding encroachments inside are, respectively, about six hundred and eighty and four hundred and eighty feet. Quite a peculiar coincidence occurs in the present position of the opening into Great Tisbury Pond with that of

1 The present inlet is a little farther inland, corresponding to the recession of the shore.
1846, which is also about the same width, while in the intervening time, about twenty-five years, an inlet has been opened and closed about three-fourths of a mile farther eastward. Most of the inlets of the south ponds, as you are probably aware, are opened artificially for the purpose of improving the fisheries and to prevent the overflow of the marshes by the fresh waters of the ponds. When once opened the width and depth of the inlets are established and maintained by the equilibrium of forces of tidal scour and sea-dash. They sometimes remain open for several months and again are closed by the first heavy storm. The most considerable movement of the entire beach occurs along the front of Great Herring Pond, in Edgartown, where the whole mass of the beach has been driven in upon the former waters of the pond a distance about equal to twice the width of the beach, the general recession being about four hundred and eighty feet.

The effect of the over-shot of sands referred to has changed, to some extent, the pond features of the shore. The group of smaller ponds between Mattakeset Bay and Great Herring Pond has been entirely obliterated and the south westerly cove of Job's Neck Pond converted into a separate pond. These changes confirm, in a degree, the tradition of the continuous pond or sound along the south face of the island and that the present series of ponds are but the inner coves or arms of this larger sheet of water.

The new opening through Cotamy beach (so called) occurred on the night of January 9-10, 1886. After a gale from the ENE. the wind shifted to WSW., still blowing a gale. The "west beach," as the portion west of the new inlet is now called, was quite low before this gale occurred, and after the shift of wind the whole beach, in longshore phrase, was a "breaker." A very high tide, one of the highest in this locality since the Minot gale, accompanied this storm. The general opinion is that at the time of the high tide of the bay the opening was first made by the outgoing or southerly current. As soon as the beach could be visited for observation the opening was already, by estimate, about one hundred yards in width.

Contrary to the usual action of the inlets or openings on the south side of Martha's Vineyard, and particularly those through Cotamy beach, the resultants of the moving sands which form the "chops" of the new inlet have been to the west. This, however, will probably prove to be but a temporary movement and eventually the opening, as all previous ones have done, will work eastward. The present condition of the beach, however, may retard this action from the fact of the comparatively small amount of material in that part of it west of the new opening, where the beach is unusually low. One of the forces which cause an easterly movement of the opening is the encroachment of the west chop upon the channel, and, by contracting it, causing a corresponding waste or cutting away of the East Chop. Formerly the higher sand hills of the beach supplied material for this encroachment. The high sand bank which existed near the outer shore line in 1871 was probably one of the causes, if not the main one, which filled up the cut made by General Warren.

A feature of interest, physically, and as a means of shelter for this exposed fishing ground, is the increase in size and elevation above high water of Skiff's Island. For the last twenty years this has been little more than a shoal, dry at high tide. By my survey of August 15 last this island now lies about southeast from the southeast point of Chappaquiddick (Wasque Point) and distant from shore to shore about one and one-eighth miles. At the date named it was about twelve hundred feet long, north and south, with a greatest width of about two hundred and ninety feet, and contained about four and a half acres. Probably for the first time in the last fifty years beach weeds and grasses have taken root and are growing upon it. It is, of course, a matter of speculation, without hydrographic data, as to whether or not the increase of Skiff's Island is due to the influence of the currents and counter-currents caused by the new opening. As the island is more
directly under the influence of the greater volumes of water passing through Muskeget channel, the new opening would seem but a small factor in the problem.

There is quite a remarkable coincidence in the geographical position of the present opening into Cotamy Bay with that of 1856, the present opening being about one-half its width east of the site of the former one. The width and depth of the respective inlets are quite similar. The width from chop to chop of the present inlet on July 1 was about twelve hundred feet.

The various surveys of the beach between the new inlet and Wasque Point show some peculiar local changes. The original upland of the south face of Chappaquiddick has been considerably abraded. The maximum waste at two points is, respectively, about five hundred and eighty and five hundred and fifty feet. On the other hand, the long tongue of beach that formed the outside of the channel that ran along this face of the island from the southeast corner of Cotamy Bay to Wasque Point, and closed there in 1871, still remains in part as an outside beach formation beyond the fast land of the island. The extension of this beach (at the point first named, where the waste of the original fast land is 580 feet) is about six hundred and twenty feet, so that there is now a beach formation about twelve hundred feet beyond the outside line of fast land. At the second point named, where the waste of original fast land is 550 feet, the present beach formation coincides with the original shore line, or is only about twenty feet beyond it. Again, about a quarter of a mile eastward the present outline of the beach is about six hundred feet beyond the original shore line of 1846. At the apex of Wasque Point the present shore line of the beach is about two hundred and seventy-five feet beyond the former shore line. This advancement of the beach along the east face of Chappaquiddick gradually decreases until, at about half a mile north of Wasque Point, the present and former (1846) shore lines nearly coincide. This coincidence of shore line continues along the whole extent of the east side of the island, showing that there has not been much action of abrasion along the pathway of Muskeget Channel. At Cape Poge, however, the waste has been considerable, owing to the salient position of the apex of the cape. The light material of the bluff, of about twenty feet in height, has given way before both northeast and southeast storms. The waste at the point of the cape is about four hundred and twenty feet. The crest of the summit of the bluff opposite the light-house is now within about forty-five feet of its foundation and is rapidly wearing away.

Along the north side of Chappaquiddick, from Cape Poge to the point opposite the village of Edgartown, the changes in the shore line have not been so great nor has the exposure been of the same character as that on the outer faces of the island.

Very truly yours,

HENRY L. WHITING.

Prof. N. S. SHALER,
ON THE CLASSIFICATION

OF THE

EARLY CAMBRIAN AND PRE-CAMBRIAN FORMATIONS.

A BRIEF DISCUSSION OF PRINCIPLES, ILLUSTRATED BY EXAMPLES
DRAWN MAINLY FROM THE LAKE SUPERIOR REGION.

BY

R. D. IRVING.
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THE PROBLEM STATED.

The following paper owes its existence to the necessity felt by the writer of having clearly defined principles upon which to proceed in revising the various classifications that have been proposed for the ancient formations of the Lake Superior region or in substituting for them some entirely new arrangement. Beyond many of the facts cited in illustration and the mode of presentation, the paper does not contain very much that is new or original; nevertheless, that a necessity exists beyond that of the writer for a clear apprehension of the principles here set forth will become evident to any one who studies carefully many of the more recent publications upon the early Cambrian and so-called Archaean formations.

The problem proposed for discussion is this: Having established in a given region occupied by the oldest non-fossiliferous and meagerly fossiliferous formations the general order of succession: (1) to determine upon the grander divisions (groups) to be made in classifying the rocks independently of their relations to the general geological column; (2) to extend these divisions to other portions of the same geological basin; and (3) to correlate these divisions with those of different and distant geological regions. This is the problem which presents itself in the Lake Superior region, at the base of the Grand Cañon of the Colorado, in central Texas, in Newfoundland, and in other portions of North America.

In any attempt to solve such a problem we can make use of one or more of three kinds of characteristics in the formations involved, viz, (1) their paleontological characteristics, (2) their lithological characteristics, and (3) their mutual structural relations. The considerations that follow are classified under these three heads, under each of which the discussion is further arranged with reference to the three divisions of the problem indicated in the preceding paragraph.
The general principles of homotaxis and of the use of fossils in classifying formations are not here under discussion. It is proposed rather, supposing a region with the general conditions above stated, to consider how such fossils as are found may be used in marking off from one another the grander groups of strata, how far they may be used in recognizing these groups at other points in the same geological basin, and how far they may be used in correlating these groups with those of the general geological column.

The use of fossils in determining the grander groups of strata.—
The object being particularly to avoid extending conclusions to an unwarrantable extent, the discussion is mainly taken up with precautionary considerations. The general order of life succession in geological time appears to have been sufficiently well established to allow the use of the differences between well developed and varied faunas in marking off the grander divisions of strata and the use of their similarities in grouping together strata for whose separation there might otherwise be an apparently sufficient reason. But when we have at our service but fragmentary faunas or single fossils we need to be very cautious indeed in drawing our conclusions. We have now constantly to remember that paleontology is based wholly upon stratigraphy, and consequently that the conclusions that we would draw from our fossils must constantly be checked by stratigraphical observations. We must equally remember the well established principles that fossil kinds vary at the same stratigraphical horizon with variations in the kind of rock and that the same fossil may return with rock of a similar character at horizons vertically far apart. But, most of all, we need to bear in mind the negative character of the evidence upon which the range of a given fossil is determined. Past experience in the discovery of fossils far above or below, or both above and below, the limits of the range laid down for them in the text-books should be sufficient to caution us against drawing too confident conclusions from meager fossil evidence, particularly with fossils which, while of relatively limited range as to certain specific characters, are yet so closely allied to other kinds as to form with them a general type prevailing throughout a great series of formations. Moreover, with the earliest fossiliferous formations, more than with any of those of later times, do we need to be cautious in generalizing on insufficient paleontological data. These formations are not only meagerly fossiliferous, but such fossils as they carry are very generally of types which have a wide range upward through the geological column. An equally wide range for them downward, among those formations which have not yet yielded fossils or which are yet to be met with in unexplored portions of the world, may reasonably be inferred. It
has been the history of progress in paleontological geology that the advance of discovery has been downward. It is but a short time since the so-called Cambrian formations were thought to be unfossiliferous. Below these, in various other portions of the world, are other formations in which no fossils, or only bare traces of fossils, have as yet been discovered, but which have about them no characters which would exclude the possibility of such a discovery in the future.

An illustration drawn from the region with which the writer is more particularly familiar may serve to give the foregoing considerations a more definite meaning. The lowest well defined fossiliferous horizon in the northwestern States of Michigan, Wisconsin, and Minnesota is the Cambrian sandstone, regarded by the best authorities as the equivalent of the Potsdam horizon of the New York reports. Unconformably placed below this sandstone is a succession of three great groups of formations of enormous volume, each separated from its predecessor by a great unconformity. The lowest one of these three groups is a gneissic and generally a highly altered one. The other two, however, have nothing about them to exclude the possibility of the future discovery in them of fossils. In the upper one of these groups, two obscure and indefinite markings have indeed been discovered, but as yet nothing more. In a remote corner of the region in question, however, is a quartzite formation which is also manifestly unconformably placed beneath the fossiliferous Potsdam horizon and equally unconformably above the lower gneissic series. It thus falls somewhere in the interval occupied by the two groups above spoken of as lying next beneath the Potsdam horizon; but its connection with either of these groups is concealed for many miles by overlying terranes. In this quartzite series have been found impressions of a linguloid fossil and a single fragmentary specimen of very questionable organic origin, which has been doubtfully referred to the genus Paradoxides. Upon this evidence has been based the conclusion that the formation holding these fossils, while lower than the fossiliferous Potsdam sandstone, should yet be thrown into the same grand division with it, and that all of the upper (Keweenaw series) and much, if not all, of the lower (Huronian or iron-bearing series) of the two groups (which, as above stated, in other portions of the northwest intervene between the Potsdam sandstone and the gneissic series) should be thrown into the same group.

The argument in favor of these conclusions appears to be about as follows: In other portions of the world the fossil-bearing strata beneath the Potsdam horizon are classed with that horizon as Cam-
brian, being conformably placed beneath it and having, in general, fossils of the same types. Here are two fossils of types found in the infra-Potsdam fossiliferous rocks of other regions; therefore this formation also should be classed with the Potsdam in one group as Cambrian. The objections to be made to this argument are (1) that, of the few fossils concerned, the linguloid kinds are of so great a known range upward that an equally great range for them downward may reasonably be inferred; (2) that the vertical range of the doubtful Paradoxides is determined by negative evidence only; (3) that, nothing whatever being known of the Pre-Cambrian life beyond the necessary conclusion that such life must have existed, there is no inherent improbability that it included linguloid and trilobitic kinds not greatly dissimilar to those of the true Cambrian; and finally (4) the conclusions are objected to because such weak paleontological evidence is allowed to overcome the counter-evidence of at least one and probably two unconformities indicative of great time gaps. The general significance of unconformities and their value in determining the limits between grand geological groups is further discussed below.

The use of fossils in establishing correlations within one geological basin.—The succession of strata having been determined for one portion of a given geological basin, i.e., of an area within which the various formations are or once were essentially continuous, the faunas respectively characteristic of the several strata are, of course, of the greatest value in establishing the grander correlations with the stratal successions in other portions of the same basin, provided, however, that the faunas are fully developed, each including a number of well characterized forms. Even in such a case, however, paleontologists are often prone to push their conclusions too far in establishing correlations in more minute detail, losing sight of the negative nature of the evidence on which the ranges of the several fossils are based, and more particularly of the influence upon the occurrence of fossil forms of slight changes in the nature of the rock. All later investigations teach us to beware of such minute correlations, even within short distances, the fossils characterizing a certain horizon disappearing above it to return again with a return of like mineral conditions, which are themselves indicative of the return of geographical conditions favorable to that particular life development. Much is said of the worthlessness of lithological evidence in establishing correlations and in tracing formations, but, except in the case of the grander correlations, and particularly for places distantly removed from one another, it is much of the same nature and value as paleontological evidence. In using either to trace formations from place to place we must constantly check by stratigraphy. It is, indeed, an exceptional region where layers of rocks can be seen in continuous exposure. Their continuity is es-
established by the discovery of similar successions of strata having similar lithological characters at numbers of points all through the distance through which it is desired to establish the continuity. Fossils may occur to confirm greatly the conclusions reached without them, but alone they are of no more value in tracing continuities of the minor subdivisions than is the lithological evidence. Both the lithological characters and the fossils of a stratum may change somewhat as we trace the layer from point to point.

The use of fossils in establishing general correlations.—But, if palaeontological evidence needs to be used cautiously when we have at command fully developed faunas, how much more cautious do we need to be when any or most of our formations are barren in fossils or contain at best a few obscure forms of doubtful range. Again, if limited fossil evidence is to be used with such caution in differentiating the grander rock groups of a region and in correlating the stratal successions of different parts of one geological basin with one another, how much more must we be careful in applying such meager evidence to the grander correlations of the ancient formations of one region with those of another and distant region and with the generally recognized great groups of the geological column.

The necessity for this caution and the nature of the questions that arise will be best understood if I take as illustrations the case of the region above cited and the very similar case of the formations met with in the bottom of the Grand Cañon of the Colorado. In each of these cases we have the Upper Cambrian clearly defined by its characteristic assemblage of fossils. In each region there intervene between this Upper Cambrian horizon and the basement gneiss two great groups of strata, which are divided from the Upper Cambrian above and from the gneiss below by great unconformities, and are, moreover, separated from each other by an equally great discordance. In each region, again, while mainly unfossiliferous, those intervening strata have afforded very scant traces of life. In the case of the Grand Cañon, these traces, in the shape of a few obscure and ill defined linguloid brachiopods, occur in the group next beneath the unconformity below the Potsdam or Upper Cambrian horizon. In the case of the region of the Northwestern States, the fossils found are the linguloid forms and the more than doubtful Paradoxides above mentioned, which are met with at a single locality in a formation that certainly lies in the interval between the Potsdam horizon and the gneiss, but is less certainly referred to the lower one of the two formations belonging in this interval—a doubt arising from the isolated position of the formation in question.

Now, in other portions of the world—for instance, in New Brunswick and Newfoundland, in North America, and in Wales and Bohemia, in Europe—are found, conformably placed beneath the Upper Cambrian horizon, great thicknesses of strata, each with a well devel-
oped and characteristic fauna of its own, constituting the Middle Cambrian and Lower Cambrian faunas. Are we to conclude, then, from the few fossils met with in them, that the Pre-Potsdam formations of the Northwestern States and of the Colorado Cañon are necessarily wholly or in part geological equivalents of the formations which in other parts of the world carry these faunas? Such a conclusion appears, to me at least, quite an unwarranted one. As stated above, the few fossils found, while such as might occur in a Lower Cambrian fauna, are yet kinds belonging to types of so great a known vertical range as to suggest their probable occurrence at much lower horizons than those of the Lower Cambrian. That a Pre-Cambrian fauna existed goes without saying; while the probability that this fauna had affinities with that of the Cambrian itself is certainly suggested by the analogy of all the later formations. Moreover, should we accept such a correlation, we are compelled to belittle a great time gap indicated in both these regions by the unconformity below the Potsdam horizon. Such unconformities as this, as is urged more fully below, must indicate long continued and geographically widely extended orographic movements followed by periods of denudation of immense duration. They cannot be dismissed as merely local phenomena.

Should we decide, however, that in these lower, unconformable formations we have to do with rocks older than those which elsewhere carry the primordial fauna, we are immediately confronted with the question as to whether they too, because of the few fossils they carry, should still be classed as Cambrian. This is merely a special phase of a much broader and, as yet, undecided question in geological taxonomy. As the geological column now stands, the grand divisions of Cambrian and Archaean are next to each other. Above the uppermost Archaean, however, and below the lowest of the Cambrian fossil horizons, we have in various portions of the world formations whose characters are in no way such as to preclude the possibility of the discovery in them of fossil remains. Moreover, a belief in the existence of life during the times when these formations were accumulated being apparently a theoretically necessary one, the history of the advance of paleontology would certainly lead us to look for such discoveries. Discoveries of such a character have, indeed, been made already; for, not to speak of the fossil finds in the Grand Cañon group of the Grand Cañon and in the quartzites of southwestern Minnesota—which formations, from my point of view, both belong beneath the formations holding the Lower Cambrian fauna—we may cite the case of the occurrence of fossil markings in that great formation of Newfoundland which has been called Huronian by the late Mr. Alexander Murray. Above these fossiliferous Huronian rocks and separated from them by an immense unconformity, the reports of Mr. Murray inform us that there comes,
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not merely the Upper Cambrian horizon, as in the case of the Colorado Cañon and of the Lake Superior region, but an enormous thickness of strata with the Lower Cambrian fauna. The question then is this: As we reach deeper and deeper into these formations are we to keep extending the term Cambrian downward with these discoveries, leaving as Archaean only those formations which are as yet not proved to hold fossils? The question thus stated leads us in turn to a yet broader one, viz, as to the relations between the terms Paleozoic and Archaean. Answers to these questions, which are quite distinct from one another, are attempted in the latter part of this paper.

LITHOLOGICAL CHARACTERS AS A BASIS FOR CLASSIFICATION.

The use of lithology in marking off the grander groups of strata.—Setting aside those cases where rocks have been in one way or another deeply altered, variations in lithological characters among sedimentary strata are indicative of original differences in methods of deposition, while similarities of lithological characters indicate, in general, similarities in conditions of deposit. Similar rocks recur again and again at different points in the geological column and are indicative of the repeated return of similar depositional conditions. Such returns occur frequently within a single group of formations and are of value in establishing the minor subdivisions of the group, but, without other strong evidence, they are of but little more than confirmatory value in separating groups from one another. Looked at in a general way, juxtaposed groups of strata, it is true, often show strong contrasts in lithological characters. But, on the other hand, they may show very considerable similarities, while structural or paleontological evidence may demonstrate their complete separateness. As an instance of this may be cited the case of the Potsdam sandstone and the Keweenaw series of Lake Superior. The upper 15,000 feet of the Keweenaw series are composed of sandstones which in general aspect often simulate the members of the Potsdam itself, though closer inspection shows generally strong lithological differences. On account of this general similarity, however, these two sets of sandstones, demonstrated by their structural relations to belong to totally distinct systems of strata, were constantly connected in one group by the earlier writers on the Lake Superior region.

Nevertheless, contrasts in the lithological characters of two series of strata, when these contrasts are the result in any large measure of a deep-seated alteration of the lower one of the two series, may constitute evidence of a high degree of value as to their distinctness, although, even in this case, such evidence would be subordinate in value to the paleontological and structural data. As an illustration we may cite, in the first place, the case of lithological contrasts which obtain in the Lake Superior country between the ancient gneissic
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group and the iron-bearing or Huronian group. The term Huronian, as is shown subsequently, has no doubt been applied frequently to quite distinct formations, but is here restricted to that group which, on the north shore of Lake Huron, in the Marquette and Menominee regions of Michigan, in the Penokee country of Wisconsin, and in the region north of Lake Superior, sustains a plainly discordant relation to the more ancient Laurentian, or crystalline schist and gneiss series. The gneissic series is composed of granites, strongly crystalline gneisses, and schists which very rarely present unmistakable evidence of a sedimentary origin and which in all cases, whether originally of sedimentary, of eruptive, or of some wholly unknown origin, have been subjected to most profound changes. The Huronian, or iron-bearing series, on the other hand (not to speak now of those eruptives which it includes and which present us with no serious difficulties in their recognition as such), is plainly made up of fragmental rocks, usually differing but little from those of later geological groups, and of certain sediments of a chemical origin. In all of these the only changes that have taken place are clearly of a metasomatic character, and each altered rock, whether of mechanical or chemical sedimentary origin, can generally be traced back without difficulty to the unaltered form.

The use of lithological characters in establishing correlations between different portions of the same geological basin.—Lithological characters have their greatest value to the stratigraphical geologist in his attempts to establish such correlations as are indicated in the heading of this paragraph. After having defined the several rock groups from one part of a single geological basin—that is, a region throughout which the various rock groups are, or once were, essentially continuous—and having established the lithological characters of each group, the geologist, with the greatest confidence, makes use of these characters in tracing the several groups to other portions of the basin. He does not ordinarily go from one end of the region to the other before making comparisons, but, beginning with the portions best known, he traces mile by mile the several groups by means of their lithological characters and stratigraphic relations. It is customary to speak very contemptuously of lithological evidence, and there can be no question that it has been used as a foundation for conclusions which it certainly cannot support. But its value in tracing formations from point to point can hardly be overestimated, being as great as that of paleontological evidence and, in my judgment, of much the same nature. As we trace formations and their minor subdivisions from place to place we must of course constantly check lithological evidence by stratigraphy. As we pass from one extremity of the field to the other, changes in lithological characters of course come in, and these changes might lead to unsafe conclusions were we to compare stratal successions
too distantly removed from one another; but when we work from point to point such changes are detected as they gradually appear, and are provided for. Now, precisely the same statements can be made with regard to the use of fossils in tracing formations. Equally with the lithological characters do the paleontological characters of a formation change as it is traced from point to point. Indeed the changes are often more abrupt in the latter case.

The Lake Superior region furnishes some admirable instances of the value of lithological evidence, both in tracing the grander divisions of the strata and in establishing correlations between the minor subdivisions of the successions displayed in different portions of the region.

In the Penokee region of Wisconsin, as is set forth somewhat fully on a subsequent page, there is a succession of formations whose relations are quite unmistakable. Lowest in this succession is a great series composed of gneiss, granite, and green schists. Resting unconformably upon the deeply denuded surface of this series is the great iron-bearing group of strata, thirteen thousand feet and upwards in thickness, while upon the eroded surface of this group succeeds, in turn, the great Keweenaw group, with an aggregate thickness of 45,000 feet, through the lower 30,000 feet of which alternate eruptive and detrital layers, the uppermost 15,000 feet being wholly detrital. All of this succession of layers above the upper surface of the gneissic series presents us with a dip to the north, or in the direction of Lake Superior. Passing now to the northern side of the western part of Lake Superior we find again a similar succession, now with a southerly dip. A section along the line of the newly built Duluth and Iron Range Railroad from the Mesabé Range, 55 miles north of Lake Superior, to the shore of Lake Superior, would show to the north a formation of gneiss and granite, unconformably reposing upon which is an iron-bearing formation that, so far as it appears at the surface, is quite identical in character with that of the Penokee region, while above this again comes the great Keweenaw series, or rather its lower portion, for its uppermost portions are concealed beneath the waters of Lake Superior. That the several formations of this succession are identical with those of the Penokee region is so manifest from their lithological characters and structural relations alone that the abundance of other evidence that presents itself as to the actual continuity of the formations of the two districts is hardly necessary for a conclusion. Returning again to the south shore of Lake Superior and extending our investigations eastward from the Penokee region as far as the vicinity of Marquette and the Menominee River, we trace all the way from the former district the gneissic terrane and its unconformably overlying, iron-bearing series. But after leaving Lake Gogebic we find that the uppermost of these terranes, instead of being simply inclined
toward the north without folding, has been more or less deeply folded in with the basement or gneissic series in such a manner that, as a consequence of the profound denudation that has since ensued, it appears now at the surface in more or less regular belts or in quite irregular patches within the area of the older rocks. But the lithological evidence as to the continuity of each of the two series is indisputable. In a similar manner we might proceed from the Marquette region to the north shore of Lake Huron and thence again to the northern coast of Lake Superior, eastward from Thunder Bay, and show that in each of these regions there exists the same succession of gneissic formation, iron-bearing formation, and Keweenaw series, each bearing the same structural relations to the others as in the regions previously mentioned, the lithological characters of each demonstrating its identity with the corresponding member of the successions in other districts.

As an illustration of the value of lithological evidence in establishing the continuity of the minor subdivisions of a great group of strata we may cite the case of the Nonesuch shale and sandstone beds of the Keweenaw series, which beds are now known to be continuous from midway in the length of Keweenaw Point to Bad River in Wisconsin, a distance of over one hundred and fifty miles, following the course of the outcrop.\(^1\) This continuity is established beyond controversy—notwithstanding the fact that in this distance the layer goes through a singular convolution in the vicinity of the Porcupine Mountains and notwithstanding also the generally forest-clad character of the region—by the recurrence at a number of points between the two extremities of the belt mentioned of the same peculiar strata in a similar position with reference to the other layers of the series. Again, the comparison of the Penokee series with the iron-bearing formations of other districts of the Lake Superior region enables us to say that the iron-bearing horizon of the Penokee district is the equivalent of the iron-bearing horizon of the Anihek district on the north side of Lake Superior, and again of the iron-bearing horizons of the Marquette and Menominee regions, and that the great limestone and quartzite formation below the iron-bearing series in the Penokee region is the same that receives so great a development below the iron-bearing horizon of the Marquette and Menominee regions. While there are very numerous points in the stratigraphy of these several districts as to which sufficient data have not yet been accumulated to enable us to make satisfactory comparisons, it is confidently expected that it will not be long before such comparisons can be greatly extended.

The use of lithological characters in establishing correlations between the stratal groups of different geological basins.—Inasmuch as the lithological characters of rocks are independent, under any or-

dinary circumstances, of times of deposit, having resulted from the original conditions of deposit, similar conditions having produced similar rocks, and since the same conditions have recurred again and again in geological time, while dissimilar conditions, in different regions of deposit, must have coexisted at all periods as they now coexist, it is a well founded and generally accepted canon of the geological science of to-day that similarities in the geological formations or groups of different regions of rock growth are of no value as proofs of equivalency, at least so far as all of the fossiliferous formations are concerned. It is recognized, of course, that there are certain horizons in the geological column which are represented in portions of the world distant from one another by formations quite singularly like one another, as is the case, for instance, with the “New Red Sandstone” horizon. But such coincidences as these are regarded as accidental. It is also recognized that the more ancient of the fossiliferous groups present a more widespread uniformity in lithological characters than is found to be the case with the later groups; but this is generally taken as indicating merely the greater extent of the earlier geological basins, that is, of the individual regions of rock growth, the continental surfaces having been less thoroughly differentiated by the elevation of mountain barriers. Neither of these well recognized facts is taken as invalidating in any measure the general truth of this canon so far as the fossiliferous formations are concerned.

When we turn, however, to the writings of those who have concerned themselves with the Pre-Paleozoic formations we find this principle very generally ignored, while a few authors distinctly deny the validity of its application to those ancient formations.

The latter view is held by a small class only, but has able exponents both in this country and in Europe, the most thoroughly elaborated and advanced position being held by Dr. T. S. Hunt, in whose later writings there is maintained a division of the Pre-Paleozoic formations into the following groups given in ascending order, viz: (1) The ancient *Laurentian* granites and granitoid gneisses; (2) the *Norian* feebly silicated, plagioclastic rocks; (3) the *Arvonian* felsites, quartziferous porphyries, etc.; (4) the *Huronian* chloritic greenstones and chloritic schists; (5) the *Montalban* micaceous gneisses and mica schists; (6) the *Taconian* quartzites, limestones, and argillites; and (7) the *Keweenian* series of Lake Superior. With the exception of the last of these, which appears to be considered as Paleozoic, though placed in its true relation to the Cambrian, all of these groups are spoken of as composed of crystalline rocks. While some doubt appears to be expressed as to the exact relation of the Norian to the Laurentian and the Huronian series, the succession as given is taken as essentially true for the entire extent of the globe, each group being regarded as separated from its predecessor by an
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Intervening land surface period or period of disturbance. As to the origin of the rocks of these several crystalline rock formations, the opinion held by this school will be best expressed in Dr. Hunt's own words:

The crenitic hypothesis, which has been proposed in the second part of this essay to account for the origin of the granites and crystalline schists, conceives them to have been derived, directly or indirectly, by solution from a primary stratum of basic rock, the last congealed and superficial portion of the cooling globe, through the intervention of circulating subterranean waters, by which the mineral elements were brought to the surface. This view not only compares the generation of the constituent minerals of the primitive rocks with that of the minerals formed in the basic eruptive rocks of later times, but supposes these rocks to be extruded portions of the primary stratum which, though more or less modified by secular changes, still exhibited after eruption, though on a limited scale, the phenomena presented by that stratum in remoter ages (Proc. Trans. Royal Soc. Canada for 1884, vol. 2, "The origin of crystalline rocks," p. 36).

The crystalline stratiform rocks, as well as many erupted rocks, are supposed to have been derived by the action of waters from a primary superficial layer, regarded as the last portion of the globe solidified in cooling from a state of igneous fluidity. This, which we have described as a basic, quartzless rock, is conceived to have been fissured and rendered porous during crystallization and refrigeration, and thus rendered permeable to considerable depths to the waters subsequently precipitated upon it. Its surface being cooled by radiation, while its base reposed upon a heated solid interior, upward and downward currents would establish a system of aqueous circulation in the mass, to which its porous but unstratified condition would be very favorable. The materials which heated subterranean waters would bring to the surface, there to be deposited, would be not unlike those which have been removed, by infiltrating waters in various subsequent geological ages, from erupted masses of similar basic rock, which, we have reason to believe, are but displaced portions of this same primary layer. The mineral species removed from these latter rocks or segregated in their cavities are, as is well known, chiefly silica in the form of quartz, silicates of lime and alkalies, and certain double silicates of these bases with alumina, including zeolites and feldspars, besides oxides of iron and carbonate of lime, the latter species being due to the intervention of atmospheric carbonic acid. The absence from these minerals of any considerable proportion of iron-silicate, and, save in rare and exceptional conditions, of magnesia, is a significant fact in the history of the secretions from basic rocks, the transformation of which under the action of permeating waters has resulted in the conversion of the material into quartz and various silicates of alumina, lime, and alkalies, while leaving behind a more basic and insoluble residue abounding in silicated compounds of magnesia and iron-oxide with alumina (ibid., pp. 58 and 59).

We have already elsewhere in this essay referred to the local development of crystalline silicates in sedimentary rocks by infiltration, and have, in another place, considered the relation of such a process to the question of the origin of primitive crystalline rocks. These we believe to have been formed anterior to the existence of detrital sediments, and by a process which excludes all so-called metamorphic, metasomatic, and plutonic hypotheses of their origin. At the same time we reject the Weruerian or chaotic hypothesis, and its modification by De La Beche and Daubrée, which we have called thermochaotic, in favor of a new aqueous or neptunian hypothesis, which supposes the elements of these rocks to have been dissolved and brought to the surface from a disintegrated layer of igneous basic rock, the superficial and last-solidified portion of a cooling globe, through
the action of circulating waters. The soluble and insoluble products of the subaerial decay, alike of igneous and aqueous rocks, are, however, supposed to have intervened in the process, especially during the period of the later crystalline or transition rocks (ibid., "The Taconic question in geology," p. 149, § 194).

The hypothesis thus defined is essentially a chemical one, demanding a certain universal and invariable order in the production of the various members of the Pre-Paleozoic groups. It is not, of course, maintained that every member of the succession must invariably be present. As in the case of later formations, so here also, the intervention of elevatory movements producing land surfaces, which receive no depositions, has produced gaps in the series. The order, however, is invariable. The conclusion then is drawn that the mineralogical character of a group of Pre-Paleozoic strata is a sufficient guide for us in establishing its place in the series; granites and granitoid gneisses wherever found are Laurentian; rocks composed mainly of anorthic feldspar and an augitic mineral are Norian; micaceous gneisses and mica-schists are Montalban; chloritic schists and greenstones are Huronian; quartzites, argillites, etc. are Taconian. The necessary corollary to the hypothesis, and one whose existence is thoroughly realized and whose truth is vigorously maintained by the distinguished leader of this school, is the complete rejection of the view, still held strongly by a large and authoritative school of geologists, as to the Paleozoic or even later age of certain of the crystalline schists.

Not attempting now to discuss this hypothesis from a chemical point of view, nor indeed in its applications to regions with whose geology I am little familiar or familiar only by reading, I will content myself by testing its validity by an application to that region with which I have had an extended and long-standing acquaintance, namely, the region from Lake Huron to Minnesota. Being of universal application, if valid at all, the facts in this region should coincide with the provisions of the hypothesis, whose failure to stand a single test of this kind should be sufficient for its rejection. Dr. Hunt, having visited various points of the Lake Superior region and having examined large collections from other points, has himself identified certain formations of the region as belonging to different members of his invariable succession, so that I shall be, in some measure, free from the danger of erroneous identifications.

Granites and granitoid gneisses indeed form an integral part of the basement formation of the Lake Superior region. With these, however, are great areas of garnetiferous and staurolitiferous mica-schist, which form, beyond question, inseparable portions of the same terrane, but which should belong to Dr. Hunt’s Montalban group. Belts of such mica-schist are developed on an immense scale in the region of northern Minnesota, where are also great areas of granite, which, at their contacts with the mica-schist—contacts traceable for-
scores of miles—in invade these schists in the most intricate manner. Thus, granitic masses, which should belong to the Laurentian and on the crenitic hypothesis should be of aqueous origin, are found to be plainly eruptive and to intersect the Montalban schists. It should also be said that the gneisses of this ancient terrane appear to fall into two classes, one constituting a phase of the mica-schists and the other—granitoid gneisses—forming portions of the great granitic masses whose contacts with the mica-schists seem to demonstrate their more recent eruptive origin.

Equally forming an inseparable portion of the great basement terrane are areas and belts of greenish, chloritic schists. These are often closely associated with schistose greenstones, our microscopic studies having rendered evident, I think, the derivation of many of these magnesian, schistose rocks, by a process of metasomatosis accompanying and following intense lateral pressure, from augitic rocks analogous in all respects to the various augitic eruptives of later times, and particularly to the eruptives called gabbro and diabase. The relation of the greenish, chloritic schists to the mica-schists just mentioned is such as to render the later formation of the former probable; but there is a complete conformity between the two, while the great granite masses which send branches into the mica-schists present precisely the same relation to the chloritic schists, which at their contacts with the granite are often intricately intersected by granite veins. These green schists should be the Huronian of Dr. Hunt's succession. Indeed, they, with more or less of the mica-schists just mentioned, and with other later rocks, are what have been mapped as Huronian for the entire region north of Lake Superior by the Canadian Survey, whose more recent publications, however, assert with entire correctness the absence of any unconformity between them and the gneissic rocks called Laurentian. The name Huronian really belongs to an entirely different group, as is further noted below.

Similar greenish schists, similarly penetrated by granitic veins at their contacts with granitic masses, have a great development on the south side of Lake Superior, where, on account of the intricate foldings in certain portions of the region, they have been variously placed by different geologists. Some have divided them between the basement rocks and the iron-bearing group above them; by others they have been divided so as to come partly at the base and partly at the summit of the iron-bearing series; while others again have regarded all the greenish schists as forming the base of the iron series and the granites penetrating them as having been erupted at a period entirely subsequent to the deposition of the whole group of iron-bearing strata. But all, I think, as is more fully explained on a subsequent page, can be shown clearly to belong to the great basement series. Thus the large area of granite on the south or Wiscon-
sin side of the Menominee River, with which are associated hornblendic schists in such a manner as to render evident the later and eruptive origin of the granite, has been regarded by Brooks as the uppermost portion of the iron-bearing series, for the reason that the dip of the layers of that group farther north is slightly to the southward of vertical, or toward the granitic mass. But this granite and the hornblendic and micaceous schists associated with it are manifestly identical with the granite and schists on the opposite or northern side of the Menominee-Huronian trough, which have been counted by Credner, Brooks, and others as Laurentian. The inclination of the Huronian beds toward the southern granite is no argument in favor of its later date, being never more than a very few degrees beyond the vertical; while throughout the trough, as indicated in a section of the Menominee region given on a subsequent page, there is a tendency toward slightly overturned dips. Moreover the large exposure of greenish schists seen at the Upper and Lower Quinnesec Falls and at Sturgeon Falls of the Menominee River, which have been placed by Brooks and others in the Huronian, are quite plainly a portion of the older series, veins from the southern granite penetrating those schists also. The entire grouping of greenish, chloritic schists, greenstone-schists, hornblendic-schists, mica-schists, and granites, the last penetrating all of the schists, is, then, precisely what is met with repeatedly on the north side of Lake Superior, as already indicated, and is met with repeatedly also in other places on the south side of the lake, where entirely similar rocks with similar relations have been placed as Laurentian by the same writers who would regard these Menominee granites and schists as a portion of the iron-bearing series. As to the position of these Menominee rocks in his classification we have Dr. Hunt’s own determinations. The Quinnesec Falls and Sturgeon Falls green schists are his Huronian; the micaceous, hornblendic schists to the south of them, along with the granite which has such an immense development in that vicinity, are all Montalban.\(^1\) In point of fact, however, all the schists concerned are but portions of a single succession, while the granite is of distinctly eruptive origin and more recent than any of them, all forming an inseparable part of the basement series of the Lake Superior region.

This same basement formation, with similar characters, is brought to view on the north shore of Lake Huron, where its contact with the overlying original Huronian group of Logan and Murray is displayed. The latter series consist of a great succession of quartzite layers, including a subordinate quantity of graywackes, often conglomeratic, and a much smaller proportion of limestone and chert, along with which are numerous intersecting and interbedded eruptive greenstones. The series is folded, but not strongly, the bowings being often so gentle that great areas occur in which the rocks are but

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\(^1\) Second Geol. Survey Pennsylvania, E, Trap Dykes and Azoic Rocks, p. 224.
little removed from horizontality.\textsuperscript{1} The rocks of this series cannot be spoken of as deeply altered, their detrital origin being always manifest, except, of course, in the case of the limestones and cherts, which are of chemical origin, and the greenstones, which are eruptives. In large measure they differ but little in this respect from the rocks of some of the later and fossiliferous formations. Although this is the original and type Huronian series, the Huronian which does duty in Dr. Hunt’s classification has no existence within the area referred to, i.e., that shown on Logan’s beautiful detailed map of the north shore of Lake Huron.\textsuperscript{2} Were we to apply Hunt’s classification to this region we should have to regard the series here displayed as his Taconian.

As I have elsewhere argued and further show in subsequent pages of this paper, the iron-bearing formations of the south and north sides of Lake Superior belong with the original Huronian of the north shore of Lake Huron, like which they sustain an entirely unconformable relation to the underlying basement formation, and like which, again, they are composed of feebly altered rocks, mainly of detrital origin. Looked at as a whole, these formations would be, on Hunt’s classification, plainly Taconian, to which position he has lately suggested that they should be assigned,\textsuperscript{3} although he had previously spoken of the whole group as Huronian.\textsuperscript{4} Nevertheless his studies of collections from these formations have led him to divide them among his Huronian and Montalban.\textsuperscript{5}

The uppermost part of the iron-bearing series on the south side of Lake Superior shows generally a great development of a peculiar mica-schist or mica-slate which is associated closely with graywackes and graywacke-slates. These mica-schists often have the Montalban staurolitic and garnetiferous character. Our own microscopical studies of them have demonstrated their derivation by mere metasomatic changes from rocks wholly of detrital origin,\textsuperscript{6} the fragmental character frequently being well preserved, even to the naked eye, while large portions of the same horizon show little change from the original fragmental condition. Thus Hunt places in the Montalban series schists which are most distinctly above rocks which are lithologically Taconian and by him accepted as such. Moreover, he has placed in the same Montalban series certain portions of the schists of Republic Mountain, which belong at the base of the iron-bearing group,\textsuperscript{7}

\textsuperscript{1}Logan: Geol. Canada, 1863, p. 844.
\textsuperscript{2}Geol. Canada, 1863, Atlas, Pl. 111.
\textsuperscript{5}Ibid., p. 657; Second Geol. Survey Pennsylvania, E, Trap Dykes and Azoic Rocks, pp. 224-225.
\textsuperscript{7}Geol. Wisconsin, vol. 3, 1880, p. 658.
the granite and associated hornblende schists of the Menominee region, which, as already indicated, belong to the basement or Laun-
rentian terrane, and even certain granite-like porphyries, which, in
the Penokee region of Wisconsin, penetrate in dike form the gabbros
at the base of the great Keweenaw or copper-bearing series. Again,
the folded slates and cleft slates of the St. Louis River, in Min-
nesota, have been identified by Dr. Hunt, after an examination of
them on the ground, as true Taconian. Had his investigations ex-
tended somewhat farther to the south and west he would have real-
ized that these same slates are directly continuous with staurolitic
and garnetiferous mica-schists, having all the true Montalban charac-
ters.

Next in order above the iron-bearing group in the Lake Superior
country comes the great copper-bearing or Keweenaw group, a series
of interstratified detrital and eruptive rocks, the latter being in
the main of the augitic, basic class, though including also some acidic
porphyries. At the base of this great succession, in the Penokee
region of Wisconsin, on the south side of Lake Superior, and again
occupying an immense area in northeastern Minnesota, is a great
development of coarse-grained, augite-plagioclase rocks, which, ac-
cording to the now most accepted lithological nomenclature, are
gabbros. These gabbros include two classes, a non-olivinitic and less
basic kind and a highly olivinitic and more basic kind, the olivinitic
kinds belonging, in general, stratigraphically below the less basic
varieties. These gabbros, which have in the aggregate a most enor-
mous thickness, are beyond question unconformably placed upon the
iron-bearing group below, in which latter category I include the
Animiké formation of the north side of Lake Superior. In north-
eastern Minnesota these gabbros, as was first determined by Mr.
W. N. Merriam, traverse in a slightly inclined and often even
nearly horizontal position the edges of the Animiké formation,
which in places they completely overlap, so as to rest directly upon
the older granites and schists. The less basic of these gabbros
are usually somewhat altered, but, singularly enough, the olivinitic
kinds are, setting aside mere surface weathering, as a rule most
extraordinarily fresh, rivaling in this respect many modern basaltic
flows, with which they have so much in common that their erup-
tive origin cannot be questioned. As further demonstrative of
such an origin, may be cited their entire lithological identity with
dike masses found traversing the Animiké series, and also their
close lithological similarity to the finer-grained, basic rocks of the
higher portions of the Keweenaw series, whose lava-flow origin is
certainly beyond question. Were we to classify these widely ex-
tended gabbros according to Hunt's order, however, we should be

geology," p. 239.
compelled to regard them as Norian, in doing which we should not only reject the overwhelming evidence of their eruptive origin, but should be identifying as Norian a formation above the Taconian, that is, at the summit of Hunt's crystalline rock succession, whereas, according to his plan, this formation should belong next to the Laurentian.

There yet remains to be identified in the Lake Superior region the Arvonia of Hunt's classification. There certainly is no such formation in the place to which that classification assigns it, namely, between the Laurentian and the Huronian, but Dr. Hunt himself has recognized as Arvonian various felsitic rocks and porphyries of the Northwest. Thus he has placed at this horizon the felsites and felsitic porphyries of the Keweenaw series of Lake Superior and certain felsitic rocks which are developed at the summit of the quartzite series of central Wisconsin, though he had formerly called both of these Huronian. Of these two sets of porphyries, which belong at quite different horizons, it appears to me that my studies have demonstrated the former—that is, those of the copper-bearing series—to be of eruptive origin, inasmuch as they often occur in dike form and present microscopically all of the characteristics of the modern rhyolites, while the porphyries of the latter horizon present nearly equally strong evidence of such an origin. The former porphyries, then, are later than all of Hunt's groups and the latter succeed sandstones and sandy quartzites which can only be Taconian.

Thus this purely lithological classification of the Pre-Paleozoic groups breaks down completely in its application to the northwestern Pre-Paleozoic. Moreover, not to enter into any general discussion of the crenitic hypothesis (against which hypothesis indeed, as it appears to me, weighty and conclusive arguments might be pressed), it may be said that there is one general consideration which presents itself as an obstacle in any attempt to apply this hypothesis to the Lake Superior region. As set forth in the foregoing quotations, this hypothesis designates all of the Pre-Paleozoic formations (the Keweenaw series being placed within the Paleozoic) as crystalline, separating them into two grand groups of primitive crystalline and transition crystalline rocks. Into the composition of the latter there entered somewhat the products of a subaerial decay of the preceding terranes. In fact, however, the great mass of that group of strata which in the Lake Superior region intervenes between the basement formation and the copper-bearing series is not composed of rocks that are crystalline in the sense of the word as here used. On the contrary, while true crystalline rocks of eruptive origin are included, as also some crystalline rocks of a chemical origin, the great mass of...
this group is composed of detrital materials accumulated most mani­festly by the same agencies working in the same manner as in the production of the later formations. These Pre-Paleozoic accumula­tions, which in the Lake Superior region lie above the gneissic base­ment formations, were once beds of sand, clay, and pebbles, and, excepting some metasomatic change and some matter introduced interstitially by infiltrating waters, are still made up, in the main, of the unaltered, fragmental materials. The language of the quotations above given is not entirely clear in this respect, but it appears to in­dicate that all of the rock groups of Hunt's Pre-Paleozoic order are crystalline and were all deposited "anterior to the existence of de­trital sediments."

I have felt it necessary to give so much space to a consideration of Hunt's system of classification for the Pre-Paleozoic groups—and in­cidentally to the crenitic hypothesis—because together they consti­tute the only logical basis for the use of lithological characters in the determination of these formations in any portion of the world. Outside of the small class of geologists who follow more or less closely the teachings of this system, however, there have been not a few others who have attempted to use lithological characters as a general means of identification of the ancient formations. Thus, Huronian rocks, and even Keweenawan in one case, have repeatedly been recognized in the Appalachians, in the Rocky Mountains, and in the far West, not to speak of other portions of the world. Un­less, however, we should accept some such system as the crenitic hypothesis, such identifications, unaccompanied by the very strong­est structural evidence, must always rest upon a very flimsy founda­tion. The great series of highly altered, crystalline, schistose rocks which in the Lake Superior country make with massive rocks the basement formation is probably sufficiently constant in general char­acters as a whole, or at least in relative amount of alteration and crystallization, to justify us in designating as Laurentian (or as Ar­chean, should it be decided to restrict that term to this basement formation) any strongly crystalline, schistose series belonging plainly below the fossiliferous formations. Possibly the future may enable us to subdivide the basement rocks into members whose characters may hold over wide areas. As yet no such thing can be done, and lithological evidence can be used in the determination of such a series as that here called Huronian (which owes its existence to processes entirely similar to those by which the later rock groups have been accumulated) only so far as we are dealing with areas that were once manifestly continuous with the type or original Huronian series, and even then this evidence should be relied upon only in proportion to the distance from the type Huronian and should always be taken as subordinate in value to the structural relations of the rocks to be identified. When we proceed to the case of rocks which have been
accumulated in regions of rock growth wholly independent of that in which the original Huronian accumulated, lithological evidence should be allowed no weight whatever.

UNCONFORMITY AS A BASIS FOR CLASSIFICATION.

GENERAL NATURE AND SIGNIFICANCE OF UNCONFORMITIES.

TRUE UNCONFORMITY.

The term unconformity applies to that geological structure which obtains when one group of strata lies upon another in such a manner that the layers of the two groups are not parallel, i.e., the layers of the upper series traverse the edges of the layers of the lower series.

Such a structure can have been produced in one way only. The lower of the two groups of strata, after having been laid down, must have been disturbed so as to take other than the normal, horizontal position before the higher strata were deposited. The disturbance, except in the unusual case of faultings, must always have been in the nature of a folding. It thus becomes evident that, in order that the layers of the upper series may traverse the edges of those of the lower, there must have been, also subsequent to or contemporaneous with the disturbance of the lower series, a period of erosion during which the crowns of the folds were more or less thoroughly removed. Now, erosion demonstrates the exposure of a land surface to atmospheric action, and consequently, in the case of an unconformity, the elevation of the lower series above the waters of the sea. A genuine unconformity, then — such as is represented in the accompanying Fig. 64, which is ideal, and also in subsequent representations of actual sections — indicates the intervention, between the periods in which the two sets of strata concerned were deposited, of a lapse of time long enough to cover (1) the folding of the lower series, (2) its elevation into a land surface, and (3) a long-continued denudation. In other words, it indicates an interval of more or less extended orographic movement, with its accompanying and following denudation. At times also, particularly when we are dealing with unconformities in
which the oldest known rocks are concerned as the underlying of two series, it becomes evident that the intervening period must have covered also the time necessary to produce a greater or less change in the rocks of the lower series. In any case, however, we have here the indication of a great time gap between the periods in which the two sets of strata were accumulated. Elsewhere this gap may be represented in part, or wholly, by various strata, with their organic remains. Here such a record is wanting. Unconformities doubtless vary greatly as to the lengths of the unrecorded intervals indicated—a point further considered below—but all genuine unconformities, such as we are now considering, must indicate lapses of time so great as to furnish prima facie evidence that the groups of strata which each such unconformity separates must belong to different periods of geological time—evidence which only the weightiest of paleontological arguments, such as the essential identity of strongly characterized and abundant faunas on each side of the gap, should be allowed to overbear.

All unconformities do not necessitate a belief in equally great time gaps. In cases where the lower of the two series is only gently folded and where the amount of material removed in the interval has been relatively small, the time interval necessary for the explanation of the structure is certainly shorter than in those cases where the close folding of the lower series, its high degree of alteration, its great masses of eruptive material, and the relatively plane nature of its extended upper surface demand an intervening period long enough to cover not only great disturbances and alterations, but also the removal of masses of material equivalent in bulk to the greater mountain ranges of to-day. In no case of true unconformity does it appear that the structure can be looked upon as a local phenomenon, demanding only a restricted and local movement for its explanation. Certain authors, indeed, have spoken of unconformities as local in their influence, but, in order that such a statement should be true, the term "local" would have to be taken as indicating, at the very least, areas measured by thousands of square miles, while, in the case of the greater unconformities, it would have to be synonymous with "continental" or even with "intercontinental."

It is true that lack of parallelism more restricted in area between strata of no very great difference in age may be produced in several ways. Thus, the phenomenon of overlap, which is explained below, may give rise to such a lack of parallelism. Even in this case, however, a considerable lapse of time between the periods in which the discordant strata were respectively deposited must be admitted. We might imagine also such a structure as is indicated in the subjoined Fig. 65, which represents a discordance in which the inclined position of the lower strata has been produced by faulting, and not by folding. In this case again, however, a very considerable time interval be-
between the discordant strata is indicated. Moreover, while we might theoretically conceive of such a structure as of restricted areal extent it is doubtful whether any such structure exists except where the faulting has been an accompaniment of a widespread mountain movement in the interval between the periods represented by the two sets of strata.

![Theoretical diagram designed to show how a discordance between two sets of strata might arise where the lower strata have been inclined through faulting instead of folding.](image)

In any much faulted or disturbed region strata of the same age or of but little difference in age may present themselves in steeply inclined and in horizontal attitudes at places in close proximity to one another. Such structures might at times erroneously suggest the existence of a true unconformity, but with a genuine unconformity they have, of course, nothing whatever in common.

**THE EROSION INTERVAL.**

Interruptions in the continuity of stratal deposition may be indicated which do not argue genuine unconformities. It is of course possible, theoretically, that a region of the sea bottom may, after a series of strata has formed upon it, receive no further detritus for a considerable period, after which further supplies of land detritus or of organic secretions may come in to continue the growth of the conformable pile. In such a case there would be nothing beyond a possible strong contrast in the rock materials or in fossil remains to indicate the intervention of a period of non-deposition. It is hardly conceivable to me, however, that such periods of non-deposition could be very long continued, unless the area should be raised above the level of the sea. Our stratified rocks, in the main, have been spread over the surface of a submerged continent, and it seems hardly probable that the supply of material should have been withheld if the area remained submerged for a very long period of time. Being raised above the sea a given area may, of course, remain through an indefinite length of time without receiving new material. Inasmuch as this raising above the sea may be produced without folding of the strata, it follows that upon further submergence new material may be deposited over the old in an essentially conformable manner. In such cases, however, the indications of the former existence of a land surface and of the intervention of a period of erosion will often be met with in the midst of the finished pile of strata. The structures which result are often spoken of as unconformities by
erosion. The phrase is an unfortunate one, however, since the word unconformity distinctly implies a lack of parallelism between the strata on opposite sides of the break, and moreover all true unconformities indicate folding as well as an intervening erosion.

Eroded surfaces among conformable strata may correspond to time gaps of fully as great length as those represented by many true unconformities. On the other hand, it is evident that they may also correspond to intervals of relatively insignificant length. In Fig. 66 we have illustrated an eroded surface among conformable strata corresponding to a relatively short interval of time. The section represents the conditions which obtain through a large part of southern and eastern Wisconsin. The pile of strata is as follows: At the base is the Potsdam sandstone, which grades upward into the Lower Magnesian limestone. By their fossils and by their gradations into one another we are justified in referring both of these formations to the Cambrian series. The upper surface of the Lower Magnesian is an irregular one, the irregularities being in part a result of erosion by atmospheric agencies. Upon this irregular surface of limestone now follows the St. Peter's sandstone, an extraordinarily widespread layer of quartzose sandstone, which ranges in thickness from over two hundred feet to less than one foot, at times even disappearing altogether, the overlying and underlying layers coming in contact. These variations in thickness are often very abrupt, revealing to us the existence on the upper surface of the Lower Magnesian of erosion irregularities over a hundred feet in vertical height. Succeeding the St. Peter's sandstone, without other indication of unrecorded lapses of time, we find a great succession of Lower and Upper Silurian strata. The time gap indicated by this structure as having intervened between the respective periods of deposition of the Lower Magnesian and St. Peter's formations must have been sufficiently long to cover an elevation of the limestone above the level of the sea and its erosion, at least to the extent indicated by the irregularities of its upper surface. But manifestly such a gap bears no comparison to what is required for the least of the genuine unconformities.

The upper portion of the Lower Magnesian limestone illustrates also an interruption in stratal deposition corresponding to a yet
smaller lapse of time (Fig. 67). Professor Chamberlin has shown in his discussions of Wisconsin geology that the irregularities of the upper surface of the Lower Magnesian limestone are only in part due to an erosion entirely subsequent to the deposition of that formation, having been, in some measure, produced by an erosion within the period of deposition of the Lower Magnesian itself. Many of the protuberances on the upper surface of that formation have a most singular brecciated structure internally, such as seems to indicate the breaking action of the waves of the sea. Forming the outer side of the protuberance, however, and lying upon and completely cloaking the brecciated interior, is a continuous layer of limestone which seems to represent the fine silt which was deposited upon the surface of the brecciated material at a time of subsequent but slight submergence of the surface of the formation. The emergence and submergence of the upper surface of the Lower Magnesian thus indicated plainly correspond to a relatively short lapse of time and seem to have been merely preliminary to the general emergence which produced the irregular surface upon which the St. Peter's sandstone was deposited.

Fig. 68 shows a form of interruption among conformable strata which presents itself to us constantly and which represents a time gap of immense duration, one which is at the other extreme from the gaps indicated by Figs. 66 and 67. In Fig. 68 we have a series of horizontal strata belonging, say, to the Cambrian period, as for instance from the Upper Mississippi Valley. Filling the bottom of a valley eroded from this formation is a river silt of the present time. OVERLAP.

Standing between the true unconformity and the simple erosion break as to length of time-gap necessarily indicated is the structure known as overlap. This structure is explained in the ordinary textbooks of geology and is illustrated in Fig. 69. The left-hand end of the figure, which must be taken as many miles in width, represents above the folded layers an essentially conformable series of strata. As the section is followed to the right the middle members of the
series thin out and disappear, the uppermost and lowermost members spreading, however, to the extreme right of the section, where they come together in a slightly discordant attitude. Such a structure as this is explicable in this way: All except the uppermost member of the series were deposited in an area gradually undergoing depression on the left and elevation on the right. As this elevation progressed the right-hand end of the section represented was elevated above the sea more and more and the middle members of the series became consequently more and more limited as to extent in that direc-

tion. Finally, the depression affected the whole of the region represented and the uppermost member of the series spread over the whole area. Such a structure as this, particularly if there be any considerable discordance between the upper and lower layers of the series, could only obtain when the intervening members were of very considerable thickness, and corresponded, therefore, to a very considerable lapse of time.

**DISTINGUISHING CHARACTERS OF TRUE UNCONFORMITIES, WITH EXAMPLES.**

**CASES IN WHICH THE OVERLYING STRATA ARE UNDISTURBED.**

*Visible superpositions.*—Unconformities are structures measured by scores and hundreds of miles, for which reason, and also because the formations below the unconformities have been more or less deeply buried underneath later accumulations, it follows that anything like a single comprehensive view of an unconformity is to be obtained only under very unusual circumstances. Such circumstances are met with, for instance, in the depths of the Grand Cañon of the Colorado, where, all cloaking by superficial detrital material or vegetation being wanting, a pile of strata many thousand feet in thickness and ranging from the Potsdam horizon upward may be seen traversing for miles the upturned edges of the great formation to which Powell has assigned the name of the Grand Cañon group. More commonly we are able to see actual superpositions or horizontal layers upon upturned strata through limited distances only. Such occurrences obtain where general denudation has carried the present surface, in the main, below the level of the ancient land surface beneath the unconformity, leaving the horizontal strata as cappings to the summits or as facings to the sides of elevations composed of the lower rocks. **By putting together a series of such occurrences in**
the same region we are enabled to work out the general character of the unconformity, though at best it will usually be but a very small portion of its whole extent that we are thus able to investigate. This is illustrated, for instance, in Fig. 70. Here the erosion which has produced the present surface intersects the unconformity in the vicinity of what was the limit of the sea in which the horizontal formations were accumulated.

Lateral contacts.—A not uncommon case is that where the surface of the formation below the unconformity makes a more or less sudden rise in elevation, later denudation, in such cases, having removed the horizontal layers from the higher portion of the old land surface and having left them over its lower portion. Such an occurrence is illustrated in Fig. 71, and it is manifest that in such cases, unless we are favored by deeply cut natural ravines crossing the contact, we may have only an abutment of the horizontal layers laterally against the tilted ones upon which to base our conclusion as to unconformity. Between such cases as that illustrated in the figure and those where more or less extended actual superpositions are visible, all degrees of variation are to be found. In such extreme but yet not so very unusual cases as that represented in the figure we must of course guard against the danger of mistaking a fault for a genuine unconformity. Various phenomena liable to occur at the contact will serve to aid us in avoiding this mistake, and particularly the occurrence in the overlying formation of more or less abundant fragments from the lower rocks. Cases are at times met with—as, for instance, those cited below as occurring at the contact of the Keweenaw series of Lake Superior and the horizontal Pots-
dam sandstone on Keweenaw Point and elsewhere—where the unconformable abutment has been against an ancient fault cliff. At some period subsequent to the laying down of the newer series a second, but relatively slight, faulting has taken place along the old fault line, in which case a singular disturbance of the edge of the overlying formation has resulted, giving rise to confusing and contradictory appearances (Fig. 72).

Basal conglomerates.—As an eroded land surface slowly sinks beneath the sea, the waves, beating on its more prominent projections and irregularities, break them down and from their ruins form new deposits. The coarse part of the material thus derived—such as the greater masses that fall from overhanging sea-cliffs, or the bowlder heaps which form at the base of such cliffs, or the shingle which collects in recesses between projecting rocky points—will remain at no considerable distance from its source, while the finer materials will be carried to distances great in direct proportion to their degrees of fineness and to the strengths of the currents acting upon them. These finer materials will thus be spread over the intervening relatively low and level portions of the ancient land surface, which portions will have been in large measure protected from the action of the waves by the silt and stream detritus which have been washed into them during the exposure of the region to the action of the subaerial agencies. The distribution of the wave-made débris is thus irregular in proportion to its coarseness, and the irregularity will be of two kinds, for not only will the distribution laterally (i.e., over the ancient land surface) be irregular, but there will be also the greatest irregularities as to the vertical distribution (i.e., the distribution in horizon) among the deposits beneath which the land surface is gradually buried. The latter irregularity will arise from the variations that will obtain as to vertical height and abruptness and nature of rock material among the projections which furnished the fragments.

The coarser fragmental materials consolidate into what are known among geologists as conglomerates, or as basal conglomerates when they lie, as they frequently do, at the contact of two discordant formations (Fig. 73). In every respect, as to position, distribution, etc., these basal conglomerates reproduce the conditions we now see obtaining along exposed and rocky lines of coast. Their occurrence is not only a characteristic feature of unconformable contact lines, but
often serves to establish the existence of unconformities when other evidence may be wanting by reason of various obscuring causes. It is true that coarse, wave-fashioned, fragmental materials may be embraced in a rock which is not geologically remote from that which furnished the fragments, as in the case of certain lavas which, flowing directly into the sea or becoming submerged beneath the sea by depression at a period not long subsequent to their eruption, may yield fragments as soon as acted upon by the waves. Similarly such limestone masses as are formed near to the surface of the sea—for instance, certain of the coral-derived masses of to-day—yield fragments to deposits of the same geological age; and it is at least conceivable that the same might be the case with certain forms of chemical sediments which have reached the indurated condition at an early period in their history. But such occurrences as these give little trouble to the experienced geologist, who knows that, with the exception of the cases cited, the inclusion of the fragments of one rock within the mass of another indicates a period of time between the formation of the two sufficient to cover the raising of the lower one from its original position beneath the sea and its induration and transformation into its present condition.

The existence of such conglomeratic masses may indeed form the main evidence upon which conclusions as to unconformity are based. We may suppose, for instance, a case of what is above called lateral contact, where the horizontal formation, underlying a level and relatively low region, comes against the edges of a series of tilted strata forming a more elevated region. Such a break is conceivably resultant from a process of faulting, in which case the discordance in attitude of the two formations at the contact may give place to entire concordance beneath the horizontal formations of the lower area. But if the horizontally placed terrane be crowded with fragments of the tilted one at and near the contact of the two, it becomes evident at once that the tilted strata acquired their disturbed position prior to the deposition of those that lie horizontally against them.

Fig. 73. Diagram designed to show the necessary irregularity in the stratigraphical distribution of a basal conglomerate at the junction of two discordant formations.
Relation of eruptives to unconformable contacts.—The erosion which the upper surface of the formation below the unconformity has suffered will frequently have truncated the eruptive masses which have penetrated that series prior to the erosion; whereas those eruptives which have been intruded at a time subsequent to the deposition of the overlying series will intersect the contact line. A consideration of this simple principle will frequently aid in the establishment of an unconformity where otherwise its existence might not be so evident. This will particularly be the case when the overlying strata are more or less disturbed, as noted below.

The general relative attitudes of unconformable formations.—Cases of very considerable unconformity occur where neither direct superposition nor lateral contacts may be obtained to establish the relation. Even in these cases, however, the unconformity may often safely be inferred from the general relative attitudes of the two formations. Suppose, for instance, a case where an extended level area, underlain by horizontally placed strata, may terminate against an elevated one composed of more or less folded and crumpled formations. While the actual contact of the two terranes may be concealed it may yet be sufficiently evident from the horizontality of the one and from the greatly disturbed and perhaps altered condition of the other that there is here a genuine unconformable break. Particularly will this be plain if the horizontal strata of the newer enter into the sinuosities of the edge of the area occupied by the older terrane. Nevertheless great caution needs to be taken in such cases as this, since such relations between horizontal and disturbed strata as are here supposed might at least conceivably obtain where the disturbed strata pass in an undisturbed condition, and conformably, beneath the horizontal strata of the lower area. But in those cases where the older formation is very much folded and is greatly different in character from the horizontal one, and particularly if its rocks are greatly altered, the presumption is that we have to do with an unconformity.

EXAMPLES.

Pre-Potsdam land surface of central Wisconsin.—The distribution and lithological character of the basal member of the Paleozoic column of the Mississippi Valley—now well established as the equivalent of the Potsdam sandstone of New York—and its relations to the formations upon which it repose render it evident that it was deposited in a sea advancing from the south and gradually encroaching on the great land mass which lies to the northward, as has been fully shown by Chamberlin.1 This encroachment continued until that portion of this ancient land mass which now presents itself at the surface in northern Wisconsin and northwestern Michigan was entirely surrounded and detached from the main mass over the

1 Geol. Wisconsin, vol. 1, 1883, pp. 119-137.
great Archaean region of Canada. A geological map of the region extending southward from Lake Superior as far as southern Wisconsin, such as that compiled by myself and published in the Fifth Annual Report of the U. S. Geological Survey, will indicate roughly how far this encroachment of the sea extended. In fact, however, the encroachment was in places somewhat greater than such a map indicates, for the sandstone has since been partly removed by the denuding agencies and the area in which the older formations are at the surface is somewhat extended. It has also resulted from this denudation that the line between the two formations is an exceedingly intricate one. High, isolated patches of the sandstone have been left within the area occupied by the older formations, while the valleys of the deeper streams within the sandstone area proper have often cut their channels for long distances down to the ancient land surface upon which the sandstone formation repose. Everywhere within the vicinity of this boundary, except where the drift covering is too great, are to be found sections most instructive in their bearing upon the relations of the sandstone to the older formations.

Nowhere are these more instructive than in that central portion of the State of Wisconsin whose geology is indicated in the accompanying map and sections. This region, moreover, is of especial interest in the present connection because, in addition to the contacts in the immediate vicinity of the common boundary of the main surface areas of the two formations, it shows others at a number of points, where there rise within the sandstone area projecting portions of the underlying basement, which owe their elevation to their greater relative power of resistance to the denuding agencies. The structure of this district has been worked out very completely by the Wisconsin survey, from the maps of which survey the map here-with presented is mainly reproduced. The original work for the larger part of this area was my own, but the map includes also considerable portions of the districts on the east and west, in which the original field-work was respectively by Prof. T. C. Chamberlin and Mr. Moses Strong.

From the large surface exposure of the Pre-Potsdam formations in the northern part of the area mapped and north of it, from the numerous smaller areas which come to the surface within the region of the horizontal formation, and from the records of numerous borings for artesian flows, we are enabled to reconstruct in the most satisfactory manner the nature of the ancient land surface upon which these horizontal formations repose. We are even able to reach a satisfactory approximation to the distribution of the different formations which compose the ancient basement where concealed by the horizontal accumulations.

This ancient surface is one made up of that class of rocks to which the name of crystalline schists has been applied. Gneiss, various mica-schists, hornblende-schists, chlorite-schists, and granites make
up the larger part of the basement. Another large part is chiefly composed of quartzites, ferruginous schists, and certain other schists and acid eruptives associated with them. Basic eruptives also occur, but are of relatively limited distribution. All of these rocks have passed through a series of profound foldings and alterations. Moreover, they are plainly divisible into two dissimilar formations: (1) a more ancient gneissic formation, which is actually continuous at the surface with the gneissic formation of the south shore of Lake Superior and almost as certainly with the great gneissic formation north of Lake Huron and east of Lake Superior, to which the Canadian geologists have applied the term Laurentian, and (2) a more recent quartzitic, iron-bearing series, whose structural relations to the gneissic series are, to be sure, not apparent within the district particularly under consideration, but whose community of nature with the iron-bearing formation of the Lake Superior country is so striking that little doubt can be entertained of the equivalency of the two. The Lake Superior iron-bearing rocks can be most plainly shown to be discordant with the gneissic formation with which we are concerned. The rational inference is that the quartzitic, iron-bearing formation of central Wisconsin holds the same structural relation.

The Pre-Potsdam land surface, whose structure and position we are thus able partly to see and partly to infer, is one, in the main, of but gentle undulation. In the vicinity of Lake Superior it reaches an altitude of about a thousand feet above the level of Lake Michigan; underneath the horizontal formations of the southern part of the map it stands at about five hundred feet below the same level, having at the present time a general southerly descent. Looked at in greater detail, however, it is seen to have numerous minor and often somewhat abrupt irregularities. The more abrupt of these have an evident genetic relation to the durability and general resisting power of the rocks which compose them. These prominences, in that portion of the ancient land surface which is still uncovered by later formations, reach at times elevations of from one hundred to six hundred feet above the general surface. Those that rise from beneath the Potsdam sandstone rise to about the same extent above the general level of the surface upon which that formation lies. There is one exception to this, however, in the case of the Baraboo Ranges, the present elevation of whose summits above the general Archaean surface is in the neighborhood of twelve hundred feet, the rock being of an unusually resistant nature.

A moment's consideration shows that the insignificant elevations which the ancient surface thus presents bear no sort of comparison to those that it must once have had. We need only to trace out some of the folds which its beds indicate to realize that there have been removed from it masses of material rivaling in bulk the greater existing mountains of the globe, and this is as true of the layers be-
longing to the later as of those belonging to the older one of the two formations concerned. What remain now are the mere stumps of mountains. Our views may vary as to the exact chronological relations of the periods of folding of these strata and of the decapitation of the folds. These two processes may or may not have been more or less contemporaneous; but whether contemporaneous or not, it is evident that an amount of material vast beyond computation was removed from this ancient land before the encroachment upon it of the sea within which the sandstone was deposited. The only measure of this material that we now possess is that afforded by the stratified accumulations of all later geological time.

![Diagram](image)

**Fig. 74.** Section across the valley of the Wisconsin River near Point Bass, Wood County, Wis., looking north. The Potsdam sandstone, which forms the surface rock everywhere on each side of the stream, is here cut through so as to show its unconformity to the underlying gneiss. Scale, 325 feet to the inch.

Contacts with the gneissic or older one of the two formations of which this Pre-Potsdam land surface is composed may be particularly well seen along the valleys of the several streams which intersect the northern edge of the sandstone area, and especially the Wisconsin and Black Rivers, with their several branches (Fig. 74). As will be seen from the map, the immediate valleys of these streams uncover narrow strips of the ancient gneisses a number of miles in length. At times these strips are no wider than the river bed itself; in other cases they extend some little distance to either side of the stream. The gneisses and associated schists stand always at very high angles and present a nearly level, truncated upper surface which is at times free from loose material and is again in places changed to a kaolinic substance. Resting horizontally upon this surface, in the valley sides or even in the immediate banks of the rivers, is seen the Potsdam sandstone. Exact contacts of the two formations are frequently to be found. When the tops of the valley sides are reached we find ourselves upon a generally level surface, everywhere underlaid by the sandstone formation, bold castellated remnants of which here and there dot the plain. The sections of the Black and Wisconsin Valleys here given, as also the views in the vicinity of Black River Falls (Pl. XXX), will serve to make this relation plain (Fig. 75). It is very evident that we are dealing in these places with the greatest kind of a geological break. Between the periods which gave rise, respectively, to the gneissic and the sandstone formations (Pl. XXXI) intervened a lapse of time sufficient to cover the alter-
ation of the gneisses from their original condition (whatever that may have been), their elevation into mountain masses, and the complete removal of such masses, this thorough truncation being indicated not only by the present folded condition of the strata, but also by the appearance at the surface of areas of eruptive granite and other coarsely crystalline rocks which we can only suppose, with our present knowledge, to have formed deep within the interior of the earth.

When we come to consider the relations between the sandstone and the newer of the two formations composing the old land surface, we find that here again there seems to be required an enormous interval of time (Pl. XXXII). It cannot, of course, if our reading of the geology of this region be correct, have been anything like so long as in the case of the unconformity between the Potsdam sandstone and the older of the basement formations; but it must have been long enough to cover the folding, induration, and removal of mountainous masses of material. These relations are illustrated partly in a section already given, viz, that along the valley of the Black River, in which the sandstone is seen to cross indifferently the gneisses of the older formation and the folded ferruginous schists of the newer. But the most interesting and striking occurrences to be mentioned in this connection are those met with in the Baraboo region farther south. An inspection of the map herewith will show that in this region there rises to the surface a large area of the newer of the basement formations, and that, stretching out thence in a direction northeastward for a distance of some fifty miles, numbers of other smaller points of this formation reach the present surface; while at a distance of some thirty miles in a southeasterly direction another group of small areas presents itself. In the Baraboo region most of the rock at surface is a quartzite of some form, but in the more northern portion of the area ferruginous and cherty schists and felsitic porphyries occur with a very considerable development, and similar porphyries make up several of the isolated areas which lie to the northeast. Borings of numerous artesian wells farther to the northeast and east indicate a very considerable distribution in that direction of a similar material beneath the horizontal formations.

In the immediate vicinity of all these areas the outcroppings of the horizontal formations are found, and not unfrequently direct
contacts, in which latter case, if the horizontal formation be a sandstone, either the St. Peter’s or the Potsdam, it is found filled with fragments or masses of the older rock. But the most striking sections are those to be found about the Baraboo Ranges. In this region the quartzite formation comes to the surface in the shape of two bold ridges, which unite at their eastern and western extremities, forming together the great mass of high land which causes the great eastern deflection in the present course of the Wisconsin River. I say present course, because it is manifest that at a former period this river had its course across the two ranges, passing through gorges which still remain, though one of them is now badly blocked with morainic drift. Between these two ranges lies a valley, into the western end of which the Baraboo River breaks from the north through a narrow gorge. Traversing then a great part of the length of the valley, this river leaves it again to the north, passing out at the gorge formerly used by the Wisconsin River. All around the outer circuit of the ranges the country is occupied by the Potsdam sandstone, which rises frequently high on their flanks and, although never reaching their uppermost swells, which lie at elevations of over seven hundred feet above the adjacent valley of the Wisconsin River, often overtops the lower elevations, particularly in the case of the northern range. The same sandstone has evidently at one time filled completely the intervening valley. This is evident from the way in which it now lies on the flanks of the inner sides of the ranges and from the fact that it still fills to the brim the eastern end of this valley. Often the sandstone remnants on the sides of the ranges are found filling depressions in the ancient surface or forming mere facings to the sides of ravines, in which cases, many in number, it is manifest that the new erosion has followed the course of the erosion of that remote period when the outlines of the ancient land surface were carved.

As one approaches these ranges from various directions fragments of the rocks composing them begin to occur within the newer formations, and this not only in the Potsdam sandstone, but in the Lower
VIEW IN THE BLACK RIVER VALLEY, BLACK RIVER FALLS, WISCONSIN.
UNCONFORMITY BETWEEN POTSDAM SANDSTONE AND ARCHAEOAN GNEISS.
UNCONFORMITY BETWEEN POTSDAM SANDSTONE AND FERRUGINOUS SCHISTS.
GEOLOGICAL MAP OF CENTRAL WISCONSIN.

Designed to indicate the character of the ante-Potsdam land surface.

UNCONFORMITY BETWEEN POTS DAM SANDSTONE AND HURONIAN QUARTZITE, SAUK COUNTY, WISCONSIN.
Magnesian limestone above it. These fragments, very small to be sure, but of quite unmistakable derivation, have been met with as much as ten or fifteen miles to the south of the southern range. Nearer the ranges they occur more frequently, until at the actual contacts between the sandstone and the quartzite genuine bowlder conglomerates are met with. At times these contact conglomerates are not very coarse, being composed of much-rolled fragments. In other cases, however, where the conditions have been favorable the sandstone has included within it great masses of the quartzite many feet in length and breadth. These occur principally where the quartzite has formed a nearly vertical or overhanging cliff in the sea within which the sand was deposited (Pl. XXXIV and Fig. 78). In other cases the waves of the sea, washing up the slopes of the not very steep dip surfaces of the ancient reefs, have formed accumulations of bowlders of considerable size, which generally present some tendency to rounding at the corners (Fig. 77).

The points at which contacts between the two formations are to be found, and at which the most striking and interesting conglomerates are to be seen, are far too many to notice in this connection. I may merely give two or three sections, along with reproductions.
of some photographs recently taken, in order to set the occurrences more plainly before the reader (Pl. XXXV). The section shown in Fig. 78 extends from some miles south of the more southerly of the two ranges, crossing both ranges and their intervening valley, and some little distance also to the north of the northern range. It is designed to show the general relation of the ancient formation to the sandstone. Fig. 79 is a section showing on a true scale the occurrences met with on the west side of the gorge through which the Baraboo River crosses the northern range to the north.

Fig. 79. North and south section through the northern one of the Baraboo Ranges at the lower narrows of the Baraboo. Scale natural, 4 inches to the mile. The Potsdam sandstone overlies the quartzite unconformably and is filled with fragments from it.

Fig. 77 and Pls. XXXVI and XXXVII are illustrations of the occurrences in the immediate vicinity of Devil's Lake, a picturesque sheet of water occupying a depression between the great heaps of drift which now block the gorge in the southern range formerly used by the Wisconsin River. Pl. XXXVII, on which is represented a mass of boulder conglomerate overlying quartzite, is of especial interest because it illustrates the way in which the conglomerate in this vicinity lies upon the gently sloping dip surfaces of the quartzite and also the irregularity in vertical distribution which such coarse conglomerates of necessity take.

Perhaps the most instructive section met with in the region is that at the upper narrows of the Baraboo River, where that stream first enters the valley between the two quartzite ranges (Fig. 80). Here the core of the northern range is seen to be composed of vertically placed and shattered ledges of quartzite and quartz-schist, the latter at times showing a very handsome transverse, slaty cleavage. Flanking these on both sides and extending in a thin sheet over most of the top of the range, in places away from the immediate line of section probably completely capping it, and here and there sinking into depressions in the ancient quartzite surface, is the horizontal sandstone. This is a purely quartzose sandstone, at times evenly bedded, at times showing in a striking manner the well known torrential lamination; with few or no quartzite pebbles, and again a fine or coarse conglomerate.

At the southern side of the section, where it comes into contact with the steeply placed and often overhanging cliffs of quartzite, the sandstone includes great masses of this rock varying from a few inches to ten or more feet in length (Fig. 80). At times these masses
have fallen away from their original positions somewhat, but in other cases they lie nearly parallel to the original bedding, representing evidently projecting and somewhat detached ledges, around which the sandstone accumulated. The conglomerate which caps the range and is shown again in the detached bluff farther north is a much finer material, made up of fragments which have generally been considerably rolled.

It is doubtful whether anywhere in the world there are to be met with among the ancient formations more admirable reproductions of the conditions which obtain at the present time on every cliffto seashore than are found in the Baraboo region. A few days' examination of this region enables one to obtain a most vivid mental picture of the conditions which obtained at the time when the sandstone was in process of accumulation. He sees great east and west rocky ridges, at times with jagged edges just awash, at other times rising into smoothed and rounded rocky islets, and again buried some distance beneath the surface of the sea, and all about and against them growing the deposits of the sand washed from them by the waves.

The bedding structure of the quartzite of these ranges and of its associated schists and felsitic porphyries, which are taken to have been great eruptive flows, I studied with a great deal of care a number of years since, with the result of finding everywhere a northerly inclination and one which increases in amount steadily from the south to the north, until in the northernmost exposures a nearly vertical position is reached. It is possible that southward dips may occur in those portions which are now covered by sandstone or drift material, but none such has ever been seen, and their occurrence is deemed improbable, because the northern inclinations have been carried quite around the united eastern and western terminations of the ranges, and because, also, if these are return folds, other occurrences of the quartziferous porphyries which now seem to form the uppermost member of the series would be expected. However this may be, we have indicated here one of nature's greater structural breaks. If we are dealing here with a portion of a single fold, as is indicated in the accompanying natural scale sketch (Fig. 81), it is sufficiently manifest that the mass of material removed from the ancient land surface before the deposition upon it of the horizontal
sandstone, if piled again in its place, would rival in elevation the greatest of the existing mountains of the globe.

Although the interval here indicated must have been less than that between the sandstones and the older gneissic formation, which is much more closely folded and deeply altered than the quartzite series, it yet was plainly long enough to cover a period of great orographic movement and a subsequent period when such parts as remained of the mountains formed were almost wholly removed. That such an orographic movement cannot have been merely local is indicated by the magnitude of its effects in this region alone. Indeed these effects are distinctly recognizable in other regions. It must have been the same movement that began the formation of the great bow which the iron-bearing series describes underneath Lake Superior, from the Penokee region on the south to the Animiké region on the north; that folded the cleft slates of the St. Louis and Mississippi Rivers in Minnesota; that produced the crumpling of the same series of rocks in the Marquette and Menominee regions on the south side of Lake Superior and of the same formation in the Vermilion Lake country on the north side of that lake; and that brought into its present condition the original or typical Huronian of the north shore of Lake Huron. The area over which the effects of this one movement may now be traced with a fair degree of certainty is some six hundred miles from east to west by four hundred from north to south. Should we include as an effect of the same movement the gentle bowing of the quartzite formation of southeastern Dakota and southwestern Minnesota, the east and west extent of this territory would be increased by between one and two hundred miles. On a subsequent page it is shown that what are probably effects of the same movement are to be detected over an area several times as large as this.

Notwithstanding all this evidence of a great time interval between the overlying undisturbed Potsdam sandstone and the folded quartzitic or iron-bearing series and notwithstanding the further evi-
vidence of the greatness of this interval to be found in the intercalation between these two series in the Lake Superior region of the great Keweenaw group, certain writers have maintained that both the sandstones and the quartzites underlying them should be counted as belonging to the Cambrian. The argument, so far as there has been any, has been something like this: The overlying undisturbed sandstones carry in the immediate vicinity of their contacts with the quartzite well characterized Pre-Cambrian fossils. The quartzite series beneath is without fossils, but its strong resemblances to the quartzite formation of southeastern Minnesota, in which certain obscure fossil forms have been met with, renders the identity of the two very probable. These fossils have a general resemblance to Cambrian forms. Moreover, no fossiliferous rocks below the Cambrian are known; therefore both formations concerned are Cambrian (Pl. XXXVIII and Fig. 82).

The equivalency of the quartzite of the Baraboo region with that of southwestern Minnesota is not certain, but, accepting it for the time being, the argument is still fatally defective, since it sets aside the very greatest of structural breaks on the evidence of fossils which might occur anywhere in the geological column, from the Devonian downward, and all of which are fossils to be expected among those formations which antedate the Cambrian.

The sub-Potsdam land surface in the Marquette and Menominee regions of Michigan.—The ancient land surface now referred to is
of course the continuation northward of that just described, but the unconformity here displayed is worthy of separate remark because of the full development of the Lake Superior iron-bearing series, as to whose equivalence with the Baraboo quartzites some doubt might be expressed. The common boundary of the sandstone and crystalline rock areas may be traced continuously in a northeasterly direction from central Wisconsin into the northern peninsula of Michigan, and across that peninsula to the shore of Lake Superior, in the vicinity of the city of Marquette. From Marquette to the head of L’Anse bay this boundary follows closely the coast of Lake Superior, which in several places intersects it, giving fine displays of unconformity along the shore cliffs. Several of these contacts were made classical in geological literature forty years since by Foster and Whitney (Fig. 83), and they are further illustrated here by sketches made from photographs (Pl. XXXIX and Figs. 84 and 85).

As in the case of central Wisconsin, so here, also, numerous isolated outliers of the sandstone formation are met with in the crystalline rock area. In the iron-mining district, in the vicinity of the Menominee River, the boundary between Michigan and Wisconsin, these outliers may be met with in a number of cases in contact with the tilted layers of the schistose group in which the iron occurs. In several mines, indeed, the iron ore, itself merely an unusually ferruginous portion of one of the layers of the schistose series, is
reached only after the removal of a certain thickness of the unconformably overlying sandstone, in which are buried numerous fragments of the iron schist.

Farther to the northward and westward the sandstone formation is found to traverse indifferently the courses of the various belts of the older gneissic and newer iron-bearing groups. These groups are both closely folded, but the great irregularities of the original surface indicated by the folds are now almost wholly planed off and the sandstone lies upon a relatively level surface. Several sections and views illustrative of the contacts of the sandstone with the two adjacent formations are presented herewith.

The Potsdam-Huronian unconformity of the north shore of Lake Huron.—At Marquette, on the Michigan shore of Lake Superior, the outcrop line of the Potsdam sandstone divides. To the west the sandstone skirts the shore as far as Keweenaw Bay, having immediately behind it a more elevated region, occupied by the higher portions of the ancient basement. To the east of Marquette it forms the shore line all the way to the eastern end of the lake, the older rocks being in this distance wholly concealed by the sandstone formation or by the waters of Lake Superior. The eastern termination of the lake is at the Sault Ste. Marie. A few miles north and again east from this point, however, the basement formations rise again from beneath the sandstone, forming most of the eastern side of Lake Superior and of the northern shore of Lake Huron (Pl. XL).

Along the shore of the north channel of the latter lake, between the St. Mary's and Thessalon Rivers, and for an unknown distance farther eastward, is the series to which the name of Huronian was originally given by Logan and Murray. Everything about this series, as I have argued elsewhere, goes to indicate its identity with the iron-bearing formation of the Marquette region and with the Baraboo quartzite series of central Wisconsin. Great portions of it are made up of indurated sandstones almost identical in character with that of the Baraboo Ranges. It is gently folded.

Along the south side of this channel of Lake Huron lies the long string of islands known as the Manitoulin group. These islands are made up of a succession of layers, having a very gentle slope to the southward and ranging from the Potsdam sandstone at the base to the Niagara limestone at the summit. As to their rock structure, these islands are merely a continuation of the belt of country which
CLASSIFICATION OF CAMBRIAN FORMATIONS.

may be traced all along the northern and western shores of Lake Michigan. Herewith are reproduced two of Logan's sections traversing the Huronian and the Cambrian and Silurian formations of the Manitoulin Islands (Figs. 86 and 87). They are drawn in both cases to natural scale. Excepting as to the sandstone formation next overlying the Huronian, which Logan regarded as the equivalent of the St. Peter's sandstone of Wisconsin, these sections are exactly as he drew them. The sandstone formation referred to has since been carefully traced through Wisconsin by the Wisconsin survey and through Michigan by Dr. C. Rominger, of the Michigan survey, as far as the westernmost of the Manitoulin Islands, with the result of showing that it represents in fact the Potsdam sandstone and Lower Magnesian limestone of the Wisconsin reports and that the St. Peter's sandstone member is the one that is wanting.

Here, then, we have the same structural break that is present in central Wisconsin, the sub-Potsdam surface of this region, composed of the deeply truncated folds of the Huronian, being, in fact, the direct eastward continuation of that of central Wisconsin.

The Potsdam-Keweenaw unconformity.—Returning now to Marquette and following the Potsdam sandstone in its western outcrop, we find it, to the west of Keweenaw Bay, abutting unconformably upon still a third formation, the great Keweenaw series, whose relation to the iron-bearing rocks in the Penokee region and in the region of northern Minnesota is such as to render its later origin unquestionable; indeed, it is such as to indicate the intervention, between the periods represented by these two groups, of a period of land erosion. The Keweenaw series then partly fills the great interval which is indicated by the relations of the Potsdam to the iron-bearing series from central Wisconsin to Lake Huron. I say partly, because the structural relations between the Keweenaw series and the Potsdam indicate again a very considerable time-gap. We have followed the Potsdam sandstone westward from Marquette to its abutment against the tilted layers of the Keweenaw series on Keweenaw Point. Following the same formation northwestward from central Wisconsin we find it in the St. Croix River region traversing the edges of the inclined layers of the Keweenaw series, against the tilted layers of which series, moreover, all along the south shore of Lake Superior, from its western termin-
nation as far east as the Montreal River, it is found abutting unconformably. A general section in northwestern Wisconsin is indicated in Fig. 88, from which it will be seen, if true conditions are represented, that, subsequent to the completion of the Keweenaw series and previous to the deposition of the Potsdam sandstone, the former was depressed into a great syncline, the whole area then elevated into a land surface, and the sides of the syncline removed, until the whole again became a relatively flat expanse.

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Fig. 88: Section from southeast to northwest in the St. Croix River region of northwestern Wisconsin, through Keweenaw series and Potsdam sandstone. Scale, about 13½ miles to the inch.

Where the sandstone borders the shore of Lake Superior, in the northwestern corner of Wisconsin and again along the south side of Keweenaw Point and thence westward as far as Gogebic Lake, very interesting instances of lateral contacts are met with. These contacts have been described in some detail elsewhere. Here we need merely to say that in each case the contact line follows in a general way the course of a Pre-Potsdam fault in the Keweenaw beds. South of the fault line, in the region of the western end of Lake Superior, and north of it, in the Keweenaw Point region, relatively elevated regions of tilted Keweenawan beds were left by the pre-Potsdam denudation. Subsequently the regions were invaded by the Potsdam sea and the Potsdam sandstone was deposited over higher and lower areas alike. This was followed by the removal of the sandstone from the higher areas, the lower areas, to the north in the one case and to the south in the other, still retaining a part of the thickness of the sandstone covering. The contact lines of the sandstone and Keweenawan areas, which were also the lines of the more ancient faulting, were affected then by some very interesting disturbances in the sandstone at the immediate contact. These disturbances for Keweenaw Point will be found fully described and illustrated in Bulletin 23 of the U. S. Geological Survey, by myself and Professor Chamberlin, where it is shown that, notwithstanding them, the facts observable along those contact lines admit of one interpretation only. It is not desirable to reproduce all of the argument here. We may merely allude to the fact that the sandstone near the contact is crowded with fragments derived from the Keweenaw series in the immediate vicinity of the contact, fragments for which, when we consider their nature, distribution, and arrangement, no other possible source can be found. The similar occurrences in Douglas County, in northwestern Wisconsin, already alluded to, have been described by Mr. E. T. Sweet, in the Wisconsin reports, and are plainly of the same nature and origin as those of Keweenaw Point. The faultings which produced
the fault cliffs against which the sandstone abuts laterally in these two districts were evidently genetically connected with the general synclinal bowing of the entire Keweenaw series.

Pre-Potsdam land surface of the Grand Cañon region.—The unconformity which has been shown by Powell and Dutton to obtain at the base of the great conformable pile of Paleozoic and Mesozoic strata, in the Grand Cañon country of Arizona and Colorado, and which has recently been more fully studied and illustrated by Walcott, presents a most striking similarity—in respect both to the nature of the formations immediately above and below the contact and to their structural relations—to the unconformable break just described as obtaining between the Potsdam sandstone and the Keweenaw series in the Lake Superior region (see PI. XXXIII).

The Tonto sandstone, which marks the base of the horizontal strata, has been shown by Walcott to belong plainly to the Potsdam horizon (Fig. 89). This sandstone traverses the edges of an immense series of gently bowed strata, whose similarity to the Keweenaw series of Lake Superior, to judge from Walcott's descriptions, is very great, inasmuch as it presents a succession of reddish sandstones interlaced with diabasic lava flows. The relation of the Tonto to this series is such as to render evident the intervention between the two of a period not only long enough to cover the folding of the lower series, but the denudation of a pile of strata fully twelve thousand feet in thickness. Yet another similarity between the Grand Cañon section and that of the Lake Superior region is the occurrence of a second great unconformity beneath the Grand Cañon series, below which break is found a great disturbed series of quartzites whose similarity to much of the Lake Superior Huronian is strong.

Cases in which the overlying strata are inclined.

If we suppose a depression to take place in the region of an unconformable contact in such manner that the ancient land surface which marks the contact assumes a more or less inclined position, certain difficulties in the way of interpreting the structure may be introduced. If the inclination be but slight and the irregularities of the existing surface be considerable, so that the old land surface is not too rapidly carried
out of sight, the case will be but little different from that where the
overlying formation is entirely horizontal. But if the depression
has been such as to produce a considerable degree of inclination and
the denudation which has produced the present surface has been
very deep, the difficulties will be greater. Let us suppose, for in­
stance, a case like that indicated in the accompanying Fig. 90. The
strata are now all considerably inclined and it may take some care­
ful observation to establish the break. In forming an opinion as to
the structure in such a case we may take into account (1) the relative
areal distributions of the several kinds of rocks which make up the
supposed discordant formations; (2) the relative lithological charac­
ters of the two formations; (3) their relative structural characters;
(4) the nature of the minor phenomena of the contact line; and (5)
the presence or absence of basal conglomerates.

Relations of the rock belts of the discordant formations.—Where
the formation above an unconformity is undisturbed the true struc­
ture is best seen, of course, in an extended vertical section cutting
through the upper horizontal formation and into the lower disturbed
one. In such a case as that we are now considering, however (i. e.,
where the overlying strata are considerably inclined to the horizon),
the present surface of the country should furnish us with a section,
corresponding to the vertical one in the former case. In other words,
a map of such a region, showing exactly and in detail the distribu­
tion of the various rock belts and areas on either side of the supposed
line of discordance, should present evidence to us of the existence of
the break. This break and the ancient land surface marking it,
being the result of an intervening denudation, should intersect the
rock areas and belts of the lower formation in such a manner as to
indicate plainly to the eye that portions of such belts and areas have
been removed. On the other hand, the rock belts of the overlying
formation should be free from interruptions other than those in­
cident to ordinary sedimentation. On a subsequent page is given a.
brief account of the unconformity of the Penokee region of north Wisconsin and Michigan, accompanied by a map showing the distribution of the rock belts of the region. This map illustrates most beautifully the principle which it is here desired to explain.

Relative lithological characters of the discordant formations.—A pronounced contrast in lithological characters between the two discordant formations is not a theoretical necessity, but it is the ordinary rule, and particularly so in the case of the ancient formations with which we are now particularly concerned. If, in our supposed case of highly inclined but unfolded strata resting against a steeply sloping wall, this wall should present rock-kinds, such as gneiss and other crystalline schists, which have been produced in some way by a profound alteration of sediments, and the overlying formation should show unaltered or relatively little altered kinds, very strong presumptive evidence of the existence of a great unconformity would be offered.

Relative structural characters of the discordant formations.—The lower formation in such a case as we are now supposing would of course be folded, the upper one unfolded, and this difference would constitute the main structural distinction between the two terranes. Cases might arise, however, in which it would be difficult to determine whether the upper formation might not really return at some point beyond the contact line, so as to be folded in with the lower formation. Other minor structural differences which will often present themselves may then be appealed to, and these minor distinctions in any case may often help greatly in establishing the unconformity. While the rock belts of the two formations may, in the neighborhood of the contact line and for the short vertical distance through which it is possible to follow them, show dips and strikes accordant with those of the layers of the upper series, they will more commonly present us with discordances in this respect. These discordances may be seen not only on the larger scale, by comparing the courses of larger belts of the two series, but also in their more minute lamination-structures. In such ancient formations as those which we are especially considering, where there may be a close folding in the lower of the supposed formations, its lamination-structure may well be the result of pressure and may lie quite out of parallelism to the true bedding of the formation; but, even if so, the discordance between a lamination of such an origin and a genuine sedimentary lamination in the formation above the unconformity is strong confirmatory evidence of the existence of the unconformity. The absence of foliation in those masses above the contact line and its presence in those below certainly indicate the production of such a structure prior to the deposition of the upper strata.

Relations of eruptives to the contact of the discordant formations.—It has already been shown how masses of eruptive material which
antedate the denudation of the intervening land surface in the case of an unconformity are truncated by the contact line. Such interruptions are of particular assistance in determining the structure where the overlying formation is inclined, for under such circumstances they often present great areas to view and may show us extended contacts with the sedimentary rocks of each of the supposed discordant formations. We may suppose, for instance, the case of a great mass of eruptive granite in the folded formation below the break. Where this mass comes in contact with the other rocks of the lower formation it penetrates them intricately in large and smaller branches. Where it is intersected, however, by the contact line and comes in contact with the layers of the upper series, it should show no such penetration, but, on the contrary, should present indications of having been the surface upon which the unfolded strata are deposited.

Minor phenomena of the contact line—basal conglomerates.—In such a case as that now supposed the question might arise as to whether the two great masses of rock on opposite sides of the contact were not brought together by a deep-seated faulting movement. An answer to this question may often be afforded by a close study of the actual contacts of the formations, where they are exposed to view. If a faulting has taken place, this will often be rendered apparent by indications of a sliding movement between the two formations and the consequent shattering of the adjacent rocks. On the other hand, if the contact be one between an eroded surface and the sediment laid upon that surface by the waters of the sea, it should present no indications of such movement and should be expected to show an insertion of the sedimentary material into the irregularities of the surface beneath. Particularly should we expect to find along such a contact, but not necessarily everywhere, fragments of the older rocks embedded within the newer, these fragments ranging perhaps from a fine sand to great angular masses weighing many tons. Such accumulations of detrital material (basal conglomerates) along a contact between two dissimilar kinds of rock are alone enough to indicate a great intervening lapse of time, unless it can be shown that the rock which has furnished them is one which was erupted directly at the surface or one which in some other way may have rapidly reached its present condition of induration and crystallization.

Examples.

Unconformities between the Animiké series of the north side of Lake Superior and the adjacent formations.—The relations borne by the Animiké series to the older schists and granites of the region north of Lake Superior furnish us with an excellent instance of an
unconformity in which the upper series has been tilted into an inclined position since its original accumulation, but in which the amount of tilting has not been great. In other words, it is a case where the conditions are not greatly different from those obtaining when the upper formation has remained horizontal.

The geology of that portion of the United States lying north of Lake Superior is shown in the map (see Pl. XLI), with its accompanying sections. Since this plate embodies a great deal of entirely new material and since the geology of the area it represents has been hitherto, so far at least as the interior is concerned, largely conjectural, it is desirable that I should give here somewhat more of an account of the structure of this region than would otherwise be necessary.

The latest formation of the region is the Potsdam sandstone, which is in the extreme southwestern corner of the area mapped, in the vicinity of the St. Louis River, between Fond du Lac and Thomson, Minn. The sandstone, here of a generally reddish cast and with a slight easterly dip, may be seen directly overlying a series of folded and cleft slates belonging in the upper part of the Ani­mi­ki series, as subsequently explained. The contact of this sand­stone with the Keweenawan rocks, which are largely displayed in the vicinity of Duluth, is concealed; but in Douglas County, Wis., at a distance of ten or fifteen miles southeast from Fond du Lac, it may be seen in very distinct unconformable abutment against the Keweenawan diabases of that district. Farther east the entire coast.

This map embodies in a condensed form the hitherto unpublished results of a large amount of study in the field. Heretofore, except along the immediate coast of Lake Superior, no attempt has been made to map this region otherwise than in the most general manner. Indeed, being a complete wilderness it has been geologically for the most part a terra incognita. Portions of the ancient canoe route along the national boundary line have been followed several times during the last sixty years by different geologists (Bigsby, Bell, Norwood, and N. H. Winchell) and the results of their desultory observations have been published in the form of itineraries. Similar publications have been made of observations made along two or three routes in the region between the boundary and the coast of the lake by N. H. Winchell and W. M. Chauvenet. A summary account, with outline map and sections, embodying all of the results in this region to date, was prepared by myself in 1881 (Monograph of the U. S. Geological Survey No. 5, published in 1883), and some of the results of the field season of 1883 were announced in a preliminary paper on an investigation of the Archaean formations of the Northwestern States, published by myself in the Fifth Annual Report of the U. S. Geological Survey, the preparation of this paper and of the map accompanying it dating from June, 1884. In the years from 1885 to 1886, aided by Messrs. Merriam, Chauvenet, and Williams, I have been engaged in a general exploration of the interior part of this region, particularly in portions hitherto entirely unknown, in which work Mr. Merriam has had the largest share, the lengths of his lines of travel, not counting minor irregularities and repetitions, aggregating to date (July, 1886) something like fifteen hundred miles. The work in this region is still in progress, but has now advanced far enough to justify the publication of this preliminary map.
UNCONFORMITY BETWEEN POTSDAM SANDSTONE AND HURONIAN QUARTZITE.
BOWDER CONGLOMERATE INCLUDED IN THE POTSDAM SANDSTONE.
BOWLDER CONGLOMERATE AND PEBBLE CONGLOMERATE OF THE POTSDAM SANDSTONE.
UNCONFORMITY BETWEEN POTS DAM SANDSTONE AND ARCHAEAN GRANITE.
QUARRIES IN POTSDAM SANDSTONE, MARQUETTE, MICHIGAN.
VIEW ON ST. MARY'S RIVER.
The color for the Vermilion Lake Iron-bearing Series is supposed to cover also some older schists. In the two western areas of granite there are included a few small patches or remnants of mica-schist or gneiss.

GEOLOGICAL MAP OF NORTHEASTERN MINNESOTA

JANUARY 1886.
of Lake Superior, to within two miles of the mouth of the Montreal River, on the boundary line between Michigan and Wisconsin, is formed of the same sandstones in horizontal position.

Unconformably beneath the Potsdam sandstone comes next the great Keweenaw series, which in this region reaches an aggregate thickness of upward of twenty thousand feet, the layers being mainly of an eruptive origin, but also in part of a detrital nature. The upper detrital division of the Keweenaw series is, however, not represented in the region, being buried here beneath the waters of Lake Superior. So far as the coast line of the lake is concerned, the characters and divisions of the Keweenawan rocks there displayed I have set forth in another publication. It will only be necessary here to recapitulate some of the most prominent characteristics. In a general way it may be said that the beds of this series have throughout their extent in northeastern Minnesota a flat dip toward Lake Superior, or in a southeasterly direction. When, however, we examine the structure more closely we discover that there is a variation in the amount of dip, from 45° (which high figure is reached only in the immediate vicinity of Duluth) to approximate horizontal, and in the direction of dip from due east to due south. These variations in the amount and direction of dip, however, are not irregularly distributed. The due eastward dips obtain at the western extremity of the coast line, whence, as we follow the layers of the series eastward, the direction of the dip is found to turn more and more to the south of east, until, midway the course of the coast, it is due southeast, or directly at right angles to the coast line, and at the eastern end of the Minnesota shore is due south. Thus it follows that the outcrops of the layers or groups of layers make a series of crescentic and concentric belts whose radii are smaller than that of the coast line itself. A complete ascending section of the series, so far as it is developed in this region, may, then, be obtained by crossing the country in a southeastward direction from the vicinity of Kekekabik Lake to the mouth of Temperance River, or by following the coast line northeasterly from Fond du Lac to the same point. A third section may be obtained by proceeding along the coast from Grand Portage Bay southwestwardly to Temperance River, but this section will be less complete than the others, partly because of the fact that some of the members of the section developed farther east are not here represented and partly also because the lowermost members of the series do not reach the coast in this distance.

In the case of either of the more complete sections we find at the base of the series an immense development of stratiform, fresh, and often exceedingly coarse olivine gabbros, the individual layers of

which, notwithstanding their complete crystallization, very coarse
grain, and lack of amygdaloidal or dense upper surfaces, seem evi­
dently to have formed great flows at the surface of the region as it
stood at the time of their extrusion. Next to the belt of country oc­
cupied by these olivinitic gabbros follows a belt in which non-olivin­
itic gabbros are confusedly mingled with intrusive, reddish, acidic
rocks of several kinds. These are the rocks exposed on the hills at
Duluth, Minn. At some little distance west of the place the lower
olivinitic gabbros are in sight. The lower one of these gabbro belts
receives a separate color on the accompanying map, the upper one
being covered by the same color that spreads over the remaining
layers of the Keweenawan series. These remaining layers are made
up in their lower portions of a succession of heavy, but sharply
defined beds of very fine-grained diabases and diabase-porphyrites,
with some interleaved detrital matter and with thin amygdaloïds,
capping many but not all layers. Next follows a series of heavy,
fine-grained, brown diabase-porphyrites, along with some intrusive,
acidic, reddish porphyrites. All these layers bear a distinct resem­
blance to the rocks which occupy a corresponding horizon in the
Bohemian Range of Keweenaw Point. There is then a succession of
relatively very thin flows, composed mainly of a fine-grained, olivine-
bearing diabase or melaphyre having a very highly vesicular, strati­
form amygdaloid, with a number of thin seams of reddish sand­
stone. Above this comes a series marked by the predominance of
dark, olivine-bearing gabbros without amygdaloids and by the great
abundance of interleaved and intrusive, red, acidic porphyrites.
Finally the uppermost layers of the series, as here developed with
a thickness of two to three thousand feet, are very distinctly bedded,
fine-grained diabases and melaphyres with strongly developed amyg­
daloïds and a considerable quantity of interstratified sandstone and
conglomerate. These layers in turn bear a striking resemblance to
those which make the upper portions of the eruptive division of the
Keweenaw series of Keweenaw Point.

Next in downward order comes the Animiké iron-bearing, slaty
series, whose relations to the adjoining formations it is now designed
especially to set forth. The Animiké rocks are exposed in four dis­
tinct areas, one of which is separated from the others by an overlap
of the great gabbro which forms the base of the Keweenaw series.
The others are separated from one another, so far as known, by drift
covering only. The first of these areas is that which, with its prin­
cipal development in Canada, along the shores of Thunder Bay,
crosses into the United States in northeastern Minnesota, the na­
tional boundary line being within this formation from the outlet of
Gundfint Lake eastward to the eastern extremity of Pigeon Point.
Around Thunder Bay the rocks of this series, which are chiefly black
slates, graywackes, argillaceous quartzites, interstratified diabase, and
gabbro layers, which are many in number and individually often have a considerable thickness, are exposed on a large scale. Immense dikes of gabbro and diabase also penetrate these layers, the gabbro dikes, which are at times several hundred feet in thickness, being noticeably much closer in character to the great gabbro at the base of the Keweenaw series than to those gabbros which are interlaced with the Animiké slates.

In the vicinity of Thunder Bay the Animiké rocks are often nearly horizontal, but show a general tendency toward a southeastward inclination. As the formation crosses into United States territory it shows more marked inclinations, which average probably about ten degrees, though at times less than this, and sometimes reach as much as twenty degrees. The national boundary line is situated within this formation from the mouth of Pigeon River to Gunflint Lake; but on the north side of the latter lake, and again to the north of the next lake to the east, called North Lake, the unconformable abutment of the Animiké series against an older formation of granite and schists is very handsomely shown. The actual contact of the two formations is not seen, but the exposures approach to within a few feet of each other and the relative attitudes of the two formations are such as to leave no question whatever with regard to the unconformity. Not only is this shown by the vertical position of the schists as contrasted with the flat inclinations of the slaty series, but also by the way in which the latter beds, to the north of the two lakes mentioned, fit into the sinuosities of outline of the older formations. The entire contrast as to lithological characters between the two sets of rocks furnishes further proof. A north and south section midway in Gunflint Lake is given herewith to illustrate these relations (Fig. 91). So far as it is developed along the national boundary line the lowest layers of the Animiké series in sight are those on Gunflint Lake. The highest layers are those in the vicinity of Grand Portage Bay, the whole succession between these points being some thousands of feet in thickness. The iron-bearing horizon at the base of this succession is lithologically identical with that of the Penokee series of northern Wisconsin and Michigan, while the black slates, graywackes, etc., which succeed the iron-bearing horizon, are in turn
The counterparts of those which form the middle and upper portions of the Penokee series. The interstratified gabbros of the Animiké are wanting, however, or are relatively rare in the Penokee region.

In attempting to trace the Animiké rocks from this area farther west and southwest we find ourselves constantly balked by the overlapping layers of the Keweenaw series. This overlap will be best appreciated on an inspection of the accompanying map (see Pl. XLIII), upon which it is shown that the basal olivine-gabbros of the Keweenaw series entirely cut out the Animiké in its surface distribution, coming, a few miles to the west of Gunflint Lake, directly into contact with the older schists. Continuing southwest, now, nothing further is seen of the flat-lying Animiké beds for over fifty miles, but in the vicinity of the south side of Birch Lake they emerge from beneath the overlapping gabbro. From here the lower members of the series, with the usual flat southeasterly dip and with the lithological characters well preserved, may be traced along the south side of the Mesabi granite range as far as the Embarrass Lakes, a distance of some twenty-five miles, in which distance they are plainly in unconformable abutment upon the granite to the north. After this they are concealed entirely, so far as present knowledge goes, by the immensely heavy drift-covering of the region, until the vicinity of Pokegama Falls, on the Mississippi River, is reached, some sixty miles farther to the southwest. Here the basal layer of the Animiké is a reddish quartzite, followed by and associated with layers of cherty iron ores, like the remaining ones of the Animiké series. These layers dip at the usual flat angle to the southeast and rest unconformably upon gneiss and granite, which are plainly the direct continuation of those of the Mesabi Range.

Southward and eastward of the line from the Mesabi Range to Pokegama Falls the rocks are mainly concealed by swamp or heavy drift covering, but a great display of the upper portions of the Animiké series is seen again along the St. Louis River from Knife Falls to Thomson, where they are cleft and folded argillaceous slates. Farther south and west these slates may be traced into continuity with mica-schists, which, on the Mississippi River in the vicinity of Little Falls, are staurolitic and garnetiferous. These upper horizons of the Animiké are the counterparts of the upper horizons of the iron-bearing series in the Penokee region and again in the Marquette region of Michigan.

The Animiké rocks of this region are thus unconformably placed upon an older series of schists and granite and lie unconformably beneath the newer Keweenaw series, the latter unconformity being indicated by the manner in which the basal beds of the Keweenaw series traverse the courses of those of the Animiké and by the folded condition of the Animiké slates in the vicinity of the St. Louis River.
Greywacke & Black Slate member
Iron-Bearing member
Siliceous Slate member
Limestone & White chert member
Granite and Granitoid Gneiss
Biotite and Amphibolite Schist, Chlorite Schist Mica Schist & Schistose Gneiss.

Scale of Map 500,000
Scale of Sections 326,000

GEOLOGICAL MAP OF THE PENOEKEE-GOGEBIC IRON REGION.
The crumplings in this case have plainly preceded the accumulation of the Keweenawan beds.

Finally, northward from the outcropping edges of the Animiké series the country is everywhere occupied by belts of closely folded slates and schists, between which are great areas of granite. A part of these schists, with the granite, makes up the older basement upon which the Animiké rests. Another part, made up of slates and other fragmental rocks and carrying great thicknesses of ferruginous material, is taken to be the same as the Animiké itself, as is further argued on a subsequent page (Pl. XLII).

Unconformities of the Penokee-Gogebic region of northern Wisconsin and Michigan.—No other so striking example of unconformity between a series of highly tilted but unfolded strata above the break and a deeply folded series below as that afforded by the Penokee region is known to the writer. Indeed, there are in this region two notable stratigraphical breaks: one between the iron-bearing series and the folded gneissic formation to the south of it; another between the unfolded but inclined iron-bearing series and the equally highly inclined Keweenaw series to the north. These breaks and the terranes which they separate are the counterparts of those just described as obtaining north of Lake Superior.

The accompanying map (Pl. XLIII) shows the distribution and structural relations of the several formations and the several principal kinds of rocks in this region. The Keweenawan and iron-bearing series both being highly inclined, the map is in fact what the vertical section is where the upper strata of an unconformity are still essentially horizontal. The region is one which is only now beginning to be at all easy of access and it is still in the main covered with a dense forest growth. Notwithstanding these difficulties and the further difficulty that in places the drift covering is considerable, the general structure of the region has been by a great deal of painstaking labor very thoroughly worked out.

The lower one of the two unconformities of this region—i.e., that between the gneissic formation on the south and the iron-bearing series next north of it—is indicated in the first place by the manner in which the belts of the former series are traversed and interrupted by the continuous belts of the upper formation. This relation is beautifully shown by the map (see Pl. XLIII) which indicates the distribution of the several rocks of the region, and this distribution is alone enough, considering the kinds of rock of which the lower series is composed, to indicate the existence of the unconformity. If the gneisses, schists, granites, etc. to the south of the break, after having been deeply cut by atmospheric denudation, had formed the sea-bottom upon which the iron-bearing series was piled by the ordinary processes of sedimentation, the relations would be precisely such as obtain here. Lest it might be argued that the
various rock masses here included under the general designation of gneissic formation may have had an eruptive origin, and therefore an irregularity in distribution, so that the base of the iron-bearing series comes necessarily into contact with different kinds in different places, I may say that, even should we accept an eruptive origin for these rocks, an unconformity is still demonstrable. If eruptive, these southern rocks have certainly not been extruded subsequently to the deposition of the beds of the iron series. Had they been so extruded, it is inconceivable that a series of eruptions different as to materials and times of extravasation should all have stopped so near to one geological horizon. On the contrary, some of them would have deeply invaded the iron-bearing series. But of such an invasion no sign whatever is to be seen, either in the geographical arrangement of the different kinds of rock, as shown by the map, or in the minor structural details observed at the contacts of the two formations. Moreover, the basal beds of the iron series contain abundant fragments derived from the more southerly granites, gneisses, and schists. It is thus plain that the southerly rocks have formed the basement upon which the iron-bearing series was built. Sediments may of course be piled upon a basement of eruptive materials of essentially the same geological age, but the case we are considering here finds no parallel in such occurrences. The gneisses, schists, granites, etc. forming the supposed eruptives are, if eruptive, certainly not to be compared with the lavas of modern times. On the contrary, their completely crystalline character and general structure would force us to believe that they solidified far within the depths of the earth, and that therefore, before they reached the surface of the bottom of the sea upon which the slate beds were accumulated, the whole region in which they occur must have been subjected to an enormous atmospheric erosion. There is here, then, a genuine geological break, even in the view that the more southerly rocks are all eruptives. But an eruptive origin for all of these rocks, thus admitted for the moment, is by no means accepted as true. The granites of the gneissic series plainly are of eruptive origin. This is made manifest by the way in which they intersect the associated schists at their contacts with them. The gneisses and schists of the series, however, are in part at least of a sedimentary origin. Some of the schists particularly retain traces of their former fragmental texture, though now mainly made up of material which has crystallized in situ. If these gneisses and schists be in any measure of sedimentary origin, then of course they passed through immensely prolonged processes of dislocation, alteration, and erosion before the deposition upon them of the earliest member of the overlying series.

The closely folded and crumpled condition of the gneissic series as compared with the unfolded condition of the iron-bearing series affords, of course, another argument in favor of the existence of the unconformity.
A further proof of the entire discordance of the two sets of rocks is afforded by the striking contrasts they present in lithological characters. This is particularly shown by the very different degrees of alteration that the two series have undergone. The once possibly fragmental sediments of the lower series are now completely crystalline, while the eruptives of the series have generally undergone most profound metasomatic change. In the upper series, on the other hand, the retention of the fragmental character is the rule and the eruptives are all of a basic character, while all of the crystalline material met with in the rocks of the series that is not referable to solidification from a molten state or to direct chemical deposition is distinctly traceable to merely metasomatic change. The rocks of the upper series are not properly crystalline schists. Those of the lower series are crystalline schists in the fullest sense of the term.

Yet another proof of unconformity is afforded by the contrast between the contacts of the granite masses of the lower series with the schists of the same series and the contacts of the same granites with the basal member of the iron-bearing formation. As already said, where the granite meets the lower schists it intersects them intricately, but where the basal beds of the iron series lie against the granite they are never penetrated by granite veins, but, on the contrary, show every evidence of having been deposited upon the granite surface.

A yet further proof is found in the discordant laminations of the two sets of rocks, when seen in contact or close proximity. This discordance is at times very marked, while in other places there is a near approach to parallelism in strike and dip of the lamination-directions of the two formations. In the newer slate and iron-bearing series the lamination, always plainly the result of sedimentary deposition, conforms of course to the general courses of the rock belts of the series, and since these courses vary considerably, as indicated on the accompanying map, the lamination-directions vary also. Hence follow discordant laminations in the vicinity of some contacts and accordant ones at others, which is precisely what we should expect along an unconformable contact line. It is no argument against this conclusion to maintain that the lamination of the older set of rocks is in this case what is known to geologists as foliation, and not the result of sedimentation. It is probably commonly foliation, that is, a structure in some measure due to the intense squeezing which the older schistose series has undergone, and very often probably occupies a position quite oblique to the original bedding directions, but it is plain that it must have been produced before the deposition of the first of the overlying slaty rocks, for otherwise the latter must have been affected also by a foliation similar in character and direction. The occurrence of foliation on one side of a contact line and its absence on the other, where this contact is one between two great
and dissimilar sets of rocks, are strongly suggestive of the existence of a great structural break. It should be said that the discordance of lamination is not made out only from closely approximated exposures, but also from actual contacts, where the basal layers of the slate series may be seen to traverse the edges of the laminae of the older formation at a considerable angle.

Finally, a convincing proof is found in the occurrence of finely developed basal conglomerates at the contact of the two formations. There are several points along the contact line where one may pass within a few steps from ledges of gneiss or schists of the older formation to others of the lowest member of the newer, the latter being crowded with fragments derived from the older rock. Even the matrix portion of the rock is composed of gneissic or schistose detritus, while a few steps further away from the contact it has graded into an ordinary quartzite or slate. The most interesting occurrence of this kind is that met with on the gorge of the Potato River in the western part of T. 45 N., R. 2 E. of the fourth principal meridian, Wisconsin, where that stream intersects the contact of the two
formations. The eastern side of the ravine presents good exposures of the lower 500 feet of the iron-bearing series and also of the schists below. At one point on the ravine side a cliff about thirty feet in height shows, obliquely traversing its face at an angle of about 45° with the horizon, the junction of the basal member of the iron-bearing series and a green schist of the lower series. The true inclination of the junction is 70° to the northwestward, the apparent lower figure being produced by the acute angle which the cliff face makes with the general strike direction. The greenish, chloritic, schistose rock of the lower series at the contact is a very profoundly altered greenstone or basic eruptive. Its very strongly marked schistose structure inclines southward, making a right angle with the contact line. Reposing directly against the wall of schist may be seen several hundred feet in thickness of a slate or slaty quartzite, whose laminae are in general parallel to the contact line. The lower sixteen inches to two and one-half feet of this slate is a finely developed basal conglomerate, including great fragments of the greenish schist, which at times reach dimensions of five by two and one-half feet in size. Fragments of all sizes of the schist occur and the matrix of the conglomerate is plainly composed largely of a fine material of the same derivation. Fragments of other rocks, such as white quartz, at times as much as eight and ten inches across, also occur. These pebbles show by their greater rounding their more distant derivation. From the conglomerate to the slate there is a rapid but not abrupt transition, the slate containing less and less of the schist detritus as it is followed to the north and being more and more composed of its usual fragmental quartz and feldspar.

It should be said here that when we look in general at the fragmental rocks of the iron-bearing series of the region we can say not only that their materials are theoretically derivable from the rocks of the gneissic series to the south, but even that there is a change in their composition as one passes along the strike of the several rock belts, which may be correlated with the change in character of the rocks which are exposed in the gneissic region to the south.

Any one of the arguments thus presented would alone be sufficient to render exceedingly probable the existence of this unconformity. Taken together they seem to constitute a complete demonstration. North of the narrow belt of country occupied by the iron-bearing series in this region and all the way to the shores of Lake Superior, the rocks of the Keweenaw series are at surface, with the exception of a belt of country in the vicinity of Chequamegon Bay, which the Potsdam sandstone underlies, and of a small area in the vicinity of Presqu'Isle River, which is also occupied by the same formation. This sandstone, as already indicated, lies horizontally upon the upturned beds of the iron-bearing series and of the Keweenaw series. The nature and general structural characters of the Keweenawan
rocks I have somewhat fully described elsewhere. Here it is merely necessary to say that the group consists of a great series of eruptive flows, alternating with which are beds of detrital material, and following which is an immense thickness of sandstone. In the vicinity of the iron-bearing series these layers stand at high angles and present in strike and dip a general-conformity with the layers of the iron series itself; but a closer inspection renders it evident that the upper surface of the iron-bearing series has suffered a deep erosion previous to the spreading upon it of the great flows of which the lower portion of the Keweenaw series is composed. This is brought out very strikingly by the accompanying map (see PI. XLIII), which indicates also that, although the iron series is in one sense unfolded, it nevertheless underwent a certain sort of corrugation prior to the piling upon it of the great Keweenaw series, its beds having been gently bowed upward along certain lines whose direction was transverse to the present courses across the country followed by the outcrops of these beds.

CASES IN WHICH THE OVERLYING STRATA ARE FOLDED.

If, instead of being simply inclined by a depression in one part of the ancient land surface upon which they lie, the strata above an unconformity are pressed together so as to take on a folded condition, still greater difficulties in the recognition of the unconformity may arise. If the bowing is but slight, the case may be but little different from that last considered. But if the folding has been close, so as to produce high inclinations, rapid returns and even overturns of the strata of the upper formation—in which folding of course the underlying formation itself must have taken part—and if the subsequent denudation has been deep, we are presented with the greatest possible obstacles in the way of working out the true structural relation between the two formations. Each may have acquired from the intense pressure accompanying the folding a schistose structure having a general uniform direction, and the laminations of both series will appear to have a generally uniform dip and strike.

Such a condition is well illustrated by the cross-section of the Menominee region of Michigan and Wisconsin given on a subsequent page (see Fig. 95). The iron-bearing series there shown accumulated in an eroded basin among strata already deeply folded. A subsequent folding process setting in with considerable force, the once horizontal strata were now bent into angulated folds and had developed in them more or less of a schistose structure, after which denudation produced the present surface. The discordance between the two formations is evident enough still in the diagram, but as seen upon the surface of the country (which, in such a region, is essentially all we are able to study) the relation is by no means so plain. In
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some cases we must often remain at fault, but in others, again, the true relations may gradually be worked out. Discordances in strike and dip at the contact of the two formations are, of course, not of frequent occurrence in such extreme cases, and perhaps the lithological contrast between the two formations may not at first sight be very striking. But such contacts as there may be, if accompanied also by the presence of basal conglomerates in the upper series, will often enable us gradually to work out the true structure.

EXAMPLES.

The Laurentian-Huronian unconformity of the north shore of Lake Huron.—The relation of the original or type Huronian of this region to the horizontal Cambrian and Silurian formations has already been referred to and illustrated by a section copied from Logan (see Fig. 85). The same section shows very plainly what Logan's views were as to the relations between the Huronian and the underlying gneisses in the same region. It has been denied that Logan believed in such an unconformity, but this section and the others accompanying it in the atlas to the Geology of Canada show that he must have done so. These sections, I am told, were reproduced from drawings by Logan's own hand. The same belief is indicated by his description in the Geology of Canada of the occurrences on Lake Temiscamingue, where the Laurentian gneiss is said to be followed by a slate conglomerate "holding pebbles and bowlders, sometimes a foot in diameter, of the subjacent gneiss, from which they appear to be principally derived." On Logan's view as to the metamorphic origin of gneiss, plainly the occurrence of such conglomerates at the base of the Huronian could only be explained by an unconformable break. Statements in less well known publications by Logan have placed

3 In a paper by Logan On the division of the Azoic rocks of Canada into Huronian and Laurentian, Proc. Am. Assoc. Adv. Sci., Montreal meeting, 1857, part 2, p. 45, the following paragraph occurs:

"In the same report is mentioned, among the Azoic rocks, a formation occurring on Lake Temiscaming and consisting of siliceous slates and slate conglomerates, overlaid by pale sea-green or slightly greenish-white sandstone, with quartzose conglomerates. The slate conglomerates are described as holding pebbles and bowlders (sometimes a foot in diameter) derived from the subjacent gneiss; the bowlders displaying red feldspar, translucent quartz, green hornblende, and black mica, arranged in parallel layers, which present directions according with the attitude in which the bowlders were accidently inclosed. From this it is evident that the slate-conglomerate was not deposited until the subjacent formation had been converted into gneiss, and very probably greatly disturbed, for, while the dip of the gneiss, up to the immediate vicinity of the slate-conglomerate, was usually at high angles, that of the latter did not exceed nine degrees, and the sandstone above it was nearly horizontal."

the matter entirely beyond doubt, showing certainly his full belief in such an unconformity.

So far as concerns that portion of the original Huronian of which I have been able to gain a personal knowledge, the principal proofs of an unconformity lie in the abundant occurrence in the upper series of fragments of the gneiss, granite, and crystalline schists of the lower and in the relatively slightly altered and gently bowed condition of the entire Huronian series as compared with the intense changes and close crumpling which the gneissic formation must have undergone. Particularly striking is the basal conglomerate to be seen about two miles to the east of Thessalon River, where the arenaceous quartzite forming the base of the series may be seen, with a gentle westward dip, resting against a gneissic rock, enormous fragments of which it carries, of all sizes and all degrees of rolling. As one passes away from the immediate contact, these fragments become smaller and tend to arrange themselves in regular zones, between which are bands of a less pebbly and more sandy nature. Where the pebbles are plentiful and for some distance from the contact, the sand itself is largely composed of a fine detritus directly derived from the gneiss. There are also included enormous fragments of various highly altered greenstones and schistose rocks which occur in place within the gneissic formation. The illustrations of this occurrence here given are reproductions of photographs (Plates XLIV to XLVII).

horizontal strata, which form the base of the Lower Silurian in western Canada, rest upon the upturned edges of the Huronian series, which in its turn unconformably overlies the Lower Laurentian. The Huronian is believed to be more recent than the Upper Laurentian series, although the two formations have never yet been seen in contact."

Some of the confusion with regard to this matter has proceeded from a singular statement made by Logan in the Geology of Canada, p. 55, which runs as follows: "The gneiss extends to the vicinity of a small stream about a mile and a half above Les Grandes Sables, and what is supposed to be the lowest Huronian mass of that part occurs about half a mile above the stream. It consists of a gray quartzite which abuts against one mass of gneiss and runs under another, and appears to be much broken by and entangled among the intrusive rock; but judging from a transverse measure in one part its thickness would not be far from five hundred feet."

It has always seemed to me in reading this statement that some printer's error must have crept into the text. We may conceive of Logan's stating that the quartzites abut against one mass of gneiss and run under another; but how he should speak of gneiss as an intrusive rock I certainly cannot understand. However this may be, having been on the ground with Logan's descriptions in my hand, I am able to say that this place shows the quartzite dipping gently to the westward in distinctly unconformable position with regard to the gneiss, fragments and masses of which occur in the quartzite in the greatest profusion. Though I saw no such appearance as would justify the statement that the quartzite lies under the gneiss I can conceive that this misconception might have arisen from the occurrence within the quartzite of large gneiss masses or from the projection of irregular protuberances into the quartzite from the surface of the gneiss. Certainly the place furnishes the handsomest example of a basal conglomerate that I have ever met with.
The general nature of the Huronian of Lake Huron has been indicated on a previous page, its chief characteristics being its fragmental nature, its slight alteration, and its gentle folding. This description will not apply at all to the larger part of the rocks which the Canadian survey has been for a number of years and still is mapping as Huronian. It is not necessary to inquire now just when and how the term came to be spread from the plainly fragmental series of the north shore of Lake Huron over these other rocks, which are in the main genuine crystalline schists. Part of the confusion has doubtless arisen from the fact that the fragmental series and the older crystalline schists are often closely folded in with one another, as is the case on the south side of Lake Superior. However this may be, it seems eminently proper that the formation of that area which Logan and Murray have mapped in detail on Pl. III of the atlas to the Geology of Canada (1863), i.e., the area along the north shore of Lake Huron, from St. Mary's River to Thessalon River, should serve as the type of the group.

The unconformity between the iron-bearing and gneissic series in the Marquette region of Michigan.—This region furnishes an instance of an unconformity in which the upper of the two formations concerned is more closely folded than is the case with the Huronian on Lake Huron, although the closeness of the crumpling does not reach such an extreme as in the Menominee and Vermillion Lake regions, subsequently noted. In the vicinity of Marquette, Mich., a belt of much crumpled and generally steeply inclined schistose rocks reaches the shore of Lake Superior, with a width on the shore-line of about five miles. The coast of the lake here has a nearly due northerly trend, facing eastward. The course of the schistose belt is at right angles to this, that is to say, it lies east and west. Followed westward, this belt is found at first to expand to a width of some twelve miles, and then to contract again until at the eastern end of Lake Michigamme, 30 miles west of the Lake Superior coast, it is little more than two miles wide. Still farther west it expands over a large area, whose limits can hardly be said as yet to be determined. North and south of the Marquette schist belt are large areas of granitic and gneissic rocks.

Two widely divergent views have been held with regard to the relations of these granites and gneisses to the schists between them. The earlier writers on the region, and especially Messrs. Foster and Whitney in their classical report, held that the granites were of eruptive origin and of a date subsequent to the formation of the various schistose rocks, whose crumpled and disturbed positions they were disposed to assign to the eruption of the granite masses on

\[1\] That the composite nature of the Huronian of the Canadian geologists has struck others than the writer will be seen from Bonney's remarks in the Quarterly Journal of the Geological Society of London for May, 1886, p. 93.
either side of the trough. Later, on account of the arguments of
Kimball, Murray, Brooks, and others, the view came to be generally
held that the granitic and gneissic rocks represented the ancient
Laurentian basement, upon which the schistose or Huronian rocks
were distributed unconformably; that, the whole region having been
subsequently affected by lateral pressure, the sedimentary rocks were
pushed into folds; and that the granitic rocks on either side were
brought to the surface by denudation. Recently the older view of
Foster and Whitney has been advocated by Mr. M. E. Wadsworth
and Dr. C. Rominger, both supporting the view by appeal to intru­
sions of the schistose rocks by granite. It is true, of course, that
these granitic intrusions might be in part quite independent of, and
of later date than, the great granitic masses, but Dr. Rominger has
shown that intrusions of the schists along their contacts with the
granite are so plentiful in certain parts of the region that it seems
necessary to conclude that such invaded schists are older than the
granitic masses themselves. On the other hand, certain of the con­
tacts of the schists with the granite are found to present admirable
eamples of basal conglomerates, the granitic and gneissic rocks
having evidently been beaten upon and broken down by the sea in
which such schists were laid down.

These entirely contradictory appearances, however, find a very
simple explanation in the view that the schistose rocks themselves
are in fact made up of two entirely distinct series: an older series of
very intensely altered and crumpled schists, in the main of a green­
ish color, which are invaded intricately by the granite at their con­
tacts with it, and a newer, feebly altered, slaty series whose contacts
with the granites and the schists of the older basement are such as
to render the intervening structural break very evident. The con­
trast between these two sets of schists as to degree of alteration and
the penetration of the one set by the granite while the others show
no such penetration were partly realized by Dr. Rominger, as in­
dicated in his reports on the northern peninsula of Michigan, in
which, however, he still continues to regard the granite masses as
newer than all the schistose and slaty rocks of the region, the high
degre of alteration of the schists penetrated by them as compared
with the smaller degree of alteration of the remaining schists being
explained by the greater proximity of the one set to the granite. In
the same report Dr. Rominger shows, however, that the relatively
unaltered slates often come directly in contact with the granite, in
which case they present a peculiar appearance, suggesting to him an
alteration by contact with the eruptive masses. The peculiar gran­
itoid quartzites, however, which he takes to have been produced by
the heat of the granite, are beyond question merely detrital deriva­
tives from the granite and often run into coarse bowlder conglom­
UNCONFORMITY IN MARQUETTE REGION.

ates, as Dr. Rominger now realizes and states. However, neither
he nor any other writer on this region seems to have realized that
the clue to the geology of the region lies in the separation of the
schists and slates into two entirely distinct and discordant series,
which are plainly the same as those of the Penokee country of northern
Wisconsin and as those of the region north of Lake Superior,
both of which regions have already been cited as furnishing in-
stances of unconformities where the upper series is only highly in-
clined without folding. They are also the same as the two discord-
ant formations of the north shore of Lake Huron. These are the
upper, relatively feebly altered, iron-bearing, slaty and quartzitic
group, or Huronian, and the lower, greatly altered, gneiss, granite,
and green-schist group, or Laurentian.

This truth thoroughly appreciated, most of the proofs cited to
establish the existence of an unconformity in the Penokee region are
found to present themselves here also. Not only are the two forma-
tions of the Marquette region manifestly identical with those of the
Penokee region, with which they are, moreover, probably directly
continuous, and therefore inferentially discordant with one another,
but such a discordance for the Marquette region may be proved on
the ground by the discordant positions of the schists of the two
series when in contact or near proximity, by the large development
of basal conglomerates where the two formations come together, by
the indifference in position of the belts of the upper series to those
of the lower, by the striking contrast in amounts of alteration of the
upper and lower schists, and by the totally dissimilar relations of
the two sets of schistose rocks to the plainly eruptive granite masses.

That all of the rocks of the Marquette belt should have been
counted as making up one formation is not at all to be wondered at.
The infolding of the two sets of schists and slates has produced, of
course, a tendency to a general parallelism in their bearings; but, to
render the case still more difficult of comprehension, the denudation
that has so deeply invaded the region has brought to light, within
the area occupied by the newer slates, patches of the underlying
older schistose basement, which patches, completely surrounded or
bordered closely on either side by the newer slaty rocks, it has seemed
necessary to regard as parts of the same formation. The matter has
been yet further complicated by a resemblance, partly very close
and partly only macroscopic, or even imaginary, between certain of
the older schists, which are in part intensely altered and squeezed
basic eruptives, and certain interbedded basic eruptives of the upper
formation. Such a difficulty as this could only be put out of the
way by the use of microscopical methods of study, and these, of
course, were unknown to all of the earlier geologists and were insuf-
ciently used by the later writers on the region.

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CLASSIFICATION OF CAMBRIAN FORMATIONS.

Herewith I give two generalized north and south cross-sections of the Marquette schistose belt, one in the immediate vicinity of the city of Marquette, the other some few miles west of the city of Ishpeming (Figs. 93 and 94). These sections are drawn to scale and are based upon a study of all the available facts with regard to the region, including those presented by all the various writers and such as have been obtained by myself and assistants. But these sections are designed now only to indicate the general relations of the two formations of the region. No such minute study as would warrant a final mapping or arrangement of the succession of layers has yet been made.

The unconformity between the iron-bearing and gneissic formations in the Menominee region of Michigan and Wisconsin.—If we proceed in a direction southward from the Marquette region (Pl. XLVIII) we cross great areas underlaid by the granites, gneisses, and schists of the older formation; but when the Menominee River is reached, at the boundary of Wisconsin and Michigan, we have crossed also at least four distinct belts occupied by the rocks of the newer or iron-bearing series. According to the mapping of the Michigan geologists, these several belts merge farther westward into a single extended area of the iron-bearing series. It is certain that this formation has a wide spread in that direction, but it is equally certain that it is not so widespread as it is represented on their maps, since they have included areas which can now be referred without question to the older formation. Just what the relative extents of the two formations in this direction are remains to be shown by further exploration. Of the several belts indicated as crossed by a line run-
ning south from the Marquette belt to the Menominee River, that one skirting the Menominee River on its northern or Michigan side and running thence west and north into Wisconsin is the most extensive. The accompanying Fig. 95 is designed to represent the general relations of the two formations and the nature of the folding of the strata in this region. As in the case of the sections of the Marquette region, this one also has been drawn to scale after a careful study of all facts hitherto published and of those gathered by myself and assistants. The two formations concerned are manifestly identical with those of the Marquette region. We have here again to do with an upper, relatively little altered, iron-bearing series and a lower, deeply altered series of gneiss and schists, with immense areas of intrusive granite. The principal point of difference between the two regions lies in the much closer folding that the Menominee rocks have received. Had the section been made farther west a larger thickness of the Huronian strata would have been shown and other folds would present themselves. All the arguments that applied in the Marquette region in favor of the existence of a discordance between the two formations apply here again. The basal conglomerates of this series are particularly finely developed and may be seen on a grand scale at the contact of the basal quartzite with the granite at the falls of the Sturgeon River.

![Fig. 95. Generalized cross-section of the east end part of the Menominee iron district in the vicinity of Quinnesec, Mich. Scale, 2.3 miles to the inch.](image)

The several belts that intervene between the one just described and that of the Marquette region are much narrower, but nevertheless seem to contain as great a thickness of the iron-bearing formation as is usual in this region. In the case of the Felch Mountain belt, which does not exceed a mile in width, all of the strata dip at a high angle to the northward, and in crossing the belt from the south to the north, after passing the middle, one passes over a repetition of the layers crossed farther south, but in an inverted order, and we have evidently to do with a case of a syncline with the sides folded closely together. Fig. 96 shows in a general way the relation between the several belts from the Marquette region to the Menominee River.

The unconformity among the schistose rocks of the Vermilion Lake region.—The schistose rocks which have already been alluded to as
CLASSIFICATION OF CAMBRIAN FORMATIONS.

having so great a development in northeastern Minnesota, north of the northern limit of the Animikie beds, form a belt which extends from Vermilion Lake in an easterly and north east direction to the national boundary line, in the vicinity of Knife and Saganaga Lakes, a distance of some sixty miles. (See map, Pl. XLI.) To the west of Vermilion Lake this belt has been traced for some miles, but is soon lost underneath the heavy accumulations of glacial drift of that region. To the north it is bounded everywhere by granitic and gneissic rocks, the granites penetrating the schists along the margin of the belt, and for some distance inward also, in a most intricate manner. A similar area of granite and gneiss bounds the schistose belt on the south over much of the distance, and here also are seen again the intricate intersections of the schistose rocks by the granite. After reaching a point some thirty miles east of Vermilion Lake, however, the great flat-lying mass of gabbro which lies at the base of the Keweenaw series of that region overlaps and conceals this granite, the overlap extending to the schistose belt itself. Another granite area lies directly athwart the course of the schists in the vicinity of Saganaga Lake, although a portion of the schist belt apparently continues farther to the northeast into Canada along the northwestern side of this granite.

Folding and the production of schistose structure by lateral pressure seem to have been pushed to the very last extreme among the rocks of this schist belt, the dips within which are generally nearly vertical, although here and there among some of the fragmental rocks of the belt close crumplings may be traced, with their sharp anticlinal and synclinal bends. The secondary schistose structure, with its accompanying metasomatic changes, has been developed to the highest degree among the rocks of eruptive as well as among those of sedimentary origin. The common structural directions of all the rocks of the belt, as to both strike and dip, and the generally prevailing schistose structure suggest at first most certainly the conclusion that all of the schists of the belt are part of one formation, or, if of two formations, that the distinction between the two is no longer recognizable.
A closer study, however, serves to render such a conclusion less evident and shows that we have among the rocks of the belt two types, in one of which the crystalline structure is complete and in which there is little or none of an original fragmental structure, while in the other the fragmental texture is still distinct and the alteration has progressed to a smaller degree. Associated with the latter schistose rocks, are found great developments of jaspy and cherty, ferruginous schists, whose identity as to nature and origin with the ferruginous schists of the iron-bearing formation of the south shore of Lake Superior and of the Animiké formation of the north shore is complete. This identity, taken together with the close similarity of some of the fragmental rocks associated with the schists of the Vermilion Lake band to the fragmental rocks of the Animiké and of the south shore iron-bearing formation, and with the additional similarity that obtains between the remaining schists of the Vermilion Lake band and those of the older or gneissic formation of the south shore of Lake Superior, suggests to us that we have here again to do with a separation into an older and a newer schistose formation. The suggestion is deepened into conviction when we further consider the fact that the supposed older one of the two groups of schists in the Vermilion Lake belt is intricately penetrated by the granites of the great areas north and south of the belt, while the same granites, where they come in contact with the supposed newer schists, have yielded to them a profusion of fragmental material, among which material are many fragments derived from the supposed older schists themselves. The conclusion is, then, that the conditions obtaining in the Vermilion Lake belt are analogous to those which present themselves in the Menominee region, already briefly described, with the difference that the folding and schistose structure due to lateral pressure have been pushed to a far greater extreme in the former region (Pl. XLIX).

RÉSUMÉ.

The examples thus presented of unconformities in which the upper formation is displaced from its original horizontal position furnish us with a graded series. The Animiké rocks lie upon the older formation with but a slight inclination, while the Penokee iron-bearing series, though still unfolded, lies with a steep dip against a wall of the older formation. Next in the series comes the case of the Huronian-Laurentian unconformity on the north shore of Lake Huron, where the upper formation is gently bowed, but is without true schistose structure. In the case of the unconformity of the Marquette region, the upper formation is crumpled, even having the folds at times overturned, with frequent developments of slaty cleavage, but still having the folds in the main open and presenting a true schistose structure only rarely. In all of these cases, least distinctly of course in the last case, the discordance of the two formations concerned is to be
made out in part from the visibly discordant positions of the rocks of the two series. But when we proceed to the next case on the list, that of the Menominee region, such discordances are no longer to be made out with any distinctness, the close folding having brought the stratiform members of both groups to too great a uniformity of inclination. Finally, in the Vermilion Lake region, the extreme pressure to which they have been subjected has brought about not only a general community of inclination between the rocks of the two groups, but has developed in the lower group and among the eruptives of the upper group so complete a schistose structure as to render the separation of the two series often exceedingly difficult. Nevertheless, that the two groups are there actually represented the general argument above presented seems to me clearly to demonstrate, while such a state of affairs as there obtains is certainly no theoretical impossibility, on the hypothesis that these schists include two entirely distinct series of rocks.

THE USE OF UNCONFORMITIES IN CLASSIFICATION.

The use of unconformities in defining the grander groups of strata.—Returning to our problem as originally stated we have next to consider how far unconformities may be made use of in defining the grander groups of strata in a region in which the succession of these strata has been determined. Further argument than that already given in discussing the nature and kinds of unconformity is hardly necessary to show that genuine unconformities, indicative of great lapses of time between the periods in which the strata on either side of the break in each case were respectively made, are of prime value and importance in determining the limits of the grander groups of the geological formations, whatever use we may make of paleontological and lithological characters in determining subordinate divisions. Such structures as the greater ones of the true unconformities, above considered, indicate lapses of time great enough to cover extended periods of mountain-making, always a slow process, and also great periods of denudation or exposure to the atmospheric agencies. It is hardly possible for us to compare such time gaps with the time necessary for the formation of definite thicknesses of strata, but the thicknesses of strata corresponding to such breaks must surely always be very great.

If we take, for instance, the gap indicated by the relations of the Potsdam sandstone to the ancient gneissic formation of the Northwest, as above illustrated by a number of examples, we find that it was long enough to cover not merely one period of rock alteration, orographic movement, and land surface exposure, but three such periods, between which were times long enough for the accumulation of thicknesses of strata aggregating over sixty thousand feet—a thickness exceeding that of the entire Paleozoic series in its greatest
development in the Appalachian region. It is true that a portion of this sixty thousand feet is made up of volcanic materials, chiefly lava flows. The accumulation of such materials may, it is true, have been more rapid than is the case with ordinary fragmental deposits; but the accumulation of such a mass of eruptive material must have occupied at least a considerable lapse of time; while more than one-half of the sixty thousand feet, or an amount approximating the maximum Paleozoic accumulations in the Appalachian region, is made up of genuine detrital deposits. When we consider that, in addition to the time necessary for the accumulation of this mass of sediment, there intervened between the Potsdam and the gneisses three periods, of rock alteration, mountain making, and complete mountain removal, it becomes plain that the time gap indicated by this unconformity must have exceeded the entire Paleozoic era. More probably, indeed, it equaled all later geological time. Each one of the three unconformities mentioned must, of course, have required a shorter period than this greater gap, but in each case the relations of the several formations are such as to indicate periods of time only comparable to the periods necessary for the accumulation of one of the great geological groups.

The use of unconformities in correlating the formations of a single geological basin.—We have next to consider the second element in the problem announced at the beginning of the paper, viz, the mutual correlation of the several successions of strata occurring in different portions of a single geological basin. For one reason or another the different districts in which these successions occur cannot be connected. Some of the formations may be wanting or later accumulations may conceal them, or, if they are technically the surface rocks throughout the interval, the drift covering may be so heavy that they cannot be studied successfully. In such a case as this, of which we could have no better instances than are found within that northwestern portion of the United States to which reference has so often been made, the unconformities prove of the highest importance in establishing the correlations. If we have a certain succession in one district, with a certain number of unconformable breaks, and a similar succession in another district, say fifty miles or a hundred miles away, with the same unconformable breaks, we can correlate the two series without hesitation, parallelizing with one another not only the several series concerned, but also the unconformities.

Such a use of unconformities can be much better appreciated from illustration. The following tabulation shows the general succession of formations in each one of the districts named, all of these districts lying within that great northwestern region of Cambrian and Pre-Cambrian rocks which, so far as the United States is concerned, extends westerly from the northern end of Lake Huron to southeastern Dakota and northward from central Wisconsin to the north shore of Lake Superior.
## Classification of Cambrian Formations

### Correlation of the Rock Groups and Unconformities

<table>
<thead>
<tr>
<th>Groups</th>
<th>North shore of Lake Huron, Canada</th>
<th>Keweenaw Point, Michigan</th>
<th>Marquette region, Michigan</th>
<th>Menominee River region, northern Wisconsin and Michigan</th>
<th>Penokee-Gogebic region, northern Wisconsin and Michigan</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Calciferous sandstone.</td>
<td>Lower magnesium limestone</td>
<td>Lower magnesium limestone</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Potsdam sandstone.</td>
<td>Lake Superior sandstone.</td>
<td>Potsdam sandstone.</td>
<td></td>
<td></td>
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<tr>
<td>Unconformity</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Keweenawan</td>
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</tr>
<tr>
<td>Unconformity</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Original or type Huronian:</td>
<td>Iron-bearing series:</td>
<td>Iron-bearing series:</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Principal kinds of rocks in order of relative abundance.)</td>
<td>Graywacke and clay slates.</td>
<td>Quartzite and quartzite-schist.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Quartzite and sandstone.</td>
<td>Quartzite and quartzite-schists.</td>
<td>Limestone, Clay slate.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Huronian</td>
<td>Graywacke and graywacke slate.</td>
<td>Mica-slate and schist.</td>
<td>Ferruginous and cherty schists.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Limestone and chert.</td>
<td></td>
<td>10,000 feet.</td>
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<td></td>
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<tr>
<td></td>
<td>Greenstones (eruptive).</td>
<td></td>
<td>Gneiss.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Huronian</td>
<td>18,000 feet.</td>
<td></td>
<td>Granite, Gneiss.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unconformity</td>
<td></td>
<td></td>
<td>Green schist.</td>
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</tbody>
</table>

Discordance and erosion interval.
### USE OF UNCONFORMITIES IN CLASSIFICATION.

|---------------------------------------|----------------------------------------------------------|-----------------------------------------------------------------|--------------------------------]|----------------------------------|----------------------------------|
| Lower magnesian limestone.            | Lower magnesian limestone.                               | Lower magnesian limestone.                                       | Lower magnesian limestone.     | Lower magnesian limestone.        | Lower magnesian limestone.        |
| **Unconformity.**                     |                                                          |                                                                |                                |                                  |                                  |
|                                        |                                                          |                                                                |                                |                                  |                                  |
| **Iron-bearing series:**              |                                                          |                                                                |                                |                                  |                                  |
| Ferruginous and cherty schists.       |                                                          |                                                                |                                |                                  |                                  |
| Sericitic quartz schist.              |                                                          |                                                                |                                |                                  |                                  |
| (Thickness unknown; mostly concealed by Potsdam sandstone.) |                                                          |                                                                |                                |                                  |                                  |
| **Unconformity.**                     |                                                          |                                                                |                                |                                  |                                  |
| Discordance and erosion interval.     |                                                          |                                                                |                                |                                  |                                  |
|                                        |                                                          |                                                                |                                |                                  |                                  |
| **Supposed unconformity.**            |                                                          |                                                                |                                |                                  |                                  |
| Granit.                               |                                                          |                                                                |                                |                                  |                                  |
| Gneiss.                               |                                                          |                                                                |                                |                                  |                                  |
| Mica schist.                          |                                                          |                                                                |                                |                                  |                                  |
| **Unconformity.**                     |                                                          |                                                                |                                |                                  |                                  |
| **Supposed unconformity.**            |                                                          |                                                                |                                |                                  |                                  |
| Granit.                               |                                                          |                                                                |                                |                                  |                                  |
| Gneiss.                               |                                                          |                                                                |                                |                                  |                                  |
| Mica schist.                          |                                                          |                                                                |                                |                                  |                                  |
| **Unconformity.**                     |                                                          |                                                                |                                |                                  |                                  |
| **Supposed unconformity.**            |                                                          |                                                                |                                |                                  |                                  |
| Granit.                               |                                                          |                                                                |                                |                                  |                                  |
| Gneiss.                               |                                                          |                                                                |                                |                                  |                                  |
| Mica schist.                          |                                                          |                                                                |                                |                                  |                                  |
This tabulation, with the descriptions already given in connection with the various illustrations of unconformities above cited, will be sufficient to show that the general succession obtaining throughout this region is as follows, in ascending order:

At the base of the succession is a series composed of gneissic and granitic rocks, with also a large development of schists. The granite is certainly in the main eruptive. The schists are very largely compressed eruptives, but also in part are of sedimentary origin. This gneissic terrane is always succeeded by a great structural break, it having been subjected to wide-reaching orographic movements, alterations, and denudations before the deposition of the next series.

The following series is a great quartzite and slate group, commonly including ferruginous horizons and also limestones and various basic and acid eruptives. This group, while presenting some characters peculiar to each district—depending partly upon original differences in local conditions of deposit, but also, and more particularly, upon the different degrees of alteration to which the rocks have been subjected in different areas—has, nevertheless, a general uniformity of lithological characters, such as to render evident its essential continuity throughout all or most of the different districts.

Next above this iron-bearing group follows a second hiatus, similar in kind and significance to that preceding it. Following this hiatus we have at times the Potsdam sandstone with a very moderate thickness. But in other cases there intervenes between this sandstone and the iron-bearing series the enormous development of detrital and eruptive rocks known as the Keweenaw series.

Finally comes the Potsdam sandstone, overlying all unconformably.

The least satisfactory portion of the tabulation is that which correlates the quartzite formation of southern Minnesota and southeastern Dakota with the iron-bearing formations of most of the other districts. The gneissic rocks of southern Minnesota are evidently the same as the gneissic formations of the other regions enumerated. Above this gneissic formation in Minnesota follows a hiatus, which is again evidently, in part at least, the equivalent of the gap which is found in the other districts to separate the gneissic from the iron-bearing series. Equally satisfactory is the correlation of the true Potsdam sandstone of Minnesota with that of the remaining districts enumerated, as well as the correlation of the unconformity which, though not actually visible, may, with entire confidence, be asserted to exist between the Potsdam sandstone in Minnesota and the quartzite series of that region with that which in the other districts is found below the Potsdam. In other words, the quartzite series of southern Minnesota lies between the gneissic formation and the Potsdam sandstone of the other regions; that is, so far as position is concerned, it may be the equivalent of the iron-bearing formations of the other districts or of the Keweenaw series or of the gap.
between these groups. With the Keweenaw series, as to lithological characters, it has almost nothing in common; with the iron-bearing groups it has in common the quartzitic character, but otherwise has little resemblance to that formation. We are helped a little, however, by a somewhat close resemblance which it bears to the Baraboo quartzite formation of Wisconsin, whose resemblance in turn to the original Huronian of the north shore of Lake Huron is a great deal closer. Again, a great development of a quartzite, the resemblance of which to the quartzites of the Baraboo region and of southwestern Minnesota is so strong that its identity with them may be taken as certain, occurs in Barron and Chippewa Counties, in northwestern Wisconsin. But in this latter region the Keweenaw series itself occurs in full force, and, although the contact of the two is concealed beneath the drift accumulations of the region, their relative geographical positions and inclinations and their striking lithological dissimilarities render it evident that they are entirely distinct formations. By this process of reasoning, making use of the unconformities so far as we can and then of lithological characters, we reach the conclusion that the Minnesota quartzite formation is probably the equivalent of the Huronian of the north shore of Lake Huron, although it has yielded somewhat obscure linguloid impressions which have heretofore never been found below a genuine Cambrian horizon. But the doubt still remains whether this formation may not, in part at least, correspond to the interval which in the Lake Superior region proper lies between the Keweenaw series and the Huronian. The only argument against such a supposition lies in the fact that it also is gently bowed, the presumption being that its disturbance was part of the general orographic movement by which the Huronian of Lake Huron and the equivalent rocks of the other districts were brought into their present positions.

The use of unconformities in establishing general relations.—Having established the general order of succession and the grander groups of the strata for a given geological province, the question which arises next in order is how to correlate these divisions with those of other geological provinces, and more particularly with the established divisions of the general geological column.

It will take but little consideration of the causes which have been at work in the production of such unconformities as have been above cited to make us realize that such breaks as these must be widespread in their influence. Great unconformities, in which the strata below the unconformity have been subjected to folding, mark periods of orographic movements which will, in general, have been extensive somewhat in proportion to the intensity of the folding process. So far as our knowledge extends, the genuine mountain-making movements have never been limited in their scope. We find a moderate instance of the width of influence of such movements in that Post-
Carboniferous upheaval which gave rise to the Appalachian mass. The effects of this movement are recognizable from the seaboard to the western plains and from the Great Lake region to the vicinity of the Gulf of Mexico. The greater part of the force was, of course, spent in the neighborhood of the present mountains themselves; but that its influence extended much farther west is indicated not only by the gentler bowings of the strata, which continue west of the mountains into the Mississippi Valley, but also by the lack of any Post-Carboniferous deposits in all the interior basin east of the Mississippi. Plainly all of this region was raised at that time permanently from beneath the interior sea, which was then shifted to the westward, to be afterwards more and more restricted in area by later mountain-making movements. Should we imagine the Appalachians to be submerged anew and to receive new horizontally placed deposits, the lapse of time indicated by the resulting discordance would fall altogether short of the time gaps indicated by the greater ones of the discordances above cited from the region of the Northwestern States, and would not exceed that indicated by the least of the discordances of that region. The amount of intervening denudation would be less in our supposed case than in the case of any of the northwestern unconformities.

It is well known, indeed, that some of the greater physical breaks in the strata of one continent may have their parallels among the strata of another continent. The interruption between the Paleozoic and the Mesozoic is intercontinental if not world-wide. Equally extensive is the great break between the Mesozoic and the Cenozoic. Each of these physical breaks corresponds to an immense change in life conditions. But, if we may judge from structural relations, from the amount of intervening denudation, and from the rank already attained by the life of the lowest of the fossiliferous Cambrian formations, neither of these great breaks corresponds in length of time interval to the break between the lowest of the distinctly fossiliferous formations and the youngest of those beneath it.

Most of the grand divisions of the geological column are based upon the paleontological characters of the several groups, but among those formations which are especially the subject of this paper, except in the highest, paleontological evidence fails; and in establishing correlations between them for regions more or less distinct from one another, we have to fall back upon mutual structural relations and lithological characters. It has already been argued that lithological characters, in the present state of the science at least, are but an untrustworthy guide in establishing such correlations. It is admitted that there are among the ancient formations some striking lithological correspondences between different regions; but how far these resemblances are significant of chronological correspondences and how far they are merely delusive must remain for the present an open question.
BASAL CONGLOMERATE IN THE SIOUX QUARTZITE SERIES NEAR NEW ULM, MINN.
VIEW AT THE JUNCTION OF THE HURONIAN AND LAURENTIAN, NORTH SHORE OF LAKE HURON.
VIEW TWO MILES SOUTH OF MARQUETTE, MICHIGAN.
GRANITE VEINS IN MICA SCHIST, ON ISLAND IN BURNTSIDE LAKE.
as Cambrian any or all of the formations which unconformably underlie that sandstone? We have already seen that beneath this sandstone there lie in this region three great series of rocks, each separated from its predecessor by one of the greatest of discordances. Is the term Cambrian to stop at the first unconformity below the Potsdam sandstone? Is it to extend to the second of these unconformities or to the third? Or is it to include, finally, the lowest of the formations of the region?

All these usages of the term have been made. In taxonomical value the term Cambrian is designed, of course, to correspond to the terms Upper Silurian, Lower Silurian, Devonian, Carboniferous, etc., which terms are based primarily upon the general continuity, for each one of the periods to which they correspond, of similar life conditions. In no case, however, has one of these terms been allowed to span any such unconformable break as the least of those beneath the Potsdam sandstone of the Lake Superior region. Minor breaks in the succession have been included within a single one of these geological groups because—although in every case of a physical break, even the smallest, a corresponding break in life-succession is found—there have been found on both sides of the break fully developed faunas of general similarity in characters; but no great break in the succession such as those with which we are now concerned has ever yet been found to be spanned by a continuity of forms. The conclusion, therefore, seems inevitable that we should not extend the term Cambrian over any such break, at least until there shall have been found closely corresponding faunas on opposite sides of the interval. Were such faunas to be discovered the greatness of the unrecorded interval would still remain and we should have indicated only a singularly long continuance of similar life-conditions. Even then the question might arise as to whether continuity of life-conditions should outweigh the great lapse of time indicated by the physical hiatus.

**SUMMARY OF CONCLUSIONS.**

In classifying the earlier clastic formations of the geological series their paleontological characters are properly used—

1. To separate the groups of a given region when the fully developed faunas of contiguous groups present strong contrasts, looked at in their entireties.

2. To collect several contiguous formations in a single group when the well developed faunas of these formations present such strong similarities as to indicate in a general way a continuity of life conditions.

3. To correlate the groups and formations of one portion of a single geological basin with those of another portion of the same basin when the faunas are well developed and the correlations are not
GRANITE VEINS IN MICA SCHIST, ON ISLAND IN BURNTSIDE LAKE.
extended to the minor subdivisions without strong accompanying
physical evidence.

(4) To establish correlations between the groups of different basins
when the similarities of the faunas compared are not confined to a
single fossil type or to but few fossil types, but extend throughout
the abundant and varied faunas.

They are improperly used —

(1) To assign to different groups the formations of a given region,
without strong accompanying physical evidence, when the faunas of
the supposed distinct groups are not sufficiently contrasted, when one
group has a fully developed fauna and the next is nearly or quite
barren, or when both groups have but meagerly developed and un-
characteristic faunas.

(2) To place several formations in a single group when the similari-
ties between the fossils of the two formations so placed together are
confined to a few forms of wholly uncertain range and when such sim-
ilarities are used to outweigh strong physical evidence of separateness.

(3) To correlate the groups and formations of different portions of
a single geological basin when the correlations are extended to the
minor subdivisions of the groups on the strength of assumed verti-
cal ranges of the species employed and when such correlations be-
tween minor subdivisions are presented without confirmatory strati-
graphical, lithological, and structural evidence, or when they are
pushed in the face of such evidence.

(4) To establish general correlations when such correlations are
based upon meagerly developed faunas or upon a few obscure forms
belonging to types of great vertical range.

Lithological characters are properly used in classification —

(1) To place adjacent formations in different groups, on account of
their lithological dissimilarities when such dissimilarities are plainly
the result of great alteration in the lower one of the two formations
and are not contradicted by structural evidence, or, if used as con-
firmatory evidence only, when such dissimilarities are the result of
original depositional conditions.

(2) To collect together in a single group adjacent formations because
of lithological similarities when such similarities are used as con-
firmatory evidence only.

(3) To correlate groups and formations of different parts of a sin-
gle geological basin when such correlations are checked by stratig-
raphy and particularly by observations made at numerous points
between the successions correlated.

They are improperly used —

(1) To place adjacent formations in different groups, on account of
lithological dissimilarities when such dissimilarities are merely the
result of differences in original depositional conditions and when such
evidence of distinction is not confirmed by or is contradicted by structural and paleontological evidence.

(2) To collect in a single group adjacent formations because of lithological similarities when such similarities are not confirmed by or are contradicted by other evidence.

(3) To establish general correlations between the clastic groups of different geological basins, except possibly when the gneissic and true crystalline-schist basement formation of one region is compared with the similar basement formation of another.

(4) To establish and determine any world-wide subdivisions of the non-eruptive basement crystallines—i.e., those which underlie the clastic groups here called Huronian—at least until very much more definite evidence of the existence of such subdivisions be gathered than has hitherto been done.

The structural breaks called unconformities are properly used in classification:

(1) To mark the boundaries of the rock groups of a given region.

(2) To aid in establishing correlations between the formations of different parts of a single geological basin.

(3) To aid in the establishment of correlations between the groups of regions distantly removed from one another; but caution is needed in attempting such correlations in proportion as the distances between the regions compared grow greater.

They are improperly ignored:

(1) When the evidence they offer as to separateness is allowed to be overborne by anything but the most complete and weighty of paleontological evidence.

TAXONOMY OF THE LOWER PART OF THE GEOLOGICAL COLUMN.

In the Lake Superior regions then, if the preceding arguments and conclusions be accepted as valid, we have, beneath the Cambrian horizon and above the gneissic basement formation, two great terranes, each of which is entitled, by its enormous thickness of strata and by the immense natural physical breaks between it and the adjacent formations above and beneath, to a taxonomical position fully equal to that assigned to the entire Cambrian group.

According to the nomenclature that has been proposed by the U. S. Geological Survey, the clastic rock masses of the earth's surface are classified in three orders of magnitude, viz., the system, the group, and the formation. The most comprehensive of these three classes is the system, which term it is designed to apply to the great divisions of the geological section defined by paleontology and recognizable the world over. Such are the Cenozoic, Mesozoic, and Paleozoic systems. Next in order comes the group, which it is designed to apply to those great divisions of the systems which are based mainly
upon paleontological distinctions, but also upon structural separate
ness, and only very subordinately upon petrography. These groups
are recognizable in various countries; they are presumptively world­
wide in their distribution, and they appear to approach an equality
in volume. Such are the Carboniferous, Devonian, Silurian, and
Cambrian groups. These divisions are groups in the sense that they
commonly include a number of subordinate members distinguishable
from one another petrographically, genetically, and even paleonto-
logically. These subordinate members finally are the formations
of this system of nomenclature, though the term formation is also
used with a vaguer signification, to cover any rock mass whose dis­
tinction from surrounding masses is desirable on one ground or an­
other.

This classification applies, as said before, to the clastic groups
only. Outside of these are the eruptive and non-eruptive crystal­
line rocks. Those last named, however, naturally have not been clas­
sified in systems, groups, etc. by the U. S. Geological Survey, because
of the doubts as to their origin and as to their structural positions
with reference to the clastic groups. Some of them are very plainly
beneath all of the regular clastic strata, while others are of disputed
position, some geological writers holding that they also belong be­
neath all clastic groups, while others regard them as altered repre­
sentatives of these groups at various positions in the geological
column.

Now, in such a classification the Keweenawan and Huronian series
of strata are certainly entitled to the rank of groups. They are so en­
titled (1) because, notwithstanding they include a considerable con­
tent of volcanic crystallines, they are nevertheless in the main made
up of genuine sedimentary strata, whose formation by the same proc­
esses which have been at work in the accumulation of later sedi­
mentaries is easily demonstrable; (2) because they have accumulated
during the existence of life on the globe, as hereafter maintained; (3)
because of their great volumes, which are not only comparable with,
but very considerably exceed those of, the ordinary rock groups; (4)
because they are divisible into subordinate members which are in
turn fully entitled to the rank of formations; (5) because of their
entire structural separateness from the oldest of the groups above
them, from each other, and from the crystalline basement rocks be­
low them; and, finally, (6) because of their presumptively wide extent.

Conditions similar to those of the Lake Superior region recur in
the Grand Cañon of the Colorado and probably also in central Texas.
In Newfoundland, again, we have unconformably placed beneath the
Cambrian, here developed with an enormous thickness and down to
its lowest known fossiliferous horizons, two mutually discordant
series, the upper one of which is entitled on the principles advocated
in this paper to full recognition as a clastic group, while the lower
one is crystalline and gneissic. In numerous other regions similar conditions have been more or less distinctly made out; but the geological column, as it is now ordinarily presented, provides beneath the Cambrian for one great division only—the Archaean. By some authors this Archaean is recognized as divisible into Huronian and Laurentian; but very few writers, even when they have recognized the independent existence of Pre-Cambrian and Post-Laurentian groups, seem to have accorded to such groups the taxonomical rank to which they are entitled. Certainly there has been no general recognition of these groups, such as would lead to the provision for them of a proper place in the general geological column. But in view of the facts summarized in this paper and of those which have been accumulated by various workers in different portions of the world, it is evident that some such provision should be made.

In attempting to make the required modification of the geological column, a most important question presents itself for settlement at the very outset. If we suppose it agreed that all clastic formations now known and to be discovered in the future which unconformably underlie the Cambrian are to be thrown out of the Cambrian group, it immediately becomes necessary to inquire whether the new groups, which must be established to hold these formations, are to be regarded as Paleozoic. Four different answers to this inquiry may be made, all but the last of which as here given have been more or less distinctly presented heretofore. We may regard all as Archaean; we may carry the term Paleozoic to the break between the Keweenaw series and the Huronian; we may restrict the term Archaean to the gneissic basement series; and, finally, we may introduce some entirely new term of equal rank with Paleozoic and Archaean to cover the formations between the gneissic series and the Cambrian.

In deciding between these different positions we can take cognizance (1) of the apparent relative extents of the time intervals between these several groups and (2) of the indications presented by them of the existence or absence of life during their deposition. The evidence under each one of these heads favors very strongly the restriction of the term Archaean to the gneissic basement terrane. The time interval between that series and the Huronian next above it was far greater than that indicated by any of the higher unconformities with which we are concerned. That this interval was so great is indicated in the first place by the relative degrees of alteration which these two series have undergone. The Huronian—i.e., that series to which the term Huronian is restricted in this paper—is, in the main, a fragmental formation, such alterations as have taken place in it being of the nature of interstitial additions to the original fragments or of minor metasomatic changes. It is essentially a clastic, and not a crystalline-schist, series. The basement terrane, or Laurentian, however, exhibits a complete crystalline development, without any or at least extremely rare traces of frag-
mental constitution, and is a genuine crystalline-schist series. With
the exception of portions of its granitic masses, evidently eruptive
among other rocks of the series, all of its members, whether origi­
nally of igneous or of sedimentary origin, have been most intensely
modified by pressure and recrystallization. Only rarely can a trace
of a former fragmental nature be detected. Basic igneous rocks
have been converted by pressure into a whole series of chloritic,
hornblende, and augitic schists. Acidic eruptives have been con­
verted into gneisses, mica-schists, sericitic schists, felsitic schists, etc.
Again, the amount of disturbance that the gneissic formation under­
went prior to the deposition of the Huronian entirely outweighs
that received by the Huronian since, while the amount of denudation
of the Pre-Huronian land surface as compared with that which fol­
lowed the Huronian was immensely greater.

As to indications of the existence of life during the deposition of
these several Pre-Cambrian groups, it may be said that we have no
satisfactory evidence of its existence previous to the time of deposi­
tion of the Huronian. That it existed plentifully when the Huronian
group was accumulating is plainly indicated, not only by the force
of the general argument based upon the high development of life
at the beginning of the Cambrian and its consequent necessary exist­
ence for great periods prior to that time nor yet by the occasional dis­
covery of obscure fossil remains, but by the abundant occurrence,
in this group, of shales and slates filled with organic matter and of
extended ferruginous strata whose original accumulation was cer­
tainly dependent upon the existence of organic matter. That the
carbon of the abundant black shales is matter of genuine organic
origin and an original ingredient, and not merely a chemically de­
posited graphite or a graphite introduced during a subsequent meta­
orphism, is rendered entirely evident by residual traces of hydro­
carbons and by chemical analysis as well as by a close study of thin
sections of the rocks, which show the carbonaceous substance they
contain to be entirely similar in character and occurrence to that
contained in the carbonaceous shales of all later formations, in which
cases its organic origin has never been questioned. It has been
assumed by some writers, who have opposed any view maintaining
the existence of life during the accumulation of these ancient forma­
tions, that the only form of carbon found in them is the graphitic
form, which, being producible, as is well known, by other than organic
agencies, is taken to be no indication of the existence of life during
the time of deposition of the rocks in which it is found. But in the
case of the Huronian the graphitic form is unusual, and when it
occurs it is plainly merely a phase of the ordinary black, carbon­
aceous matter of the carbonaceous shales. Moreover that organic
matter was concerned in the original accumulation of the great iron
horizons of the Huronian is a conclusion not reached by a purely
theoretical comparison of these horizons with the iron horizons
of later times, as the Carboniferous for instance, but is shown by
the abundant visible occurrence of such organic matter in these iron
horizons themselves, whose present developments have been conclu­
sively shown, from a study of field conditions and of hundreds of
thin sections, to have been, in large measure, the result of a silicifi­
cation of beds closely comparable with the Coal Measure iron carbon­
ates. Carbonate of iron and organic matter are constant associates,
and there was in the Huronian quite as much of both as in any of
the latter groups except the Carboniferous.

Finally, we may cite in favor of a restriction of the term Archsean
to the Pre-Huronian basement formation the general tendency, among
those geologists who have made the most extensive studies of the
crystalline basement schists, to the view that the exact conditions
which gave rise to them have never been repeated in later geological
time.

It seems desirable to restrict the term Archsean to the basement
crystallines, because of the greatness of the time interval between
that series and the next succeeding it, in comparison with any of
the later interruptions of the geological column; because of its in­
tensely altered condition and generally unique characteristics, as
compared with those of any of the later groups; and because of the
lack of definite evidence of the existence of life during its production,
while life plainly existed at the time of the deposition of the earliest
of the succeeding groups. But it is not so evident that we should
extend the term Paleozoic over the rocks which this restriction would
throw out from the Archsean and over those newly established groups
which intervene between the Cambrian and the Archsean as hereto­
fore recognized. If the term Paleozoic is to be used to cover all
formations accumulated after the beginning of the existence of life
on the globe we should, of course, extend it downward over the
groups in question. But such is certainly not its ordinary use, inasmuch
as it is commonly applied to a grand life system which, while
progressive from the earliest Cambrian to the latest Carboniferous,
is, nevertheless, a coherent whole when compared with the later
Mesozoic and Cenozoic life systems. It may be that future discov­
eries of fossils among the Pre-Cambrian and Post-Archsean formations
will develop the fact that the genuine Paleozoic life extended over
the times of their accumulation also, but at present we have no means
of deciding as to this, and it seems that we might, not improperly,
make use of some term of equal taxonomic value with Archsean and
Paleozoic with which to cover all Pre-Cambrian and Post-Archsean
formations yet discovered or to be discovered. I say to be discov­
ered, because there is no reason to suppose that there are but two
groups of strata between the Archsean and the Cambrian. The time
intervals indicated by the unconformities between the groups already

1 Origin of the ferruginous schists and iron ores of the Lake Superior region: Am.
discovered as belonging to this interval and between them and the Cambrian on one side and the Laurentian on the other are such as to suggest the probability of the existence somewhere in the geologically unknown portions of the world of other grand groups of Pre-Cambrian strata. That such groups will be discovered in the future and that life systems will be made out for them, imperfect to be sure, the whole past history of paleontological discovery and advance justifies us in expecting. Few persons who have not had their attention particularly drawn to the matter realize what extensive portions of the earth's surface are as yet geologically terra incognita. Such an arrangement as this would have the especial advantage that it would furnish us with a term to cover any strata found anywhere in the world to belong in the interval between the Cambrian and Archaean without forcing us to classify them more minutely. As has already been seen, as long as these Pre-Cambrian strata have failed to furnish us any characteristic faunas, we must be at fault in attempting to correlate with one another the Pre-Cambrian groups of widely separated regions.

It may be thought that the same advantage could be obtained by using some one term in the group column of the geological classification to cover all such known and as yet unknown groups; in which case the term Paleozoic would extend downward over all groups save the basement gneisses. The objection to this arrangement would be that it would relegate such great series of strata as the Huronian and Keweenawan to the formation column; whereas, while paleontological evidence as to their title to rank as groups fails, in all other respects these two grand series of strata are fully entitled to rank with the greater geological groups, with which they more than compare in thickness and in the lengths of the time intervals by which they are separated from each other and from the preceding and succeeding divisions. Were the paleontological evidence forthcoming it is to be expected that it would confirm the right to this high rank indicated by the physical evidence.

The Carbonaceous shales (bearing traces of hydrocarbons), the associated iron carbonates, and the lime carbonates which form great members of the Huronian series constitute sufficient evidence of the existence of life to place these groups within the zoic series. They do not, however, show sufficiently definite traces of distinct forms of life to justify the assertion that it was of the character of that to which the term Paleozoic has been applied. It seems, therefore, desirable that a new term should be introduced of equal classificatory rank with Paleozoic, indicating that these great Pre-Cambrian and Post-Archaean series are zoic in character and that they cannot, as yet at least, be admitted to the Paleozoic series proper. In an article in the American Journal of Science for 1887 (page 373), I advocated the adoption of the term Agnatozoic (ἀγνωτός, unknown; ζωή, life).
life), indicating at once the presence of life and its unknown character. A recognized objection to this term may be based upon the consideration that if definite faunas shall be discovered in these formations or in any of them the term Agnotozoic would be inapplicable. To this it may be replied that it is improbable that such discoveries will be made in all of the formations included under this term and that it will still be needed for the residue. If definite faunas are found in any of them and these prove to be Paleozoic in character, the formation containing them will simply be transferred to the Paleozoic series and the remainder of the formations left under the term Agnotozoic. If, on the other hand, the faunas prove to be diverse from the Paleozoic, a new zoic group bearing a name appropriate to the discovered life will be required in any case, whether the term Agnotozoic or any other imaginable term be now applied to the formation.

Some of my colleagues upon the survey, however, prefer the more non-committal term Eparchean, signifying simply the position of these formations upon the Archaean. To this term the same objection applies as to the preceding, that the discovery of a definite fauna would necessarily call for an appropriate zoic classification, under the canons of good nomenclature. In short, it may be safely remarked that, while there is an imperative demand for a separate term adapted to the present needs of the science, any term now proposed must be held subject to future limitation or entire replacement, if any sufficiently distinctive paleontological discoveries shall be made.

The following table shows the arrangement of formations suggested, in which the terms Agnotozoic and Eparchean are both introduced:

<table>
<thead>
<tr>
<th>Systems</th>
<th>Groups</th>
<th>Systems</th>
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<tbody>
<tr>
<td>Paleozoic</td>
<td>Carboniferous.</td>
<td>Paleozoic</td>
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<td></td>
<td>Devonian.</td>
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<tr>
<td></td>
<td>Silurian.</td>
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<tr>
<td></td>
<td>Cambrian (Lower Silurian)</td>
<td></td>
</tr>
<tr>
<td>Agnotozoic</td>
<td>Keweenawan.</td>
<td></td>
</tr>
<tr>
<td>or</td>
<td>Huronian.</td>
<td></td>
</tr>
<tr>
<td>Eparchean.</td>
<td>(other groups?)</td>
<td></td>
</tr>
<tr>
<td>Archaean.</td>
<td>Laurentian (including Upper)</td>
<td>Archaean.</td>
</tr>
<tr>
<td></td>
<td>Laurentian.</td>
<td></td>
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THE STRUCTURE
OF THE
TRIASSIC FORMATION OF THE CONNECTICUT VALLEY.

BY
WILLIAM MORRIS DAVIS.
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TRIASSIC FORMATION OF THE CONNECTICUT VALLEY.

BY WILLIAM MORRIS DAVIS.

The physical history of the Triassic formation of the Connecticut Valley may be considered under three heads: First, the conditions of its accumulation; second, the structure that it now possesses; and, third, the mechanical disturbance by which the present structure has been produced.

I. THE CONDITIONS OF ACCUMULATION.

ORIGINAL AREA OF DEPOSIT.

The Triassic strata rest unconformably on steeply upturned schists and gneisses. It may therefore be supposed that an old land of crystalline rocks, long exposed to denudation, was for a time and in part submerged, and that the body of water thus formed became the seat of deposition of the waste brought from the area that remained uncovered. The present extent of the formation measures about ninety-five miles north and south, from Long Island Sound, where it runs under the sea, nearly to the northern boundary of Massachusetts, and from fifteen to eighteen miles east and west in central Connecticut and southern Massachusetts, where it is broadest. The original area was greater than this, as there has been demonstrable loss by marginal erosion, but it is generally thought that the loss has not been very great.

We are not, however, confined to this conclusion by a very strong line of argument. The rapid change from finer sandstones and shales that generally appear in the central parts of the formation to the coarse sandstones and conglomerates that characterize the margin is usually cited as implying a narrow limitation of the area of deposit; but it is not yet demonstrated that the finer central strata are the equivalents of the coarser marginal layers; the latter may mark localities on the advancing shore during submergence that were favorable to the formation of coarse deposits, while the former may correspond to a later date of more general submergence; moreover, in some cases the finer shales approach close to the present margin of
the formation. No isolated outliers of the formation have yet been discovered, unless the little Southbury-Woodbury area in western Connecticut be so regarded, but the region around the area that is still covered by the Triassic rocks has been elevated to an altitude and during a time sufficient to have suffered much loss by Post-Triassic erosion. The general freedom of the same surrounding region from the igneous rocks so closely associated with the Triassic formation in its various areas along the Atlantic slope may also suggest its escape from Triassic submergence; but in our present state of knowledge concerning the cause of this peculiar association it can hardly be employed in this argument. It therefore does not seem impossible that the original Triassic area may have been much larger than the present; but the burden of proof lies clearly on those who would contend for what now appears to be so far beyond the necessities of the case.

The only notably peculiar conditions attendant on the period of deposition were those connected with the intrusion and eruption of broad sheets of igneous rock. We do not here find great masses of breccia, as in the Mesozoic of Pennsylvania, or heavy beds of exceptionally coarse conglomerate, as in the same formation in Virginia, which require unusually active or powerful processes in their accumulation. Very coarse conglomerates, with boulders from two to four feet in diameter, are known in few localities in the Connecticut Valley, and these are in all cases close to a possible shore of derivation. The deposition of the aqueous rocks may therefore be in general described as rather commonplace, presenting the ordinary variety of conglomerates, sandstones, and shales; they are mostly of a red or brown color, but the shales are sometimes dark and bituminous, with impressions of fish and of land plants; occasional thin seams of coal have been reported and a small but significant bed of impure, grayish limestone makes its appearance among the shales. The little that is known of the sequence of these rocks will be stated below.

IGNEOUS ROCKS.

There is a more special interest connected with the occurrence of the igneous rocks that constitute so characteristic a part of the formation. They are generally described as dolerites or diabases, but, as lithological questions do not enter into this report, they will here be called by the old indefinite name of "trap," which is at present significant enough in considering their physical history. They occur as dikes, breaking across the sedimentary beds; as intruded sheets, driven between the beds and closely conformable to them; and as contemporaneous overflows, lying upon the beds that had been formed at the time of their eruption and buried under the later deposits. The distribution of the trap rocks was carefully worked out in Connecticut by Percival and illustrated with much accuracy in his remark-
able geological map of that State published in his Geology of Connecticut, 1842, and here in part reproduced as Plate LII; but he gave little attention to the structural differences between dikes and sheets. The middle part of the map is here represented, to show the Triassic district between the adjacent crystalline areas and the trap ridges within the Triassic area. The township names and the lines of water-parting given by Percival are omitted, and the railroads and several names are added. The dotted and broken lines in the crystalline areas show the strike of the schists; the trap ridges are dotted within their boundary lines. The various letters and numbers refer to the text of Percival's report. Attention is called to the general parallelism between the oblique structural lines in the neighborhood of the Hanging Hills and the strike of the schists shown in the northeastern and southwestern corners of the map.

Hitchcock mapped the trap ridges in Massachusetts for his report on that State, published in 1841; he gave little attention to their distribution and to the topographic form that they determine, but recognized the contemporaneous origin of the overflows.

Dikes.—The dikes do not present any peculiar or important features, as yet observed; they are variable in thickness and attitude and no system has been found in their distribution; they are probably to be regarded as lines of supply for the intrusions and overflows.

Intrusive sheets.—The intrusive trap sheets occur, as far as now determined, only along the western border of the southern half of the formation, and do not extend into Massachusetts. They are known by their generally compact texture and by the induration they have caused in the overlying sandstone. East Rock, a conspicuous bluff north of New Haven, is the southernmost member of this series. West Rock, and the long, broken ridge running northward between the towns of Hamden and Bethany, and Cheshire and Prospect, are most likely of the same intrusive origin, but this region has not been fully explored. Southington, Bristol, and Farmington have no representative of this sheet, but a broken ridge, similar to the one above named, appears in Avon and extends across Simsbury and Granby, beyond which it has not been recognized. The proof of intrusion of this northern member is not complete, as no contacts with the overlying sandstone have yet been found; but, where it was examined about the Barn-door Hills of Granby, the eastward slopes present nothing of the scoriaceous texture that ordinarily characterizes the upper surface of overflows. The smaller ridges near the Quinipiack and Farm Rivers have not yet been sufficiently studied for description here.

The numerous interruptions in the ridges formed by these trap outcrops might be regarded as indicating so many independent intrusions and the curvature of the ridges might mean that the sheets.

1The map was published in 1844.
were intruded after the bending of the adjacent strata by which they were guided; but an explanation more consonant with that demanded by the structure of other parts of the formation contradicts this view and suggests that the several ridges above named are parts of only one or two large continuous sheets that were intruded while the sedimentary beds were still horizontal and that afterward suffered dislocation at a time when the whole formation was disturbed. The evidence for this will be presented under the next general head, but it may be now briefly stated that intrusive sheets are well known elsewhere among horizontal beds in which they have produced very little disorder, so that the supposition here made is entirely admissible on general principles; that the relative attitude of the several members of the intrusive ridges is closely imitated in that of the ridges formed by the overflow sheets, whose dislocation must have been the result of subsequent external force; and, finally, that the relative positions of the ridges formed by the intrusive and the overflow sheets are such as very strongly to suggest a single control in their determination.

Overflow sheets.—The trap sheets formed by contemporaneous eruption and overflow are on many accounts the most important members of the formation. They are recognized by the scoriaceous texture of their upper surfaces, by the absence of induration from baking in the overlying sandstones, by the occurrence of sediments filling the little amygdaloidal cavities in the upper surface of the sheet, and by the presence of fragments of trap, often more or less water-worn, in the next overlying beds. The discovery of these several indications is a matter of difficulty, owing to the heavy covering of drift that so generally obscures the desired lines of contact, but they have been found at a sufficient number of localities to leave little doubt in the matter. Beginning at the southern end of the formation, we find that fragments of trap occur in the overlying sandstone at the north end of Pond Mountain, and the upper surface of the sheet making this ridge is very scoriaceous where it is exposed, for two miles along the western side of Saltonstall Pond. The same may be said of several localities on the eastern slope of Toket Mountain; contacts were found at two points on this sheet showing the amygdaloidal cavities of the trap surface neatly filled with fine, sandy sediment. The north end of Lamentation Mountain, south of Berlin village, is cut across by a small stream, disclosing similar contacts and inclusions. The upper surface of the trap sheet that forms the picturesque Hanging Hills, northwest of Meriden, is highly vesicular over large spaces. Mt. Tom, in Massachusetts, is overlaid with a sandstone in which trap fragments have been found. The sheet of trap that caps Deerfield Mountain farther north is covered by a sandstone giving the same evidence. All these are therefore considered overflows. Thin sections of specimens taken from the last two lo-
calities were studied some years ago by Prof. B. K. Emerson, of Amherst College, and a series of specimens from the other localities have lately been submitted to Mr. J. E. Wolff, of the U. S. Geological Survey, for preliminary examination. Microscopic observation thus gained confirms the evidence gathered in the field.

The above localities represent different points in the series of high trap ridges or mountains that extend, with more or less interruption, from Long Island Sound through the whole length of the formation. The smaller trap ridges that accompany these mountains must also be considered contemporaneous overflows, as far as their character is determined at all. They were called "anterior" and "posterior" ridges by Percival, according as they stand to the west or to the east of the main ridges, and these terms may properly be continued, as they are now seen to indicate relative age as well as attitude. The anterior trap is so vesicular on its upper surface that its outcrop is commonly described by Percival as an "amygdaloidal ridge." Well exposed contacts of its trap with the overlying sandstones have been found as yet only in the gorge of the Farmington River at Tariffville and in a railroad cutting at the same village, Prof. W. North Rice, of Wesleyan University, having pointed out these excellent localities. The upper part of the trap is vesicular, with an irregular surface, and the adjacent sandstone contains numerous water-worn pebbles of trap. The rocks near to the anterior ridge at the north end of Toket Mountain furnished sections that were considered by Mr. Wolff to contain small water-worn fragments of trap. The posterior ridges are better exposed. The two members posterior to Pond Mountain gave good evidence of their character; the eastern of the two is covered by a deposit largely composed of trap waste, and the western is associated at its northern end with a heavy conglomerate in which trap boulders, up to four feet in diameter, are found. The ridge posterior to Toket Mountain is at one point called a dike by Percival, but the only reason for this seems to be its steep inclination. It is closely conformable to the strike and dip of the adjoining sandstones and conglomerates, but no contacts with them were found. The posterior ridge that crosses the Aramamit River at Rock Falls, a few miles southwest of Middletown, is covered by a shaly sandstone inclosing trap pebbles, one of which, lying about six inches over the highly vesicular surface of the trap, was beautifully water-worn. The ridge apparently posterior to Mt. Tom, on the Connecticut River, well exposed in a quarry by the railroad three miles north of Holyoke, Mass., is covered by a sandstone containing plentiful fragments of trap. Other localities giving equally decisive evidence will doubtless be found.

It thus appears that a good number of the many large and small
trap ridges in the central and eastern part of the formation are the outcropping edges of overflow sheets. Many ridges remain to be examined to discover if they give independent evidence of a similar origin, but meantime there are two good reasons for anticipating the results of such investigation. First, if this closely associated series of ridges contained both intrusions and overflows it would be difficult to explain why the contacts thus far discovered should give evidence for overflows only, especially when it is remembered that the indurated sandstone on the back of a dense intrusion is much less easily worn down than the unbaked sandstone on the vesicular surface of an overflow. Second, there is ground for believing that nearly all these ridges are the disconnected or repeated outcrops of only three trap sheets that have apparently been multiplied by faulting; so that the proof of overflow for one ridge would hold good for many others. Their separate origin by independent eruptions involves great complexity of arbitrary hypotheses; their origin in three periods of eruption allows the reduction of a seemingly most complicated structure to a relatively simple one and permits the correlation of many similar forms in a natural and connected system. It is not desired to affirm that all the central and eastern ridges can be referred to some one of these three periods, but there is good probability that three periods suffice to account for by far the greater number of ridges. Nor is it intended to imply that the trap sheets formed in these three periods were the products of single outpourings of lava, for evidence has already been discovered indicating that the posterior ridge at least is a composite flow of two or three dates, separated by intervals too short for the deposition of more than a thin film or coating of sediments. The evidence of the former continuity of the sheets now disjointed will be discussed in detail under a later head; it lies essentially in the similarity in the sequence of beds, both aqueous and igneous, encountered in crossing over one of the trap "mountains" from below the anterior ridge on the west to beyond the posterior ridge on the east, and when this similarity is recognized it is impossible to avoid the conviction that the several "mountains" and their subordinate anterior and posterior ridges are but repetitions of a single series of strata, broken into separate blocks, dislocated by faults, and curved by faint folding at a time when the general monoclinal structure was produced.

STRUCTURAL SIGNIFICANCE OF OVERFLOWS.

All the trap sheets of the central and eastern part of the formation except the undetermined ones by Farm River may, therefore, be treated as overflows, and as such they gain a great value as conformable members of the formation. Their resistance to erosion has enabled them to stand up in strong ridges, easily traced across the country, while the softer shales and sandstones are ordinarily worn
down and buried under the drift; it is, therefore, chiefly from the trap overflows that a knowledge of the structure of the Connecticut Triassic is to be obtained and a measure of its thickness determined. The structure is described further on, as far as it is now known.

SEQUENCE AND THICKNESS OF THE TRIASSIC SERIES.

The order and thickness of the Triassic deposits are determinable as soon as the faults whereby single beds may be repeated are detected and allowed for. Much more work in the field is needed before this can be done finally, and a good topographic map is necessary to make full use of the material thus gained; but a preliminary statement of the series as now understood may be permitted. The estimates here given are necessarily very rough and hardly represent more than the general order of the quantities involved. The column reads in natural order from top to bottom.

<table>
<thead>
<tr>
<th>Beds</th>
<th>Thickness in feet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conglomerates, sandstones, and shales</td>
<td>2,000 to 3,000</td>
</tr>
<tr>
<td>Posterior trap overflow</td>
<td>50 to 150</td>
</tr>
<tr>
<td>Sandstones and shales</td>
<td>300 to 500</td>
</tr>
<tr>
<td>Main trap overflow</td>
<td>300 to 500</td>
</tr>
<tr>
<td>Shales with thin limestone</td>
<td>100 to 300</td>
</tr>
<tr>
<td>Anterior trap overflow</td>
<td>50 to 150</td>
</tr>
<tr>
<td>Shales</td>
<td>500 to 500</td>
</tr>
<tr>
<td>Shales, sandstones, and conglomerates</td>
<td>3,000 to 3,000</td>
</tr>
<tr>
<td>Intrusive trap sheet</td>
<td>200 to 400</td>
</tr>
<tr>
<td>Sandstones and conglomerates</td>
<td>500 to 2,000</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>7,000 to 10,500</td>
</tr>
</tbody>
</table>

It is very possible that an additional local layer of trap belongs somewhere above the posterior overflow and that another intrusion replaces the one here named in the southeastern part of the district.

Main trap overflow.—The most important member of this series, judging from its persistence as well as from its massive thickness, is the main trap overflow. It forms the great crescents of Pond and Toket Mountains, reappears in Paug Mountain and in the long ridge leading up to Middletown Mountain, is repeated in Lamentation Mountain and the short ridge supplementary to it on the south, rises again in the several masses of the Hanging Hills, and thence is easily followed in more or less disjointed ridges beyond the gap of the Farmington River. Its equivalent in Massachusetts has not yet been certainly determined, for, while the sheet that forms Mounts Tom and Holyoke is the heaviest of that region, the limestone that in Connecticut lies below the trap of the main ridge here lies above it. For this reason it may be that Mounts Tom and Holyoke are formed by the sheet called the anterior or amygdaloidal trap in Connecticut; this can doubtless be determined in another season’s field work.
Anterior trap overflow.—The anterior, amygdaloidal or lower trap overflow may be mentioned next. It appears first at the northern hook of Toket Mountain; it is next found as a more or less continuous bench or ridge on the western slope of the "mountains" formed by the main overflow, even beyond the Farmington River, and it very likely extends into Massachusetts, as above suggested.

Limestone.—The little bed of limestone, described by Percival, is of peculiar interest and importance. At the time of the old State survey, about fifty years ago, this bed was quarried for burning at a number of points, but at present better lime is easily obtained from other districts, and nearly all the quarries are abandoned and obscured. Wherever found in Connecticut, this limestone bed always lies at the lower part of the shales, between the main and the anterior overflows; and this fact alone gives strong reason for concluding that its several different outcrops are repetitions of the same stratum. There is nothing inherently unlikely in this conclusion, while the reverse supposition, that the several outcrops represent separate beds, requires at least five independent but identical repetitions of a complex sequence of eruptions and depositions and is excluded by the very weight of its improbability.

Posterior trap overflow.—This upper overflow accompanies all the ridges of the main sheet from the seacoast up to and beyond the Farmington River. Its horizontal distance from the main sheet varies somewhat with the dip and thickness of the intervening beds, but not more than might be expected.

The remaining members of the series have not been mapped with sufficient detail for description at the present time, but, far as they are known, they present no contradictions to the hypothesis here outlined. From the work already done, there is good reason to think that an orderly arrangement of the whole formation may be determined by a fuller study, and, apart from its theoretical interest, this may be of value in guiding future explorations for the coal seams that have been suspected among the bituminous shales, in case any such work should be attempted again.

THE SOUTHBURY-WOODBURY TRIASSIC AREA.

The towns of Southbury and Woodbury, in western Connecticut, include a small Triassic area in the valley of the Pomperaug, about eight or ten miles north and south by three or four miles east and west. The trap ridges are numerous and make strong outcrops, but the sedimentary beds are seldom seen and no contacts between the two could be found in a week's careful search. The sequence of deposits, as determined in the southern part of the basin, is roughly given as follows: Several hundred feet of sandstones and conglomerates at the base; next a thin amygdaloidal trap; then two hundred or more feet of shales, containing fish scales and calcareous beds; then a
heavy sheet of trap. Other members were indicated above this, but they were everywhere covered with the plentiful drift. In the northern part of the basin the sandstones were hardly to be found; the trap sheets are there more expanded, consisting of heavy sheets below and above and an amygdaloidal sheet between; sedimentary layers are doubtless intercalated in this igneous series.

II. THE STRUCTURE OF THE FORMATION.

GENERAL ATTITUDE.

The appearance of a continuous monocline in the Connecticut Valley, with a general eastward dip of twenty or thirty degrees, is so distinct that the detail of structure whereby it is interrupted has received little attention. There are, however, good reasons for believing in interruptions of continuity by faults nearly parallel with the strike, with upthrow on the east in practically all observed cases, and also in departures from the eastward direction of dip in the neighborhood of the curved trap ridges and at some other points; and both these irregularities are of great significance in explaining the character of the mechanical deformation that the strata have suffered and the structural control of the peculiar topography of the Triassic areas.

CLASSES OF FAULTS.

The faults may be described, beginning with well proved examples of small throw and passing to more hypothetical cases of much greater displacement. It may be remarked, in introduction, that Prof. B. K. Emerson several years ago described a fault of moderate throw at Turner's Falls, in Massachusetts, which causes a single sheet of trap to do double duty and form two parallel ridges. About the same time the writer presented reasons for believing that Lamentation Mountain was but a repetition of the trap sheet that forms the Hanging Hills. The case may be now presented in greater fullness.

Oblique faults.—The first locality that threw light on the systematic arrangement of the faults was near South Britain, in the Pomperaug Valley, within the small western Triassic area, illustrated in Fig. 97. Here the paired outcrops of a conglomerate overlaid by the thin amygdaloidal trap appear five times in a third of a mile, every pair being distinctly out of line with its neighbors and the displacements always involving a moderate upthrow on the east of a fracture running obliquely to the strike of the beds. The actual fractures are, as usual, nowhere to be seen, as the outcrops have but little prominence on a grassy slope, but there can be no question whatever of their occurrence.

Returning to the Connecticut Valley, Pond Mountain, east of New Haven, a fine crescentic ridge formed by the southernmost outcrop
of the main trap sheet, presents several distinct examples of similar faults, always with upthrow on the east; they are to be found near its southern end, where the Shore Line Railroad and the highroad to Branford cross the ridge, and at several notches farther south; their displacement contributes liberally to the eastern curvature of the southern hook of the ridge. The relative attitude of the trap sheet to the underlying sandstone leaves no doubt of the existence of the faults; for, if the sandstone layers on the south of a fault were continued northward along their strike, they would lead directly into the trap on the north, and, besides this, every fault is indicated by a gap in the otherwise continuous trap ridge. The direction of the faults seems to be about northeast.

A little ravine on the outside of the northern hook of Toket Mountain coincides with a dislocation visible in the lower surface of the trap, with an upthrow of about ten feet on the east; the topography of the ridge suggests the existence of several other breaks of this kind.

Faults of still greater throw, but otherwise similar to those of South Britain and Pond Mountain, are presumably the cause of the deep gaps that break through the Hanging Hills, northwest of Meriden. These are not yet directly proved by observed dislocation in the underlying sandstone, as its outcrops are few; but the attitude of the several hills as seen from the south is very suggestive of faulting, for the gaps are sudden interruptions in a massive lava flow that most reasonably must have been continuous when it was poured into the old Triassic sea and the bluffs stand a little higher on the east than on the west of the supposed fracture. In Percival's map of this district,
the lines drawn to indicate the boundary of the trap represent rather than be inferred from his outlines.

It is very probable that the deeply indented Holyoke Range in Massachusetts, the northern curve of the series of ridges that rise in the Hanging Hills at their southern end, owes its irregularity to similar transverse fissures. The trap sheet in every block of the ridge between adjacent gaps, as far as examined, has a strong dip to the southeast and strikes northeast and southwest, very obliquely to the general eastward course of the range; and the sandstone and conglomerates overlying the trap on the western side of the gap, if continued along their strike, would run into the trap sheet on the eastern side of the gap. The upthrow would in all cases be on the eastern side of the fault. The fault at Turner's Falls, described by Professor Emerson, is of similar character.

A number of faults, closely related to those just described, must be inferred between the trap ridges north of the Hanging Hills. The gaps on the range here run obliquely about thirty degrees east of its general northward trend, and the supposition that these gaps mark fissures with upthrow on the east would account for the systematic overlapping attitude, or, as Percival called it, the "advancing order" of the successive members of the range, Short Mountain, High Rock, Farmington and Talcott Mountains and others. The gaps do not break through the main trap sheet alone, but interrupt the anterior amygdaloidal ridge and its overlying limestone in a most systematic manner. The probable cause of the oblique intersection of the range by the faults and the reason for the advancing order of overlaps in its several members will be presented later.

**Strike faults.**—All the examples thus far described are of tolerably easy recognition, because the dislocation is not great and corresponding members of the formation may be seen not far out of line on the two sides of the fracture. In all such cases the fault line makes a considerable angle with the strike of the faulted beds, but in the examples yet to be considered the fault line is essentially parallel to the strike, and therefore causes repetition of strata in a series of parallel outcrops; and at first sight the corresponding members in such cases are entirely independent and unrelated. The first clear evidence of this structure found by the writer was again close to South Britain in the Pomperaug Valley, which may therefore be said to have furnished the key to the Triassic structure. Although far separated from the Connecticut Valley, the topography and the implied structure of the two areas are so closely alike that it seems legitimate to carry evidence from one to the other. In this interesting locality a single series of beds, consisting of the conglomerate, amygdaloid, shales, and heavy trap already mentioned, is faulted so as to present three successive outcrops, with upthrow always on the east,
as shown in Fig. 98. The beds in each block vary somewhat in dip, but in other respects are closely similar. If the trap sheets had been sedimentary rocks, the repetition by faulting must have long since been discovered. A short and low ledge of trap in the northern part of the valley that follows the westernmost fault line is the only obscure member of the series, and this may be regarded as a small mass of trap standing between branches of the fault.

![Fig. 98. Inferred structure of the district shown in Fig. 97. The two faults of larger throw, by which a single sheet of trap is repeated in three ridges, are proved by the threefold repetition of a series of beds comprising sandstone, conglomerate, amygdaloidal trap, shale, and heavy trap.]

It will be remembered that no evidence could be given in the first section of this report as to the intrusive or overflow origin of the trap sheets in the Pomperaug district; but an argument based on the faults just described gives sufficient reason for supposing that, whatever their origin, the sheets had their present position in the stratified series before the tilting and faulting took place. There are only three suppositions to be considered; first, that they were overflows; second, that they were intrusions, thrust in before the faulting; and, third, that they were intrusions thrust in during or after the faulting. In either the first or the second case, they necessarily were tilted and faulted with the adjacent stratified beds. The third case may be excluded by the reductio ad absurdum, for it requires that six separate intrusions should arrange themselves independently in a determinate and systematic manner. The same line of argument may be applied to several other trap ridges of this district.

The ridges east of Woodbury (Fig. 99), in the same western Triassic area, offer another illustration of the same faulted structure, although the evidence for it might commonly be thought less conclusive, because it does not rest on a repetition of sedimentary strata; but a visit to the spot leaves little doubt as to the meaning of the structure. The ridge-making beds in two similar groups of hills east of the village consist of a lower and an upper sheet of compact trap, separated by an amygdaloidal layer; shales probably occur between these sheets, but they are nowhere to be seen. The similarity in the structure and topography of the two groups is so striking that one cannot resist the belief that they are composed of the same set of trap sheets, repeated by a fault with upthrow of five or six hundred feet on the east in the intermediate valley. The several low ledges of
unevenly jointed trap on the western side of the valley may be fragments of the sheets caught in the fracture, as suggested in the figure.

FIG. 99. Map and section of trap ridges near Woodbury. The topography is indicated by sketched contours, with hachures for trap bluffs. The lower sandstone slopes are all covered and the northern bluff of the western group of ridges is quite buried in drift. The crystalline rocks appear on the east. The section suggests an interpretation of the surface forms.

Faults of the same character and of equal or greater throw must occur in several parts of the Connecticut Valley, if the line of argument thus far followed be carried to its legitimate conclusion. The doubt in certain cases lies entirely in the difficulty, caused by the heavy drift covering, of finding a sufficient number of outcrops to establish the complete sequence of beds already described, and not in any contradictions where the beds are seen or in any inherent improbability of a faulted structure; and it must be borne in mind that the systematic relation of these strike-faults to one another and to the faults already described counts strongly in favor of their occurrence. They may be described in order from south to north along the main trap overflow, after noting that the separation of the crescents of Pond and Toket Mountains is caused, not by a fracture, but by a transverse anticline, as will be described below.

A fault of nearly one thousand feet throw may be inferred between Toket and Paug Mountains; a fault of less throw probably runs
through Paug Pond, separating Pang Mountain from the long range that runs north between Durham and Wallingford, and rises between Middletown and Meriden, in the high ridge known as Middletown Mountain, near its northern end; similar displacements explain the separation of Lamentation Mountain from Middletown Mountain and the breaking of the former into two parts. Lamentation Mountain and the Hanging Hills must still be considered parts of the same main sheet, dislocated by a fault of several thousand feet, the largest of the series, in the valley followed by the New Haven and Hartford railroad. In all these mountains the same sequence of beds is more or less completely presented: a sandstone with shales at the base of the western slope, a bench or ridge formed by the amygdaloidal trap of the anterior sheet, a series of shales with a limestone bed near its base next in order, the heavy trap sheet forming the main ridge, this overlaid with sandy shales, and followed at last by the posterior ridge or upper trap sheet. Going farther north, the oblique faults already mentioned are encountered.

Marginal faults.—A very considerable fault or series of faults is indicated along the eastern margin of the formation, for this only can explain the sudden appearance there of the crystalline rocks, in face of the continuous eastward dip of the bedded series close to their boundary. This is especially conspicuous in the district of the two southern crescentic ridges from Durham to the Sound; the beds here are often coarse conglomerates, undoubtedly derived from the crystalline ledges to the east, and yet their dip is persistently to the east up to the very last outcrop visible, excepting in the hooks of the crescents, where the attitude of the beds changes, as will be shown below. The measure of the total upthrow of the crystalline rocks along the margin of the formation will depend on the number and value of the step-like faults west of it; but on the east of Pond and Toket Mountains the throw must be several thousand feet.

SYSTEMATIC ARRANGEMENT OF FAULTS.

The faults now described are arranged in a systematic manner. The upthrow is always on the east, so that a single bed is repeated in several outcrops and the directions of the faults in certain definite areas are essentially parallel, for the difference between the strike-faults and the oblique faults does not arise so much from a change in the direction of the fractures as from a change in the strike of the fractured beds. All the numerous faults south of Hartford trend north-northeast or northeast. Farther up the valley, they turn more to the west, and for a time run north or north-northwest. It is owing to this systematic arrangement of the faults that the adjacent trap ridges overlap in the orderly manner that impressed Percival as one of their most peculiar features. On the southern half of a crescentic curve that is made up of several dislocated and overlapping mem-
bers, such as Pond Mountain, in a small way, or the Hanging Hills, on a larger scale, the south end of a northern member always stands west of the north end of a southern member, thus forming the "advancing order" of Percival, as in Fig. 100; on the northern hook of

![Fig. 100. Arrangement of overlap produced when the beds strike to the left of the fault line; advancing order.](image)

the crescents, this is reversed into the "receding order," as in Fig. 101, that characterizes the range from Bloomfield, Conn., to the Holyoke Range in Massachusetts and is found again in corresponding attitude

![Fig. 101. Arrangement of overlap produced when the beds strike to the right of the fault line; retreating order.](image)
on the north end of the Deerfield trap sheet at Turner's Falls. It should be remarked that it is not the crescent that compels this orderly arrangement, but the arrangement that compels the crescent. Besides this, there is necessarily a tolerably constant proportion be-
between the throw of a fault and the overlap of the adjacent ridges, and in this is to be found the reason for a well marked peculiarity of the Triassic topography; in following the main trap ridges northward, the westward offset of the successive mountains is proportionate to their southward overlap. The systematic arrangement of the faults, therefore, deserves as much emphasis as the occurrence of the faults themselves, and a less complete chain of evidence suffices for their demonstration than would properly be demanded in case they were without visible relationship.

The obscurity of the Triassic monoclinal structure has been greatly increased by a general belief in the Post-Triassic intrusion and disturbing action of the trap sheets; for, if the sheets had been sedimentary beds, like the mountain-making sandstones in Pennsylvania, hardly any other explanation than the one here suggested could be imagined to account for their repeated appearance. Being of eruptive origin, ordinary stratigraphic interpretation has been long denied them. Once fully recognized as contemporaneous overflows, they take their proper place as guides to the structure of the whole formation.

The faults thus far considered have all been discovered where they intersect the trap ridges; but it must not be inferred from this that they are limited to these localities and that no faults occur in any other. The fractures are probably continued along their strike for a distance many times greater than their throw, and the larger master-faults may run ten or twenty miles or more. Many faults may be limited to the sandstone areas, and thus for the present elude detection. It is probably in some such way as this that explanation will be found for the evident general relation between the curvature and interruptions of the overflow and intrusive trap sheets. Their curves are convex in the same direction, their members overlap in the same order, and the similarity in the disposition of the two series of ridges is too great to be attributed to independent forces. No faults are yet directly proved by the repetition of a sequence of strata about the ridges of the intrusive sheet, and their independent discovery is made difficult by the absence there of subordinate sheets parallel to the main intrusion and of a guiding limestone bed; but an examination of the ridges on the ground and an inspection of Percival's map strengthen the conviction that the intrusive ridges are subject to the same system of dislocation as that discovered among the overflow ridges. It is, of course, possible that intrusions should occur after the general disturbance of the formation as a whole and that the intrusive lavas should be guided into curved sheets, following the attitude of the bedded rocks; but it can hardly be thought possible that the disconnected members of such intrusions should arrange themselves so as to overlap in the same order as that found in the overflow sheets several miles away. The intrusive sheets, there-
fore, as already stated in the first division of this paper, must be regarded as having taken their place in the formation, like the overflows, before the period of tilting and faulting, while the strata were still continuous and horizontal. Their value as guides to structure is much less than that of the overflows until they are demonstrated to follow the bedded rocks conformably, and this demonstration is difficult in a region so heavily drift-covered.

**FAULTS WITH REVERSED THROW.**

The rule that faults have the upthrow on the eastern side is open to few exceptions. Perhaps half a dozen cases are known in quarries and cuttings where uplifts of a few feet on the western side of a fracture have been noticed; but these have no effect on the topography and would hardly claim mention were it not for the suspicion that the western margin of the formation, in some localities, is cut off by a fault of considerable strength, with this reversed direction of throw. This suspicion is based on the variable distance between the western ridges of intrusive trap and the boundary of the formation as marked on Percival’s map, and therefore assumes, in the first place, that the intrusive sheet has an essentially conformable attitude in the sedimentary series; in the second place, that the sediments do not rapidly vary in thickness; and, in the third, that the boundary is correctly mapped. The first assumption is not contradicted wherever the attitude of the sheet can be determined, little is known about the second, and the third is warranted by the confidence gained in the remarkable accuracy of other parts of the map. There is, to be sure, much heavy drift in many parts of the marginal region, for the boundary in nearly all its length follows a valley, and it remains for future investigation to determine whether the suspected fault really exists; but meantime the possibility of such a fault should be accounted for.

**FOLDS OF THE CRESCENTIC RIDGES.**

A second style of departure from the generally accepted monoclinal structure is the change in the strike and dip of the beds so as to maintain a conformity with the curvature of the crescentic or hooked trap ridges, to which reference has already been made. The curvature of the ridges with their convex side to the west has long been noticed. Percival recognized it as a general form, and detected the parallelism between the aqueous and the igneous beds in this type of structure; he made especial mention of the latter peculiarity in the striking example near Beckley Station, described below. Hitchcock found it in Massachusetts, but did not follow it in detail and was probably unaware of the completeness of its display in southern Connecticut.
The hook at the northern end of the curved trap ridge near Beckley Station, on the Berlin and Middletown Railroad, is small enough for easy observation; its curvature is sharp and the sandstone outcrops near it are numerous enough to make a satisfactory case. The trap sheet changes its strike by 120° in half a mile, and its dip of 25° or 30° is always directed toward the center of its curve; the sandstone below it presents just the same changes of attitude. Curvature of outcrop like this on a generally horizontal surface clearly implies a faint folding or dishing of the beds that appears to be thoroughly characteristic of Triassic structure. It is repeated over and over again on a larger or smaller scale and, when associated with faulting, gives sufficient reason for the many curious topographic forms of the Connecticut Valley. The absence of outcrops on the eastern side of the "dish," where the curvature would consequently be convex to the east, is to be accounted for by the eastward dip of the "dish" as a whole and by the occurrence of faults along its eastern side. This is neatly shown at Beckley, where the fault that truncates the "dish" is indicated by a repetition of the same detail of topography in a second curved trap ridge immediately east of the hook that terminates the long curve of the first.

Pond and Toket Mountains (Fig. 102) give an ideal illustration of this structure. The first is the simpler form of the two. In spite of the strong bending of the trap sheet that forms the ridge, the adjacent beds above and below it depart in the same way from the general strike of the monocline. This is, to be sure, only a corollary to the demonstration of the contemporaneous overflow of the trap sheet upon the bedded rocks, but it is an interesting and valuable one. The parallelism appears not only along the main ridge, but in the neighborhood of the posterior trap sheets as well. The latter are peculiarly suggestive, as the two ridges, called by Percival the first and second posterior ridges, are almost certainly the western and eastern outcrops of a single trap sheet; for here alone in the whole Triassic area is the truncating fault far enough away to allow both sides of the trap "dish" to reach the surface; here only is a trap-ridge found convex toward the east. It is most satisfactory to find that so thoroughly exceptional an occurrence admits of so simple an explanation, completely in sympathy with that given to the whole region. The first or normal posterior ridge dips to the east and is convex to the west; the second has its faint convexity eastward and the sandstones below and above it dip to the west. Unfortunately, the complete oval outcrop of the sheet is interrupted on the northeast and southeast, where the trap is either hidden under drift or carried away by irregular faulting. It is, indeed, by but a small distance that the eastern outcrop escapes concealment in the present

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1 This explanation of the crescentic ridges was suggested by the writer several years ago. See Bull. Museum Comp. Zool. Harvard Coll., vol 7, No. 9, 1883.
stage of denudation, for the crystalline rocks appear only a few hundred feet east of it, and the trap itself is much disturbed and broken, as if the heavy fault that here follows the margin of the formation had run close by it and shattered it.

The hooks at the ends of the Toket Mountain crescent next north of Pond Mountain are strongly turned in; the adjacent beds follow them accurately wherever visible. A significant variation on the simple type of Pond Mountain is found here in the indentation of the western face of the ridge a little north of its middle, as if it were affected by the faint beginning of a transverse anticline which, if carried to its completion, would separate the mountain into two parts. Such a separation is already accomplished in the posterior ridge (Fig. 103), whose two curved members correspond to the northern and southern lobes of the main crescent; their eastern outcrops are cut off by the strong marginal fault. The sandstones and conglomerates within the crescent also present a double curvature, perfectly in sympathy with the turning of the trap sheets. Toket Mountain may indeed be regarded as showing in an uncompleted
form the very structure which, when further evolved, has caused the separation of the Pond and Toket crescents in the present stage of erosion. As the degradation of the surface progresses, the indentation of the western margin will become deeper and deeper, until at last, if sufficient depth of erosion be allowed, the main ridge will be worn into two separate members. The once continuous posterior ridge has already reached this stage. It cannot be doubted that the main trap overflow once stretched over the valley that now divides the Pond and Toket crescents, whence it has been worn away in the reduction of the surface to the present form.

There are no other examples so simple as these. The great range that curves from the Hanging Hills on the south to the Mount Holyoke range on the north and the smaller Deerfield range are complicated by faulting, as already described; but in as far as they are curved they correspond closely with the typical structure of the crescents. Their attitude is very significant in one respect. On the assumption that their trap sheets were once of larger area than at present—and this is not at all improbable, for it is likely enough that they are dissevered parts of a single sheet—some reason should be found why they turn so strongly toward the eastern margin of the formation about Amherst and leave so large an area free from trap between them. The simplest reason for this is that the Amherst district between the two trap curves has been elevated more than the country north or south of it. This in turn would require that the foundation of the Triassic formation should here approach nearer to the present surface of the ground than it does elsewhere. Now, it is precisely in this part of the whole Triassic area that the only outcrop of the fundamental crystalline rocks appears, forming Mount

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**Fig. 103.** Bird's-eye view of an ideal dissection of Pond and Toket Mountains mapped in Fig. 102. The fault separating the Triassic and crystalline rocks is drawn as a vertical face; the exposed slopes of the trap sheets are shaded with closer lines than those drawn over the rest of the surface. Although lacking detail, the diagram may serve to illustrate the homology between the two parts of the main trap sheet in the separate mountain ridges and the two parts of the posterior sheet in the small ridges within the Toket crescent.
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Warner. This separation of the Mount Holyoke and Deerfield ranges would therefore appear to be a large example of a late stage in the process so faintly begun in the indentation of the western face of the Toket crescent. The absence of a ridge of intrusive trap near the eastern margin of the Mount Warner crystalline area confirms what has been said as to the limitation of intrusive sheets to Connecticut.

It may be mentioned that the little ridges north of Toket Mountain, marked with much detail of curvature on Percival's map, are disappointing when examined on the ground. Their outcrops are very irregular, not nearly so smooth and continuous as the map indicates, and no adjacent sandstones are visible. No definite statement can be made concerning their arrangement.

The influence of curvature of the trap sheets on the topography of the valley is especially instructive in illustration of the variety of form developed by slight changes in a simple type of structure, and, with the exception of the smallest ridges, no form is presented in duplicate. It is as if one example of each stage in the variation is all that should be needed to enforce this lesson.

SUMMARY OF STRUCTURE TO BE ACCOUNTED FOR.

The simplicity of igneous action implied by regarding all the many trap ridges as the product of a few intrusions and eruptions and the ease of explanation gained by looking upon curved ridges as the outcrops of slightly folded beds are equaled by the economy of material allowed by associating a series of step-faults with the monoclinal attitude of the formation. A thickness of thirty or forty thousand feet would be required if the monocline were unbroken; about ten thousand may suffice if faults occur as commonly in the sandstone areas as among the trap ridges. We must therefore conclude that, whatever hypothesis is suggested for the mechanical origin of the Triassic structure, it must explain how the whole series of beds, igneous as well as aqueous, has been broken into a number of long, rather narrow, parallel-sided blocks, how the beds in every block have been tilted over to the east and sometimes faintly bent into dish-like form, and how the blocks are all dislocated by faults with upthrow almost constantly on the eastern side.

MECHANICAL ORIGIN OF THE TRIASSIC MONOCLINE.

CONDITIONS OF THE PROBLEM.

It will be well, in entering on this problem and before attempting its solution, to consider its conditions and requirements. These may be best appreciated by following the historical method and reviewing the suggestions that have been made towards its explanation.

Oblique deposition.—The idea once advocated that the present attitude is the original attitude, and that the monoclinal structure is
simply an extended example of oblique deposition, is inadmissible: First, because in such case the conglomerates on the eastern side of the formation in the Connecticut Valley could not dip, as they do, toward the land from which their fragments were derived, and, second, because the evidence of faulting, accompanied by tilting, is too distinct to be longer overlooked. The first condition of the problem is therefore the simple one that the strata have actually been disturbed in some way, and do not now lie as they were deposited. This is almost self-evident, and is mentioned chiefly from its historical interest and to clear the ground for what follows.

Contemporaneous disturbance.—It has been suggested in explanation of the Triassic monocline in New Jersey, which in many respects is similar to that of the Connecticut Valley, that the tilting went on progressively with the deposition. Apart from the mechanical difficulties that this involves, it would be inapplicable to the Connecticut Valley, because it presents no explanation of the systematic repetition of the similar sequences in the deposits already mentioned. It has been shown above that the similarity of the sequences is best explained by supposing the corresponding members in different localities to be parts of a once continuous single stratum, either aqueous or igneous, while the repetition is regarded as the effect of faulting subsequent to the time of deposit of the uppermost repeated stratum. We thus have the second condition that, at least as far as the Connecticut Valley area is concerned, the disturbance occurred after the deposition was essentially completed, and therefore involved the whole thickness of the formation.

Disturbance by intrusions.—The constant association of numerous trap ridges with the Triassic strata early gave rise to the supposition that the outburst of their igneous rocks was the sufficient cause for the tilting of the adjacent aqueous beds. This was perhaps natural enough at a time when the disturbance accompanying intrusion and eruption was exaggerated, and when the contemporaneous origin of many of the trap sheets had not been perceived, but from the present point of view it is inadequate. In the first place, the greater number of the Connecticut trap sheets are old overflows, contemporaneous in origin with the strata that inclose them and with which they have therefore been passively disturbed by external force. Further, the dikes that have been discovered breaking across the bedded rocks exert no noticeable influence on the attitude of the beds about them, and the few trap sheets that have been intruded among the lower strata are almost limited to the western border of the formation in Connecticut. They do not appear in Massachusetts. No peculiar attitude or structure is to be found in the strata adjacent to them that cannot be, both in quality and quantity, paralleled or exceeded in other parts of the formation. Their ridges are curved and interrupted in essentially the same manner as that so characteristic of the larger...
ridges of overflow sheets. In this connection it may again be noted that dikes and intrusive sheets are well known elsewhere in regions of horizontal strata where their entrance has produced no more disturbance than was necessary to give them room; and it should be remembered that to admit the theory that the Triassic disturbance was caused by the trap intrusions is accepting an explanation that does not explain, for no sufficient reason has yet been given to show why the intrusions should take shapes at once so peculiar and so systematic. Therefore, when it is seen that the peculiar attitude of the intrusive sheets, in all essential features, is imitated in the attitude of the overflow sheets that cannot possibly have been concerned in their own distortion, it is legitimate to conclude that the distortion was accomplished by a force external to both intrusive and overflow sheets, which together yielded before it.

The third condition of the problem, therefore, requires, that the disturbing force shall act upon the formation from without, after the entrance of the intrusive trap sheets, and that the whole formation shall passively suffer under this disturbance.

*General tilting and faulting.*—The explanation of the monoclinal structure that has been most commonly followed regards it as the result of a broad tilting, with more or less vague faulting, of a once horizontal formation by an undefined external force. This explanation also leaves much to be explained, but it is satisfactory in so far as it involves, at least by implication, a disturbance not only in the Triassic strata, but in the fundamental and adjoining crystalline rocks as well; for it is reasonable that the area over which the disturbance acted should not be closely limited to the area where its effects are now seen in the tilted sandstones and traps; nor should its penetration below the surface be measured merely by the depth of the Triassic formation. A great depth of penetration is indeed required by the magnitude of the faults, already described. It cannot be supposed that the disturbance which originated the faults that dislocate the main trap overflow faded away within the thickness of the Mesozoic rocks; 'it is demanded by the surface structure that the faults have depth proportionate to their throw and commensurate with their length, and this would carry them far down into the underlying schists and gneisses. This is, moreover, entirely in accordance with the hypotheses concerning the general deformation of the earth's crust; the thickness of rocks involved in the deformation may indeed be measured by tens or hundreds of miles. A fourth condition thus demands that the external disturbing force required in the third shall affect a greater mass than that of the Triassic rocks alone.

*Relation of severed Triassic areas.*—It has been suggested in recent years that the eastward monocline of the Connecticut Valley and the westward monocline of New Jersey might be lateral remnants
of a broad Triassic area whose central part had been high uplifted, forming a broad, anticlinal structure, the arch having been worn away, leaving only the buttresses remaining. It may be remarked that the former continuity of the Triassic strata across the whole breadth of the supposed arch is not essential to this explanation and that the occurrence of locally supplied conglomerates on the western side of the Connecticut Valley area, and probably also on the eastern side of the New Jersey area, points against it. The suggestion has, however, the strong recommendation of recognizing that there was some community of disturbance in the adjacent Triassic areas and that the disturbance affected broad areas and great depths of the earth's crust in a systematic manner. The similarity of the several Triassic areas on the Atlantic slope is very striking. From Nova Scotia to the Carolinas the several isolated strips of this formation present many resemblances, not only in materials, but also in attitude and structure. This is especially the case in regard to the areas in Nova Scotia, the Connecticut Valley, the little Southbury-Woodbury district in western Connecticut, and the large extension in New Jersey and Pennsylvania. Just as the similarity in the old lavas over all these areas points to their origin from a deep-seated source, as Professor Dana has suggested, so the similarity in the character of the distortion that they have suffered points to a general rather than to a local force for its production.

This fifth condition, therefore, indicates that the disturbing force was felt over a region so large as to embrace several of the isolated Triassic areas, and, further, it at least suggests that the action of the force and the character of the resulting disturbance were determined less by the structure of the relatively local and superficial Triassic deposits than by that of the wide-spread ing and deep-reaching crystalline mass on which they generally rest.

Character of the disturbing force.—The character of the disturbing force that produced the monoclinal structure cannot be sharply defined, but the following considerations may give some indication of it. The several Triassic areas are associated rather closely with the eastern margin of the greater area of Appalachian disturbance. Their trend is approximately parallel to the larger structural lines of the mountain system, and the depression of the troughs in which their beds were collected as well as their subsequent deformation may be naturally associated with a continuation of the disturbances that had in Pre-Triassic time accomplished the greater part of the Appalachian folding. The structure of the whole region is consonant with this supposition, for it bears many marks of yielding in sympathy with the Appalachian system. It will therefore be well to bear in mind a probable sixth condition, that the disturbing force, whose magnitude and area of application were defined in the fourth and fifth, was a long-enduring and slow-acting horizontal compression, exerted in an east and west or southeast and northwest direction.
The relation of the processes will depend largely on the texture and attitude of the rock masses. In a case where the yielding chiefly takes the form of tilting and slipping, it must be noted that the number of slipping surfaces, or “faults,” and the amount of motion upon them, or “throw,” will vary along the strike of the schists with the variation of schistose structure. When the slabs are thin and offer equal ease of slipping, many faults close together and of small throw may be formed. Where massive gneiss occurs, the slabs may be much thicker between the divisional planes, and the faults will be fewer and probably of greater throw.

**FORMATION OF THE FAULTED TRIASSIC MONOCLINE.**

The attempt may now be made to apply these processes to the case of the Connecticut schists and gneisses, remembering that they have probably been disturbed to great depths and that they are covered with a relatively shallow layer of Triassic strata. Their condition is roughly illustrated in Fig. 104. As they are here supposed to be in the attitude they held before the Triassic monocline was formed, their position is necessarily somewhat a matter of conjecture; their regularity is probably exaggerated. Two dikes are added to the diagram, one on the left to feed the intrusive trap sheet, the other on the right to supply the successive overflows that appeared at certain times during the depression of the basin and the accumulation of the sediments; three volcanic cones are indicated at the points where the second dike came to the surface during its periods of activity. All of this, of course, is highly diagrammatic; the vents or fissures from which the overflows were supplied are not yet identified and may have been at different points; the dike that fed the intrusion is still undiscovered. Nothing definite can be said as to the number of divisional planes that will be formed between the great slabs of schist and gneiss or of the amount of slipping upon them when the crush comes; but they may be represented by the structural lines in the figure. The upper edges of the slabs have been worn down by Pre-Triassic erosion, so that every slab is beveled off at such an angle with its dip as to form a continuous and nearly level land surface on which the Triassic deposition began when the region as a whole was depressed and submerged.
Having reached this point of view it may be found profitable to leave the Triassic strata out of consideration for a time and give more attention to the rocks that underlie them.

**ACTION OF COMPRESSION ON TILTED SCHISTS.**

The fundamental rocks have already been described as schists and gneisses, generally dipping at steep angles; their strike is variable, but in the region of the Connecticut Valley it is commonly somewhat east of north. How would these fundamental rocks yield if acted on to great depths by a horizontal compression force, directed at right angles to their general strike? A brief digression may be permitted for the more deliberate approach towards the answer to this question.

A homogeneous part of the earth's crust, subjected to a horizontal crushing force, yields by minute, intimate rearrangement of its parts, whereby its horizontal measure in the line of the force is diminished and its compactness and vertical measure are proportionately increased. The development of cleavage and foliation is generally associated with this kind of deformation.

A region composed of stratified or laminated rocks yields, under the same conditions, by slipping one surface on another, accompanied by more or less bending. If the laminae or slabs are not already at right angles to the compression, the surface of the region is elevated and its breadth is reduced. If the strata are horizontal, as in cases ordinarily considered, they will escape from a horizontal crush by folding or wrinkling, the measure of the corrugations depending in part on the thickness of the strata. Such folding ends when the divisional planes are at right angles to the compression, the folds are then "closed," and further compression is accomplished by intimate rearrangement.

If the laminae plunge at about a constant angle through the whole depth of the mass possessed by the compression, they will slip upon one another as they are tilted over, so as to bring the divisional surfaces more nearly at right angles to the compression and no folds need appear. If the dip of the laminae vary with the depth, they will generally yield by changing their attitude so as to smooth out their corrugations and become straight and vertical. In both cases the surface of the region will be elevated.

If the force of compression vary with the depth, so as to introduce a shear, deformation by slipping of slab on slab may continue after the slabs are at right angles to the direction of the force. Overturned beds are presumably connected with some such style of distortion.

There is necessarily, in natural cases, a general interaction of these various processes. Heavy compression will produce intimate rearrangement at the same time with folding or tilting and slipping.
Deposition continued while depression lasted, but it was stopped when the fundamental schists began to writhe and rise under the growth of the irresistible compression. The great slabs slip one on another; their dip is increased, and on the east they are even thrown over past the vertical. Their upper surface, on which the Triassic beds rest, is no longer united, continuous, and nearly level; the slabs are separated by faults of greater or less throw and their beveled edges are canted over at an angle equal to their change of dip. The overlying beds, unable to support themselves unbroken on this uneven foundation, settle down upon it as best they may. It seems as if an explanation of the Triassic monocline might be found in some such mechanism as this.

The result is illustrated in Fig. 105. The essential characteristics of the Triassic structure appear at once. The dip is all in one direction and of tolerably constant amount as long as the slabs of schist are canted over to the same side, whether the dip of the slabs is constant or not. Numerous faults fracture and dislocate the unconformable surface layers; the length of the faults and the amount of throw vary, depending on the continuity and thickness of the slabs of schist beneath; the upthrow is on the side of the direction of dip, without regard to the hade of the fault; the strike of the schists determines the direction of the faults.

This last point offers satisfactory means of testing the hypothesis. The systematic arrangement of the faults and their oblique intersection with the trap ridges have already been described; these are most conspicuously exhibited about the Hanging Hills and farther south. After carrying the hypothesis thus far, it was a gratification to find that, on prolonging these oblique fault-lines until they reached the crystalline rocks to the northeast and southwest, they led directly to districts where, according to Percival's map, the strike of the gneisses and schists is most regularly developed and in a direction that coincides closely with the line of the faults. The accordance is most distinct, and it can hardly be doubted that the strike of the controlling fracture-lines in the Hanging Hills is determined by the trend.
of the structure-lines of the old rocks beneath them. It remains to be seen whether the change from the “advancing” order of overlap in the southern district to the “receding” order shown farther north in the Barn-door Hills of Granby will admit of similar explanation.

The solution of the problem need not be followed further until additional tests are applied to it in the field. One of these tests will be the examination of the adjacent schists to determine whether they are faulted or not, as the hypothesis indicates. There are, however, two special cases that need consideration, namely, the shallow, boat-like folds that determine the crescentic outcrop of the trap ridges, and the suspected fault along part of the western margin of the formation, with upthrow on the west, instead of on the east, as usual.

**Origin of the crescentic ridges.**—The size of the crescentic curves varies so greatly as to suggest different processes in their formation. The faint folds on which they depend may be in part the direct result of lateral compression, as perhaps in the small curve described near Beckley Station. But their association with faults is too important to be overlooked; it may be seen on close examination in Pond Mountain; it is conspicuous in the curving ends of the great Hanging Hills, Mount Holyoke range. It is therefore advisable to ascribe the flat folds as well as the faults to some reaction from the rocks beneath, and a sufficient cause for this may be found in a change in the number and the amount of dislocations in the slabs of underlying schist in passing along their strike, as illustrated in Fig. 106. The beds lying on a foundation thus molded might accommodate themselves to it by simple folding, if the slabs of schists were thin and
their faults small, and thus such a structure as that of Toket Mountain might be produced; if the slabs were thicker and the faults heavier, the dislocations would appear at the surface, as in the Hanging Hills. A cause for such changes in the value of the displacements as are here indicated is suggested in the next paragraph.

Faults with reversed throw.—The occasional occurrence of minute faults with upthrow on the western side of the fracture might be ascribed to unexplained accident, without injury to the main hypothesis; but the suspicion of a strong fault along part of the western margin of the formation, with upthrow on the same side and without change in the direction of dip, demands special consideration to see if it can be simply accounted for by the hypothesis here proposed.

The following suggestion (illustrated in Figs. 107 and 108) is offered in explanation of it: It seems admissible to assume almost any underground irregularity in the attitude of the fundamental schists, so greatly are their surface outcrops known to be contorted. Suppose, therefore, a curve introduced in the general plunge of the slabs, as

here represented; when the mass yields to a crushing force, the slabs in general will take a steeper position, but the local curve will flatten itself out and produce a displacement with uplift on the west, as shown in Fig. 108. Therefore, wherever the straightening of a folded slab produces an uplift on the west of a divisional plane greater than the uplift on the east that results from the general change in the
inclination of the whole series of slabs, the faults will find their upthrow on the unusual side. This relation of the two forms of distortion seems to have been rare. When the convexity of the folded slab is turned toward the dip of the future monocline, then straightening and slipping combine and the throw of the fault is locally increased. The change in the value of a fault along its strike, as required in the production of the crescentic ridges, may thus be in part produced.

The control of surface structure by dislocations in deep-lying rocks may perhaps find application in other regions than the Triassic areas. The faulted monocline of Tennessee stands greatly in need of some such explanation, and indeed, wherever unconformable masses are deformed together, reactions of the lower on the upper, such as are here suggested, should be looked for. Such a disturbance probably awaits the now horizontal Cretaceous rocks of northern France, where the sharply folded layers of the Carboniferous strata run beneath them from Belgium. Specific information concerning the process of disturbance of the Triassic rocks in the Connecticut Valley will be sought by continued investigation in the field.
SALT-MAKING PROCESSES

IN THE

UNITED STATES.

BY

THOMAS M. CHATARD.
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<td>522</td>
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SALT-MAKING PROCESSES IN THE UNITED STATES.

By THOMAS M. CHATAKD.

INTRODUCTION.

The various elements which go to make up the cost of an article of commerce are found exemplified in the simplest and clearest manner in the salt industry. The raw material, the brine, has no other value than that given it by the cost of sinking the well and pumping; the fuel used is, so far as practicable, unsalable refuse; the machinery is of the simplest character, there being but little opportunity for the use of labor-saving devices; manual labor, mostly of a comparatively unskilled character, is almost exclusively employed; and the handling, transportation, and distribution of the product are effected in the cheapest manner, the foreign article being to a large extent brought in as ballast and sold at rates but little above those at the port of shipment. Moreover, a fierce domestic competition has cut down the price of the home product to a figure which leaves but little profit even to the more favorably situated manufacturer, and in the struggle for existence success can be expected only by those who practice intelligent economy and endeavor to improve their own methods by the careful study of the most improved practice at home and abroad.

In the course of a trip to some of the principal salt-making centers in the eastern part of the country, made in the summer of 1885, for the purpose of collecting information which might be available in a prospective study of the alkali deposits of the West, the preparation of a paper of the nature of the present one was suggested by one salt manufacturer and advocated by others.1

They considered that the work, if properly done, could not fail to be of advantage to the industry, recognizing the fact that they were not obtaining the best practicable results; but they were unwilling to make any extensive changes in their methods without a previous study of other methods and results, for which they had neither time nor opportunity. The foundation for such study is the

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1 This paper was prepared in the spring of 1886, but its publication has been delayed. It has since been, in part, revised, but the details of manufacture are those collected in 1885. (March, 1888.)
collection of manufacturing statistics from the native works and their careful comparison with each other and with the best results of foreign practice. Foreign statistics are usually obtainable, salt works in most countries being either managed by the government or carried on under strict governmental supervision; but in this country, although considerable information is given by the Syracuse reports and those of Michigan and more is scattered through various journals, no regular collection, embracing the entire country, has ever been attempted.

My instructions and the time allotted for my trip did not then permit anything to be done in this direction, but subsequently explanatory letters and lists of questions were sent to some of the principal manufacturers. The result was that, while some sent complete information, even to the smallest details, others returned answers lacking in important points and still others did not reply at all. Under the circumstances no extended comparisons can be attempted; the present paper should be considered as only preliminary and as published in the hope that the manufacturers, seeing what is intended, will be willing to aid in any future study of the question.

That such information should be hard to get is not surprising, for in most cases the manufacturers keep no such records of work as would furnish it, and moreover they dread that, if it is published, their own business may be damaged. That this fear arises from a misunderstanding of the purport of the investigation is shown by the fact that nearly every one of the manufacturers with whom I had an opportunity to talk was willing, when the scope of the work was explained to him, to afford me every facility in obtaining information.

In the present paper will be found a short account of the chemistry of brine, with some useful tables, followed by descriptions of the different methods employed in this country and the results obtained by them, and also some references to foreign practice. The accompanying plans have been furnished by practical salt-block builders, either as completed drawings or in the form of detail sketches, from which the plans have been made; it is believed that they represent the latest forms and that they are fairly typical. Finally, an attempt will be made to institute some comparisons between the various methods to determine their relative efficiency and economy, including such observations looking to their improvement as the information collected may suggest.

CHEMISTRY OF BRINE.

The chemistry of brine is, for practical purposes, very simple. We have in most cases but one valuable constituent, the salt, and one obnoxious ingredient, the gypsum or sulphate of lime. To remove the latter and to obtain the former as completely and as cheaply as
possible being the ends sought for in all the processes, the required operations must be of a simple character.

Chloride of sodium, or common salt, when pure and in masses of some size, is transparent and colorless; but as it occurs in nature as rock salt it is usually more or less colored and rendered opaque by impurities. It has a specific gravity of 2.16 and crystallizes in cubes, although, in the presence of certain salts, rarely found in brines, it can form octahedra. If a solution of salt is evaporated slowly the cubes which form on the surface arrange themselves together to produce the well-known "hopper" forms. In rapidly evaporating solutions the crystals, being produced more quickly, are much smaller and unite, forming thin sheets which tend to impede further evaporation; hence the use of butter and other grease in grainer work to cut the grain, the presence of the very thin skin of grease on the surface of the liquid tending to prevent the formation of the surface sheet of crystals. When the solution is kept boiling no such addition is necessary, as the agitation of the brine is sufficient to break up the sheet as fast as it is formed, and the same effect is produced by the motion of the "self-rakers" used in some works. The salt crystals do not contain any water of crystallization, but take up small portions of the mother liquor between their adhering surfaces, thus making the salt less pure, as well as causing the crackling which takes place when salt is rapidly heated.

One hundred parts of pure water at 60° F. (15.5° C.) dissolve 35.9 parts (Poggiale), so that the saturated solution contains 26.47 per cent. of salt and has a specific gravity of 1.2055. These results, however, can be obtained only by careful working with chemically pure salt and distilled water. In practical work differences will always be observed, and the other constituents of the brine exercise more or less influence on its salt contents when saturated. Table I, at the end of this paper (p. 527), prepared by Dr. F. E. Englehardt, of Syracuse, N. Y., State chemist for the salt works, will be found correct for brines of good quality.

The presence of lime and magnesian salts to an amount above a certain small limit will of course increase the readings of the salometer or of other forms of hydrometer, mother liquors at Syracuse rising even to 150° salometer. An increase of temperature above the standard temperature of the instrument will, by expanding the liquid, lower the reading.

2 The salometer is a hydrometer having the point to which it sinks in pure water marked 0 and the point to which it sinks in saturated brine marked 100. The saturated brine is made by dissolving the best solar salt in pure water and the standard temperature for the determination of the points is that of the brine in the wells, 52° F. 11.3° = C. (G. H. Cook, Ann. Rept. Supt. Onondaga Salt Springs for 1851, p. 35).
SALT-MAKING PROCESSES.

IMPURITIES OF BRINE.

Of the impurities in the brine the sulphate of lime is the most important, since it is almost always present, cannot be got rid of by any cheap practical process, and is a continual source of trouble and expense throughout the manufacture.

SULPHATE OF LIME.

As crystallized at ordinary temperatures from solution in water or brine it forms gypsum or hydrous sulphate of lime containing 21 per cent. of water, though sometimes with only one-half as much water.¹ When the solution is at or near the boiling-point, the sulphate of lime is thrown down in a condition approaching the "anhydrous" state, that is, containing no water of crystallization, becoming perfectly so as it lies on the more highly heated bottom or sides of the pan, kettle, or grainer pipe. The following table gives the solubility of one part of gypsum and of one part of anhydrous sulphate of lime in parts of pure water at different degrees of temperature:

<table>
<thead>
<tr>
<th>Temperature</th>
<th>One part gypsum dissolved in</th>
<th>One part anhydrous sulphate of lime dissolved in</th>
</tr>
</thead>
<tbody>
<tr>
<td>At 30° F. = 0° C.</td>
<td>415 parts of water</td>
<td>525 parts of water</td>
</tr>
<tr>
<td>At 84.5° F. = 29° C.</td>
<td>366 parts of water</td>
<td>488 parts of water</td>
</tr>
<tr>
<td>At 71.8° F. = 22° C.</td>
<td>327 parts of water</td>
<td>473 parts of water</td>
</tr>
<tr>
<td>At 95.6° F. = 36° C.</td>
<td>259 parts of water</td>
<td>458 parts of water</td>
</tr>
<tr>
<td>At 100.6° F. = 39° C.</td>
<td>268 parts of water</td>
<td>466 parts of water</td>
</tr>
<tr>
<td>At 105.8° F. = 41° C.</td>
<td>170 parts of water</td>
<td>498 parts of water</td>
</tr>
<tr>
<td>At 127.4° F. = 53° C.</td>
<td>370 parts of water</td>
<td>474 parts of water</td>
</tr>
<tr>
<td>At 161.6° F. = 72° C.</td>
<td>391 parts of water</td>
<td>456 parts of water</td>
</tr>
<tr>
<td>At 186.8° F. = 87° C.</td>
<td>417 parts of water</td>
<td>528 parts of water</td>
</tr>
<tr>
<td>At 212° F. = 100° C.</td>
<td>438 parts of water</td>
<td>572 parts of water</td>
</tr>
</tbody>
</table>

These results by Marignac² show that sulphate of lime is most soluble at about 100° F., being less soluble both above and below that point. Solutions of sulphate of lime have, however, a great tendency to supersaturation; that is, when a solution is evaporated it holds more of the sulphate in solution than it normally should. In a solution evaporated at ordinary temperatures 0.618 per cent. of sulphate of lime was found, while, according to the table, at 75° F. only one part in 479 should exist, or 0.21 per cent. A solution saturated at ordinary temperature contained 0.438 per cent. and began to form a deposit at the end of twelve hours. This gradually increased, so that at the end of twenty days there remained but 0.18 per cent. in solution; but when a portion of the original solution

was raised to boiling, an abundant deposit resulted, and after boiling a few minutes the solution contained but 0.218 per cent., having thus deposited at once two-thirds of the sulphate present. Hence the utility of a boiling heat for the rapid precipitation of sulphate of lime.

**Solubility in brine.**—The presence of chloride of sodium in such a solution increases the amount of sulphate of lime dissolved, which, however, diminishes as the brine becomes concentrated by evaporation. The annexed analyses by Goessmann of an original brine and of the “finished pickle” or saturated brine, resulting from the evaporation by solar heat, give the following results:

<table>
<thead>
<tr>
<th></th>
<th>Original brine (sp. gr. 1.1235 = 05° salom.) at 70° F.</th>
<th>Pickle (sp. gr. 1.3062 = 100° salom.) at 70° F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulphate of lime</td>
<td>0.5772</td>
<td>0.4119</td>
</tr>
<tr>
<td>Chloride of calcium</td>
<td>0.1533</td>
<td>0.2467</td>
</tr>
<tr>
<td>Chloride of magnesium</td>
<td>0.1444</td>
<td>0.2433</td>
</tr>
<tr>
<td>Chloride of potassium</td>
<td>0.0119</td>
<td>0.094</td>
</tr>
<tr>
<td>Bromide of magnesium</td>
<td>0.0021</td>
<td>0.010</td>
</tr>
<tr>
<td>Carbonate of protoxide of iron</td>
<td>0.0044</td>
<td></td>
</tr>
<tr>
<td>Chloride of sodium</td>
<td>15.807</td>
<td>28.789</td>
</tr>
<tr>
<td>Water</td>
<td>83.5747</td>
<td>73.946</td>
</tr>
<tr>
<td></td>
<td>100.000</td>
<td>100.000</td>
</tr>
</tbody>
</table>

It is a question how far these high percentages of sulphate of lime may be due to supersaturation, since, as we have seen, Marignac obtained a solution in pure water, containing 0.438 per cent., and the conditions under which such brines are obtained are favorable to supersaturation. The solubility of sulphate of lime in solutions of salt of different degrees of concentration and temperature has not so far been studied from this practical standpoint, or, at least, results, if obtained, have not been published, and, owing to this lack of data, it is not possible at present to give any decided and definite opinions concerning the best way of getting rid of the sulphate before proceeding to make salt. Even laboratory investigations will have but little value, comparatively, if not made from the point of view of the practical salt maker and with a thorough knowledge of manufacturing conditions, where the low price of the product and the consequent need for simplicity of method must be considered at every step.

**Removal from brine.**—It is, in the laboratory, an easy thing to remove the impurities. Chloride of barium precipitates the sulphuric acid completely, leaving chlorides of calcium and magnesium, which remain in the mother liquor; carbonate of soda precipitates the

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lime, magnesia, and oxide of iron, leaving sulphate of soda in solution; if both are used in proper proportions, we can get an almost chemically pure solution of chloride of sodium. The cost of these chemicals, as well as of all others which have been proposed for this purpose, is, however, too great to permit their use for the purification of brine, although carbonate of soda is used to purify ordinary salt so as to render it fit for dairy purposes.

If we take the analysis of the finished pickle already given, which may be considered as a good, typical result of evaporation at ordinary temperatures, we shall find that for every 280 pounds of salt 8.25 pounds of carbonate of soda would be required to precipitate the magnesia and lime. The cost of this soda is generally considered too great to allow its use for this purpose, although the great decrease in expense for stoppages, lay-offs, and repairs might compensate and even show a balance in its favor. If ammonia-soda works should be established in a salt-making district, the crude bicarbonate of soda obtained in the process should be produced very cheaply, and it would be suitable for this purpose if the brine is heated, as it should always be, to promote the precipitation of the lime. At least it may be said that this method of purification is worthy of careful consideration, and local circumstances must decide how far it may be capable of application.

In default of a chemical precipitant, we are compelled to consider the application of heat alone as giving any reasonable prospect of improvement, and for that the data are, as remarked, insufficient, although Goessmann, in the paper already quoted, says: "The separation of sulphate of lime is particularly rapid near the point of saturation. * * * It is greatly influenced by the temperature applied for accomplishing that end," and "higher temperatures, above 213° (100° C.), increase the separation," while the experiments of Maignac, as well as those of Cousté and of Storer, give the same results.

Since the separation increases with the temperature, the deposition of the sulphate of lime is greatest at the hottest places, such as the bottoms of the pans, the steam pipes of the grainer system, or the plate heaters of the vacuum system. The form or position of the heated surface has little or no influence on the rate of deposition or the amount of the deposit, which adheres with equal tenacity to the upper and under portions of the grainer pipes and as firmly to the perpendicular sides of the plate heater as to the horizontal plates of the pan bottom. As the scale thus formed is a very poor conductor of heat, the useful effect of the heating surface is continually diminishing as the scale grows thicker, and, as a result, either the rate of evaporation diminishes or, if maintained, more fuel is needed to produce the same quantity of salt. In either case the regularity of
the crystallization of the salt is disturbed and the work must stop, sooner or later, in order that the necessary “scaling” may be done.

It would seem evident, therefore, that the deposition of the sulphate and the crystallization of the salt should, if practicable, be separate processes, and that the apparatus to be used for the former purpose should be specially constructed, since it is to be exposed to a high heat and speedily becomes coated with a closely adhering layer of a non-conducting material which can be removed only by a good deal of rough chipping and hammering. The form and mode of construction of such an apparatus should, therefore, be such as to facilitate the operation of scaling, while giving strength, durability, and compactness.

Where direct firing is employed, a properly constructed pan should comply with most of these conditions, and the description of the pans at Aussee, under the section treating of pan processes, gives hints which may prove of value in this direction. For the grainer system it is advisable to use some form of “plate heater,” which is a series of boxes built up of iron plates and connected by iron pipes so that steam may pass freely through them and thus boil the brine in the heater tank. The sulphate is deposited on the plates; therefore, to facilitate scaling, the members of the series must be so connected as to be detached from one another without difficulty and, when cleaned, be put together again so that all joints are tight. Moreover, as crusts will gradually form on the inner side of the plates and thus reduce their heating effect, they must be so put together as to permit the scouring which will be needed from time to time, though at much longer intervals than the scaling.

As the steam pressure in such a heater must be sufficient to rapidly heat the brine to boiling-point, it is evident that to construct an apparatus which shall fully satisfy all these conditions is by no means easy and that there is a great field for mechanical ingenuity. Practical experience has shown that one square foot of plate is sufficient for seven and three-fourths square feet of evaporating surface and that for uninterrupted running extra heaters should be provided, so that the cleaning shall not interfere with the crystallizing process. As the higher the temperature of the brine the more complete the separation of the sulphate, a cover for the tank sufficiently tight to maintain a steam pressure inside and thus raise the temperature will aid the action, and this cover will be necessary for saturated brines. Without it crystallization would set in at once and cause a deposit of salt along with the sulphate; if the brine is not saturated and the tank is open, the time required to evaporate the excess of water will perhaps be sufficient to effect the separation of all the sulphate precipitable at the normal boiling-point. Under any circumstances some sulphate remains in the brine and will be depos-
SALT-MAKING PROCESSES.

...alyzed with the salt; but the quantity will be proportionately so small that the pans or grainer pipes should rarely need scaling.

It must be remembered that this pre-heating of the brine does not mean any increase in amount of fuel used. The heat thus communicated to the brine is utilized in the after evaporation, and the exhaust steam from the heaters can be used either in a grainer or for raising the temperature of the cold brine so that it shall go to the heater nearly at the boiling-point. A great deal of the iron and other impurities would thus be got rid of before the brine reaches the heater and the accumulation of mud in the latter tank materially lessened.

The chlorides of calcium and magnesium, being much more soluble than the salt, remain in the mother liquor, but, by continued boiling, the chloride of magnesium gradually becomes basic, making the solution turbid and setting free hydrochloric acid, which attacks and rusts the iron of the pans. Chloride of magnesium tends to make the salt fine-grained, sharper in taste, and more rapidly soluble. Hence, for curing meats in warm climates, where speedy action is desirable, salt made from brines rich in these chlorides, such as the brines of the Kanawha and the Ohio Rivers, is preferred to the harder-grained northern salt.

FUEL IN RELATION TO PRODUCT OF SALT.

The economical application and thorough utilization of heat is the basis of the salt industry, and the value of any given process depends upon its efficiency in this respect, while the cost of the fuel required to make a bushel of salt from the brine of a district is the determining factor in considering the ability of the region to hold its own in business competition. We shall be aided in the discussion of this question if, before examining the various processes in use, we compare from this point of view the brines of a few typical localities.

In the following table the average salt contents is given, the amount of coal required being taken from Englehardt's table:

<table>
<thead>
<tr>
<th>Region</th>
<th>Salt in brine</th>
<th>Coal for one bushel of salt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warsaw, N. Y</td>
<td>23.0</td>
<td>41</td>
</tr>
<tr>
<td>Syracuse, N. Y</td>
<td>18.5</td>
<td>41</td>
</tr>
<tr>
<td>Saginaw, Mich</td>
<td>17.5</td>
<td>44</td>
</tr>
<tr>
<td>Pomeroy, Ohio</td>
<td>7.5</td>
<td>112</td>
</tr>
</tbody>
</table>

The concentrated brine of Warsaw, therefore, requires the least coal, the Pomeroy brine the most; but the cost of fuel at Syracuse is greater than at Warsaw and much greater than at Pomeroy, where the salt works are situated at the entrances of the mines and burn
the unmerchantable slack and top coal, while Saginaw, consuming the offal of the lumber mills, utilizes a material otherwise absolutely worse than useless. For this reason the competition of Saginaw overshadows all other regions. The sawdust and offal produced by the great lumber interests, though utilized as far as possible for other purposes, remain in enormous quantities and if not burned must be removed at considerable expense. Hence it is a positive economy to manufacture salt, even should the price obtained for the product barely cover the cost of manufacture. The salt industry is, therefore, here closely connected with the lumber interest, the exhaust steam from the mills being utilized in grainers, which are heated by direct steam when the mills are not running, while the pan blocks are also fired with the offal. Without this extremely cheap fuel, Saginaw would have great disadvantages as compared with other sections; with it, the market for its product is simply regulated by the cost of transportation. Salt-making is there but a side issue; the offal must be got rid of, and if the price received but covers the cost the mill-owner is content and still has in his favor the amount it would cost him otherwise to get rid of the waste. It is therefore evident that, so long as the lumber of that section holds out, Michigan will continue to control the market, for her brine supply is abundant and the salt must be made and sold, even if no profit is realized. The Salt Association of Michigan, managed with great skill and energy, is constantly extending its field of operation, and while the introduction of its product into new markets may, for a time, be attended by no profit, and even perhaps by a slight loss, yet the general result is satisfactory to those interested.

No change in the tariff can affect this position in relation to the other regions. Any rise in price consequent on an increase of the duty on foreign salt would but give the Michigan Association the means to pay transportation charges to more distant points than it has hitherto reached and thus widen its sphere of operations, while, with salt on the free list, Saginaw must suffer less than any other section.

The position of Syracuse in relation to the strength of its brine and the cost of its fuel is less satisfactory than that of any of the other districts, and the results of outside competition and consequent low prices realized are shown by the long lines of idle salt blocks, with their tall chimneys standing as monuments of a departing industry.

SALT-MAKING PROCESSES.

In examining and comparing the different processes we shall find that they fall into three groups, according to the character of the heat employed and the mode of application: (1) Use of solar heat, or solar salt manufacture; (2) direct artificial heat, or kettle and pan processes; (3) steam heat, or grainer methods.
SOLAR SALT.

There is but little to be said in this connection about solar salt, by which is meant all salt made by solar heat without the use of fuel. The name is more particularly applied to salt made at Syracuse and other places by evaporating the brine on shallow wooden vats or "covers," so called because provided with light, movable roofs, arranged in such a way that they can be easily shoved over the vats when it rains. The name "bay salt" is given to that made by the evaporation of sea water in shallow pits on the seashore, so arranged that the sea water can be admitted as needed and systematically concentrated and freed from impurities, as far as practicable, before the salt is allowed to crystallize.

In both cases the evaporation and crystallization are comparatively slow, but they yield a product indispensable for many purposes, which brings, in general, a higher price than boiled salt, as the crystals, being formed slowly, are larger and harder than those made by artificial heat and dissolve much less rapidly, and are, therefore, preferred for "heading" and "layer" in packing meat and fish.

APRONS.

The cover process as followed at Syracuse and Saginaw has been often described and fully studied. A great improvement in the process as at present conducted at Syracuse consists in the use of "aprons" in place of the "deep rooms" and "lime rooms" of the earlier method. An apron is a very wide, shallow trough, which conveys the brine from the wells to the salt fields, and is fifteen to twenty feet wide by two to three inches deep. Upon this the brine, kept at a depth of about half an inch, flows slowly, the grade being one inch fall in 100 feet, depositing the gypsum and being delivered in a saturated condition to the covers. Under the aprons are deep rooms or tanks so placed that, in case of rain, the brine on the apron can be discharged into the deep room, where it is protected from dilution, remaining there till the return of fair weather, when it is pumped back onto the apron, from which all rain-water has been drained.

The great advantage of this improvement lies in this, that the brine is concentrated and purified while being transported to the covers, the great length and width of the aprons, the shallowness of the layer of brine and its complete exposure to the sun, air, and wind greatly facilitating purification and evaporation, while permitting the use of the entire number of covers for salt making, instead of having as formerly one-third of the total number taken up for lime rooms and deep rooms. In this way the production of solar salt for the

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season has been brought up from 50 bushels per cover, or surface
16 by 18 feet, to from 70 to 80 bushels, and one manufacturer, of great
care and experience, informed me that his production for the season
of 1884 averaged 92 bushels per cover. As the capital invested in
covers is considerable, the economy of the aprons is readily seen.

BAY SALT.

Bay salt has been made for many years at various points on the
Atlantic coast, but the climatic conditions are not favorable and the
low price of foreign salt from Turk's Island, the Mediterranean, and
other points more favorably situated has not encouraged any exten­
sive operations of this character. In California considerable bay
salt has been made, amounting to 30,000 tons in 1883, the product of
1884, owing to unfavorable weather, being reduced to 25,000 tons.

KETTLE AND PAN PROCESSES.

KETTLE PROCESS.

This is the original Syracuse method and arose in the use of the
potash kettle, the largest boiling apparatus obtainable by the first
salt-makers. In 1788 the first salt was made at a spring on the shore
of Onondaga Lake by simple boiling over an open fire. As an im­
provement the kettle was set in an arch of mason work; next we
find the kettles in pairs, and in 1793 four kettles were combined,
forming a "block," a term which has ever since been applied not
only to kettle works but also to pan and grainer plants.

Up to the present time, kettles have been exclusively used at
Syracuse; for, although a few attempts have been made to introduce
pans, yet the weakness of the brine and the large amount of gypsum
in it have caused such experiments, at best somewhat desultory in
their character, to be speedily given up. The Annual Report of the
Superintendent of the Onondaga Salt Springs for 1851 gives plans
and accounts of some interesting experiments in this direction, but
it would seem that no success was realized, for the systems have not
come into general use, though having points about them of apparent
value.

When in 1860 the first brine well was bored at Saginaw, the Syra­
cuse kettle process was adopted, but it has gradually gone out of use,
being replaced by more economical pan and grainer processes, and
the reasons for this are very plain.

The kettle system originated as stated above, and gradually the
number of kettles in a block was increased until thirty or even forty
kettles were placed in a line from the fire space to the chimney.
As the length of the line increased it was necessary to have larger fires,
so that the end kettles might receive sufficient heat; and, as this

meant too high a heat for the forward kettles, arches were built under the first ten or twelve, protecting them from too high a temperature, but certainly not leading to any economy of fuel. Again, there being no communication between the kettles, each one is an individual and must be attended to as such, and there is no regularity in the process, as the kettles are small, holding about one hundred gallons each, and the forward kettles boil vigorously while the rear ones do not boil at all. As the panning or removal of the gypsum depends upon a quiet, regular boil of the liquid, only a few of the kettles can really be properly panned by even the most skilled workman, and the quality of the salt made at the front is very different from that made at the rear, owing to the difference of heat and the consequent variation in rapidity of evaporation. Moreover the scale or "blocking" increases with the heat, not only in quantity, but also in hardness and in the tenacity with which it clings to the sides and bottom of the kettle, thus cutting off a large proportion of the heat effect. The result of all this is that not more than two-thirds as much water is evaporated in a kettle block, with a given quantity of fuel, as can be evaporated in a properly constructed steam boiler.

A brine of 66.5° salometer (sp. gr. 1.128) is stated as producing forty to forty-one bushels of salt to the ton of coal (2,000 pounds Blossburg coal).1 To produce a bushel of salt from such brine, 263 pounds of water must be evaporated (see Table I), which should require 43.5 pounds of coal at six pounds water to one pound of coal, which is but three-fourths of the boiler effect, as shown in Table II. Taking the evaporation at 6.1, we ought to get 46.5 bushels instead of 40.5 bushels, a loss of six bushels, or of 14.81 per cent., while if compared with the full boiler effect, when we should get 60 bushels to the ton, we have a loss of 19.5 bushels, or nearly 50 per cent., being one-third of the total productive power. It must, however, be well understood that the high effects obtainable in carefully constructed boilers, with pure water and good coal, can never be obtained with brine and slack coal in any form of salt works, the effect of slack being usually stated as three-fourths that of lump coal of the same variety. A clear idea of what is lost and how it is lost, however, is the foundation of any attempt to make a saving. The kettle system, nevertheless, cannot compete with other methods and must speedily disappear.

STEAM KETTLES.

A modification of the kettle system, namely, heating the kettles with high pressure steam (40 pounds pressure), is in operation in the Warsaw district and is claimed to give a satisfactory return in salt (65 bushels) to the ton of coal, but the repairs in such a system

must be considerable, and it has many of the defects of the other form.

Vacuum Pans.

Rittinger, by a series of experiments, 1 found that a great saving in fuel could be effected by heating the brine in a closed vessel in which a partial vacuum was maintained by the action of a pump driven by water power. By then compressing the steam thus evolved, its latent heat was liberated and used to heat a new portion of brine. The results showed that by the use of 12.7 horse power of pump, 5.5 cubic feet of brine was evaporated per hour and that the combustion of one pound of dry wood evaporated 16.2 pounds of brine, or two and one-half times as much as by direct heat. A portion of the salt was deposited as minute, hard, glistening cubes, the balance forming a compact, very hard crust on the walls of the boiler. The vacuum system as improved by Piccard and others has been introduced into several works in Europe, and very careful experiments have been carried on to determine the best form of apparatus and the economy of the system as compared with the usual methods. The best account of the development of this process is found in a series of articles by C. von Balzberg, 2 which shows that when the apparatus is new and all the surfaces are clean the economy in fuel is great; even where water power was not available for the working of the compressor, six pounds of salt were obtained by the combustion of one pound of coal. This rate of production, however, speedily sinks, owing to the deposition of sulphate of lime on the heating surfaces, and the general result of the operations, as summed up by M. von Arbesser, 3 shows that while the vacuum system is correct in theory its practical availability depends upon the amount of gypsum present in the brine. The development of the plate heater previously mentioned is the result of attempts made to remove this objectionable impurity.

The vacuum process has been introduced near Warsaw by Mr. J. M. Duncan. The machinery, as described to me, consists of three vacuum pans, each having three divisions. The top and bottom divisions are connected by a number of vertical tubes passing through the middle division, which is used as a steam jacket to heat the brine. The brine is made to circulate through the pipes by having the central tube much larger than the others. The first pan is heated by direct steam and works with a vacuum of eight inches; the exhaust steam of the first heats the second, where a vacuum of 15 inches is maintained, while in the third pan, which depends for its heat on the exhaust steam of the second, the exhaustion is carried on as far as practicable. The minute hard salt crystals mentioned as having

2 Ibid., 1878, pp. 469, 486, 491, 524; 1879, p. 151; ibid., 1880, pp. 622, 637.
3 Ibid., 1884, p. 683.
been observed by Rittinger were also obtained in this apparatus, which was said in 1885 to be in successful operation.

PAN PROCESSES.

The pan process, long known in Europe, was introduced in Syracuse in 1852, but was soon abandoned, although there is no reason, considering the composition of the brine, why proper arrangements should fail to give good results. In other sections pans are extensively used, and Pl. LIII represents the usual form. The pan is 100 feet long, 23 feet wide, and 10 inches deep, and is divided by a cross-partition into the front pan, 45 feet long, and the back pan, 55 feet. The sides of the pan incline outward and meet the draining boards which extend along the sides. The foundations are of stones, the furnace walls of common brick with linings and arches of fire brick. A forced draught, supplied by a rotary blower, is used, and the fuel is anthracite slack burned on a perforated grate. The dimensions and other details are indicated in Pl. LIII, made from sketches and information kindly furnished by Dr. W. C. Gouinlock and Messrs. Van Kirk & Olive, of Warsaw, N. Y. In some cases the grates are put in on an incline, the back being the higher part, and the arch is made much shorter than in the drawing, say 10 feet. Bridge walls are also used, but in most cases are absent. The pans are made of one-fourth-inch boiler iron, riveted and caulked, and are supported by the outside walls, by the division walls between the fires for a certain distance, and, beyond that, by piers succeeded by a system of deflecting walls designed to effect a more thorough utilization of the heat. The fire gases pass to the stack, which is intended to be used for two pans and is placed midway between them. Where the pan is divided into front and back pans, as in the drawing, the brine is brought to complete saturation in the back pan, depositing a portion of the sulphate of lime and then passing into the front pan, where the salt is made, usually at boiling heat (220° F. = 105° C.). The correctness of this principle will be discussed further on.

Another arrangement of flues is that in which two fires are used for each pan, the division wall between them running the entire length of the pan. On either side of the central wall, midway between it and the side walls, is a wall running parallel with it and extending from the front wall to within a short distance of the rear wall, making two sets of two flues each. At the front ends of the two central flues are the fires, the fire gases passing along the central flues to the end of the pan and returning by the outside flues to the front. In this arrangement the stack is at the front.

SHORT PANS.

I have also seen short pans, 35 feet long, heated by a single fire placed on one side of the end of the pan, with four parallel flues,
the fire gases passing through the first (outside) flue, returning through the second, back to the rear through the third, and finally returning to the front through the fourth. This arrangement is said to have worked very well, but at the time of my visit the owner was lengthening his pans to 50 feet, and intended to use twin fires with single return flues, as in the preceding arrangement. Much better results were expected from these changes, which are interesting as indicating that the lower efficient limit of length of pan lies at or above fifty feet, and that the flue system, at first used, while probably giving a good effect, so far as the mere using up of the heat is concerned, did not distribute it so equally over the pan bottom as to admit of a regular production of an average salt in all parts of the pan, which is the foundation of successful pan work.

The pans spoken of had been running for one year and showed but little “buckling” at the end of that time. The workmen informed me, in the absence of the proprietor (who, however, told me the same thing afterwards) that the pans were never shut down for scaling, but only for repairs, and that the pans then in use had been running for more than two months without changing the brine, which was still of very good color and making a good, clean article of salt. The scale as it forms is loosened by long-handled hammers and is raked out without interrupting the process. The removal of the scale is rendered more easy by the fact that the brine does not boil, the temperature being kept at 170° to 180° F. (76° to 82° C.). The brine is also carefully settled before it enters the pans, and no forced draught is used. The results obtained were good, being 16 barrels (each of 5 bushels = 280 pounds) to the ton of coal, but with the improvements then being made 20 barrels were expected.

CONSTRUCTION AND MANAGEMENT OF PANS.

The width of pans is regulated by the distance to which the workman, standing by the side of the pan, can conveniently reach with his tools to rake out the salt and detach the scale. As the draining boards on either side of the pan are about three feet wide and the workman stands on the sidewalk outside of the draining boards, 24 feet actual pan width, measured over all, is the utmost limit allowable, making 15 feet from sidewalk to central line of pan. Fifteen feet seems, however, too great a distance for good work, twelve feet being much nearer a correct allowance. In the English works 25 feet is the greatest width given to pans, but there the sidewalk is between the pan and the draining boards, so that the workman stands close to the edge of the pan. It is a question whether in this respect American practice is not faulty.

It is very true that there are some advantages in having the draining boards directly on the edge of the pan, but there are also some disadvantages, notably the continued leakage at the juncture of the
draining boards and the pan. Moreover, the width of the draining boards decreases the practicable width of the pans and increases the difficulty of properly working in the central portions, causing that part of the work to be slurred over, to the detriment of the pan. Especially is this the case when three fires are used, as, in that case, the central line of the pan is the hottest portion and must be watched with peculiar care. Where the draining boards are on the edge of the pan, the salt is raked directly onto them and the drainage flows back into the pan, making undoubtedly easier work than in the English form, where the salt is raked to the side of the pan, lifted up with perforated copper shovels and thrown on the draining boards, which are separated from the pan by the width of the sidewalk. Moreover, in shoveling the salt across, the sidewalk receives more brine from the drip of the shovel, so that the floor cannot be kept as clean and as dry as in the American manner. Notwithstanding all this, the English form has substantial advantages in drainage and after-handling as well as in allowing much easier work at the pan.

Boiling the brine in the front pan to make salt and keeping the back pan at a lower temperature would seem, from what has been already said concerning the influence of a high temperature in promoting the separation of the sulphate of lime, to be really an end-for-end method. If what is thus stated be correct, the brine should be boiled to bring it to full saturation and the salt made at a lower temperature. Such a system would furnish an excellent article of salt and be more economical as tending to prevent, as far as possible, the formation of “pan scale” in the crystallizing pan. It must be clearly understood that only a portion of the sulphate of lime can be taken out by bringing the brine to saturation at a boiling heat in open vessels, only a little more than is taken out by a lower temperature, but it is just this “little more” that does the damage, burns out the pans, makes the leaks, and causes the expensive lay-offs. It separates while the brine is being brought to boiling and before the salt begins to form; it goes to the bottom and is laid hold of by the hot iron and sticks there. The addition of fresh brine increases the evil, for it also brings a little more to be separated at once and to join the rest on the bottom, continually making the scale thicker. Now, it is perfectly well known that, if a kettle of water be placed over a fire and if the inside of the kettle be clean and the water which evaporates be regularly replaced by fresh water, no amount of heat under the kettle can raise the temperature of the metal above a certain point, the excess of heat being transferred from the kettle to the water and from the water to the steam. But suppose we furnish our kettle with a soapstone or clay lining, what will be the result? If we make the lining thick enough, our iron pot will be red hot before the water even boils. Now, this is what occurs when the scale of sulphate of lime attains a certain thickness; it is a very poor con-
ductor of heat, and as the brine and the iron are no longer in contact, the heat that the iron receives cannot pass off as it did before, and so the iron under the scale becomes red hot. In time the scale cracks at some point so that the brine can reach the red hot iron; the effect is shown in the vigorous boiling at that point and if it occurred in a high-pressure boiler an explosion would be the almost inevitable result. As it is, the chances are good that the plate is cracked; at any rate it will be found that the bottom has sagged at that point, the sagging being due to the overheating. The sagging increases the evil; for, when a stoppage has occurred, when the pan has been scaled, when all cracks have been mended, and the work has been started up again, it will be found that the "pockets" made by the sagging give increased facilities for the deposit of scale, for when the scale gets into the hollows it is no longer possible to detach it by means of the tools in general use. Moreover, the usual form of pan construction increases the difficulty of keeping the pan clean, the overlapping joints and the projecting rivet heads giving the best of holding ground for the scale.

**Austrian pan construction.**—To remedy this difficulty various changes have been suggested, of which the following is an example: At Aussee, in Austria,\(^1\) the plates are carefully and smoothly cut, "butted" together, and riveted to bars \(\frac{4}{5}\) inches (132 mm) wide and \(\frac{3}{4}\) inches (66 mm) thick, which lie under the joints of the plates and form a sort of grating, as there is a bar under each seam, whether long or cross. The plates are \(4\frac{3}{5}\) inches (1,054 mm) long, 14\(\frac{3}{5}\) inches (394 mm) wide, and \(\frac{1}{4}\) of an inch thick, and are double-riveted to the bars. The rivets are \(\frac{7}{8}\) of an inch (15.4 mm) in diameter, with flat heads sunk in flush with the surface of the plate. In this manner the surface is smooth, allowing easier and more complete removal of the salt and scale, while the frame-work of bars gives the whole greater stiffness and durability. While this construction would undoubtedly mean a greater first cost than the ordinary method, yet every part of the work except the putting together can be done at the shop, the amount of repairs should be much less and, when necessary, much more easily made, particularly on account of the small size of the plates. The large plates of the ordinary form soon become buckled, and, when burned out or cracked, the only way to repair the damage is either to cut the whole plate out or to put on a patch to be the center of fresh trouble. What it means to put a tight patch on a sagged and uneven bottom any one who has done it knows. If the system of saturation and crystallizing pans is adopted such a construction would probably be necessary only for the saturation pan, as in the other pan only salt scale could form

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under ordinary circumstances, and this, though annoying, is not nearly so dangerous.

Small plates are also used in the English pans, particularly over the fire. There the plates are 4 feet by 1 foot and \( \frac{3}{4} \) of an inch thick, increasing with the distance from the fire to 4 by 2 feet and 4 by 4 feet, the thickness diminishing to \( \frac{3}{4} \) of an inch.

The use of steel plates has also been found of advantage, particularly near the fire end. Making the bottom convex instead of flat is said to hinder the sagging, and, in this connection, it is well to call attention to the cast-iron pan bottom of the Kanawha or Pomeroy system, to be described later, as possibly giving some hints of value.

**ECONOMY OF HEAT.**

The construction of fire space, arches, and flues, as given in the plan, is very simple, too simple, perhaps, when we consider that the proper conduct of the process demands that the fuel shall be completely burned and that the heat given out shall be utilized entirely and in such a manner that all parts of the pan bottom shall, so far as practicable, be heated equally or, at least, that no great differences of temperature shall exist in different parts of the same pan. An inspection of the foreign pan systems shows a great variety in construction to attain these ends, not only in the grates, air chambers, etc., but also in the arches and flues. For example, experiments carried on in 1869, at Hall, in Austria, showed that it was very advantageous to arch the fire space in such a manner that the fire gases were deflected downward and made to pass through an opening a little above the level of the grate bars; back of this opening, a wall slanting backward at an angle of forty-five degrees caused the current to ascend to the pan bottom. Air was also admitted above the fire and thus a complete and smokeless combustion was obtained and the formation of a non-conducting coating of soot on the pan bottom prevented. Moreover, it was found that, by this complete combustion, the action of the fire gases on the iron of the pan was much lessened and repairs were much diminished, so that the results of three years' work showed a great gain in every respect over the ordinary arrangements.

Again, the use of generator gas has been extensively studied with very satisfactory results, as also the employment of steam in aiding combustion and preventing the formation of slag. The advantages of a forced draught, as in Pl. LIII, have received much attention and it is highly recommended, particularly if the air is previously heated by waste heat. The use of a blast dispenses with much of the chimney draught, and the heat otherwise required for this purpose can be utilized not only for heating the blast air, but also for warming the brine in the preliminary stages of treatment. To have a natural draught the products of combustion must pass to the chim-
ney heated to a certain degree above the atmospheric temperature, and the amount of heat thus lost is much greater than that required to operate the blower.

The amount of heat necessarily lost in any process of combustion can be accurately calculated; the residual heat is alone available for work and the economies practiced are devoted to realizing the fullest effects of this residue.

For our most valuable and accurate information on this subject we are indebted to European sources, particularly to the French, German, and Austrian engineers. On the continent of Europe the salt industry, as furnishing an article in universal use and able to stand a large tax in proportion to its cost, is a favorite subject of taxation and is either a government monopoly or under strict governmental supervision. Every salt-work supports a number of officials who, however, are carefully trained in their duties, which they perform in a most systematic manner, and the results of all experiments, often quite elaborate, are very accurately recorded. Where, as in Austria, salt is a monopoly, the price received for it is many times greater than the cost of production, and so, for various reasons, the industry is often carried on at places so disadvantageously situated that, in open competition, the works would be compelled to cease operation. Nevertheless, it is to the interest of the directors of such works that they shall make the most economical showing possible under the local conditions, and thus it will be often found that it is from such works, run apparently in defiance of ordinary business principles, that our most valuable information is obtained.

In America and England experiments are rarely carried out, or, if made, the results are kept secret, the manufacturers thinking that they are doing better than their neighbors and fearing that publicity may damage their interests. That this course is based on ideas altogether erroneous was shown to me by the attempts to collect information mentioned at the beginning of this paper, and it is to be hoped that the salt-makers of this country may find it of benefit to themselves to meet from time to time for intelligent discussion of their methods and to learn from one another how improvements can be made.

Pan flue construction at Varangeville.—As an example of the detail and thoroughness with which the problem of heat utilization is worked out in a European manufactory, the following description of the process at Varangeville, in the Department of Meurthe, may prove of interest:

At this place the saturated brine, made by dissolving rock salt, is purified by lime. The product is a "coarse fine" salt, and the boiling goes on for weeks without drawing off the brine, the scale being

removed every four weeks. The pans are 23 feet \((7\text{ m})\) wide and 63 feet \((19\text{ m})\) long, with twin fires, which are arched over, so that the front of the pan is not unduly exposed. The fires are set so low that the top of the arch is almost on a level with the floor of the flues, the fire gases passing through openings in the arch. For about two-thirds the length of the pan there is a system of deflecting piers and short walls, arranged on lines radiating from the openings in the arch, so as to diffuse the heat equally under the bottom of the pan. A division wall between the two fires runs the entire length of the pan. At about one-half the length of the pan a wall starts from each side wall and runs toward the center wall to within about three feet of it, making an angle with it of about 45°, and from the ends of these walls, other walls, parallel to the central wall, run nearly to the end of the pan, leaving a space, so that the fire gases on each side return in a flue made by building a third wall extending from the rear wall to within a short distance of the angle wall. At the end of this third wall the gases turn again and pass through the flue formed by the third wall and the outside wall. The parallel flue circulation, it will be seen, though somewhat more complicated, is very similar to the return flues already described.

The form of grate used is a step grate of peculiar construction and the fuel is bituminous small coal and slack.

The pans are covered by a low roof, and the sides with shutters which are kept closed except when the men are lifting the salt. The object of closing the pans is to utilize the steam which is led by wooden conduits lined with tile to the steam pan placed at the end of the fire pan and a little above it. This pan has the same width as the fire pan, and a length of 44½ feet, and the steam circulates through two sets of three parallel flues, in which it passes to the rear, returns to the front, and then, going back to the rear, escapes to the chimney.

In this system 100 pounds of "coarse fine" salt are made by the consumption of 39.47 pounds of the fuel used, while 100 pounds of the finest table salt take 59.51 pounds. The evaporative effect measured by the first result is \(7\frac{1}{4}\) pounds of water for one pound of coal burned, a very high effect and probably equal to the full evaporative power of the fuel.

On each square foot of fire-pan surface 2,400 pounds of salt are made in a year, and the fire pans furnish 92 per cent. and the steam pans 8 per cent. of the total product.

**ENGLISH RESULTS.**

In the great salt-making district of Cheshire, England, the natural advantages of production and transportation furnish the cheapest salt in the world. The brine is saturated and very cheap, the manufacturers paying a royalty only on the amount of salt actually manufactured; the coal is low priced and of good quality; no packages
are used, and the transportation facilities are unsurpassed, as canals and railroads extend in all directions, and it is but a short distance to Liverpool, with water communication all the way.

The work is directed to producing large quantities and the results are two tons of common or one and one-half to one and three-fourths tons "stoved" salt per ton of coal. The pans vary in size, the largest being 135 by 25 feet and 1½ to 2 feet deep. The workmen are paid by the number of tons made, the production being 20 tons and over per man per week. Figures have been given as high as 33½ tons a week per man, but this result is doubtful. Profits are very small, the large companies, where the facilities are greater and the work better regulated, making the best showing.

AMERICAN RESULTS.

In the United States, as has been said, it is difficult to get information as to the yield of salt per ton of coal, but the statements furnished by some of the most careful and successful manufacturers show that sixteen barrels (4,480 pounds) of salt to the ton (2,240 pounds) of good bituminous coal is a large yield, only to be got from saturated brine, careful work, and pans in good condition; and yet that means an evaporative effect of only 5.72 pounds of water to the pound of coal, the real evaporative power of which is not less than 7 pounds and probably nearer 8.

Fourteen barrels of salt per ton of coal may be taken as good average work and all figures above sixteen barrels may be viewed with considerable doubt when given for pans of ordinary construction. These figures may be and often are given in good faith, but the persons making the estimate deceive themselves; with their plants they do not and cannot get the yield they claim.

SUGGESTIONS FOR EXISTING PAN BLOCKS.

Pan works can be constructed to give high yields per ton of coal; but, as has been seen, the plant construction becomes more complicated and the first cost greater. With the present plants good work can be done if care be taken to observe the following points:

1. The brine should be the strongest and purest obtainable from the wells, from which, if sunk in rock salt beds, all surface waters and upper brines should be carefully excluded.

2. The combustion of the fuel must be complete, and, therefore, smokeless, for which purpose the draught air should be warmed, by waste heat, in some simple manner.

3. To precipitate the sulphate of lime as far as practicable, the lime should be brought to saturation at boiling heat and, when salt begins to form, drawn off into the salt pans. If the brine is fully saturated when pumped, enough fresh water can be added to give time for this precipitation.
(4) The salt pans should be run at the lowest temperature that will yield the required grade of salt; 170° to 180° will give a very good quality. Too heavy firing wears the pan and wastes the fuel.

(5) Frequent and careful record of the strength of the brine and of the temperature of the fire gases as they pass into the chimney will be found valuable in connection with the comparison of the amount and character of the fuel consumption with salt production made at regular intervals.

(6) No money should be wasted on buildings; but good, well kept machinery, economical arrangement, and strict cleanliness will always be found to pay.

STEAM OR GRAINER PROCESSES.

The grainer system is peculiarly American; for, although the principle was not new when introduced in Michigan, or even in the Kanawha region, yet its value under the circumstances which exist in both sections has caused great development and improvement. In the Kanawha and Ohio regions weak brines had to be boiled down; in Michigan the lumber mills furnished enormous quantities of exhaust steam, so that a process by which salt is made by steam heat recommended itself at once, and there can be no question of the superiority of this method over all others when exhaust steam is available or where weak brines are to be boiled down. The issue between the advocates of pans and those of grainers can only properly refer to those cases when we have concentrated brines and no exhaust steam. Whether under such circumstances it is more economical to burn the fuel directly under the pan or whether we get more real effect from combustion under a boiler using the steam as a heat conveyor, and thus evaporating the brine, is a much vexed question. The advocates of either method adduce arguments apparently unanswerable in support of their views; elaborate calculations can be worked out and each side is well supplied with instances of poor work by the other system. To settle this question, so important to this industry, carefully collected, accurate statistics of good work by both systems are needed, and until they are obtained any comparison must be of the nature of guess-work.

USE OF HIGH OR LOW PRESSURE STEAM.

The grainer plant consists of the boilers and the grainers. As to boilers, various forms are used, all, however, high pressure, the connections, pipes, etc., being designed for that system. From the results of the Kanawha process, however, it is difficult to see why the high-pressure system should necessarily be followed, unless as copying the Michigan process, which, using exhaust steam from high-pressure engines during the day and live steam from the boilers during the night, must have all its pipes and connections made accord-
ingly. A low-pressure system gives a better evaporative effect for the fuel than high pressure, and if the latent heat of the steam is utilized as far as possible, and the steam condensed, low-pressure steam gives comparatively better results. In such a system it is not pressure that is wanted, but evaporative effect, and while of course the higher the temperature and the pressure the greater the available heat, yet the gain would seem to be purchased at too great a cost when we consider the extra expense of a high-pressure installation, where every connection must be carefully made and where the repair of leakages, especially in the larger pipes, is difficult and expensive. In a properly arranged grainer system, the latent heat of the steam should be utilized to the greatest practicable degree; that is, the final exhaust should be not steam, but condensed water, which should be returned to the boiler without delay. The latent heat of steam decreases when the temperature rises; thus at 212° F. (100° C.) the latent heat is 966.6°, or a pound of dry steam at 212° can, in condensing to water at 212°, raise 966.6 pounds of water, at 32°, 1°, or to 33°. If water at 60° is taken and we desire to raise it to 212°, we have 212°—60° = 152°, the number of degrees required to raise each pound of water from 60° to 212°. Hence we have \( \frac{966.6}{152} = 6.36 \) pounds, the amount of water at 60° which can be raised to 212° by the condensation of one pound of steam at 212°. The decrease of latent heat consequent on increase of temperature is shown by the following table, which is practically correct:

<table>
<thead>
<tr>
<th>Temperature °F.</th>
<th>Indicated pressure Pounds.</th>
<th>Latent heat °F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>212.0</td>
<td>6</td>
<td>966.6</td>
</tr>
<tr>
<td>209.5</td>
<td>5</td>
<td>950.1</td>
</tr>
<tr>
<td>207.1</td>
<td>15</td>
<td>937.2</td>
</tr>
<tr>
<td>205.4</td>
<td>30</td>
<td>902.2</td>
</tr>
<tr>
<td>203.6</td>
<td>45</td>
<td>877.3</td>
</tr>
<tr>
<td>201.2</td>
<td>66</td>
<td>857.4</td>
</tr>
<tr>
<td>204.3</td>
<td>75</td>
<td>834.3</td>
</tr>
<tr>
<td>212.7</td>
<td>100</td>
<td>855.9</td>
</tr>
</tbody>
</table>

Hence we see that the use of high-pressure steam means a loss of latent heat. The steam, however, should be dry, since any water which may be in a given quantity of steam diminishes, by so much, the amount of latent heat.

Pl. LIV gives a plan of a grainer system furnished by Mr. D. K. Allington, of East Saginaw, Mich., and is a good example of the prevailing form of construction. The outside cistern receives the brine from the well and in it the brine is “limed.” Two steam settlers bring the brine to saturation or as near to it as the needs of the grainers will allow, and from the steam settlers the brine is drawn
into the direct grainers, where the salt is in great part made. The direct grainers are heated by coils of three and one-half inch pipe, which hang in the brine a short distance above the bottom of the grainers and through which passes the exhaust steam of the mill engine; a direct connection with the boilers allows the use of live steam when the engine is not running. The return grainer is heated by the exhaust of the direct grainers and receives the brine drawn off from them. On the caps of the grainers are the draining boards on which the salt is piled when lifted.

**CHAPMAN'S PIPE SYSTEM.**

To Mr. A. W. Chapman, of Saginaw City, Mich., I am indebted for a plan and a description of his ingenious arrangement of pipes, by which either exhaust or live steam can be used, at pleasure, in any one or all of the six grainers and two settlers of the system. The settlers may also be run by the grainer exhaust, provision being made for carrying the exhaust of any or all of the grainers to either or both of the settlers. In this manner the use of the steam is easily regulated and the system, at first sight quite complicated, is in reality very simple.

The grainer process has been introduced into Germany, where grainers 150 by 18 feet and 2 feet deep are used, and the pipes are so arranged that they can be raised out of the grainer when the salt is to be lifted. A grainer is lifted every five days and great saving over the pan methods is claimed.¹

**RELATION OF SALT PRODUCT TO GRAINER SURFACE.**

In respect to results the capacity of grainers is usually reckoned by the number of square feet of grainer surface required to produce a barrel of salt in twenty-four hours, which is got by dividing the total number of square feet by the daily production in barrels. The Saginaw exhaust steam blocks average one barrel of salt to every 32 to 36 square feet of grainer and to every 2.5 horse power of boiler capacity.

**DAY AND NIGHT PRODUCTION IN MICHIGAN.**

In these blocks it is generally found that more salt is made while the engine is running than when the steam is taken direct from the boilers. This paradox is explainable in this manner: During the day the demands of the mill require hard and careful firing and the boilers are run to their full capacity, the engine feed being, to take a given case, an 8-inch pipe and engine exhaust 10-inch; boiler pressure, 80 pounds; exhaust pressure, say, 15 to 17 pounds. We have, therefore, a 10-inch pipe carrying steam at 15 pounds pressure to supply the grainers. When the mill is stopped, direct con-

nection with the boilers is made by a 4-inch "bleed pipe," and the steam pressure is nominally 75 pounds; nominally because there is no such control of the steam pressure at night as exists during the day, when the demand for mill power at once detects any falling off in steam pressure. Taking it, however, at 75 pounds and the exhaust steam pressure at 15 pounds, we have this result: A 10-inch pipe is carrying 15 pounds steam in one case and a 4-inch pipe is carrying 75 pounds steam in the other. The areas of the two pipes are to each other as the squares of the radii, or as 25:4. Multiplying by the pressures we have 25 x 15 = 375; 4 x 75 = 300; 5:4.

Hence the 4-inch pipe is carrying only four-fifths as much steam as the larger one, friction and radiation not being taken into consideration, as complicating the question. In order that the 4-inch pipe shall carry as much steam as the 10-inch one, the pressure must be increased in the ratio, 4:5::75:93.75, or we must have a pressure of 93.75 pounds. The same result is obtained without altering the pressure by enlarging the bleed pipe. In Mr. Chapman's plan the bleed pipe is 6 inches.

**COMPARISON OF GRAINER RESULTS.**

In the case of those grainer blocks run by steam, made especially for the purpose, or "live-steam" blocks, the returns are, for reasons already given, rather scanty. Nevertheless some of the works have reported very fully and others have sent enough to give a general idea. As is usually the case, the works most liberal with information are found, on comparison of results, to be doing the best work, it being generally easy to detect any raising of figures, unless the raising is calculated for each item. Two instances will be given as sufficient for the present.

<table>
<thead>
<tr>
<th></th>
<th>No. 1</th>
<th>No. 2</th>
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<tbody>
<tr>
<td>Steam pressure, boiler</td>
<td>75 to 80</td>
<td>50</td>
</tr>
<tr>
<td>No. horse power to one barrel salt made per day</td>
<td>1.34</td>
<td>1.60</td>
</tr>
<tr>
<td>Square foot grainer to one barrel salt made per day</td>
<td>20.52</td>
<td>22.60</td>
</tr>
<tr>
<td>Barrels salt made to 2,000 pounds coal burned</td>
<td>15.55</td>
<td>14.88</td>
</tr>
<tr>
<td>Barrels to a man (per day)</td>
<td>40.00</td>
<td>38.80</td>
</tr>
<tr>
<td>Water evaporation per pound of coal</td>
<td>6.47</td>
<td>5.70</td>
</tr>
<tr>
<td>Strength of brine (salometer)</td>
<td>90°</td>
<td>100°</td>
</tr>
<tr>
<td>Pressure of grainer exhaust</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>Diameter of feed pipe (steam)</td>
<td>6</td>
<td>4</td>
</tr>
</tbody>
</table>

In comparing these two columns we see at once that No. 1 is doing much better than No. 2, and this would speak in favor of higher-pressure steam; but in the one case a 6-inch steam pipe is used, in the other only a 4-inch pipe. Hence the grainers of No. 1 get far more steam and use up in the distance from boiler to grainer ex-
The evaporation in No. 1 is superior to No. 2 in the proportion 6.47 : 5.79 :: 100 : 89.46 and also superior to what has been stated of pans on page 517. The production as there given for good work is 16 barrels to 2,240 pounds coal, while the production of No. 1 is 17.41 barrels for that amount of coal. So far, grainers would seem to have the advantage, and many considerations seem to show that this system is the system of the future. The pan method is capable of great improvement and may, without great difficulty, be made to surpass the best results yet obtained from grainers; nevertheless, it must be remembered that the grainer method is still in its infancy, and it will not have attained its growth until it can show an evaporation of 8 pounds water to the pound of good coal, or 280 pounds of salt for every 100 pounds of coal, with no pipe scale in the grainer. That this will yet be done there is no reason to doubt, but to do it will require much more careful investigation and study on the part of manufacturers than has been hitherto given to the subject. Many valuable hints may be drawn from an examination of the Kanawha process, which for this reason is now to be described. As it is at present it could not be adopted in the more northern regions; but, when we consider the surrounding circumstances, it is much nearer a perfect method than any of the others.

KANAWHA OR POMEROY METHOD.

Although this process has been in operation for some forty years and has already been described to some extent,\(^1\) it has so much to recommend it and the evaporative power of the fuel is so fully realized that it has seemed advisable to give some account of it; for in principle it is available not only in salt making, but also in other branches of chemical manufacture where the economical evaporation of large amounts of dilute solutions, together with fractional crystallization, is a desideratum.

_Description of Juhler's Works._—For the description and the data from which the accompanying plan has been made (Pl. LV) I am indebted to Mr. John J. Juhler, of Pomeroy, Ohio, who not only aided me during my visit to his works, but also in correspondence since has been most ready in answering questions and in directing my attention to points which I should otherwise have overlooked. The dimensions and details of operation are taken from his White Rock Furnace, and represent typical works carefully run and giving results stated by other manufacturers to be among the very best.

The characteristics of what may be called the Ohio region are cheap fuel and weak brines which, though very impure, are nevertheless practically free from gypsum. The principle of the method

Scale, k' - 1 foot.

CROSS - SECTION

PLAN of
GRAINER BLOCK
D.K. Allington Archt.
EAST SAGINAW, MICH.

SECTIONAL PLAN VIEW
KANAWHA SYSTEM
works of
J.J. Johler
POMEROY OHIO
is the boiling of the brine in a steam chest, by which a portion of the impurities is rendered insoluble and a large supply of low-pressure steam is obtained that is utilized in the further evaporation of the brine. Owing to the large amount of the very soluble "mother liquor salts" fractional crystallization must be resorted to; for, if the brine at different stages of the process be evaporated beyond certain points, the resulting product will be too impure. Hence the grainers are arranged at different levels, so that the mother liquors can be drawn from one to the other, giving a series of products of which the early ones are ready for market, the later being redissolved in the settlers. In this way the process is practically a continuous one, the concentrating brine passing from one to the other of the settlers and grainers in regulated succession, depositing, in its passage, salt of various grades, and the mother liquor, loaded with impurities, going to the bromine works, where that valuable constituent is extracted and the residue itself made into a marketable product.

In this most instructive process the aim is to have nothing but condensed water and ashes as waste; since, were it not for the by-products, many of the works would be forced to suspend operations, owing to the low price to which salt has been forced through domestic competition.

The brine, as pumped, has a specific gravity of 1.062 (9° B., 34.5° salometer), every hundred pounds of brine containing, on an average, 7.4 pounds of salt, 90.5 pounds of water, and 2.1 pounds of impurities, or in the proportion 1:12.3:0.28. As it takes 100 pounds of coal, run of mine, to make 100 pounds of salt, we have 1.6 coal = 1 salt = 12.3 water, or 1 coal = 7.69 water evaporated, a result far in excess of the figures given above for high-pressure steam. The steam has a pressure of about four pounds, and all the pipes and connections are of wood except the grainer pipes, which are copper, and the steam is thus carried with the minimum of condensation and applied with an almost maximum effect.

The brine is pumped into a large tank, in which the small amount of petroleum that accompanies it is separated. When first pumped it is clear and colorless, but it soon turns reddish from the oxidation of the carbonate of iron in it. From the tank it flows through a trough, in which it is heated by steam pipes and is conveyed to the front of the furnace, where it enters the first division of the steam chest.

The furnace walls are built of stone, with a lining of fire-brick which extends 12 to 15 inches above the stone wall, and on which the steam chest rests. The grate surface is 12 feet long by 9 feet wide, and the distance from grate to bottom of steam chest is 8 feet 4 inches. No bridge wall is used, the length of grate being sufficient to bank up the fire sufficiently high. The fire-door is on the side,
the front being closed with the exception of the spaces above the grate for raking down and removing clinkers. The grate bars are either of the ordinary construction or else broad bars with perforations. Chimney draught is used, together with some steam, and the fuel is either the run of mine or else the slack and top coal from the mines, at the mouth of which the works are situated. The fuel is cheap (the first costing about three cents a bushel, the other two cents), but it contains a large amount of ash and clinkers; hence the peculiar construction of the fire space and grates.

The steam chest in which the brine is boiled is in three divisions, connected by copper pipe. Each division has a cast-iron bottom 1 inch thick, made by placing together side by side 11 pans, each 10 feet long and 3 feet wide, having ends 12 inches deep and sides 8 inches deep, except the two end pans, which have each one side (the end side) 12 inches deep. By bolting these pans together we have a single pan 33 feet long, 10 feet wide, and 12 inches deep, having divisions 8 inches high running across it every 3 feet. The seams of the divisions are thoroughly caulked, either with iron filings or (the better but more expensive way) with cloth dipped in white lead.

Resting on the divisions and bolted to the inside of the side plates is the side planking, 4 inches thick and 4 feet high, the seams being horizontal. The ends of the steam chest are formed by bolting to the outside of each of the end sides of the pan the so-called “damper,” a cast-iron plate 1 inch thick and 2 feet high, having sides which extend back about 8 inches on the outside of side planking; the remaining portion of the ends is filled out with 4-inch planking bolted to the inside of upper edge of damper and grooved into the ends of side planking. Across the top of the tank so formed are six iron joists, let in flush with the upper edge, on which the top planks, also 4 inches thick, are laid. The tightening of the seams of the planking is effected as follows: In the center of the ends of each section of the pan is cast a lug which takes the square head of a long bolt extending upward through the end of a cap timber. These bolts are threaded, and by screwing down the nuts all horizontal seams are drawn tight. Either end of the cap has a piece bolted to the under side, so that a wedge can be driven between this projection and the outside top plank, thus drawing up all the seams of the top.

The steam chest rests on the top of the fire-brick wall, and for this purpose each lower corner of each section of the bottom has a projection cast on it about six inches long. The space between the divisions, 30 inches, is arched with fire-brick, and the connection between the divisions is made by a copper pipe opening below the surface of the brine, so that the level is the same throughout. In this steam chest the brine is boiled till it reaches 15° to 18° B., depending upon the needs of the grainers for brine, the steam pressure car-
ried being about four pounds. The brine, deeply colored by sus­
pended oxide of iron, is then drawn off and flows into the first mud
settler, reaching it on the upper side of the water-tight central par-
tition; passes to the farther end, then through a low place cut in the
top of the partition back to the head of the settler, whence it goes
to the second mud settler to make the same round. By this time
the iron mud is deposited and the brine, already much concentrated,
flows to the first or the second “draw settler,” as needed, where it
concentrates until ready to deposit salt, unless the grainers require
it before it reaches that point, which is 23° B. (sp. gr. 1.178). From
the drawsettlers it goes to grainers 1 and 5, where it deposits the
best salt. When the brine in No. 1 attains 24° to 25° B. it is drawn
into No. 2, while that in No. 5 reaches 26° to 27° B. and then goes to
No. 4. Nos. 2 and 4 give a quality of salt but little inferior to that
of Nos. 1 and 5.
The mother liquor of No. 2 and No. 4 goes at 29° B. to No. 3,
where, still depositing salt, though of an inferior kind (No. 2), it
reaches 31° B., when it is drawn into the “peacemaker” or smaller
grainer, where it concentrates to 34° to 35° B., being then transferred
to a “bitter water cistern” and rising to 37° B. In each of these
some salt is deposited; but it is so impure that it is redissolved in
the first mudsettler. The heavy mother liquor is now ready for the
bromine works, where it is distilled with sulphuric acid and chlorate
of potash, yielding, when properly managed, about one pound of
bromine for every two barrels of salt made.
The residue of the bromine distillation is then neutralized with
lime and evaporated. It deposits some agricultural salt, and the hot
liquid, consisting mainly of chlorides of calcium and magnesium, is
run into oil barrels, solidifies on cooling, and is sold, being employed
for making the non-freezing liquid of the Pictet ice-making process.
The settlers and grainers, with the exception of the “peacemaker,”
are each 180 feet long and made of 4-inch lumber, pine or poplar,
preferably the latter. The steam connections are all of wood, being
made of pine or poplar logs with a 6-inch bore, the copper pipes being
5 inches in diameter, 1/8 of an inch thick, connected by goosenecks to
the headlogs at upper end of grainers and passing through the lower
end. The condensed water runs to waste, experience having shown
that no further benefit can be derived from the small amount of heat
thus lost.
The absence of sulphate of lime, one of the most important points
connected with this brine, permits the use of the light copper pipe
to which, in great measure, the high evaporative result is due.
The low-pressure steam allows the use of wood in constructing the
steam chest and in making the steam connections, by which we
get a material of very low conducting power at a very low cost.
The steam is thus delivered, with but little loss of its heat, into
pipes made of a metal of high conducting power, which is not lessened, as in other brines, by the formation on the pipes of a coating of non-conducting gypsum, continually increasing in thickness and retarding evaporation in proportion.

Were there no gypsum in the northern brines, the cost of production would be much lessened, for the time required for scaling in both pans and grainers amounts to a considerable fraction of the running time, without taking into consideration the gradual decrease in evaporative effect. Any method of brine purification by which the amount of sulphate of lime can be materially reduced at a low cost will add much to the efficiency of any of the salt-making processes, and it is in this direction that laboratory investigation may be of value.

CONCLUSIONS.

Comparing the different systems by their evaporative effect and taking the best results in each, we obtain the following:

<table>
<thead>
<tr>
<th>System</th>
<th>Evaporative Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kanawha system, low-pressure steam, 1 pound coal evaporates</td>
<td>7.69 pounds</td>
</tr>
<tr>
<td>Grainer system, high-pressure, 1 pound coal evaporates</td>
<td>6.47 pounds</td>
</tr>
<tr>
<td>Pan system, direct heat, 1 pound coal evaporates</td>
<td>5.72 pounds</td>
</tr>
</tbody>
</table>

It must be understood that these results, as well as all others given in this paper, are to be considered only as approximations. To secure results which shall have real value, we need accurate reports from a large number of works, reports giving not only the principal details of manufacture, but also the average composition of the brine and mother liquors and the average evaporative power of the fuel. Such information must be at hand before anything more than desultory work can be done in this field. The necessity for improvement in existing processes can be left to the consideration of those engaged in the business. The selling price of salt is certain to go below what it is at present, and it is of interest to all that the common stock of knowledge shall be in every way increased, so that, in the great competition, capacity, intelligence, and practical common sense shall not be hampered by ignorance of what has been accomplished in the past, what can be done in the present, and what may be looked for in the future.

The item of labor in the different systems has also received attention, but in the absence of sufficient data only approximations can be given. So far as learned it ranges from 26.66 per cent. to 34.21 per cent. of the total cost. The grainer works using self-rakers give, of course, a lower outgo in labor expense; but, in general, the apparatus does not seem to meet with favor. As generally run, self-rakers do not allow sufficient time for the proper crystallization of the salt; but if they can be so regulated as to overcome that difficulty they ought to have considerable value, as demonstrated in other branches of chemical manufacture.
CONCLUSIONS.

In concluding it may be said that, as a whole, the salt Industry of the United States, while conducted with energy and skill, is capable of much better work than that done at present. That it is, as a rule, a very profitable business cannot be said, since in many sections a net profit of five cents a barrel is more than is really obtained. The present plants are able to furnish a supply much larger than can find a fairly profitable market; the struggle for existence, already serious, must become even sharper, and the survival of the fittest will be exemplified in the case of those who unite sound business methods with a progressive and scientific spirit in dealing with a manufacture worthy of the most careful study.

To those who have so kindly, and at the sacrifice of valuable time, contributed the data upon which this work is based my sincere thanks are due. They will recognize their information in these pages, and if they consider that the use here made of it will benefit their industry the labor of preparing this paper will be well repaid.

TABLES.

The appended tables will be found of much value. Table I, prepared by Dr. F. E. Englehardt, gives figures of production, which, being obtained by calculation, are somewhat higher than can be obtained in practical working. Table II contains the results of the experiments made in 1842 by the Navy, under the direction of Walter R. Johnson, U. S. N. These were made with great care, and are frequently quoted in engineering literature.

TABLE I.

### TABLE 1 — Continued.

<table>
<thead>
<tr>
<th>Salinity degrees</th>
<th>Buoyancy degrees</th>
<th>Specific gravity</th>
<th>Per cent. of salt</th>
<th>Weight of a gallon of water at 90° F.</th>
<th>Gallons of water required for a bushel of salt</th>
<th>Gallons of water to produce a bushel of salt</th>
<th>Pounds of salt required for each pound of coal used</th>
<th>Pounds of salt that can be made with a pound of salt</th>
<th>Pounds of coal required for a pound of salt</th>
<th>Pounds of coal required for a pound of coal used</th>
</tr>
</thead>
<tbody>
<tr>
<td>63</td>
<td></td>
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### Table II.

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<th>Variety of coal.</th>
<th>Physical characters of the coals</th>
<th>Composition of the coals in 100 parts.</th>
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<td><strong>ANTHRACITES.</strong></td>
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<td><strong>BITUMINOUS COKING COALS.</strong></td>
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TABLES.

TABLE II — Continued.

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<td>1. Pittsburgh, Pa.</td>
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<td>2. Beaver Meadow Slope No. 5, Pa.</td>
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</tr>
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<td>3. Forest Improvement, Pa.</td>
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<td>4. Peach Mountain, Pa.</td>
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<td>5. Lehigh, Pa.</td>
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<td>7. Lykens Valley, Pa.</td>
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<td>8. Natural coke, Va.</td>
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TABLE II—Continued.

Evaporation.

Steam produced in pounds, corrected for the temperature of the water in the feed cistern.

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<th>Variety of coal</th>
<th>By one of fuel from 90°F.</th>
<th>By one of fuel from 70°F.</th>
<th>By one of fuel from 60°F.</th>
<th>By one of fuel from 50°F.</th>
<th>By one of fuel from 40°F.</th>
<th>By one of fuel from 30°F.</th>
<th>By one of fuel from 20°F.</th>
<th>By one of fuel from 10°F.</th>
<th>By one of fuel from 0°F.</th>
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</thead>
<tbody>
<tr>
<td>ANTHRACITES.</td>
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<td>10.465</td>
<td>505.54</td>
<td>7.399</td>
<td>6.171</td>
<td>5.350</td>
<td>4.730</td>
<td>4.110</td>
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### TABLE II—Continued.

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<th>Variety of coal</th>
<th>Evaporation</th>
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<td></td>
<td>Steam produced in pounds, corrected for the temperature of the water in the feed cistern.</td>
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<tr>
<td></td>
<td>By one of fuel from</td>
</tr>
<tr>
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<td>fuel from</td>
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<tr>
<td>FREE-BURNING BITUMINOUS COALS.</td>
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<tr>
<td>2. Neff's, Md.</td>
<td>8.133</td>
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BITUMINOUS COKEING COALS.

<table>
<thead>
<tr>
<th>Variety of coal</th>
<th>Evaporation</th>
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<tbody>
<tr>
<td></td>
<td>Steam produced in pounds, corrected for the temperature of the water in the feed cistern.</td>
</tr>
<tr>
<td></td>
<td>By one of fuel from</td>
</tr>
<tr>
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<td>fuel from</td>
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FOREIGN BITUMINOUS COALS.

<table>
<thead>
<tr>
<th>Variety of coal</th>
<th>Evaporation</th>
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<tbody>
<tr>
<td></td>
<td>Steam produced in pounds, corrected for the temperature of the water in the feed cistern.</td>
</tr>
<tr>
<td></td>
<td>By one of fuel from</td>
</tr>
<tr>
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<td>fuel from</td>
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<tr>
<td>1. Pittsburgh, N.Y.</td>
<td>7.630</td>
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<td>2. Cumberland, Ind.</td>
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WOOD.

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<th>Variety of wood</th>
<th>Evaporation</th>
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<td>Steam produced in pounds, corrected for the temperature of the water in the feed cistern.</td>
</tr>
<tr>
<td></td>
<td>By one of fuel from</td>
</tr>
<tr>
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<td>fuel from</td>
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<tr>
<td>Dry pine wood</td>
<td>6.050</td>
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### Table II — Continued

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<th>Variety of coal.</th>
<th>Mean temperature of—</th>
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<td></td>
<td>The air on entering below the ash-plt.</td>
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<td>BITUMINOUS COKE.</td>
<td>92.05</td>
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<td>WOOD.</td>
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<td>Dry pine wood.</td>
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### Table II—Continued.

<table>
<thead>
<tr>
<th>Variety of coal</th>
<th>Deductions relative to the heating power of the fuel.</th>
<th>Heat escaping with the gases of combustion, etc., equivalent to evaporative power in pounds of water.</th>
<th>Heat escaping with the water of combustion equivalent to evaporative power in pounds of water.</th>
<th>Heat escaping in consequence of the (hygrometric) moisture of the air in pounds of water.</th>
<th>Water evaporated in the steam boiler, in pounds.</th>
<th>Total calculated evaporative power of the fuel. in pounds.</th>
<th>Loss sustained by the escaping gases, water of combustion, etc., in per cent.</th>
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<td>1. Beaver Meadow Slope No. 3, Pa.</td>
<td>0.2250</td>
<td>0.1288</td>
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<td>4. Allinson and Templeman's, Md.</td>
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<td>3. Plotin (Cunard's), N.S.</td>
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<td>0.0790</td>
<td>0.0760</td>
<td>0.0760</td>
<td>12.0740</td>
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<td>4. Liverpool, England</td>
<td>1.2500</td>
<td>1.0000</td>
<td>0.0790</td>
<td>0.0760</td>
<td>0.0760</td>
<td>13.7500</td>
<td>16.40</td>
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<td>5. Newcastle, England</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>6. Scotch coals, Scotland</td>
<td>1.0970</td>
<td>0.0810</td>
<td>0.0690</td>
<td>0.0760</td>
<td>0.0760</td>
<td>8.6450</td>
<td>8.09</td>
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<td><strong>WEST OF THE ALLEGHENY MOUNTAINS.</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>1. Pittsburgh, Pa.</td>
<td>1.0380</td>
<td>0.0500</td>
<td>0.0130</td>
<td>0.0760</td>
<td>0.0760</td>
<td>7.3490</td>
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<td>2. Cannelon, Ind.</td>
<td>1.3860</td>
<td>1.3860</td>
<td>0.0820</td>
<td>0.0760</td>
<td>0.0760</td>
<td>7.4720</td>
<td>37.30</td>
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</table>

a Average loss, 14.10 per cent.  
b Average loss, 14.27 per cent.  
c Average loss, 17.41 per cent.  
d Average loss, 18.11 per cent.
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<thead>
<tr>
<th>Variety of coal</th>
<th>Atmospheric air at standard temperature and pressure required for one pound of fuel</th>
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<tr>
<td></td>
<td>In cubic feet</td>
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<td><strong>ANTHRACITES.</strong></td>
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</tr>
<tr>
<td>1. Beaver Meadow Slope No. 8, Pa.</td>
<td>260.730</td>
</tr>
<tr>
<td>2. Beaver Meadow Slope No. 6, Pa.</td>
<td>372.380</td>
</tr>
<tr>
<td>3. Forest Improvement, Pa.</td>
<td>288.160</td>
</tr>
<tr>
<td>4. Peach Mountain, Pa.</td>
<td>240.860</td>
</tr>
<tr>
<td>5. Lehigh, Pa.</td>
<td>625.850</td>
</tr>
<tr>
<td>7. Lykens Valley, Pa.</td>
<td>287.270</td>
</tr>
<tr>
<td><strong>FIRE-BURNING BITUMINOUS COALS.</strong></td>
<td></td>
</tr>
<tr>
<td>1. New York and Maryland Mining Company, Md</td>
<td>203.300</td>
</tr>
<tr>
<td>2. Neff's, Md</td>
<td>360.000</td>
</tr>
<tr>
<td>3. Esby's &quot;coal in store,&quot; Md.</td>
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</tr>
<tr>
<td>4. Atkinson and Templeman's, Md.</td>
<td>328.980</td>
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<td>5. Esby's and Smith's, Md.</td>
<td>171.160</td>
</tr>
<tr>
<td>8. Lycoming Creek, Pa.</td>
<td>262.180</td>
</tr>
<tr>
<td>9. Que's Run, Pa.</td>
<td>209.000</td>
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<tr>
<td><strong>BITUMINOUS COKEING COALS.</strong></td>
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<tr>
<td>1. Barr's Deep Run, Va</td>
<td>320.130</td>
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<tr>
<td>2. Crouch and Shandy's, Va.</td>
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</tr>
<tr>
<td>3. Midlothian, 999-foot shaft, Va.</td>
<td>260.960</td>
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<tr>
<td>4. Creek Company's coal, Va.</td>
<td>263.170</td>
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<tr>
<td>6. Chesterfield Mining Company, Va.</td>
<td>305.060</td>
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<td>8. Tippcane, Va.</td>
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<td><strong>FOREIGN BITUMINOUS COALS.</strong></td>
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<td>1. Pictos (from New York), N.S</td>
<td>232.510</td>
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<tr>
<td>2. Sydney (Cunard's), N.S</td>
<td>341.010</td>
</tr>
<tr>
<td>3. Pictos (Cunard's), N. So</td>
<td></td>
</tr>
<tr>
<td>4. Liverpool, England</td>
<td>251.000</td>
</tr>
<tr>
<td>5. Newcastle, England</td>
<td></td>
</tr>
<tr>
<td>6. Scotch coals, Scotland</td>
<td>213.330</td>
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<td><strong>WEST OF THE ALLEGHANY MOUNTAINS.</strong></td>
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<tr>
<td>1. Pittsburgh, Pa</td>
<td>268.250</td>
</tr>
<tr>
<td>2. Cannelton, Ind.</td>
<td></td>
</tr>
<tr>
<td><strong>WOOD.</strong></td>
<td></td>
</tr>
<tr>
<td>Dry pine wood</td>
<td>281.930</td>
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OF THE
HEAD OF ChESAPEAKE BAY.
BY
W J McGEE.
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THE GEOLOGY OF THE HEAD OF OHSAPAKEY BAY.

By W. J. McGee.

INTRODUCTORY NOTE.

The investigation here recorded was made under the joint auspices of the U. S. Geological Survey and the U. S. Fish Commission, for the purpose of determining the probable success of an artesian boring at Fishing Battery station, off Spesutie Island, five miles south of Havre de Grace, Md., and near the head of Chesapeake Bay. The field study occupied a portion of July, 1886. The necessary journeys were made chiefly in a steam launch belonging to the U. S. Fish Commission and in part on foot. The routes traversed and the extent of the examination are sufficiently indicated in the body of the report and on the accompanying detailed map by the specifically described and numbered points. The tract was subsequently revisited for the purpose of making the photographs reproduced in the accompanying plates.

The large-scale map (Pl. LVIII) is mainly reduced from a U. S. Coast Survey chart, supplemented by culture and hydrography from the Martenet map of Maryland (1883), and the small-scale map of part of the Middle Atlantic slope (Pl. LVII) is transferred and reduced from the U. S. Geological Survey base map of the United States (not yet published), the "fall-line" and a few divides being added. The stereogram of the Middle Atlantic slope, forming Pl. LXVIII, was constructed by Mr. J. H. Klemroth from various data, a portion of which were kindly furnished by Mr. B. A. Colonna from the unpublished materials of the U. S. Coast Survey.

Whatever value the results of the investigation may have should be credited largely to Prof. Spencer F. Baird, Commissioner, Maj. Thomas B. Ferguson, Assistant Commissioner, and Mr. L. R. Grabill, station superintendent, of the U. S. Fish Commission, who provided the means of transportation, subsistence, and shelter and afforded every possible facility in the prosecution of the work.
Although the investigation was made de novo so far as the tract about the head of Chesapeake Bay is concerned, previous studies had indicated the general character of the phenomena of that portion of the country.

The geography and the salient topographic and geologic features of the tract specifically studied were known in a general way from rapid railway journeys across it, from the old reports of Dr. Philip T. Tyson, the State agricultural chemist of Maryland twenty-five years ago, from the more recent geologic reports of the neighboring State of Pennsylvania, and from a variety of other sources.

Moreover, the structure of the tract was inferred, in a more detailed way, from that found to exist at carefully examined points of analogous geographic position farther southward. It had been observed that in the Middle Atlantic slope the broad crystalline terrane everywhere flanking the eastern base of the Appalachian Mountain system extends oceanward to about the head of tide in the coastal bays and estuaries; and, since it was known that the northern extremity of Chesapeake Bay is the head of tide, it was inferred that this crystalline terrane occurs and has its outer margin there. Investigations along the eastern border of the crystalline belt from Baltimore through Washington, Fredericksburg, Richmond, and Petersburg had also revealed the existence of a remarkable clastic formation to which the name "Potomac" had been applied, lying unconformably upon the eroded and irregularly crenulate margin of the zone of crystalline rocks. This formation had been found to comprise two distinct portions, (1) the lower, a peculiar felspathic or kaolinic, friable sandstone, or arkose, with intercalated beds of quartzitic gravel, containing abundant remains of a luxuriant but unique flora, on the basis of which it had been tentatively referred to the late Jurassic or early Cretaceous, and (2) the upper, a plastic, highly colored, and often ferruginous clay, without distinctive fossils, but, by reason of the absence of marked unconformity therewith, provisionally united with the lower sandstone member; and it was inferred that this Potomac formation extends northward to and beyond the head of Chesapeake Bay and overlaps the crystallines there. Observations along the same line had shown, too, that everywhere, in passing from the area of the crystallines to that of the clastics, the larger rivers—the Patuxent, the Potomac, the Rappahannock, the James, the Appomattox, and the Roanoke—have, probably during Quaternary times, deposited great deltas of gravel, sand, loam, and boulders upon the inland border of the latter area, and that these deltas, together with the intervening plains and divides, have

been fashioned by coeval waves and oceanic currents into terraces of great extent, rising to altitudes of several hundred feet above present tide; and it was inferred that the Susquehanna had built up a similar delta during the ice period and that this delta and the adjacent exposed portions of the Potomac terrane are terraced. Finally, detailed study of the common boundary of the crystalline and clastic terranes had brought to light a line of displacement coinciding approximately with that boundary and extending at least from the vicinity of Fredericksburg to and somewhat beyond Washington, had shown that the land on the eastern or oceanward side of this line of displacement is thrown while that on the west is heaved, and had indicated that the displacement itself is either a fracture or an abrupt monoclinal flexure; and it was inferred that this line of displacement passes through some part of the tract about the head of Chesapeake Bay, affecting the deposits there as the equivalent deposits farther southward are affected.

To some extent these inferences guided the investigation and determined the nomenclature employed in the field and adopted in the following pages.

The results of the investigation in the determination of the local stratigraphy are set forth in section vi (pp. 634-638); its results in the elucidation of the Quaternary history of the Middle Atlantic slope are stated in section vii (pp. 638, 639); and its results in the solution of the local and general artesian water problem, as well as the specific application of each of the principal and collateral lines of study, are summarized in the succeeding and final section (pp. 640-647). These short sections accordingly constitute a synopsis of the immediate results of the principal lines of investigation; but it is believed that some substantial contributions to systematic geology are contained in the subsections on the general hydrography (pp. 550-557) and on the analysis of topography (pp. 558-564) and in the section on the displacement (pp. 616-634).

In a measure, the paper illustrates the methods pursued in, as well as the results obtained by, the Potomac division of geology. Of the two great geologic processes involved in aqueous action only that of deposition has hitherto been utilized in interpreting local and general geologic history. Yet it is evident that the period represented by each deposit must be represented elsewhere by the complementary degradation; and in some cases the history of a region can be interpreted from the topographic forms resulting from degradation, as well as from the formations, with their contained fossils, resulting from the correlative process. Such genetic study of topographic forms (which has been denominated geomorphology) is specially applicable in the investigation of the Cenozoic phenomena of the eastern United States and has been successfully employed in the region herein described; and, probably for the first time, important practical con-
elusions, involving the consideration of hypogeal structure and orogenic movement, have been based on the interpretation of topography and on inferences from the present behavior of the streams by which the topography has been determined.

I. GEOGRAPHY.

THE GREAT NATURAL DIVISIONS.

The Middle Atlantic slope, within which Chesapeake Bay is embosomed, is naturally divisible into three regions marked by distinctive geologic structure and topographic configuration. They are as follows: (1) the Appalachian zone, made up mainly of corrugated and closely folded Paleozoic rocks and characterized by a topography determined conjointly by corrugation of heterogeneous strata and long-continued erosion; (2) the Piedmont region, formed of highly tilted crystalline rocks and in general characterized by a diversified topography determined by long-continued erosion of a terrane of variable obduracy; and (3) the Coastal plain, built up of slightly inclined Mesozoic and Cenozoic formations, corraded to a limited depth by the great rivers flowing from the last-named regions and to a still less depth by the smaller streams originating within its own area, and thus characterized by a topography of low relief determined almost wholly by the hydrography.

It is only from the James River northward that the westernmost of these regions, the Appalachian, falls within the Atlantic drainage slope and has contributed an important share of materials to the later deposits forming the Coastal plain. South of that river the zone is generally drained to the westward, most of its waters finding their way into the Mississippi, but a small portion flowing directly into the Gulf.

The Piedmont and Coastal plain regions are not only sharply distinguished by geologic structure and topographic configuration, but are just as sharply separated by an abrupt change in the character of their water courses from clear, rapid, rock-bottomed streams of high declivity, in the former region, to muddy, sluggish, mud-lined, and sometimes tidal canals and estuaries, with trifling declivity, in the latter region, and the locus of transition from one phase to the other is everywhere marked by a rapid or fall. In the northern part of the Middle Atlantic slope this “fall-line” (as it has been appropriately and expressly designated by different authors) occurs at tide level, and generally some distance within the Piedmont terrane. Such is the case on the Delaware River, which has its falls at Trenton, a mile or two above the coastward margin of the Philadelphia gneiss; on the Schuylkill, which is tidal to a point a mile or two within the gneiss; on the Susquehanna, which falls over granites and schists three miles above its mouth and the same dis-
tance above the easternmost outcrop of these rocks; and on the Potomac, which rapidly descends to tide-level two or three miles above Washington and the gneissic margin. In the southern part of the same area the fall-line remains at tide-level, but coincides closely with the margin of the Piedmont rocks. Thus, the Rappahannock falls forty or fifty feet within two miles at Fredericksburg, and at the same time passes from the crystallines to the non-lithified clastics; the James, notwithstanding its larger size, falls nearly as rapidly at Richmond and simultaneously enters the Cenozoics; and in the Appomattox there is a still greater fall at Petersburg, where the stream at once enters upon the friable terrane and into tidal waters. Still farther southward, within the Southern Atlantic slope, the fall-line remains as distinct as in the north and continues to coincide with the eastern margin of the Piedmont rocks so closely that Tuomey1 long ago attributed the falls to the obduracy of these rocks; but meanwhile it gradually rises as the width of the coastal plain increases, although the rivers are generally so small at the crossing of the fall-line that their altitudes there are materially affected by size and by distance from tide-water (the determinants of base-level), and the rise is hence variable. The altitude of the falls of the Roanoke at Weldon is 44 feet; that of the Tar at Rocky Mount is about the same; that of the Neuse at Smithfield is 100 feet; that of the larger and more direct Cape Fear at Averasboro’ is only 35 feet; that of the Wateree 10 miles above Camden is 135 feet; that of the Congaree at Columbia is 129 feet; that of the much larger Savannah at Augusta is 125 feet; that of the Ogeechee at the shoals below Mayfield is 210 feet; that of the Oconee at Milledgeville is 220 feet; and that of the Ocmulgee at Macon is 250 feet above the level of the Atlantic.2

In general, the passage from the one to the other of these regions is less abrupt on the uplands separating the water-ways than in the river channels, the swells and ridges, the regularly concave valleys, and the generally soft contours developed by slow degradation of a homogeneous terrane, all of which characterize the Piedmont region, passing gradually and often imperceptibly into the broad plains and plateau-like divides separated by steep-sided and flat-bottomed valleys, which characterize a considerable part of the Coastal plain; but about the head of Chesapeake Bay, and indeed commonly in the north, the boundary is distinctly marked on the one hand by a prominent line of wooded hills forming the irregular, stream-notched escarpment of an undulating plateau two hundred and fifty to three hundred and fifty feet high, and on the other hand by a low, faintly terraced plain overlooked by the hills and rising only about one

1 Rept. Geol. South Carolina, 1848, p. 140.
2 Most of these altitudes are from Swain’s Report on the Water Power of the Southern Atlantic Watershed, Tenth Census U. S., vol. 16, 1885, p. 688.
hundred feet above tide. The position of this boundary is indicated on any accurate map by the parallel Pennsylvania and Baltimore and Ohio Railways, the former of which everywhere occupies the westernmost margin of the Coastal plain, while the latter cuts the extremities of the Piedmont salients, and at Havre de Grace ascends the granitic slope some distance for the sake of a safer location for its bridge across the Susquehanna.

THE GENERAL HYDROGRAPHY.

For nearly a hundred miles above Capes Charles and Henry, Chesapeake Bay is a simple extension of the Atlantic Ocean, averaging perhaps twenty miles in width. Like the shoreward portion of the ocean overspreading the extensive submarine terrace made known through the observations of the U. S. Coast Survey, it is shallow and bottomed with sand and mud, and, like the Atlantic from Sandy Hook to Cape Fear, it has low and sandy shores. Above the mouth of the Potomac it begins to assume a fluviatile aspect and contracts in width to about six miles at Cow Point (just above the mouth of the Patuxent) and to barely four miles just above Annapolis, the average being perhaps ten miles. For nearly a hundred miles above the mouth of the Potomac the bay gradually approaches the Piedmont escarpment, and then, changing its direction near Baltimore, extends parallel therewith to its head, 35 miles above. In ascending this upper part of the bay, between the mouth of the Potomac and that of the Susquehanna, the shores (particularly the western) exhibit progressively less and less of the sand-beach character of the lower portion, the adjacent hills gradually rise from a few feet above tide to altitudes of fifty, one hundred, and sometimes two hundred or more feet, and precipitous or even undercut banks, kept clear of talus by wave and tide, become more and more common. The affluents of the bay are estuarine toward their mouths, the lengths of the estuarine portions varying with the volume; and, notwithstanding the greater area drained by the tributaries from the west, the greater number (at least above the thirty-eighth parallel) enter the bay from the east, fully three-fourths of the Maryland-Delaware peninsula shedding its waters into the bay. Low, labyrinthine peninsulas, and islands bounded by tortuous tidal canals, characterize the eastern shore of the bay throughout the major portion of its length; while the western shore is every where higher and, particularly between the mouths of the Potomac and the Patapsco, much less diversified. Marshes, too, are prevalent on the east and much less common on the west. Briefly, the aspect of Chesapeake Bay, at least above the mouth of the Patapsco, is that of a drowned river, deflected westward.

Although the largest of all, Chesapeake Bay (together with the Susquehanna River, of which it is the tidal continuation) is one of the series of similar fluvi-o-estuarine water-ways constituting the most
conspicuous hydrographic feature of the Middle Atlantic slope. In an important respect the behavior of the largest three of these (the Delaware, the Susquehanna, and the Potomac) is alike noteworthy. After successfully battling with the rock-ribbed Appalachians and the cragged granites of the Piedmont region and triumphantly breaking through the last of their barriers with unchanged courses, they suddenly turn at right angles, on reaching the low-lying plain, to hug the frowning Piedmont escarpment, and do not resume their former courses for scores of miles; after vanquishing the great mountains they are overcome by a sand-bank little higher than their depth. And it is an even more remarkable fact that the drainage of the coastward and interstarine peninsulas is predominantly to the southwest, i. e., landward rather than seaward.

This anomalous behavior of the water-ways indeed extends throughout the Coastal plain portion of the Middle Atlantic slope. The James, the Appomattox, and the Roanoke exhibit pronounced deflection at the fall-line and many of the smaller streams are similarly deflected toward the Piedmont escarpment on reaching the plain.

II. TOPOGRAPHY.

GENERAL CONFIGURATION.

As seen from the head of the bay, the Piedmont escarpment simulates a range of wooded hills two hundred to three hundred and fifty feet above tide, notched to its base by the Susquehanna, and to less depths by Swan Creek, Wilton Run, Principio Creek, and Northeast River, while the fringing lowlands appear to form an undulating plain of half that altitude, generally dropping sharply down in a cliff shore to the bay and its affluents. But the better view from any of the granitic salients shows that the apparent range of hills is only the marginal portion of a strongly undulating plateau, extending and rising gently west and northwest as far as the eye can reach, while the coastal fringe is then seen to consist of a series of low terraces, each rising but little above its next lower neighbor, and sometimes distinguishable with difficulty from it, interspersed with gentle slopes, all more or less modified by erosion not merely along important rivers and streams, but as well in the ravines and gullies occupied only during freshets; for the materials of which the terraces and the intervening slopes are built are incoherent and are as rapidly cut away by the miniature torrents of rill and rivulet as by the mighty torrents of the river. Thus, about the head of Chesapeake Bay, the region of the crystallines is an unequally degraded plateau, faintly terraced along its flanks, while, within, its summits are not referable to any definite plane or system of planes save its own mean surface; and the region of the non-lithified elastics is a low, monotonous plain, the altitude of which, except in the imme-
diate vicinity of streams, varies slightly in different parts and is approximately constant over considerable areas, with here and there an isolated eminence of one hundred and fifty to two hundred feet or more which curiously marks the landward extremity of the Cretaceous greensands.

Only two noteworthy eminences occur in the Coastal plain within the tract specially studied, viz: Maulden's Mountain and Bull's Mountain, both on the east side of the bay, nearly opposite Havre de Grace; but several slighter eminences occur in neighboring portions of the tract within the broad doab² between Northeast and Elk Rivers. The altitude of the former (roughly determined trigonometrically) is 242 feet and that of the latter probably a trifle less. The mean altitude on the east side of the bay is perhaps half of this, or 100 to 125 feet, while Spesutie Island and the adjacent mainland, and indeed the western border of the plain generally, are much lower, rising to maximum altitudes of only thirty or forty feet. Spesutie Island averages little more than ten feet in altitude; the greater portion of the Swan-Romney Peninsula is less than twenty-five feet above the waters of the bay; and Havre de Grace and Perryville are built on terraces rising fifteen to thirty-five feet above tide. There is thus a landward inclination of the inland margin of the Coastal plain, and in the shallow trough defined by this slope and the Piedmont escarpment lie the bay and its estuarine affluents, notably the apparent extension of the bay, Northeast River. Indeed, topographically, Chesapeake Bay itself is but a continuation of the gently undulating Coastal plain; for, although the shores everywhere drop sharply down to tide level, exposing numerous admirable sections fifty to one hundred feet in height, the depth of water seldom reaches eighteen feet and averages only about ten feet; and, were the land elevated twenty-five feet, the bottom of the bay would form a terrace-plain more uniform than any of those now existing at higher levels.

SUBORDINATE CONFIGURATION.

The local land configuration is determined (1) by terracing and (2) by the hydrography.

(1) Although conspicuous by reason of their great extent, the terraces affect the relief only subordinately; and, moreover, they cannot be investigated or described in detail without more accurate topographic maps of the region than any now in existence. But certain notable topographic features connected with the terrace system are worthy of mention: (a) Some of the marshes of the tract appear to be silted-up, fluviatile estuaries; yet most of those in the western and southern portions are irregular and discontinuous, are independ-

²A useful Persian word, meaning “two waters,” applied to the point or promontory lying between two streams immediately above their confluence as well as to the confluence itself. Employed by Medlicott and Blanford (Manual Geol. India, 1879, pt. 1, p. 410).
MAP OF THE HEAD OF CHESAPEAKE BAY.

Showing the Distribution of the Columbia Formation.

The relative coarseness of materials is indicated by the size and thickness by the closeness of the figures.

Scale 1: 220,000 - 5 miles to 1 inch.

Scale 1: 320,000 - 5 miles to 1 inch.
ent of drainage lines, and apparently occupy depressions corraded by tidal currents during the emergence terminating the terrace period.

(b) On Elk Neck, i.e., the doab between Northeast and Elk Rivers, there occur a number of insulated eminences rising from a faintly terraced plain to altitudes of one hundred and fifty to two hundred and forty feet, the most conspicuous of which are Maulden's Mountain and Bull's Mountain. They appear to be wave-worn remnants of the Cretaceous greensand, whose peripheral portions were dislodged, mingled with erratic débris, and swept into adjacent depressions during the terrace epoch, and they appear to owe their present existence to the brevity of that epoch.

(2) Separating the Susquehanna River from the bay (which is really but its estuarine portion), the streams of the tract represented on the map (Pl. LVIII) may be divided into three categories, viz, (a) those which lie northwest of the fall-line and have high declivity to their mouths; (b) those which cross the fall-line and have high declivity above, while they are estuarine toward their mouths; and (c) those whose entire courses are within the Coastal plain.

The first category is represented by the Susquehanna and its tributaries. The Susquehanna flows in a steep-sided but flat-bottomed trough incised in the Piedmont plateau, about a mile in width, of which it occupies practically the whole; and during freshets its waters, instead of spreading over a flood plain as do those of most rivers, rise upon and corrade the precipitous sides of its picturesque gorge. Its bluffs are from two hundred and fifty to three hundred and fifty feet in height and of ever varying aspect, forming now mural precipices, in the crevices of which stunted cedars sometimes take root; then clean-cut salients and cusps of naked rock, separated by deeply notched chasms down which streamlets rush and plunge; and elsewhere gentler slopes, in which the black rocks are verdure-mantled. Within this veritable cañon the broad Susquehanna seethes and foams over rugged ledges of schist and huge bowlders, descending 80 feet in 12 miles. These rapids terminate at Port Deposit, the head of navigation, and the velocity of flow diminishes there, although it remains sufficient to keep the channel free from débris to the lower end of Watson's Island, just above Havre de Grace, where the waters begin to feel the effect of the tide and the channel becomes alluvium-lined. Here, too, the gorge widens and the Piedmont plateau in which it is excavated overlooks the Coastal plain in a rugged escarpment. Watson's Island itself, rising in solid ledges of gray granite seventy-five feet or more above the river, is a part of this escarpment.

The relation of the gorge to the plateau in which it is excavated is illustrated in Pl. LVI, reproduced from a photograph taken from the Baltimore and Ohio Railway bridge, 95 feet above tide; and a
nearer view of one of its bluffs (Mt. Ararat, the second point on the right in Pl. LVI) is given in Pl. LIX.

It may be noted in passing that throughout its gorge the Susquehanna River hugs its left shore the more closely; and apropos to the hypothesis of dextral deflection of rivers by terrestrial rotation (commonly known in Europe as Baer's law), specifically applied by Kerr to the water-ways of a portion of the Middle Atlantic slope and recently discussed in more general terms by Gilbert, Davis, Hendricks, Baines, and others, it may be mentioned that the different water-ways of the Middle Atlantic slope are not only inconsistent in their behavior at and above the fall-line, but in many cases the same stream has not behaved uniformly since the excavation of its gorge was initiated.

The tributaries of the Susquehanna within the area represented on the map are mere brooks, rarely reaching the dignity of mill streams.

\[1\] Geol. North Carolina, vol. 1, 1875, pp. 9-12.

\[2\] Thus, in the corresponding part of its course, the Potomac not only closely hugs its south shore, but is terraced on the north side alone; Accotink and Pohick Creeks are neutral; the Occoquan affects its north shore, though not very decidedly, while its terraces prevail on the south; Neabsco Creek tends slightly toward its north shore; Powell Creek is neutral; the Quantico tends, though not strikingly, toward the south shore; the Choppawamsic hugs its north shore; Acquia Creek approaches the south side of the valley above the head of tide and is deflected to the south below, though its north bank is generally the steeper; Accaquack and Potomac Creeks tend southward; below the fall-line at least, the Rappahannock approaches its north shore, but is most extensively terraced on the south; the Massaponax generally seeks its north bank; the Ni, the Po, and the Ta, above their falls, appear to tend slightly, and the Taponi (which they unite to form) tends decidedly, to the north and east; the Mat tends decidedly to the north, while the Mattaponi (formed by the last four streams with unisyllabic names) beyond the fall-line closely hugs its north bank and has a flood plain a mile wide on the south; the upper Chichawominy (above the mouth of Brooke Creek) washes its south bank and has its flood plain all on the north, though the main bottom, slightly elevated above flood stage, is wholly on the south; the same river below the mouth of Brooke Creek has a flood plain 40 rods wide, the south side of which it generally approaches, while the slopes to the northward are steep, and a broad terrace, just above the reach of freshets, occurs on the south; Brooke Creek hugs its south bank, but has a broad terrace on the south and steep bluffs on the north; the James has high bluffs on the north rising rapidly from and overlooking the river, and, although it is deflected southward immediately outside the fall-line, it has its present flood plain and many terraces miles in width on the south; Swift Creek approaches its north bank and is strongly deflected in the same direction; the Appomattox appears to be neutral, though its valley is deflected northward, while its terraces are widest on the south; Rowanty Creek tends slightly to approach its north bank; Stony Creek and Nottoway River appear to be neutral; the Three Creeks tends northward inconspicuously; the Meherrin at Hicksford decidedly hugs its north bank and has its flood plain and widest terraces on the south; Fontaine Creek seeks the south side of its present narrow flood plain, but has steep slopes on the north and on the south a level bottom a mile wide, probably within the reach of freshets; and the Roanoke at Weldon in like manner generally approaches the south side of its narrow flood plain, although this plain is bounded by steep bluffs on the north and by broad, low terrace plains on the south. The cause of this anomalous deportment of the Atlantic slope streams is under investigation.
MT. ARARAT, SUSQUEHANNA RIVER.
All alike enter the river in narrow, V-shaped valleys over falls or rapids which generally reach their maximum declivity a few hundred yards above the mouth of the stream. Lapidam Creek may be taken as the type of all. It is formed in part by springs and in part by a number of brooklets which gather among the rounded Piedmont hills rising to various altitudes, one to four miles back from the river. These brooklets sometimes flow over fine alluvium, again over residuary clays, and rarely over bed rock, in regularly concave and alluvium-lined dales which unite, perhaps a mile from the Susquehanna, in a broad, concave valley so well lined with alluvium and the débris from the surrounding hills as to afford a considerable area of tillable soil. Thence for the first half mile toward the river the declivity of the valley gradually increases, the concavity of the valley bottom gradually sharpens, the alluvium diminishes, and the brook flows over either solid rock or beds of large bowlders, and in the next half mile (within which the constantly growing stream descends fully 100 feet) the gorge becomes V-shaped, not only alluvium but even the bowlder beds completely disappear, and in the bottom of a shadowy glen the waters leap and plunge from ledge to ledge in a succession of cascades. Within perhaps three hundred yards from the river the declivity diminishes, the longitudinal profile of the stream quickly becomes concave, the rush of its waters is checked, and it finally enters the river through a short, bowlder-lined channel of only sufficient slope to give moderate velocity to the stream.

The second category of streams is represented by Swan, Principio, and Mill Creeks. Swan Creek, which may be taken as the type, is eight or ten miles long and, like the Lapidam, is formed mainly by the union of a number of brooklets draining the undulating surface of the Piedmont plateau. For the first three or four miles of its course it flows in a broad, alluvium-lined valley and seldom reaches solid rock. Below, the valley gradually deepens and assumes the V cross-section as the alluvium disappears from its bottom, and the stream either reaches the rock or flows over bowlder beds of its own deposition. Some five miles from its mouth (at the upper grist mill) the pebbles and bowlders encumbering the channel and measuring the competence of the stream during freshets (and thus its declivity and velocity) range from an inch to perhaps a foot in diameter; three-fourths of a mile below, the bowlders have increased to maximum dimensions of three or four feet; and in another three-fourths of a mile the gorge is constricted and steep-walled, and the stream flows either over solid ledges or over bowlders of its own transportation, five, ten, and even fifteen feet in diameter, while a tributary brooklet falls 50 feet in the last 100 yards of its course. This locus of maximum declivity occurs just above the lower grist mill, 300 or 300 yards above the Baltimore and Ohio Railway. Below the rapids the slope of the stream rapidly diminishes to just enough to give it
a flow of two or three miles per hour at summer stage, its bed becomes lined first by bowlders, in half a mile by gravel and sand, and within a mile by sand alone. The estuarine portion of the stream then commences, and it expands rapidly from a width of ten or twenty feet to an average of perhaps half a mile. In the upper third of its estuarine portion the stream is sometimes flanked by marshes and in its lower two-thirds generally either by steep banks or (for perhaps one-tenth of the entire length of both shores) by sheer precipices ten to thirty feet high. It is navigable at mid-tide for a steam launch drawing three and a half feet up to about half a mile below the mouth of Wilton Run, and by skiffs to the third elbow, 40 rods from the county road at Temple Hill.

The other representatives of the category, Principio and Mill Creeks, behave like Swan Creek in their upper courses, and below expand into considerable estuaries, generally bounded by steep banks, which are, however, rarely so precipitous as to afford good sections. They are not navigable save by the lightest craft.

The third category of water-ways is represented by Northeast, Elk, and Sassafras Rivers, and their tributaries, Cabin John Creek, Pond Creek, Lloyd's Creek, Turner Creek, Back Creek, etc. These streams alike (with the exception of Northeast River, which heads in the Piedmont region in southern Pennsylvania, but enters the Coastal plain several miles above the head of Chesapeake Bay) originate in the gently undulating coast region and are formed by the union of streamlets flowing in shallow, alluvium-lined valleys, and neither the streamlets themselves nor the secondaries and primaries which they unite to form cut through their alluvium and the débris from the surrounding hills and reach the subterrane until they descend to tide-level. Their profiles, so far as can be determined without instrumental measurement, are closely similar and of normal character—i. e., the stream has maximum declivity toward its source, which progressively diminishes with increasing volume and imperceptibly passes into the sensibly horizontal line represented by the estuarine portion, thus forming a curve approximately parabolic in form, concave upward. In their estuarine portions these streams seldom exhibit alluvium above high tide level and the formations flooring the region are exposed along their shores, where the erosion is not fluvial, but the effect of waves and littoral currents, and the detritus brought in by the streams, as well as the still greater quantity derived from the retreating estuarine shores, is deposited either in the estuaries themselves or in adjacent portions of the bay. The valley sides, the low estuarine walls, and the shores of the bay are alike gashed by gullies and ravines cutting into the interfluvial plains and giving origin to secondary and tertiary systems of ravines, all forming large angles with their principals, collectively constituting an intricately ramifying drainage system and producing a diversified topography;
but the drainage system is yet in nascent condition and some of
the terrace-plains, particularly the lowest, have not yet been com-
pletely invaded by the water-ways.

The configuration of the shores of estuaries and bay is determined
by waves and littoral currents acting upon an unequal land surface
of variable general altitude.

Northeast River (the broader of the two convergent streams which
appear to form Chesapeake Bay by their union, although in fact it
is only a good-sized mill stream), is navigable nearly to Northeast,
where it becomes marshy and gradually loses its estuarine character.
Perhaps one-fourth of the total length of shore from this point to
its mouth is marshy, something over three-fifths consists of slop­
ing banks of variable steepness, ten to thirty feet high, and perhaps
one-tenth consists of banks so precipitous as to exhibit sections of
the strata. The best of these sections are at points exposed to the
action of waves generated within the bay. On Elk River the pro­
portion of marshy and sloping shore is greater, and few sheer preci­
pices occur above Turkey Point and Wroth's Point, though the flank­
ing bluffs are higher than those of Northeast River. About one­
third of the shores of Sassafras River below Frederick is marshy,
nearly one-half consists of steep banks still higher than those of the
Elk, and thus fully one-tenth of the length of both shores of its
estuarine portion consists of precipitous cliffs affording numerous
admirable sections, from ten to seventy-five feet high. Both the
Elk and the Sassafras are navigable throughout the portions shown
on the detail map (Pl. LVIII). Thus, in these estuaries and in
those of the smaller streams as well, the prevalence of precipices is
proportional to the proximity of the bay and the accessibility to
waves and currents originating therein under the influence of the
prevailing winds.

The bay itself, which is a water body of sufficient size for the gen­
eration of violent waves, is generally bounded by steep and precipi­
tous shores. From half a mile south of Havre de Grace Light to the
mouth of Swan Creek the shore is a nearly continuous precipice
twenty to forty feet high, sometimes encumbered by talus and oc­
casionally broken by streamlets, with their accompanying marshes,
or by steep-sided ravines. From the mouth of Swan Creek to Locust
Point, on SICESUTIE Island, there are similar precipitous bluffs, but
of progressively diminishing height, that at Locust Point rising but
ten or twelve feet above tide, while south of this point the west
shore of the bay is generally but slightly elevated above the bay and
is either marshy or sandy. On the north, from Perryville to Stump's
Point, the shore is generally a steep but not precipitous bank ten
to twenty feet high, but near the latter point it becomes a talus­
encumbered precipice. Farther eastward the general altitude of the
land increases, and from Poplar Point to Carpenter's Point more
than one-half of the shore is a sheer precipice twenty-five to fifty feet high, sometimes entirely free from and never greatly obscured by talus. Along the east shore of the bay, from Red Point to Turkey Point, the altitude of the land is still greater, ranging from five or ten feet up to 240 feet in the "mountains" and averaging probably 100 feet, and, except where interrupted by marshes at the mouths of streamlets, it is a nearly continuous precipice. At Red Point the cliff is perhaps forty-five feet high and quite free from talus; below Bull's Mountain it is fifty or sixty feet; at Rocky Point there is a clear exposure of fully seventy-five feet; and, although there is a considerable talus at the immediate base of Maulden's Mountain, a few hundred yards farther south there is a succession of cliffs affording a continuous section of the strata from the summit of the mountain to tide level, about two hundred and forty feet. For a length of one and a half miles around Turkey Point there is a practically talus-free cliff averaging not less than seventy-five feet in height; from Wroth's Point to Grove Point the land remains high, but, by reason of the streams there entering the bay, three-fifths of the distance is either marshy or talus-encumbered; Grove Point affords a continuous precipice fully a mile long and sixty to eighty feet in mean height, and from Betterman's landing (where the Sassafras may be supposed to embouch) to Howell's Point there is a nearly continuous cliff of about equal height.

ANALYSIS OF TOPOGRAPHY.

The great topographic features of the tract are complex in genesis and character and systematically inseparable from those of the Atlantic slope generally, of which they form a part. They are discussed in certain of their aspects in sections v and vii.

The minor topography is coeval with and determined by the hydrography, and its definition, classification, and correlation with that of other regions involve classification of the drainage. Hydrography, indeed, affords the only natural basis for a genetic taxonomy of the prevailing classes of topographic forms; for it is the only constant factor in their determination. There are two antagonistic categories of processes by which the internal structure and external configuration of the visible crust of the earth are developed. The first is the result of forces generated within the sphere, and, in the broader sense as well as in the narrower, it is covered by the term deformation. The second, which comprises degradation and deposition, is the effect of forces acting without, and may be designated gradation.¹ Now, the processes of the first category are predominantly hypogeal and quite subordinately superficial in effects.

¹ These great processes are supplemented and modified by alteration, comprehending lithification and its antithesis, decomposition and disintegration combined, and also by extravasation; and two classes of the processes of gradation, viz glaciation and wind action, are anomalous in operation and effects.
and operate unequally in time and space, culminating only locally
and temporarily. The processes of the second category, on the other
hand, are superficial and are constantly and everywhere operative,
with only limited range in intensity; and, by them all, minor and
many major features of the terrestrial surface are directly deter-
mined. It is true that Lesley thirty years ago regarded the mount-
ain as the fundamental topographic element; that Richthofen rec-
ognizes the upland and the plain (aufragendes Land und Flachbö-
den) as primary classes of configuration comprehending all minor
elements of topography; that Dana groups topographic forms as
(1) lowlands, (2) plateaus or elevated table-lands, and (3) mountains;
and that these related allocations are satisfactory for the purposes
for which they are employed. But the implied classification in all
these cases is morphologic rather than genetic and is based upon
superficial and ever-varying if not accidental characters; and if it
were extended to the endless variety of forms exhibited in the topog-
raphy of different regions it would only lead to the discrimination of
a multitude of meaningless and unrelated topographic elements. The
classification of topographic forms proposed by Davis, who regards
“special peculiarities of original structure” as a primary and “de-
gree of development by erosion” a secondary basis, and Richthofen’s
arrangement of the categories of surface forms as (1) tectonic mount-
ains, (2) mountains of abrasion, (3) eruptive mountains, (4) mount-
ains of deposition, (5) plains, and (6) mountains of erosion, in addi-
tion to depressions of the land, are more acceptable, since they
are based in part on conditions of genesis. But it is clearly recog-
nized by modern students of dynamic geology that water-ways are
the most persistent features of the terrestrial surface and the most-
widely applicable systems of classification of the surface configura-
tion of the earth thus far proposed have been based substantially on
hydrography. Thus, Powell, Löwel, and Richthofen classify valleys
by the conditions of their genesis; Gilbert classifies drainage; and
Philipson, unduly magnifying the stability and genetic importance
of the water-parting, classifies the hydrography through its divides;
and, although these geologists have not dwelt upon and have perhaps
failed to perceive the relation, the same classification is as applica-
tible to every feature of the local relief as to the streams by which the
relief was developed.

1 Manual of Coal and its Topography, 1856, pp. 125 and 126.
2 Führer für Forschungsreisende, 1886, p. 631.
meeting, 1884, p. 428.
5 Führer für Forschungsreisende, 1886, pp. 651-683. (1) Tektonische Gebirge, (2)
Rumpfgebirge oder Abrasionsgebirge, (3) Ausbruchsgebirge, (4) Aufschüttungsge-
birge, (5) Flachboden, und (6) Erosionsgebirge.
6 Ibid., Die Hohlformen des Festlandes, p. 634.
7 Studien über Wasserscheiden, 1883, pp. 13 et seq.
(1) The hydrography developed upon terranes affected by deformation, both before and after submergence, has already been satisfactorily classified. Powell years ago denominated valleys established previous to displacement of the terrane by faulting or folding, *antecedent valleys*; valleys having directions depending on displacement, *consequent valleys*; and water-ways originally established upon superior and subsequently transferred to inferior terranes by the complete degradation of the superior, *superimposed valleys*; and these valleys were separated into orders determined by relation to strike, and again into varieties determined by relation to subordinate attitude of the terranes traversed. Gilbert adopted the same general classification and so extended it as to include certain special genetic conditions. Tietze, in the course of his investigations of the Seni-rud (or Kizil Uzen) and other rivers in the Alburz Mountains of Persia, independently ascertained the characteristics of the class of water-ways comprehended by Powell under the term antecedent; Medlicott and Blanford observed that many of the Himalayan rivers are of like genesis; and Rätimeyer, Peschel, and others have recognized the same genetic class of water-ways; but none of these foreign geologists has discussed their taxonomic relations. Löwl, who upon a priori grounds denies the possibility of antecedent drainage, has developed an elaborate taxonomy of valleys, which he groups as (a) tectonic valleys, and (b) valleys of erosion (Erosions-thäler); the first of these categories is separated into two classes, viz, valleys of flexure and valleys of fracture, and these in turn into several subclasses determined by the character of the deformation and its relations to structure; and the second, whose genesis is attributed to retrogressive ("rückwärts fortschreitende" or "rück­schreitende") erosion, is indefinitely separated into several ill defined classes and subclasses determined by structure, climate, and various other conditions. The second of Löwl's categories is recognized also by Philipson. Still more recently Richthofen, neglecting antecedent drainage and designating the superimposed class of Powell *epigenetic*, has formulated a classification of the remaining types of continental depressions (Die Hohlformen des Festlandes) as

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1 Exploration of the Colorado River of the West, 1875, pp. 163-166.
3 Geology of the Henry Mountains, 1877, pp. 143-144 and elsewhere. The conditions are incidentally specified later.
6 Über Thalbildung, 1884, p. 90.
7 Ibid., pp. 1 et seq.
8 Ibid., pp. 44 et seq.
9 Studien über Wasserscheiden.
(a) orographic depressions (Landsenken), (b) tectonic valleys, and (c) sculptured valleys; and the last two categories are separated into classes and subclasses, corresponding fairly with those of Löwl, determined by their relations to structure and by various genetic conditions.

These several systems of classification have much in common; their differences are largely due to the diversity of the regions in which the investigations of their respective authors have been prosecuted, and, combined, they probably comprehend all the topographic types which it is at present necessary to discriminate.

The American classification and nomenclature, particularly, is unobjectionable as applied to montanic hydrography; but it does not apply to the perhaps equally extensive drainage systems and the resultant topographic configuration developed on emergent terranes, either (a) without localized deformation or (b) with localized deformation of less value in determining hydrography than concomitant erosion, terracing, and reef building; neither does it apply to the minor hydrography in those regions in which the main hydrography is either antecedent or consequent; nor does it apply even to the original condition of the superimposed drainage of montanic regions.

Upon terranes emerging without localized displacement and upon equal surfaces not yet invaded by valleys, the streams depend for their origin on the convergence of the waters falling upon and affected by minor inequalities of the uneroded surface, and for their direction upon the inclination of that surface; they are developed proximally (or seaward) by simple extension of their courses with continued elevation and distally by the recession of the old and the birth of new ravines; and, since in the simple case it follows from the law of probabilities that the receding ravines retain approximately the old direction and the new ravines depart therefrom at high angles, the drainage systems thus independently developed are intricately but systematically ramified and more or less dendritic in form. Löwl, Philipson, Richthofen, and other continental, as well as different British and Indian geologists, and Lesley in this country, indeed recognize this type of drainage; but they do not correlate it with the montanic types, and Löwl's designation for the process by which it is generated ("rückschreitende Erosion," or retrogressive erosion) does not apply to either the completed drainage or the coincident topography, while Lesley's designation for the drainage itself ("quaquaversal arborescent") does not apply to the process of development.

1 Führer für Forschungsreisende, 1886, pp. 634-644.
2 Über Thalbildung, 1884, p. 85.
Although its subordinate phases are not yet discriminated on a genetic basis, the type or order of drainage independently developed on undisturbed emergent surfaces is sufficiently distinct and important to be regarded as co-ordinate with the type represented by the entire group of categories recognized by Powell and clearly defined by Gilbert. Such hydrography (which, either in its natural condition or superimposed, characterizes many plains, some plateaus, and the sides of large valleys of whatever genesis) may be termed autogenous, while the drainage systems imposed by conditions resulting from deformation (which characterize most mountainous regions) may be termed tectonic. Gilbert's classification of drainage may then be so extended as to include topography as well as hydrography and so amplified as to apply to the tract under consideration, as follows:

Drainage systems and the resulting systems of topography are—

Type 1.—Autogenous.
Type 2.—Tectonic.

Order A.—Consequent upon—
Class a.—Displacement before emergence; and
Class b.—Sudden displacement after emergence.

Order B.—Antecedent; and

Order C.—Superimposed—
Class a.—Through sedimentation or subaqueous deposition (when the superimposed drainage may be autogenous);
Class b.—Through alluviation or subaerial deposition; and
Class c.—By planation (in which two cases the superimposed drainage may simulate the autogenous type).

Within that portion of the Coastal plain lying about the head of Chesapeake Bay the drainage is autogenous and has fashioned a coincident topography modified by littoral action along shores; but by reason of the recency of the emergence the drainage is yet nascent on the one hand and by reason of the initiation of submergence it is obsolescent on the other hand; and so the topography yet retains subaqueous characteristics at the heads of the drainage lines and is recovering the same characteristics at their mouths.

(2) In the portion of the Piedmont plateau falling within the tract mapped in Plate LVIII, the strata are highly inclined or vertical, and it is hence evident that the hydrography is not autogenous. At the same time the drainage system is reticulate or dendritic, simulating that of the plain in the distribution of its members. It is therefore inconceivable that it can be determined either by structure or (since the magnitude of the displacement by which the strata were inclined far transcends that of the drainage system) by conditions antecedent to the deformation. It follows that the hydrography must be superimposed.

1. The co-ordinate type of topography determined by glacial action, and the types determined by vulcanism, wind action, etc. do not require consideration here.
Now a superimposed drainage system may or may not indicate the type, order, and class to which it originally belonged. Thus, prevalent but yet partial coincidence in direction of its members with the trend of strata might prove that the original drainage was tectonic, indicate that it was consequent, and suggest that the displacement occurred after emergence; a symmetric dendritic form might indicate either that the original hydrography was autogenous or that the system was superimposed by planation or alluviation, etc. So the genesis of the hydrography may be inferred with a greater or less degree of certainty from its relation to structure.

Since the Piedmont strata in the tract examined are approximately vertical, heterogeneity of terrane has exercised an approximately constant effect on topographic configuration at all stages of erosion since the area emerged from the sea and its rocks assumed their present attitude. Now on the higher portions of the area—i.e., on the strongly undulating plateau north of Port Deposit and southwest of Lapidam, as well as on the plateau farther westward—the spurs, knobs, and divides are of exceptionally obdurate rock, from which it would appear that at the time of development of the hydrography these unusually obdurate portions of the terrane resisted disintegration and corrosion and deflected the water-ways toward and upon those portions of the terrane in which the rock was less obdurate; and the coincidence of the hydrography with heterogeneity of the terrane proves that the drainage system was developed on the terrane itself. At the same time the symmetrically dendritic forms of the drainage and the consequent relation between the value of local relief and the size of streams proves that the hydrography was autogenetically developed on an approximately plane surface, while the absence of alluvium and of confining highlands alike show that it was not superimposed through alluviation. It follows that the drainage here is superimposed through planation or through base-level degradation so perfect that the old water-ways were completely obliterated.

In the southeastern and lower portions of the plateau, on the contrary, the eminences do not coincide with exceptionally obdurate strata, nor do the valleys coincide with exceptionally soft or easily weathered rocks; the hills and ridges are as frequently of soft as of hard rock, and consequently are low and irregular as compared with those of the northwestern part of the plateau; the slopes are variable, and the valleys are frequently obstructed by hard ledges producing falls and rapids in even the upper portions of the water-ways, far within the fall-line; yet the hydrography is dendritic. Accordingly, it appears that the drainage, while of the autogenous type, is independent of the structure of the rocks over which the streams now meander. So the drainage system of this part of the Piedmont plateau would seem to have been originally autogenous
and superimposed on the tilted crystallines forming the present terrane.

Throughout nearly the whole of the crystalline area the streams have carved out a topography in which the local relief, the width of valley, the ruggedness of bluff, and the magnitude of the topographic elements generally, vary directly and uniformly with volume of water; but along its margin the terraces of the Coastal plain have sometimes invaded its lower portion and the contours are sharpened by the active corrasion resulting from lowering of base-level.

RÉSUMÉ.

Recapitulating, the tract mapped is naturally divisible into two distinct topographic districts: The first is a strongly undulating plateau averaging something over 300 feet in altitude, slightly inclined eastward, with a deeply crinulate but nevertheless sharply distinct margin, within which the drainage is dendritic and in the western part affected by, but to the east independent of, the unequal obduracy of the terrane; within which the larger streams, originating at a distance, have carved deep and narrow gorges and the smaller streams flow in inosculating and winding valleys nearly to their embouchures, and then in narrow and deep canons, while all streams lie above base level and are rapidly corrading their beds. The second district is a gently diversified plain, averaging perhaps 100 feet in altitude, inclined westward, particularly toward its inland margin, within which the relief is in part original and determined by the conformation of the surface as it emerged from the sea and in part determined by hydrography, and within which the drainage is autogenous, but affected by original conformation, while the streams are everywhere at base level and drowned toward their embouchures.

III. THE GEOLOGIC EXPOSURES.

So variable are the different formations of the region in the several exposures that the differences exceed the resemblances, and, since the local diversities are due to local causes, the characteristics of the formations cannot be elucidated by generalized description with sufficient minuteness for the purposes of the local student. Accordingly, the descriptions of a number of representative exposures are transcribed from the field note-book without material alteration. Irrelevant details, however, and (generally) those relating to topography have been omitted and the taxonomic relation of each deposit (only deduced as the investigation approached completion) is generally indicated, while the observations are generalized and their relations and significance are set forth in sufficient detail for the use of the comprehensive student in other sections.

The exposures described are located and consecutively numbered as in the following pages on the accompanying map (Pl. LVIII).
WESTERNMOST EXPOSURES.

1. Lapidam Creek.—A number of natural and artificial sections, fairly representing the geology of the Piedmont plateau, flanking the south side of the Susquehanna, occur along this creek. Generalizing these, it may be said that the terrane is granite and associated hornblende and rarely chloritic schists, vertical or dipping south-southeast at high angles, with occasional veins of quartz. The superficial deposit on summits and slopes is a red, residuary clay, derived from the decay of the crystalline rocks, reaching a maximum observed thickness of ten or twelve feet. The upper valleys and ravines are lined with alluvium of maximum observed depths of five to eight feet, although where probably thickest its bottom was not seen. The alluvium is largely formed of red, clayey materials washed down from the slopes and in general is more or less sandy. Both the residuary clays and the alluvium contain occasionally angular pebbles or boulders of local rocks, but absolutely no erratic material occurs at any altitude. The summits of knolls and ridges generally expose obdurate rock: vein quartz, exceptionally siliceous hornblende schist, etc.

2. Quarry Point.—Here a prominent salient, perhaps 200 feet high, is formed of compact, somewhat siliceous, hornblende schist, dipping south-southeast 75° to 80°. The same obdurate stratum finds a general topographic expression in a ridge extending north-northeast fully a mile, where it gradually passes into the strongly undulating surface of the Piedmont plateau. At this point the plateau assumes the character normal on the north side of the Susquehanna River, and the geologic structure is also exhibited. As on the south side of the river, the subterrane remains granitic and schistic, and the superficial covering remains a residuum derived therefrom, without any admixture of foreign matter.

3. Red Hill.—On approaching the margin of the Piedmont plateau the character of the mantle of superficial débris gradually changes, and nowhere is the transition better exemplified than here. Red Hill itself is a prominent landmark, conspicuous at considerable distances by reason of its altitude (probably nearly 400 feet) and the red color of its soil, which is a residuum derived from hornblende and chloritic schist, with no admixture of erratic material. On the east and south this hill is flanked by a clearly defined terrace widening southward, in which direction it forms a broad salient extending to Swan Creek, at the upper grist mill. The altitude of this terrace is probably 275 or 300 feet, and its variations in altitude are but ten or fifteen feet. In area it reaches perhaps a square mile. In general this terrace appears to be carved out of the Piedmont crystallines, and the unconsolidated superficial débris consists of residuary matter, with abundant fragments of local rock; but in certain portions
566 GEOLOGY OF CHESAPEAKE BAY.

(particularly in depressions and along its margins) the resquary clay is intermixed with silt or fine loam, weathering white, and contains a considerable element of well rounded quartzite pebbles, generally one or two inches in diameter, just such pebbles, indeed, as characterize the Potomac formation everywhere toward its western margin and also form a common feature in the Quaternary.

4. Upper grist mill.—At this point the alluvium and the stream gravels were examined in order to ascertain the relative amounts of local and erratic material, and it was found that fully 98 per cent. of the pebbles and boulders are local, while a few are of well rounded quartzite up to three inches in diameter. Two or three subangular fragments of ferruginous pudding-stone of quartzitic pebbles, such as characterize the Potomac formation generally, were also found. A very few quartzite pebbles were found on the divide to the southeast.

5. Lower grist mill.—At this point Swan Creek has practically no alluvium or stream pebbles, since it rushes furiously through a narrow, steep-sided gorge, sometimes over solid ledges of schist and again over well rounded, local boulders from one foot to fifteen feet in diameter, with very few small pebbles; but on some of the gentler slopes, particularly in the vicinity of the church half way between the mill and Red Hill, considerable accumulations of well rounded, quartzitic pebbles and a few blocks of ferruginous pudding-stone occur. The prevalent superficial deposit is, however, residuary, red clay, intermixed with local rock fragments.

It was not ascertained whether the quartzitic pebbles of upper Swan Creek represent the Quaternary deposits or whether they represent a Post-Quaternary residuum of the Potomac.

6. Havre de Grace reservoir.—The reservoir from which the city of Havre de Grace is supplied is located on one of the most prominent salients forming the margin of the Piedmont region. It is representative of all. It is a rounded cusp 240 feet high, carved out of hornblendic schist, which by its decay has given origin to a dark-red, residuary clay abundantly intermixed with fragments of the schist, but without any admixture of foreign debris at its summit. Some thirty or forty feet below the apex of the cusp there is, however, an indefinite terrace gashed by gullies exposing residuary, red clay like that of the summit, intermixed with foreign loam or silt and containing numerous rounded and subangular pebbles and boulders of quartzite and other Appalachian rocks up to a foot or more in diameter, as well as local angular boulders reaching diameters of five feet. This pebble bed is unquestionably Quaternary, since the erratics are larger and less perfectly rounded than those of the Potomac formation; and, with the single exception of Maulden's Mountain, it is the highest observed occurrence of unmistakably Quaternary deposits.
Exposures along the Piedmont Margin.

On approaching the Susquehanna River from the south the topography along the line of the new Baltimore and Ohio Railway undergoes a gradual but distinct change. Toward Swan Creek the profile exhibits a succession of broad, level, mesa-like plains, separated by moderately wide valleys; but toward the Susquehanna these plains become so contracted and the intervening valleys so constricted that the profile exhibits little more than a succession of narrow, round-topped ridges separated by steep-sided, V-shaped gorges. This change in configuration is due to the fact that in ascending the Piedmont escarpment to the point selected for the bridge the railway gradually leaves the coastal plain and intersects the Piedmont salients.

With the decrease in altitude southward from the bridge there goes a corresponding change in the constitution of the superficial deposits.

7. High bridge.—At the southwestern end of the magnificent Baltimore and Ohio bridge the railway intersects the extremity of the reservoir salient and exposes a section nearly a quarter of a mile long and 40 feet in maximum depth. Toward its northern extremity the rock exposed is rather friable, argillaceous and sometimes hornblendic schists (readily disintegrating into a gray or cream-colored clay) trending NNE. and dipping SSE. from 80° to 90°. In the southern part of the same section massive granite is exposed. Both schists and granite are overlaid by a heterogeneous mass five to fifteen feet in thickness, largely residuary, but in part a talus washed down from the upper slope; yet, notwithstanding the presence of the Quaternary deposit near the summit of the salient, not more than half a dozen erratic pebbles were found among the unconsolidated materials.

8. Havre de Grace.—In the second spur to the south the slopes are less steep; and, while the massive gray granite (quarried for the piers of the bridge) is overlaid by a talus-like mass only two to six feet thick, the proportion of erratic material is even less than in the last section. The streamlets here have a more rapid flow and their channels are chocked by huge boulders.

9. Orchard.—The cutting here is about fifteen feet deep and exposes two to four feet of moderately homogeneous loam, with a few irregularly disseminated pebbles obscurely stratified toward the base and graduating into a stratum of coarse sand and gravel, containing occasional boulders up to fifteen inches in diameter, averaging one foot in thickness. The smaller pebbles of the loam and gravel bed are mainly quartzite and well rounded, while the larger fragments are angular, local, or sublocal. The gravel bed conforms to the irregularly eroded surface of decomposed gray granite.
10. Red Bank.—The ten-foot cutting here exhibits some three feet of loam similar to that of the last section, with a bed of gravel (mainly angular and local), together with a half dozen peculiar bowlders at its base, the whole reposing on the eroded surface of hornblende gneiss weathering into homogeneous clay of remarkably bright-red color.

11. Fair ground.—Here the thickness of the loam has increased to ten feet and it has become much more homogeneous, though a few pebbles are disseminated throughout. Below it is somewhat sandy and obscurely stratified and passes into cross-stratified, coarse sand and gravel, containing few pebbles, with bowlders up to one foot in diameter. The pebbles are mainly quartzite and well rounded, though in part local and angular or subangular, while the bowlders are wholly local and angular. Most of the bowlders and many of the pebbles have their largest planes horizontal. In this section occurs the southernmost exposure of granite. Its surface is irregularly eroded and it is completely disintegrated.

12. Wilton Run.—Several sections on both sides of Wilton Run exhibit essentially the same succession of deposits as those already described. The run itself has a flood-plain 150 to 200 yards wide, made up of coarse gravel and loam, while its channel is encumbered by pebbles and bowlders over one foot in diameter, its declivity being slight.

13. Swan-Wilton divide.—The cutting at this point exposes eight feet of Quaternary loam, massive at summit but passing down into cross-stratified sand, either phase containing a few well rounded quartz pebbles and a less number of subangular fragments of ferruginous pudding-stone, both apparently derived from the Potomac. Most of the erratic pebbles are arranged in definite lines, in which occurs also local angular blocks and flat slabs (with major axes coinciding with the stratification) up to two or two and one-half feet in diameter. In short, the section is similar to that at Swan Creek bridge, save that the stratification is less distinct and the materials are generally finer.

14. Swan Creek bridge.—The railroad cutting here appears to afford a typical exposure of the marginal phase of the coastal plain Quaternary. The superior member is massive loam five or six feet in thickness, containing a few irregularly disseminated pebbles (both local and erratic). This loam passes down into coarse, massive sand, with numerous disseminated pebbles and occasional flat slabs and angular bowlders, reaching 18 inches in diameter. Although generally stratified, this sand is locally so destitute of structure, so homogeneous, and so largely composed of granitic debris as to render it difficult to decide from small specimens whether it is not decomposed granite; but the disseminated bowlders set the question at rest. The stratification is most definite about the junction of the loam and sand, and here, too, occur most of the bowlders, which are sufficiently
numerous to form perhaps one-tenth of a continuous line or rank at the base of the cutting were they placed side by side. A considerable proportion of the bowlders are firm, ferruginous pudding-stone, evidently not in situ and doubtless derived from the Potomac. The pebbles, too, are so largely of well rounded quartzite and of so uniform size as to render it difficult to decide that the mass is not Potomac.

15. Round Hill.—On approaching the Piedmont escarpment from any point along the railroad there is a rapid diminution in thickness of the Quaternary deposits with ascent, and the erratic materials very quickly disappear. Thus, at Round Hill, which rises only about one hundred and fifty feet above tide, there is absolutely no erratic material among the abundant angular fragments of hornblende-schist distributed throughout the residuary, red clay capping the eminences, nor does any erratic material occur on the still higher hills to the north.

Indeed, in general, on the south side of the Susquehanna the marginal Piedmont slopes are steep and practically destitute of the Quaternary accumulations which are so well developed in the contiguous portions of the Coastal plain.

On the north side of the Susquehanna the Piedmont slopes are gentle and there is a more gradual transition into the plain, and characteristic Quaternary deposits occur at greater altitudes.

16. Frenchtown.—At the north end of the Baltimore and Ohio bridge, granite rises from tide nearly to the railway level, 90 feet above, and is overlaid by loam identical with that of the Swan Creek bridge section. About a mile northeast of the station there is an exposure of four feet of this loam. It is massive, generally homogeneous, somewhat sandy, with pebbles irregularly disseminated abundantly in its lower part and rarely above. These pebbles are mainly of quartzite, well rounded, and reach two inches in maximum diameter; a few are of granite, quartz, etc., angular or sub-angular in form. Although no large bowlders were observed in the section they doubtless occur in the loam in this vicinity; and an angular mass of granite four by five by eight feet lay on the surface a few yards away.

![Fig. 109. Section on Mill Creek-Susquehanna divide.](image)
and abundant below, and identical with that of the last section. It is not very clearly demarked from the middle member (No. 2), which is white, cream-colored, and pink, plastic clay and fine sand, containing lines of well rounded quartzite pebbles of uniform dimensions, the whole presenting just such an aspect as may be seen in typical sections of the Potomac formation along the Potomac River. At its base this division is heterogeneous and contains a few local subangular fragments, the whole sometimes united by a ferruginous cement. The basal member (No. 3) is decomposed gray granite.

18. Cross-Road Hill.—On ascending the gentle slope toward the Piedmont plateau the superior granitic deposits appear to attenuate; but on the summit of this hill, 175 or 200 feet above tide, there are a number of bowlders of quartzite and quartz, as well as of gabbro and granite, up to four and one-half feet in diameter, nearly all angular and subangular, which undoubtedly represent the Quaternary, and the soil in the vicinity is abundantly charged with fine, quartzitic gravel unquestionably derived from the Potomac. A few hundred yards nearer the railway and fifty feet lower, a roadside cutting exposes white quartzite gravel, well rounded, approximately uniform in size (about one and one-fourth inches in diameter), undoubtedly Potomac and in situ.

19. Watson's Island.—The craggy boss forming the southern-central part of this island is of massive gray granite, in part covered by residuary clay which is practically destitute of foreign materials. The loamy phase of the Quaternary was not observed higher than about 100 feet above tide in this vicinity, at which altitude it forms an extensive terrace slightly inclined toward the bay.

20. Perryville.—From Frenchtown to Perryville the summit of the granite diminishes in altitude from ninety to only about fifteen feet above tide, and disappears beneath the waters of the bay perhaps a quarter of a mile east of the Pennsylvania Railroad bridge at the latter point. The rocks are variable, sometimes granitic, again hornblendic, and 300 yards east of the bridge there is a stratum or dike of greenish-black, coarsely crystalline rock tentatively termed gabbro. The trend is NNE, and the dip 75° or more to the ESE. In the immediate vicinity of Perryville the surface of the crystalline terrane appears to be an old carved terrace of uniform altitude. Upon this surface lies a heterogeneous mass of angular bowlders of all sizes and shapes, together with a few smaller pebbles, the whole embedded in sandy loam five to ten feet thick. The bowlders are generally sublocal, while the major portion of the pebbles are of quartzite and other Appalachian rocks. The bowlder bed is overlaid in turn by massive loam, containing occasional pebbles and bowlders irregularly disseminated. There is a typical exposure of this loam in a railway cutting 10 feet deep 300 yards north of the
station, where the material is extracted for brick. The loam is massive and somewhat clayey in aspect, though readily standing in vertical or even overhanging walls. When freshly exposed it is yellowish brown in color, but, like the Quaternary loam of the Potomac, James, and other rivers, it weathers white, and the abundant but minute scales of mica arrange themselves parallel to the face of the section, giving it a glistening surface. The major part of the material is impalpable silt, intermingled with scales of mica, sand grains of various degrees of coarseness, occasional pebbles, and a few bowlders which seem to be equally common in all parts of its depth. The pebbles and bowlders are so few in number that in a surface of 1,000 square feet only the following were noted: One well rounded quartzite pebble two and one-half inches in diameter; a half dozen of less size, one of which was subangular; one of six inches in diameter and subangular; a rounded pebble of argillaceous schist five inches in diameter; an angular pebble of the same material three by five by five inches; and perhaps as many more not carefully examined. In addition there were some score, possibly a hundred or more, pebbles two inches or less in diameter. The whole therefore constitutes so unimportant a part of the mass as not to interfere with its use as material for brick. Still larger rock-masses evidently occur in the loam, for a score of bowlders averaging (exclusive of the largest) perhaps two feet in maximum dimensions, and one three by five by eight feet, evidently encountered in making the excavation, lay at the base of the section. All of the bowlders were sublocal, i.e., of Piedmont and not of Appalachian rocks. The quartzite pebbles were Appalachian, and those of argillaceous schist probably Piedmont, though possibly Appalachian also.

The loam in this section closely resembles that of the Columbia formation in the southern part of Washington and in Alexandria, save that it is destitute of stratification so far as could be observed and that the disseminated pebbles and bowlders do not occur in the latter. It forms a terrace some thirty-five feet in altitude, gently inclined to the eastward.

EXPOSURES ALONG THE MARGIN OF THE COASTAL PLAIN.

21. Temple Hill.—A sand-pit in the roadside here exposes a section of the surface deposits, in which the upper third is of massive loam with a few disseminated pebbles, passing rapidly downward into coarse, cross-stratified, rusty-brown sand, with a very few rounded quartzite pebbles and a few of other materials, angular and often flat in form. The base of the sand was not seen, but the Quaternary sand and loam in this section may be regard as the upward continuation of the next.

22. Gravel Spring.—A number of springs in this vicinity issue along the plane of contact between the continuation of the brown
The geomorphological features described in the text include:

1. **Swan Creek elbow.** Although the exposures are unsatisfactory, the Quaternary at this point appears to consist of massive loam similar to that of the Perryville section, which forms a uniform terrace twenty or twenty-five feet in altitude. The terrace escarpment is a steeply sloping bank sometimes exposing pebbles and boulders. Two of these boulders are conspicuous for their size—about ten or fifteen feet in maximum diameter respectively.

2. **Swan Creek.** Here loam passing down into stratified sand and gravel, with occasional boulders, is imperfectly exposed in a steep slope, which at base becomes vertical and exhibits firm, finely laminated, and readily cleavable, arenaceous clay, white, cream-colored, and gray, containing minute stems and traces of vegetal matter and one or two obscure leaf impressions. This laminated clay is unquestionably Potomac. Its junction with the Quaternary was not seen, but it probably rises eight to ten feet above tide. A sharply angular boulder of massive, gray granite, eight feet in mean diameter, derived from the Quaternary, lies at the base of this section.

3. **Swan Bay.** At this point there is a bluff twenty-five or thirty feet high, of which the upper ten feet consists of massive loam, the succeeding five feet mainly of gravel and pebbles, and the next ten feet of cross-stratified sand, the basal portion of the section being obscured by a talus, which is of such form as to suggest the presence of impervious Potomac clays, rising four or five feet above tide behind it. The constitution of the Quaternary loam, gravel, and sand is substantially identical with that of the same deposits in the Sand Point section, although the materials average somewhat coarser.

4. **Swan Point.** On the eastern side of a narrow promontory, 25 feet high, separating the estuary of Swan Creek from the bay, there is a fine section, perhaps 200 yards long. The uppermost member is loam, with disseminated flat pebbles and horizontally laid flat slabs, graduating downward into cross-stratified sand and gravel, both of which are practically identical in character with the corresponding divisions of the Sand Point section, save that the sand is somewhat coarser and more irregular in size and that the pebbles are not so well rounded. There is a marked accumulation of boulders and coarse pebbles at the base of the sand and gravel stratum. The loam is about seven and the sand ten feet in thickness. The basal member of the section is pink, cream-colored, and purple,
WHITE BLUFF.
massive, plastic clay, distantly jointed, and so tenacious as to break down in prismatic blocks, bounded by jointage planes, which become worn by the waves into pebbles and bowlders up to 18 inches in diameter. It is in all respects a typical exposure of the superior or clay division of the Potomac formation. Its summit rises eight or ten feet above tide, but gradually declines northward and disappears within a quarter of a mile, to reappear again at rare intervals along the west side of the bay. In this section, as in most of those about the head of Chesapeake Bay, the beach is encumbered with pebbles and bowlders derived from the Quaternary deposits, which form a trustworthy index to the character and relative abundance of the coarser materials of these beds, and which were therefore carefully noted. Here the littoral bowlders form perhaps two-thirds of a rank (or continuous line if the bowlders were placed side by side); 50 per cent. are angular, 35 per cent. subangular, and 15 per cent. rounded; in material perhaps 50 per cent. are quartzite, 25 per cent. gabbro, 10 per cent. granite, and the remaining 15 per cent. various; the largest is 1½ by 3½ by 4 feet. The pebbles do not differ materially in abundance or character from those of the Sand Point section.

27. Swan Doab.—At this point the nearly continuous precipitous bluff overlooking the head of the bay from the west is forty or forty-five feet high and exceptionally free from talus. The upper portion exhibits loam with disseminated pebbles and a few slabs, the whole perhaps 10 feet thick, graduating imperceptibly into cross-stratified sand and gravel, with large pebbles which frequently occur in definite layers. The bowlders and flat slabs occur at different horizons, but are most abundant about the junction of the loamy and gravelly members. The pebbles and bowlders along shore are somewhat less abundant than in the Swan Creek section (which is typical for this portion of the tract), but are larger, more sharply angular, and more frequently occur in heaps of angular fragments of identical rock, evidently formed by the breaking up of a large mass.

28. White Bluff.—The best section on the west side of the bay occurs at this point. It is represented in PI. LIX. The bluff is about thirty-five feet in height. The uppermost member is brownish loam identical with that of the neighboring sections, save that it is exceptionally fine, homogeneous, and free from pebbles, shading downward into gray and whitish, sandy loam, with micaceous scales which give that stratum a glistening, weathered surface. Below it is a band of dark-brown, sandy loam generally conspicuous by reason of its wetness, water trickling down from it over the lower part of the precipice when the earth is exceptionally wet. It contains a few disseminated pebbles. Next occurs a sharply defined bed of whitish loam, becoming hard and firm on exposure and in the vicinity weathering into miniature pinnacles and turrets whose apices mark exceptionally firm layers one or two inches in thickness, which are generally invisible in
fresh exposures. It contains a few disseminated pebbles, generally angular, and several lines of rounded pebbles, the whole forming 1 or 2 per cent. of its mass. It rests on a yellowish-brown, sandy loam, generally massive, but containing a few lines and pockets of coarse sand and pebbles, throughout which are scattered occasional rounded pebbles, with a few flat slabs and a bowlder or two. This becomes stratified below, the bedding planes being marked by lines of incipient cementation which project from the face of the cliff in narrow shelves; and here horizontally laid slabs of Triassic shale etc. become abundant, as also do the rounded and irregular pebbles and bowlders, which here constitute perhaps 10 per cent. of the mass. It graduates downward into a heterogeneous mixture of coarse loam, sand, gravel, etc., in which the bowlders are less abundant, but larger. At the base of this stratum is a rather friable, ferruginous sand in which pebbles and bowlders are accumulated. Locally this is stained black and cemented by the peculiar black, glossy, ferruginous cement characteristic of the Columbia gravels. Next occurs dense, tenacious, massive clay, mottled, purple, and cream-colored, with a few vertical jointage planes sometimes marked by ferruginous crusts. Its surface is irregularly eroded. With the recession of the cliff it breaks up into prismatic blocks one foot to three feet in diameter, which become worn into bowlders by the waves and are washed along the beach for hundreds of yards. It is unquestionably the upper division of the Potomac formation.

The littoral pebbles are sufficiently abundant to nearly pave the beach. Sixty per cent. of them are well rounded quartzite. One-third of a rank of bowlders occurs, of which 50 per cent. are angular or subangular granite, 25 per cent. angular or subangular gabbro, and the balance mainly rounded quartzite, the maximum dimensions being four feet.

29. Sand wharf.—Here the first and third members of the last section are well developed, but somewhat modified. The loam of No. 1 is only two feet thick, but massive, loess-like, compact, and practically destitute of pebbles, while its lower portion (which may correspond to No. 2 of the White Bluff section) is a bed of obscurely stratified molding sand, quite free from coarse material. No. 3 is six feet thick and exhibits a few horizontal lines of rounded pebbles and occasional sharp-edged, flat fragments, irregularly disseminated. The lower part of the bluff is talus-covered and there are but few bowlders on the beach.

In the face of this section the bedding is horizontal, but the strata dip westward 1:7 or 1:8. Whether this is due to original deposition or to subsequent dislocation was not determined.

30. Fishing station.—The upper portion of the talus-encumbered bluff at this point exposes five to eight feet of massive loam similar to that of the Sand Point section, graduating downward into sand,
generally cross-stratified, and both contain a few disseminated pebbles and bowlders.

31. Sand Point.—A precipitous bluff extends from Sand Point, perhaps a quarter of a mile to the east. It is frequently free from talus, and rises to a terrace plain thirty or thirty-five feet high, the terrace being only slightly undulating save along the margin overlooking Pond Creek on the west and a marsh on the east. The character of the Quaternary deposits here approaches that displayed at Wild Duck Bluff, represented in Pl. LXI.

The upper ten to fifteen feet of the precipice is loam, generally massive but sometimes obscurely stratified, particularly in its lower portion, the discriminable strata being either firm, white, glistening and pinnacly banded a foot or more in thickness or exceptionally sandy strata underlaid by unusually clayey layers and rendered visible by their wetness. The loam here, as in other sections on the west side of the bay, is, however, massive throughout the greater portion of its thickness and manifests a disposition to break up into prismatic blocks along vertical cleavage planes, and, where so thick that the massive portion is protected from superficial weathering by several feet of its upper portion, it exhibits incipient lithification, the uniformly disseminated cementing material being apparently calcareous. Very rarely there are found rather friable, calcareous incrustations similar to those which occur in loess associated with Loess-Kindchen and frequently the cleavage surfaces are thinly coated with a pulverulent, whitish crust of calcareous aspect. This loam graduates rapidly into stratified sand and gravel, coarsest above. Disseminated pebbles and flat slabs occur in the loam and culminate at its base. In the upper two-thirds of the loam they constitute not more than 1 per cent., and in the lower portion perhaps 2 to 3 per cent. of the mass.

The coarse sand and gravel forming the upper five feet of the cross-stratified member are quite coarse, many pebbles being two to ten inches in diameter. This member is sometimes loosely cemented, the cement being ferruginous, sometimes a red or brown oxide and again the glossy black oxide occurring in the Columbia gravels at Washington.

Below the gravelly stratum the materials become finer and more homogeneous and the mass becomes a bed of fairly uniform, stratified, coarse sand and gravel, with disseminated bowlders. This extends down to tide level.

The predominant material of the pebbles is quartzite, and 75 per cent. are rounded. Most of these quartzite pebbles were derived originally from the Appalachian terranes, but immediately from the Potomac formation.

The bowlders along shore are abundant—forming, perhaps, a rank and a half—and reach six feet in diameter. Gabbro predominates,
granite follows in order of abundance, then greenstone, schist, vein quartz with chloritic or micaceous intercalations, chloritic slate, quartzite, etc., and one semi-crystalline quartzite bowlder two and a half feet long containing abundant brachiopod impressions. Of these, the gabbro and the granite and part of the greenstone and schists are sublocal, but most of the remainder undoubtedly came from the Appalachians far to the northwest.

In this, as in neighboring sections, the horizontally laid, flat slabs constitute a conspicuous element in the mass, since they are moderately abundant and frequently project from the face of the cliff. They are generally sharply angular, but sometimes have their angles slightly worn. In size they vary from perhaps a quarter of an inch thick and three inches long to three or more inches in thickness and two or three feet in width and length. One of these slabs, of greenish-gray, hornblende schist, defined by cleavage and jointage planes, was about three-quarters of an inch thick, an inch wide at one end and two inches at the other, and about eighteen inches in length, its angles being quite unworn. The greater portion of the slabs are of upper Piedmont and Appalachian rocks, very few being of granite, gabbro, and other sublocal rocks. In this section the most abundant material is brown or reddish, arenaceous shale or sandstone unquestionably derived from the Triassic, and the same material is common in other sections. Next in order of abundance come various shales and shaly limestones, sometimes subcrystalline, but in general undoubtedly Paleozoic.

32. Spesutie Narrows. — This section also is a quarter of a mile or more in length, extending westward from near the head of Spesutie Narrows. It is a nearly continuous exposure of loam and gravel forming a gently undulating terrace some twenty-five feet in altitude, of which the upper ten feet consist of loam and the next five to fifteen feet of gravel, with a variable talus everywhere concealing the base of the cliff. The loam is fine, compact, generally homogeneous and massive, loess-like, and in general aspect identical with that of the last section. It contains sparsely disseminated pebbles and bowlders (which are generally flattened) in all parts of its thickness. Seventy-five per cent. of the larger fragments are flat slabs, three to eighteen inches in diameter, one-fourth inch to three inches in thickness, all lying with their largest planes horizontal. Most of these slabs are sharply angular, but a few are subangular. Occasionally angular or well rounded, small pebbles of various rocks also occur and nearly all of the smallest pebbles are well rounded and of quartzite. In places obscure stratification is exhibited by the loam, usually in the form of light-colored bands near its base, visible from a distance, but inconspicuous on close examination.

Below, the loam graduates imperceptibly into gravel and coarse loam and sand, an important element of which is well rounded peb-
bles two to eight inches in diameter (averaging smaller and generally more worn than in the Sand Point section); indeed, all of the pebbles and coarser grains in this gravel bed are well rounded. A subordinate element in the gravel bed is large boulders, reaching five feet in diameter, which are generally angular, sometimes subangular, and rarely rounded. The gravels are sometimes cemented or deeply stained by iron oxide, generally red, but sometimes the peculiar black, glossy, granular compound already noted as characteristic of the Columbia gravels.

The beach is paved with pebbles and boulders, the latter forming perhaps one rank and generally less angular than those of the last section. The pebbles in order of abundance are quartzite, quartz, more or less siliceous shale (probably from the Appalachians), greenstone, granite and gneiss, gabbro, and (rarely) limestone or calcareous shale; while the boulders in order of number are gabbro, granite, quartzite, with lenticular intercalation of chloritic slate etc., vein quartz, and chloritic and siliceous slates or schists. The flat slabs in the loam are sometimes quartzite, but generally arenaceous shale. One is a large segment (one-third) of a well worn, ellipsoidal quartzite pebble ten inches in greatest diameter, apparently cleft by impact. Some of the quartzite in pebbles and boulders is quite coarse, the grains averaging a quarter of an inch and reaching an inch in diameter.

33. Spesutie Island.—Towards its northwestern extremity the shore of Spesutie Island is a talus-burdened cliff six to ten feet high. The greater part of the exposure consists of loam identical with that of the preceding sections. At base this loam becomes sandy and gravelly, and sometimes exhibits stratification. The pebbles and boulders are less abundant than in the last section, and also smaller, more uniform in size, and better rounded.

34. Locust Point.—This northeastern angle of Spesutie Island rises ten to fifteen feet above tide in vertical cliffs, which are generally kept clear of talus by the waves. The cliffs are chiefly of loam, which is essentially identical in character with that of the last two sections, is five to eight feet in thickness, and contains slabs and disseminated pebbles, the whole graduating downward into sand and gravel. This gravelly bed, which sometimes rises five feet above tide, is somewhat finer than in the preceding sections, and boulders are much less abundant. One boulder, three feet in maximum diameter, of rather coarse-grained, white quartzite, exhibited peculiar slickensided planes of distinctive character whereby it might be traced to its original locus.

The eastern and southeastern shores of the island are low and seldom expose good sections; but the few seen maintain essentially the same character as those of the north shore.
35. Stump's Point.—The exposures here are imperfect, but distinctive. The whole bank (fifteen or eighteen feet high) is generally talus-obscured, but occasionally exposes loam resting upon coarse sand and gravel, while just above tide-level there occurs at one point jointed, ferruginous clay, sometimes purple or cream tinted, but generally rich dark red in color, at another a bed of white, laminated sand and quartzitic gravel two feet in thickness, and at still another a low bank of pink and white clay, with a few lines of white quartzite pebbles, all unquestionably Potomac. The shore is encumbered with piles of bowlders which, at least in large part, appear to be carried thither during spring freshets.

36. Poplar Point.—The rather obscure section exposed at this point in the talus-encumbered cliff, forty or forty-five feet high, is noteworthy chiefly by reason of the unconformity between the Quaternary gravel and the Potomac. Toward its eastern extremity a bed of white, cream-colored, and pink sand and clay characterized by softness and clearness of tints rises thirty or thirty-five feet above tide and is sharply distinct from a heterogeneous mass of gravel and loam, with flat slabs and bowlders, culminating at the base, while 200 yards west the Potomac is represented only by a firmly indurated, ferruginous sandstone exhibiting the tubular and corrugated character common in this vicinity, rising only five to ten feet above tide and overlaid immediately by five to ten feet of massive, sandy loam, containing a good many disseminated pebbles and angular blocks, which passes upward into cross-bedded gravel and coarse sand with abundant bowlders, the superior member of the Quaternary being locally absent. One-half of the littoral bowlders here are of local ferruginous sandstone, while the remainder (constituting, perhaps, a rank) are, in order of abundance, gabbro, quartzite, various hornblendic and chloritic schists, and vein quartz, both Piedmont and Appalachian. One subangular bowlder of quartzite was 4 by 6 by 7 feet in dimensions.

37. Wild Duck Bluff.—The very satisfactory section exposed here is represented in Pl. LXI. The upper portion is massive or obscurely bedded loam, more sandy than that on Sposutie Island and along the west shore of the bay, with occasionally flat slabs, while a few pebbles are disseminated throughout the member. It graduates rapidly downward into cross-stratified sand of variable coarseness, with a few scattered pebbles and occasional lines of gravel, rare scattered bowlders, and a small number of flat slabs lying horizontal. This in turn graduates into a stratified gravel bed with abundant bowlders, culminating below, the extreme base being a pavement of bowlders and coarse pebbles. Two-thirds of the larger pebbles and bowlders in this and the superjacent strata are well rounded, 25 per cent. are subangular, and the remainder are sharply angular. Associated with them, particularly toward the base of the lower
member, there are angular or rounded fragments of Potomac clay. Among the smaller pebbles quartzite predominates, followed by different varieties of gneiss, gabbro, quartz, ferruginous sandstone or pudding-stone derived from the Potomac etc., those of quartzite being generally rounded and those of other materials being angular or subangular. The basal member of this section is regularly stratified clay or fine sand containing abundant kaolinic particles, white, green, pink, purple, and mottled. In its bright and clear but soft colors it simulates the upper division of the Potomac, the iron-ore clays of Tyson; but in composition it approaches the Potomac sandstone as typically developed at the mouth of Aquia Creek and elsewhere on the Potomac River. It is partially lithified by ferruginous cement at the summit, and hence, and because the material resists erosion better than the Quaternary gravels, it forms a definite and continuous shelf in the face of the cliff fully a quarter of a mile in length.

38. Carpenter's Point. — At this point the Quaternary appears to be altogether absent or represented only by occasional boulders lying on the surface and along the shore; and the precipitous cliff 40 feet in height consists of massive sand belonging to the Potomac, generally purple in fresh exposures and weathering gray, but sometimes beautifully mottled in purple, pink, red, cream, snow-white, and a great variety of intermediate tints. The sand is frequently cemented by iron, forming a brown ironstone used locally as a building material. A number of boulders occur along the shore, having evidently reached that position through the recession of the cliff and the consequent undermining of the Quaternary boulders dotting the terrace out of which the point is carved. One of these is of gabbro, subangular and 4 by 6 by 8 feet in dimensions; two-thirds are quartzite, subangular or rounded; one is of Appalachian quartz, and the rest are gabbro and granite.

39. Seventy-sixth meridian. — This section is similar to the last, save that the Potomac sand is overlaid by five feet of massive or obscurely stratified, sandy loam with a few irregularly disseminated pebbles of quartzite, rarely more than one-half inch in diameter, together with a few small ironstone fragments.

40. Factory Point. — Here a partly artificial excavation exposes five to ten feet of loam and sand, generally irregularly stratified, but sometimes massive, containing gravel, sometimes accumulated in lines and pockets and most abundant toward the base, which forms perhaps 10 per cent. of the entire mass. The pebbles forming this gravel are well rounded, almost exclusively quartzite, and up to two and a half inches in diameter, though seldom above one and a half inches. Beneath occurs a massive, vari-colored, plastic clay, with some lines of gravel, the whole distinguishable only with difficulty.
from the superior member. In some portions of the section, indeed, it was found impossible to clearly discriminate the two divisions, the superior of which is unquestionably Quaternary, while the inferior is just as unquestionably Potomac; but in other portions of the section there is a distinct line of demarkation, sometimes emphasized by ferruginous accumulation.

41. Factory.—At this point the railroad cutting affords a section identical with the last in all features save that the Quaternary and the Potomac are everywhere readily distinguishable and that the phase of the latter exposed in the last section passes down into fine, white, cross-stratified, and delicately tinted sand.

The last two sections lie outside the limits of the Quaternary loam and gravel in their normal development and the superior gravel and sand are evidently in large part rearranged materials of the Potomac.

THE BORING WITHIN THE BAY.

42. Fishing Battery station.—The boring is 140 feet in depth. For the first 100 feet the materials penetrated were found to be fine sand, undistinguishable from the alluvial sand forming the bottom of the bay. At about this depth occasional layers of coarse sand and fine gravel (up to a quarter of an inch in maximum diameter) were encountered. At 112 feet the boring was checked, probably by either a bowlder or a ferruginous crust, and a few similar obstructions were met with at different greater depths. All of the materials brought up in the progress of the boring present the aspect of alluvium; no loam such as that of the upper member of the Quaternary, no coarse gravel such as forms its base, no large bowlders such as everywhere occur within the Quaternary here, and no trace of materials resembling those of the Potomac were anywhere found. Water rose in the boring nearly to tide level — about 5 feet below the surface of the artificial island on which Fishing Battery station is located. It is weakly saline and slightly charged with free carbonic acid. It appears unquestionable that the entire boring is in super-Quaternary alluvium.

EXPOSURES ON THE EAST SIDE OF THE BAY.

43. Hance’s Point.—The uppermost deposit exposed in the section at this point is obscurely bedded and massive, sandy loam and sand, with some disseminated quartzite pebbles, averaging five feet in thickness and passing rapidly downward into a pebble bed perhaps one foot thick. The pebbles seen in place are mainly quartzite and well rounded, seldom above two and never above six inches in diameter. A few littoral pebbles and small bowlders occur, the largest being of gabbro, angular, 1 by 1½ by 2½ feet in dimensions. Below the gravel there are 30 feet of variegated, massive, sandy clay, containing nodules and sheets of carbonate of iron, unquestionably Potomac.

This is the northernmost point at which normal Quaternary loam could be found along the bay shore.
44. **Roach's Point.**—A precipitous bluff here exposes three feet of pebbly and sandy loam reposing unconformably on 30 feet of distinctly stratified, white, cream-colored, and pink clays.

45. **White Point.**—This point receives its name from the white, cream-colored, or light-pink, plastic clay of which it is formed.

46. **Red Point.**—The salient to which this name is applied exposes a precipitous face of 50 feet, of which the upper third is white or light-colored and irregularly stratified Potomac clay, with many crusts of carbonate of iron, and at base an accumulation of corrugated sheets of ironstone embedded in vermilion-red clay, from which the point takes its name. This division is sharply distinguished by a ferruginous crust and sudden change in friability from subjacent massive, pink, purple, white, and variegated clays which extend to tide level.

Here and at White Point littoral bowlders are wanting and pebbles are quite rare.

47. **Rocky Point.**—The section at this point is eighty or one hundred feet high. At summit is a six-foot layer of loam etc., which appears to be a talus, the surface rising rapidly for twenty or thirty feet and then gently to the summit of Bull's Mountain. Below occur white and pink clays, with carbonate of iron and ironstone, and some sandy layers, the continuation of the Potomac clay of Maulden's Mountain. Very few pebbles and bowlders encumber the beach, though it is abundantly dotted with ironstone.

48. **Maulden's Mountain.**—Although its colloquial and cartographic designation is a misnomer, this eminence at once forms the most conspicuous topographic feature on the eastern shore of the bay and affords the most comprehensive geologic section in the entire tract examined. Its altitude, determined trigonometrically from Havre de Grace, is about two hundred and forty feet, and, although there is no single continuous section from base to summit, the exposures in a number of scars and those in the superb sea cliff at its base, combined, exhibit the succession of deposits from tide level to within ten or fifteen feet of its gently rounded apex. The general aspect of the eminence and its best exposures are represented in Pl. LXII.

The uppermost deposit is an irregular sheet of fine, massive, friable loam, with rare quartzitic pebbles up to two inches in diameter, most abundant at base and sometimes forming pockets in depressions of the subjacent surface, resting upon the unequal and gullied surface of the succeeding member. The maximum thickness observed was six feet of loam and five or six inches of gravel. This member is evidently the homologue of the Quaternary loam and gravel found elsewhere in the tract.

Beneath occurs a homogeneous bed of greensand, generally massive, but sometimes obscurely stratified, some fifty feet in thickness. This
graduates downward into stratified and slightly glauconitic sands, some fifteen feet in thickness, sometimes containing fine, quartzitic gravel and occasional ferruginous crusts, which in turn either repose conformably upon or pass rapidly into massive, sandy, and very slightly glauconitic, black or dark-gray, pyritous clay weathering gray. This stratum is 20 feet thick and is generally sharply demarked below by a structural line, though it more closely resembles the subjacent Potomac clays than the superjacent greensand.

Beneath the pyritous clay bed occurs a white and pink, plastic clay, massive throughout the upper 25 feet of its thickness, but somewhat variable in composition. Near its summit there is a laminated mass showing obscure impressions of irregularly branching, twig-like, endogenous stems, and in a number of places it is locally carbonaceous and ligniferous, and rarely contains pockets of quartzitic pebbles. Forty feet beneath the summit of this member it becomes sandy and contains great quantities of tubular and corrugated ironstone, in masses two to five feet thick, breaking off into fragments five to ten feet long with the recession of the cliff; 20 feet lower it exhibits at several points beautifully cross-stratified, pink, gray, and variegated sand, containing balls and distorted fragments of plastic clay; and toward the base of the cliff it again becomes a fine, plastic, massive clay, sometimes dark and carbonaceous, but elsewhere exhibiting all the hues of the rainbow. This succession is not, however, at all constant, but changes materially in every 100 yards of the half mile of continuous exposure along the base of the mountain.

Along the shore perhaps a half dozen quartzite and granite bowl ders occur, all well rounded and up to two feet in diameter. There are also a few pebbles, generally of quartzite.

49. First meridian.—The succession of deposits here is identical with that of Turkey Point and the deposits themselves retain the same characteristics; but the continuous section exposed in the precipitous face of a bluff half a mile or more in length and fully 75 feet in average height is noteworthy, in that it exhibits three characteristic types of unconformity between the Quaternary deposits and the subjacent Potomac clays, one of which was not observed elsewhere.

(1) Throughout the section the surface of the Potomac is generally undulating and locally ravined, rising to maximum altitudes of sixty or seventy feet above tide, and in the deepest ravines sinking beneath tide level; and, since the thickness of the Quaternary is moderately constant, the irregularities of the present surface coincide generally with those of the subjacent surface, and the new ravines frequently follow the old.

(2) A second type of unconformity is exhibited in Pl. LXIII, which apparently represents a section through a sea-cliff of Potomac clays formed during a definite stage in the advance of the Quaternary
waters, and exhibits the intermingling of local and erratic materials which occurred during the existence of the sea-cliff and ceased when the waters rose above its crest.

(3) The third (and unique) type of unconformity is illustrated in Pl. LXIV. The inequality of the junction plane here extends to and culminates in the inferior strata of the Quaternary; and, moreover, the projecting boss of obscurely laminated Potomac clay exhibits internal displacement, crumpling, and evident tumefaction, such as might have been occasioned by lateral compression from the direction of its steepest side. The condition of both deposits is such as to suggest that a low sea-cliff similar to that illustrated in Pl. LXIII was formed here and that while the intermingling of local and erratic debris was yet in progress an ice floe (similar to but probably larger than those occurring in the head of the bay every winter) was forced and held against it by the prevailing winds until at least partially melted.

50. Turkey Point.—The Quaternary is here greatly expanded and forms by far the most conspicuous portion of the exposure.

The section is one-half mile long and fully 100 feet in height and varies considerably in different portions; but where best exposed (e.g., in the portion of the cliff exhibited in Pl. LXV) the Quaternary consists of (1) massive loam five to ten feet in thickness, with flat pebbles and slabs disseminated throughout, but most abundant at base, graduating rapidly into (2) a stratified pebble bed five to fifteen feet thick, which in turn shades into (3) cross-stratified, coarse sand and gravel, with disseminated bowlders and pebbles sometimes reaching a thickness of sixty or seventy-five feet and at its base frequently (particularly in depressions of the subjacent surface) becoming a bowlder bed.

The loam is somewhat more sandy and very much more friable than its homologue on the west side of the bay, and the disseminated pebbles and bowlders are smaller, but the horizontally laid flat slabs are identical in character, equally sharp angled, and nearly equally abundant.

The pebble bed differs from that found at a corresponding horizon on the west side of the bay only in the better rounding of the pebbles and the greater rarity of angular and sublocal fragments. Fully 75 per cent, of the material is quartzite and perhaps one-half of the remainder is of other Appalachian rocks.

The sandy stratum is generally cross-bedded and occasionally contains pockets or lines of gravel sometimes a foot or two in thickness and 100 feet in length, as well as bowlders of all sizes up to five or six feet in diameter, in all portions of its thickness, but most abundantly below. It is sometimes cemented by iron oxides, particularly in the pebbly zones, in which sometimes the pebbles exhibit the glossy, jet-black coating characteristic of the Columbia gravels.
Littoral bowlders are so abundant as to quite pave the beach. They are generally angular or subangular and reach maximum dimensions of six or seven feet. Quartzite predominates, followed in order of abundance by gneiss, hornblende and other schists, gabbro, quartz, etc. There are also great quantities of local ferruginous sandstones derived from the Potomac.

Toward the base of the section the Potomac clays are nearly everywhere exposed, the summit being irregularly eroded and consequently rising to altitudes varying from one or two to forty or fifty feet above tide. At the eastern extremity of the section, where they are best exposed, these clays exhibit the usual variety of colors—pink, cream, purple, white, etc.—are massive and plastic, contain considerable quantities of carbonate of iron disseminated in plates and irregular masses, and form a vertical cliff 30 feet in height.

51. Wroth's Point.—The section exposed at this point is in a precipitous escarpment of a gently undulating terrace some thirty feet in altitude. It exhibits at the top a foot or two of sandy loam, passing into cross-stratified sand, with some quartzite gravel and occasional bowlders, also mainly of quartzite, all of which are rounded. The base of the cliff is generally talus-burdened, but occasional outcrops of white and pink, plastic clay, unquestionably Potomac, occur near tide-level. Very few pebbles and bowlders encumber the shore; both together would not pave one-tenth of the beach.

52. Grove Point.—Here again the Quaternary attains a notable development and the two distinct phases shown in the accompanying plates are exhibited. The superior member of the normal phase (seen only in the extreme left of Pl. LXVI and forming the base of the cliff illustrated in Pl. LXVII) is homogeneous loam, seldom more than five to ten feet in thickness, massive or obscurely stratified, but less clayey and more rapidly breaking down under exposure to the elements than that on the west side of the bay. It graduates imperceptibly into cross-stratified sand, with lines of pebbles and scattered bowlders, many of which are horizontally laid, and occasional flat slabs, all most abundant toward the summit of the member, where they sometimes form a definite pebble bed. The larger bowlders occur indiscriminately at all levels in this member, and the pebbly layers are equally inconstant in position, occurring sometimes at summit, again at base, and again at one or more horizons anywhere between the summit and the base, sometimes being entirely absent. Loamy strata are also intercalated in the sand at different horizons, but always in the upper half, while in its lower portion there are occasional bands of purple, pink, and white, plastic clay unquestionably derived from the Potomac. Sometimes this redeposited clay is only slightly intermixed with sand, which is distributed through it in single grains or in minute pockets containing a dozen or two grains or in larger masses, but more frequently the
clay and sand are approximately equal in amount and intermixed in considerable masses (say one-eighth to three-eighths of an inch in diameter), so that a section through the material in any direction exhibits a flecked or mottled aspect, exactly such an aspect as characterizes the Potomac sandstone in typical exposures. Again, the clay may occur either in rounded pebbles, generally an inch or more in diameter, or in small irregular or angular masses, sometimes distorted by compression. Toward the base of the Quaternary deposits the gravel is usually cemented along one, two, or more planes and forms firm, ferruginous crusts, often conglomeratic, projecting from the face of the cliff. Generally the heaviest of these crusts is either at or within a few inches of the base of the member. Its base conforms to an unequally eroded surface, and thus ranges from five to thirty or forty feet above tide.

The pebbles and bowlders constitute about 2 per cent, of the mass of the Quaternary and are sufficiently abundant along the beach to form perhaps two-thirds of a pavement. Three-fourths of the bowlders are quartzite; the most conspicuous one seen is gabbro, sharply angular, and 3 by 6 by 9 feet; the next in size is quartzite, 4 by 6 by 7 feet. Two-thirds of the bowlders are rounded. The pebbles do not differ materially from those of the last section, though they average smaller and are generally better rounded.

In the portion of the cliff shown in the right of Pi. LXVI the Quaternary deposits assume a distinctive aspect quite unlike the normal one exhibited in the greater number of sections described. The definite division into distinct beds of loam, gravel, cross-stratified sand, etc., disappears, the mass assumes uniformity in composition from base to summit, bowlders practically disappear and pebbles become rare, cross lamination and bedding become obscure (though certain partially lithified lines are prominent in weathered exposures), the entire mass assumes a dead, ashen-gray color (evidently due to the complete oxidation of the materials before or during deposition), and on exposure in cliffs the mass becomes eroded and weathered into a series of acute cusps or pinnacles, vertically scored and separated by deep, narrow gullies. This phase of the Quaternary is better exhibited at Ordinary Point, where, moreover, its relation to the terrace system is more clearly displayed.

The basal member of the section (to the left in Pi. LXVI) is black, massive or obscurely laminated, carbonaceous, plastic clay abounding in pyritous nodules, lignite, and indeterminate plant impressions. Traced northward this clay becomes lighter in color and within a mile gradually assumes the character of the plastic, variegated clay so well exposed at Maulden's Mountain and elsewhere. Occasionally it exhibits stratification, and at one point is cross-laminated, and the thin laminae of clay intercalated between layers of fine, white sand yield abundant leaf impressions, the only recognizable fossils found
in the tract studied. These leaf impressions have been examined
by Professors Newberry, Fontaine, and Ward, who pronounce most
if not all of them new species, but regard their general facies as dis-

tinct from those of the Raritan clays of New Jersey and those of
the sandstone member of the Potomac formation, but perhaps interme-
diate between them. None of the leaves has yet been identified spe-
cifically or even generically; but, with the exception of one or two
ferns and a single conifer, they are dicotyledonous.

Within this section the gradual transition of the Quaternary, in
passing from the central into the peripheral portions of the area of
deposition, is clearly exhibited. Toward the extremity of the promo-
ontory the Quaternary loam is sandy but massive and loess-like, the
pebble beds are well developed, the cross-stratified sand is coarse, the
bowlders are large, abundant, and sharply angular, and the basal
bowlder-beds are a prominent feature, while the beach is literally
paved with pebbles and bowlders derived from the formation; but in
passing from the bay proper into the Elk River estuary the entire
series attenuates, the loam becomes silty, the pebble beds become in-
conspicuous or disappear, the bowlders become progressively smaller,
rarer, and better rounded, and the basal gravel-bed is sometimes ab-
sent and inconspicuous when present, while the gravel-paved beach
becomes more and more and at last almost exclusively sandy.

53. Howell's Point.—The slower peripheral modification in the
direction of the greatest extension of the Quaternary deposit is dis-
played by this southernmost section of the series in conjunction with
those of Turkey Point and Grove Point.

The exposure here occurs in the precipitous and talus-free escarp-
ment of a terrace nearly one hundred feet in height, eaten into by
the waves generated not only in the head of the bay, but, under the
prevailing southwesterly winds, in the body of the same great estu-
ary.

Where the entire series of deposits is best developed, the upper-
most member is massive loam similar to that of Sand Point and
Spetsutie Narrows, but more distinctly stratified (especially toward
the base) and generally more sandy. It is seldom over ten feet thick.
As on the west side of the bay, this loam contains occasional flat
slabs of quartzite, Appalachian clay slates, and Triassic shale, as well
as a few of Piedmont gneiss and schist, all of which lie horizontal
or slightly tilted. Only two or three bowlders were seen in place,
one of which was very coarse quartzite, two or three feet in diameter.

The loam everywhere graduates into the subjacent gravel, some-
times rapidly, but sometimes quite imperceptibly. This gravel bed
is sometimes well developed, but is often insignificant, and in general
quite inconstant. Below, and never clearly demarked from the
gravel, occurs obscurely stratified and sometimes cross-bedded, sandy
loam, thirty or forty feet in thickness. In general it is massive
MAULDEN'S MOUNTAIN, FROM THE SOUTHWEST.
UNCONFORMITY BETWEEN COLUMBIA AND POTOMAC FORMATIONS.
UNCONFORMITY BETWEEN COLUMBIA AND POTOMAC FORMATIONS.
SOUTHEASTERN EXTREMITY OF GROVE POINT.
STEREOGRAM OF THE MIDDLE ATLANTIC SLOPE.

By W.J.McG. Geologist.

Horizontal Scale 1: 2,380,000 = 35 mi., 4 in.

Vertical Scale 1: 25 ft. = 35,000 ft. - 4 in.
toward the summit, where it consists of a homogeneous mixture of silt, coarse and fine sand, large pebbles, and rare bowlders, but occasionally it is stratified throughout, the planes being lines of pebbles and horizontally laid, flat slabs, or flat, rounded, ellipsoidal, and irregular masses of tenacious Potomac clay. The coarser pebbles and bowlders are most abundant toward the summit, where they are sometimes inseparable from the pebble bed proper, but the average size of pebbles and bowlders increases toward the base, where also the stratification is less distinct, but more prevalent. They are sometimes locally cemented by brown oxides of iron above, and at base there is a layer (sometimes double or triple) of firmly lithified, ferruginous pudding-stone.

Though derived from a deposit fifty or seventy-five feet thick, the littoral pebbles and bowlders do not form more than one-third or two-fifths of a pavement for the beach. Seventy-five per cent. of the pebbles are quartzite and well rounded, the remainder consisting of various Piedmont and Appalachian rocks, half of which are rounded or subangular. They are notably less abundant and better rounded than in the Grove Point section. The bowlders form perhaps one-third or one-half of a rank. They are, in order of abundance, quartzite, granite, gneiss, various greenstones, argillite (both Appalachian and Piedmont), and gabbro, with one of a peculiar clinking trap. The last (8 by 2 by $\frac{1}{2}$ feet) was the largest seen. The next largest was a subangular quartzite slab, 1 by 4 by 5 feet. The bowlders are notably better rounded, smaller, more largely quartzitic, and less abundant than in the last two sections.

Below the foregoing members, and everywhere sharply distinguishable therefrom, is a massive, obscurely bedded, greenish-black or dark-blue, tenacious clay, weathering whitish gray. It is generally carbonaceous and abounds in fragments and bands of lignite and partially lignitized wood, as well as in pyritous nodules, and sulphuret of iron appears to be disseminated in amorphous condition, since the entire mass effloresces with sulphurous odor and the water of springs flowing from the surface of the clay has a sulphurous taste. Sometimes the clay is massive, elsewhere uniformly stratified, and again obscurely laminated. Throughout the greater part of the mile-long section the surface of the clay is uniform and coincides closely with the lamination; but at the extreme eastern end the distinctly stratified layers are sharply cut off by a Pre-Quaternary ravine and the clays disappear below tide level. This unconformity and the local structure are exhibited in Pl. LXIX. The inferior formation is unquestionably identical with that of Grove Point, and hence represents the upper division of the Potomac.

**EXPOSURES ALONG ELK RIVER.**

In ascending Elk River the Quaternary deposits become less and less conspicuous, particularly on the eastern shore, partly by reason
of their progressive attenuation and partly by reason of the imperfection of the exposures; for, instead of precipitous bluffs such as commonly form the shores of the bay, there are here only talus-burdened slopes, save at the extremities of a half dozen of the most prominent salients. The Quaternary does not, however, attenuate uniformly, as the following sections, each representative of its latitude, indicate.

54. Tackara's Point.—The precipitous cliff at this point ranges from twenty-five to forty feet in height and exposes Quaternary deposits reposing on the Potomac. The Quaternary maintains the general character exhibited at Turkey Point, but is greatly attenuated. It comprises (1) two to five feet of loam, graduating rapidly into (2) an obscurely stratified pebble-bed, one to three feet thick, containing a few flat and sharply angular slabs, which in turn passes into (3) three to five feet of cross-stratified sand, with disseminated pebbles and bowlders; at base this division merges into (4) two or three feet of coarse sand and gravel, with abundant pebbles reaching 14 inches in maximum diameter, the largest of which is a slightly rounded mass of corrugated ironstone such as occurs within the Potomac in the immediate vicinity. The pebbles and bowlders exposed in the section are predominantly quartzite.

The beach pebbles form a quarter of a pavement; 50 per cent. of them are well rounded, 30 per cent. are mere worn, ferruginous fragments of local origin, while the remainder, of which perhaps half are well rounded, are of various materials and conditions of abrasion. There are two-thirds of a rank of bowlders, all either well rounded or subangular; 50 per cent. are quartzite, 25 per cent. greenstone, 10 per cent. vein quartz or chloritic schist intersected by vein quartz, and the remainder various. This enumeration does not include the bowlders of local ironstone, which are as abundant as those of all other materials combined.

The basal brown sand and gravels of the Quaternary rest on obliquely laminated, buff or dirty yellow sand, containing abundant glistening scales of mica and many ferruginous bands, as well as occasional enormous ferruginous nodules filled with white, sandy clay. Although undistinguishable from the Quaternary at a distance, this sand is found on close examination to exhibit a definiteness and a constancy of structure never observed in the Quaternary; the contained ferruginous matter is unlike that of the Quaternary, but identical with that of the Potomac; while in the northern part of the section it is replaced by delicately tinted clays; and accordingly it is unquestionably Potomac.

55. Elk Bluff.—The finest exposure on the lower Elk River occurs here in a bluff 75 feet high, of which the lower 45 feet consists of white, pink, mottled, and sometimes beautifully banded clays of the Potomac formation, unconformably overlaid by 35 feet of Quaternary
deposits, which here reach exceptional thickness for this portion of the tract.

The superior member of the Quaternary is five feet thick and consists of coarse, sandy, and somewhat gravelly loam, with a few disseminated pebbles of well-rounded quartzite and occasional sharply angular, flat slabs, most of which are Triassic shale. Below, it becomes gravelly and passes into 20 feet of stratified and cross-bedded, coarse sand and fine gravel, constituting the coarsest medial division of the Quaternary seen about the head of the bay. The entire division is highly ferruginated and there are a number of prominent jet-black bands stained by the glossy, ferruginous cement observed in other sections. Many of the pebbles and bowlders, particularly of greenstone and granite, but sometimes even of quartzite, are completely disintegrated.

A third of a pavement of beach pebbles, predominantly quartzite and generally well rounded, occurs, as well as one-half a rank of subangular or rounded beach bowlders, up to three feet in diameter, mainly of quartzite.

Although no angular bowlders and few sharply angular pebbles were observed here, while both were observed at Grove Point and Howell's Point, the proportion of subangular pebbles and bowlders is larger and the assemblage of coarse materials presents a notably less worn aspect than at these points.

56. Corn Landing.—In the precipitous bluff, ranging from thirty to fifty feet in height, just below the landing, the Quaternary is six to ten feet thick, loamy and homogeneous above, but quickly passing into a bed of current-bedded, coarse sand and loam, with abundant pebbles and occasional bowlders. The pebbles are noticeably more heterogeneous in size, material, and form than at Howell's Point or even in other sections on Elk River. Perhaps 50 per cent are quartzite, 20 per cent consist of a great variety of Piedmont rocks, and another 20 per cent appear to represent various Appalachian rocks, while the remainder are Triassic shale, sandstone, or trap, or are indeterminable. Not more than 50 per cent of the pebbles are rounded (and these are mainly quartzite), 25 or 30 per cent are subangular, and the remainder are either sharply angular or almost imperceptibly worn.

Perhaps an eighth of a rank of rounded or subangular bowlders occur on the beach, 75 per cent of them are quartzite and the remainder are mainly of greenstone, with a few of granite and one of gabbro. The gabbro bowlder is about six cubic feet and two of the quartzite bowlders are each about ten cubic feet in dimension. The beach is only sparsely dotted with pebbles.

Below the Quaternary occur sometimes laminated, buff sands like those of Tackara's Point, and again the characteristic pink, white, and purple clays of the Potomac.
57. Betterton's Landing.—The intermingling of local debris derived from immediately subjacent formations, which to a variable extent characterizes the Quaternary deposits throughout the tract examined, culminates at this point, and in consequence it was found impossible to certainly discriminate the formations exposed in the thirty-five or forty foot cliff. The greater part of the section is made up of irregularly stratified sand, with rare bowlders and pebbles, in most respects simulating the medial member of the Howell's Point section, but containing more abundant and heavier intercalations of Potomac clay, and also perceptibly glauconitic throughout. The surface of the subjacent carbonaceous Potomac clay is irregularly gullied; sometimes it disappears beneath and again rises fifteen or twenty feet above tide; and at one point it contains a great mass of ferruginous sandstone in hollow cylinders and corrugated plates.

58. Lloyd's Creek.—Here also there is notable intermingling of immediately derived and remotely derived debris in a bed twenty or twenty-five feet thick, which forms the greater part of the exposure. At the summit of this bed, but not sharply demarked from it, occur quartzitic gravel and stratified sand with a few disseminated bowlders and flat slabs and a dozen quite large quartzite bowlders; while perhaps one-tenth of a pavement of pebbles, evidently derived from this horizon, encumbers the beach. Beneath the bed there is the usual carbonaceous Potomac clay, rising five to fifteen feet above tide.

59. Concretion Reach.—A precipitous bluff, rising to the general level of the plain south of the Sassafras River and overlooking this reach, evidently affords a typical section of the Potomac as developed in this part of the tract.

As usual in good sections, the superior member of the Quaternary is loam, here ten or fifteen feet thick, massive and homogeneous, but more friable than on the west side of the bay, and containing an unimportant element of greensand. Below it contains a few flat slabs, horizontal or slightly tilted, and at the base it graduates rapidly into a bed of gravel and coarse sand five to eight feet thick, the gravel being most abundant above and sometimes becoming concentrated into a definite pebble bed. A few bowlders are disseminated throughout the gravel and sand, but the littoral bowlders derived from this horizon form only one-fifteenth or one-twentieth of a rank, and reach maximum dimensions of about four feet. They are nearly all rounded or subangular and the majority consist of quartzite. Pebbles from the same horizon sparsely dot the beach; 70 per cent. are of quartzite and quartz, well rounded; the remainder are various. The base of the Quaternary undulates and is generally marked by ferruginous crusts and a conspicuous concentration of bowlders and pebbles.
SECTION AT HOWELL'S POINT.
GENERAL SECTION AT ORDINARY POINT.
UPPER TERRACE AT ORDINARY POINT.
Beneath the Quaternary is a bed of massive, homogeneous greensand, rising thirty or forty feet above tide. Above, this greensand is ferruginous, the iron segregating on weathering into irregular, bubble-like crusts, which give a coarsely vesicular appearance to the mass; but below it becomes finer, more clayey, and less glauconitic than toward the summit and abounds in concretions of fantastic shapes, reaching six or eight feet in length and two feet in diameter and sometimes half a ton in weight.

60. Burley's Creek.—The Quaternary is not well exposed here, but rounded pebbles and bowlders, evidently derived from it, besprinkle the beach and form perhaps one-tenth of a pavement. Almost the entire bluff is made up of homogeneous greensand, in which, as at Concretion Reach, the glauconite is less abundant below; but at its base there is a peculiar, jet-black, plastic material, assuming on the beach a smooth, lustrous surface, which wrinkles and takes impressions like heated asphalt, unquestionably representing the summit of the Potomac.

61. Greensand Reach.—Here again the Quaternary is typically exposed and consists of five or six feet of loam reposing upon a bed of sand and gravel five to eight feet thick. The loam is practically destitute of pebbles and flat slabs, and the inferior member (in which the gravel is generally quartzitic) contains few bowlders, which are most abundant toward its summit. The base of the Quaternary is usually marked by a ferruginous crust.

The littoral bowlders are notably smaller and less abundant than in the sections to the north, nearly all are quartzite, with half a dozen of granite, one or two of gabbro, one of micaceous greenstone, one of vein quartz, etc.; the largest (of subangular quartzite) is 1 by 1½ by 4 feet and the maximum dimensions of the others do not exceed two and one-half feet. The pebbles are nearly all quartzite and quite well rounded.

Below occurs normal greensand, rising forty or forty-five feet above water level.

62. Ordinary Point.—The section at this point is especially instructive, since it exposes the structure of three terraces, as shown in Pl. LXX.

The northwestern part of the section intersects the uppermost terrace and appears to afford a typical exposure of the Quaternary for this part of the tract. It is represented in Pl. LXXI. The superior member is loam, similar to that in the last two sections, with a few disseminated fragments. It is three to six feet thick, and either graduates rapidly into or reposes conformably upon the upper

1 It should be pointed out that Pls. LIX, LXI to LXV, LXVI and LXXI do not exhibit the minute structural details described in the text as satisfactorily as do the photographs from which they were reproduced.
pebble bed. This bed generally graduates imperceptibly into the body of the medial member, which is ten or twelve feet thick and, as usual, consists of gravel and sand irregularly stratified and sometimes cross-bedded; but elsewhere (as shown in Pl. LXXI) the transition from pebble-bed to cross-stratified sand is abrupt. The pebbly layer is made up mainly of pebbles one to three inches in diameter, with occasional horizontally laid, flat slabs and a good many bowlders, this being the principal bowlder horizon. The member is most homogeneous immediately below this horizon, where also it is more irregularly and less conspicuously stratified and more uniform in size of materials than either above or below—the mass becoming a nearly homogeneous mixture of loam, coarse sand, and fine gravel, with a few noticeable lines of sand and loam; and, although no exposures of the Potomac clay occur within five miles, a distinct band of closely jointed clay, 150 feet long, is found (seen opposite the shoulder of the figure in the plate), which is unquestionably derived from the Potomac. Toward the base of the member the pebbles increase in abundance and occasional bowlders occur, both being sometimes cemented into a ferruginous sandstone or pudding-stone. The most conspicuous ferruginous crust, however, occurs in the subjacent greensand two feet below its summit (at the feet of the figure in the right background). This greensand, which is in no respect specially noteworthy, descends to tide level forty or fifty feet below.

In the medial terrace the succession, as shown in Pl. LXX, is somewhat different, the loam disappearing or shading into the subjacent division, which thickens greatly, loses its definite stratification, and assumes the heterogeneous character of a subaqueous talus, containing a considerable element of greensand and other local débris and consisting in part (perhaps 20 per cent. of its mass) of impalpable silt, in which the coarser materials are embedded.

In the lowest terrace the superior deposit, which is stratigraphically continuous with the normal Quaternary loam of the highest terrace through an attenuated talus constituting the soil and subsoil of the medial terrace, though manifestly much more recent in origin, is ten or fifteen feet thick, and consists of sand or loam intermixed with impalpable silt or mud, the whole weathering into pinnacles and turrets with glistening surfaces, exactly as do the Quaternary deposits at low levels on the lower Potomac and James Rivers, and, in brief, assuming a characteristic and widely distributed phase, which may be designated the “low-level phase” of the Quaternary loam of the Atlantic slope. This phase is exhibited elsewhere in the tract—e. g., in the eastern extremity of the Grove Point section, about the mouths of the smaller streams and in the lowest terraces generally—but nowhere else can its relation to the prevalent superficial deposits be so readily ascertained. Below it passes gradually or by intercalation into a pebble bed corresponding to the inferior member of the
normal section, which also contains a sufficient element of silt to form a matrix for the pebbles.

The pebbles and bowlders (which do not exceed two and one-half feet in diameter) are mainly of well rounded quartzite and are more abundant than in any of the last three sections, forming perhaps one-third of a pavement along the beach. Over 75 per cent. of the pebbles are less than one inch in diameter.

63. *Turner’s Creek.*—Here again the Quaternary appears to be typically exposed toward the summit of a precipice 35 feet high, of which the greater part consists of normal greensand. The superior member consists of massive, friable loam, with a line of gravel (mainly well rounded, white quartzite pebbles), perhaps one foot thick, at its base. Half a dozen small and well rounded bowlders, together with a few pebbles, lie along the shore. They are chiefly of quartzite, and none exceeds 18 inches in diameter.

64. *Back Creek.*—The bluff just below the mouth of this creek is 25 feet high and exposes only normal greensand, except at the extreme summit, where there are obscure beds of loam, gravelly below. No bowlders occur along shore and there are very few pebbles as large as an inch in diameter.

65. *Back Creek Neck.*—A precipitous bluff about forty feet in height at this point apparently affords a typical section for this part of the region. The uppermost stratum is loam, homogeneous, massive, fine, compact, clayey but friable, and five to eight feet in thickness. Below, it graduates rapidly into a gravel bed two to three feet thick, which is also massive and homogeneous. It comprises some 50 per cent. of loam similar to that above, perhaps 30 per cent. of sand of various degrees of coarseness, and the remaining 20 per cent. of the mass consists of well rounded quartzite pebbles one-fourth of an inch to one and one-half inches in diameter. At its base there is a discontinuous, vesicular, ferruginous crust, from half an inch to three inches in thickness, inclosing the largest of the pebbles. A few pebbles dot the beach and a dozen well rounded quartzite bowlders up to 15 inches in maximum dimensions were observed along a quarter mile of shore. Thirty feet of greensand, identical with that of neighboring sections, occur beneath the gravel.

**IV. THE FORMATIONS.**

**ALLUVIUM.**

The entire tract is notably free from subaerial alluvium, for the streams northwest of the fall-line have high declivity and have cleanly swept their channels, while those on the southeast have deposited their detritus either in their own ever-widening estuaries or in the bay. Even the marshes are frequently almost destitute of alluvial accumulations. Indeed many of them owe their existence to
depression and partial submergence of an unequally eroded surface, of which the configuration was determined, in part, by the estuarine currents of an earlier epoch during which the oceanic waters encroached upon and overspread the area.

The subaqueous alluvium appears to be commensurate in extent with the bay and the confluent estuaries. There is no means of determining its thickness save that afforded by the boring at Fishing Battery station, which extends 140 feet into the alluvial sands, with no indication of reaching their base. This whole thickness (and perhaps as much more) appears to represent the super-Quaternary deposits of the Susquehanna and its affluents.

THE COLUMBIA FORMATION.

STRUCTURE AND COMPOSITION.

Although its members are bound together by partial identity in composition, by conformity, and in many cases by intergradation, the Quaternary deposits about the head of Chesapeake Bay are, nevertheless, separable at a glance into two divisions whose differences are more striking than their resemblances. The sections exposed on Speasntie Island and the adjacent mainland, on the opposite side of the bay, and generally toward the center of the area of deposition, exhibit the succession shown in the accompanying generalized section (Fig. 110).

Described in detail the succession is about as follows:

(1) Soil and subsoil, sometimes overlaid by and intermixed with aeolian and littoral sands and the superficial wash of rivulets and rills, one foot to two feet thick.

(2) Loam or brick clay, either massive or obscurely stratified, brown, gray, buff, or yellowish brown in color, somewhat calcareous, and, where typically developed, slightly cemented probably by carbonate of lime, and thus remarkably loess-like in appearance; jointed, the jointing being such as to separate the mass into polygonal fragments one-fourth of an inch to two inches in diameter toward the surface, but sometimes one, two, or three feet in diameter.
below the reach of superficial oxidation and decomposition; with well worn pebbles, horizontally laid, flat slabs, and rounded bowlders fortuitously disseminated, but most abundant toward the base, which combined form perhaps 2 or 3 per cent. of the entire mass. The pebbles are predominantly well rounded and from a small fraction of an inch to two inches in diameter, but a considerable proportion are subangular and nearly as many are sharply angular. Fifty per cent. or more are South Mountain quartzite, fully 25 per cent. are of shale, sandstone, etc., identical with those of the Paleozoic formations of the Susquehanna Valley above South Mountain; while the remainder, including a notable element of generally angular Triassic fragments, are Piedmont; and it is commonly the farthest-traveled pebbles that are best rounded, though sharply angular fragments of quartzite and the transmontane rocks occasionally occur. The flat slabs vary in thickness from one-fourth of an inch to three inches, and in length and width from two or three inches to as many feet; some are quartzite and a few are of hornblendic and micaceous Piedmont schists; but at least 50 per cent. are either (1) calcareous or arenaceous shales, such as form an important part of the Paleozoic series of Pennsylvania, or (2) red and brown shale and micaceous sandstone identical with those of the Triassic. Nearly all of these slabs are sharply angular, although many of them are quite friable. The bowlders are of similar rocks, though the proportion of Triassic material is decidedly less; and they, too, are generally sharply angular. The loam in which the coarser materials are embedded consists in part of finely comminuted clayey particles, in part of just palpable grit, and in part of sand grains varying in dimensions from the limit of visibility to a considerable fraction of an inch in diameter; and in some sections these elements approach equality in volume. The sand grains large enough for examination with the naked eye are in large part sharply angular, but many are rounded. They consist of a variety of materials, quartz being predominant. The thickness of the member averages perhaps ten or twelve feet.

In composition, structure, and general appearance, the loam approximates that forming the summit of the Quaternary deposits at the embouchures of the Patuxent, Potomac, Rappahannock, James, and Appomattox Rivers upon the Coastal plain; but it differs therefrom in the direction of greater heterogeneity—i.e., it contains a greater proportion of impalpably fine material and of the disseminated calcareous matter to which the incipient lithification is apparently due, as well as a greater number of far-travelled pebbles and angular bowlders of considerable dimensions; and it differs in the same direction, and still more widely, from the fine, homogeneous, and regularly stratified “Albany clays” where typically developed along the Hudson River and about Lake Champlain.
(3) Beneath the loam and either (1) sharply distinct from, though conformable to it, or (2) graduating into it, sometimes imperceptibly and again by interstratification, there generally occurs a gravel bed of perhaps 50 per cent. of pebbles from one to twelve inches in diameter, usually well rounded, about 30 per cent. of smaller pebbles, also rounded, some 5 per cent. of bowlders, and the remainder of commingled sand and loam similar to that forming the superjacent member of the section. Where coarsest, this pebble bed exhibits no definite structure; but, where the materials are finer, it is more or less distinctly bedded and sometimes cross-stratified. Its pebbles and bowlders are like those of the fourth and fifth members, from which, indeed, it is frequently inseparable. It is somewhat ferruginous, and its materials are sometimes cemented either by the ordinary ferric oxide or by a peculiar glossy, jet-black oxide, probably ferrous, at least in part. When clearly defined, the member ranges in thickness from one or two to ten or twelve feet.

(4) The pebble bed generally graduates imperceptibly into a mass of brown, buff, or yellowish sand and loam, containing many pebbles and bowlders, either irregularly disseminated or accumulated in layers and pockets. The finer materials appear to be identical with those forming the second member of the series, save that impalpable matter is rare or altogether absent and that a notable element consists of balls and patches of either plastic clay or kaolinic sand, evidently derived from the Potomac formation. The coarser element consists (1) predominantly of well rounded pebbles, similar to those of the third and fifth members, which are sometimes so abundant as to constitute 20 or 30 per cent., though they generally do not exceed 5 or 10 per cent. of the mass, and (2) subordinately of angular pebbles, flat slabs, and bowlders, also similar to those of the contiguous members. The pebbles are generally accumulated in layers, but are sometimes fortuitously distributed throughout the division, as the bowlders and flat slabs generally are. The member is prevalently stratified, sometimes regularly, but more commonly quite irregularly, many of the layers being lenticular or otherwise discontinuous. Cross-stratification is also prevalent and characteristic; indeed, few finer examples of cross-stratification occur in the Trias of either the east or the west, in the Jurassic and Cretaceous of the western plateau region, or in the deltas and current-deposited loams of the old Lakes Lahontan and Bonneville than in some of the exposures of this member on the east side of the bay. Ferruginous cementation and staining occasionally occur at different horizons, generally in the pebble beds. The observed thickness of this member ranges from almost nothing in the westernmost outcrops to fully one hundred feet in Turkey Point, where it is the most conspicuous member of the formation.

(5) At its base the cross-stratified sand either graduates into or rests upon a bed of gravel, generally thinner and of finer materials
than the third member of the series, but abounding in angular bowlders. The matrix enclosing the coarser matter is sand and loam, undistinguishable from that of the fourth member, and where the deposit is finest it exhibits like structure. It is occasionally stained and cemented by ferric and ferrous oxides, and locally becomes a ferruginous pudding-stone or sandstone. Its maximum thickness is perhaps ten feet, though it is seldom over five.

The lower three members of the section vary materially in different parts of the tract; they sometimes become united in a single mass, largely made up of bowlders and other coarse materials, as toward the mouth of the Susquehanna; elsewhere the coarse upper and lower members become finer, and eventually undistinguishable from the intercalated member, particularly toward the southeast, where the entire division attenuates, and thus in another way becomes indivisible. By reason of this local variability in composition, it is impossible to estimate the proportion of the different materials of which each individual member is made up in the general section or otherwise to compare them accurately in general terms.

In the constant inferior division of the Quaternary which the three members form when combined and in the central part of the area occupied by it, bowlders of a foot or more in diameter constitute probably something less than 5 per cent. of the volume; pebbles from an inch to a foot in diameter form perhaps 10 or 15 per cent.; gravel, comprising pebbles from one-tenth of an inch to an inch in diameter, forms some 15 per cent.; impalpable particles form perhaps 15 per cent., and the remainder consists of loamy particles and fine and coarse sand.

Counting as bowlders all masses over a foot in diameter, perhaps 50 per cent. are either sharply angular or have their angles only slightly worn, 25 per cent. are such as are ordinarily styled sub-angular, while the remainder are well rounded. Classified with respect to materials, some 50 per cent. of the bowlders are of granite, gabbro, and various local or sublocal schists, and represent the Piedmont formations; perhaps 20 per cent. are of chloritic and related schists and slates, argillite, vein quartz containing chloritic and other schists in its interstices, and various sandstones and shales, ranging in texture from subcrystalline to friable, including a few of Triassic traps, etc., all similar to those of the western part of the Piedmont region and contiguous portions of the Appalachian zone; while the remaining 30 per cent. consist mainly of quartzite and subcrystalline sandstone, firm, arenaceous shales, etc., similar to those of the Appalachian Paleozoic formations. The local and sublocal bowlders are mainly angular or slightly worn; the upper Piedmont representatives are generally small and well rounded, though a considerable portion are subangular and a smaller fraction (particularly among those in the summital and the
basal portions of the division) are sharply angular, while 90 per cent. or more of the quartzite and other Appalachian fragments are well rounded; and most of the remainder are sharply angular, flat slabs similar to those of the upper division.

Of the pebbles from one inch to a foot in diameter, fully 75 per cent. are of quartzite or of worn and weathered quartz so similar to the quartzite in aspect as not to be discriminated without careful examination, and at least five-sixths of these are well rounded. The remaining pebbles are about equally divided between sublocal rocks and materials evidently brought from the upper Piedmont and Appalachian regions; about one-half are sharply angular, at least one-third are subangular, and the remainder are well rounded.

The gravel does not differ materially in character from the larger pebbles, save that a somewhat greater proportion consist of quartzite and are well rounded. Although it is evident that the primary source of the quartzite forming the gravel and larger pebbles was the quartzite formations of the eastern Appalachians, the disproportionate abundance of these pebbles, their uniformity in dimensions, their identity in size, form, and mineral character with those of the Potomac, their associations with pebbles of Potomac clays, and the occasional occurrence of unmistakable Potomac arkose in connection with them, all combine to prove that this conspicuous element in the Quaternary series was derived immediately from the subjacent Potomac beds.

Neither the sand grains and loam nor the flat slabs which are everywhere a conspicuous element of the lower members of the Quaternary deposits in the region, differ materially from those of the second member of the series.

Members 1 and 2 as thus described constitute the superior division and numbers 3, 4, and 5 the inferior division of the Chesapeake Bay Quaternary. In brief, the superior division consists of loam and rock-flour apparently of remote derivation, with both well rounded and sharply angular, far-traveled erratics sparsely disseminated, while the inferior division consists of gravel and sand, in large part at least of local derivation, with some far-traveled, angular and rounded, but many more local, angular boulders, and an important element of pebbles derived originally from a distant but immediately from an adjacent formation.

DISTRIBUTION AND LOCAL VARIATION.

The land area occupied by the Quaternary in the tract examined and its relative coarseness and thickness in the different portions of its extent are exhibited on the accompanying map forming Pl. LVIII, in which relative coarseness is indicated by size and relative thickness by closeness of the figures; but the composition of the deposit is even more variable than either thickness or coarseness.
At many points along the margin of the Coastal plain, particularly about the mouth of the Susquehanna River, the deposit comprises only two sharply distinct members, the upper consisting of loam or brick clay of such homogeneity that it is employed for the manufacture of brick, although unusually abundant and large bowlders are irregularly distributed throughout it, and the lower consisting of angular local or sublocal blocks embedded in a scanty matrix of coarse sand and gravel predominantly of local origin; while elsewhere in the same vicinity, particularly along the line of the Pennsylvania Railway, north of the river, the formation consists mainly of sandy loam passing downward into not strikingly different loamy sand, sometimes cross-stratified, containing occasional disseminated pebbles and bowlders (generally local, but sometimes erratic), and resting on the crystalline rocks, either with or without an intercalated bowlder bed; and in some other localities among the steep slopes of the Piedmont margin, as at the Havre de Grace reservoir, only a semi-erratic bowlder bed is exposed, the loam having been degraded if it was ever deposited. A few miles southeastward from the fall-line, however, the deposits thicken and gradually assume the character represented in the general section (see Fig. 110).

Toward the northeastern angle of the head of the bay and along Northeast River the formation attenuates and becomes practically imembral, and a considerable if not a predominant part of it consists of local débris: e.g., in the sections observed at the factory near the town of Northeast, where 50 per cent, or more of the materials of the formation are evidently derived from the immediately subjacent Potomac formation.

On the east side of the bay, the deposits again gradually thicken from north to south, but do not assume typical character nor even definite bipartition north of Maulden's Mountain; while over this eminence there is almost no representation of any portion of the formation save the superior loam, and even that is greatly attenuated. The formation attains its maximum observed thickness and in other respects a typical development, however, immediately south of Maulden's Mountain, at Turkey Point and Grove Point, and elsewhere about the mouth of Elk River.

On Elk River, as on the Northeast River, the deposits attenuate and contain an increasing proportion of local débris upstream, but neither modification is progressively uniform; the attenuation is rapid from Turkey Point to a line somewhat above Tackara's Point lying in the lee of Maulden's Mountain; local thickening occurs in the lee of the saddle between that eminence and Bull's Mountain, as exemplified at Elk Bluff; attenuation again becomes rapid for two or three miles; while above Corn Landing the deposits become gradually less and less conspicuous, and the proportion of local material (which includes a considerable element of greensand) in the formation varies
inversely with its thickness. Everywhere above the latitude of Maulden's Mountain the quinquemembral structure becomes inconspicuous, and even the characteristic bipartition of the formation is indefinite at and above Corn Landing.

Along Sassafras River the formation, which is well developed at the embouchure, retains its thickness and normal character only as far east as the mouth of Lloyd's Creek, when it suddenly and rapidly attenuates and becomes inconspicuous in the banks of the upper portion of the estuary, the superior division being reduced to five or six feet in thickness, and the inferior to an inconspicuous and discontinuous pebble bed, as at Back Creek Neck, while beyond both divisions appear to attenuate still further and either die out or merge into the there inconspicuous littoral phase of the formation—the “Estuary sands” of Chester.

Descending the bay, which approximately coincides in direction with the major axis of the formation, the thickness of the upper division diminishes slightly if at all, but the clayey or loamy gives way to a sandy aspect and the mass becomes friable; for, although the included sand becomes progressively finer, the proportion of impalpable powder, upon which the consistency depends, constantly diminishes. At the same time the lower division attenuates, its materials become finer, and eventually it becomes inseparable from the loam.

Throughout the tract the proportion of angular pebbles and bowlders is directly and the degree of rounding of these constituents is inversely related to thickness of deposit. About Havre de Grace and the mouth of the Susquehanna generally, the bowlders are almost exclusively and the pebbles are predominantly angular; beyond the mouths of Swan and Principio Creeks an important share of the bowlders exposed in every section are worn, while the pebbles are predominantly rounded and subangular; on Northeast and Elk Rivers angular bowlders and pebbles are exceptional; on Sassafras River they are rare and above the locus of most rapid attenuation frequently absent, while both pebbles and bowlders are thoroughly worn; and in the heavy deposits of Howell's Point there are only sparsely scattered angular fragments distributed among abundant well worn pebbles and bowlders. It is noteworthy, too, that near the mouth of the Susquehanna, and along the fall-line generally, the coarser débris consists of materials of various degrees of obduracy indiscriminately intermingled, while on the opposite side of the tract only obdurate materials—predominantly quartzite—occur at all frequently.

In short, the coarser materials which form so conspicuous a feature of the formation in its central portion diminish in abundance in all directions from the mouth of the Susquehanna, and the proportion of angular fragments and the angularity of all fragments
decrease concurrently and their dimensions diminish in an even greater ratio; the evidently far-traveled, impalpable rock-flour of the loam at the same time gradually disappears; the element of local débris becomes increasingly important; and the formation, as developed about the head of the bay, everywhere attenuates peripherally. There is thus a peripheral transition from heterogeneity to homogeneity, and concomitant transition from distinctive individuality to community with the subterrane.

THE LOW-LEVEL PHASE.

In a number of cases a peculiar local modification of the formation takes place: It gradually changes from the character normal to that part of the tract into a heterogeneous, talus-like mass, which in turn graduates into irregularly stratified, whitish, gravelly silt or fine sand, much resembling the alluvium of the coastal portion of the Atlantic slope rivers. This phase of the deposit always occurs at low levels, and generally about the mouths of small streams flowing into the bay or into the estuarine portions of the larger tributary rivers, where it forms the lower terraces. It is well exemplified at Grove Point and Ordinary Point, as illustrated in Pls. LXVI and LXX. It may be designated the “low-level phase” of the formation.

ALTITUDE AND ATTITUDE.

Throughout its area the formation rests on an irregularly eroded surface, the altitude of which ranges from some two hundred and fifty feet above to an unknown but probably commensurate depth below present tide level, the unconformities, as already indicated, belonging to two genetic classes, viz, (1) those due simply to deposition on an unequal surface and (2) those due to combined modification of and deposition upon an unequal surface. The latter class is represented by two distinct types, illustrated respectively in Pls. LXIII and LXIV. The configuration of the old surface is approximately parallel with that of the present, although the latter, by reason of the terracing and the high base-level, is always the more uniform, and the deposits thus constitute a mantle of variable thickness, alike covering considerable eminences and descending into the lowest valleys, while the new ravines commonly coincide with the old.

On Reservoir Hill, near Havre de Grace, the formation rises about two hundred feet above tide, but does not exhibit its normal character; and on the north side of the mouth of the Susquehanna it reaches altitudes of perhaps fifty feet less, though it is not well developed here, the exposures on the northwest side of the bay serving only to indicate its character, but not its maximum altitude along the deeply corraded margin of the Piedmont plateau. On the east side of the bay it attains its greatest observed altitude on Maulden's Mountain, where it occurs 240 feet above tide. Everywhere about
the shores of the bay it descends toward the mouths of the affluents, frequently passing into the low-level phase, when its base generally disappears below tide level; and in general its relations to the subterrane and to the topography about the head of the bay are such as to indicate that it formerly lined the shores and the bottom of the bay universally, but that in consequence of the expansion of the bay and the concomitant destruction of shores by wave-action it has been removed from these shores during the process of their transformation from gentle slopes to precipitous banks, as ideally shown in Fig. 111.

Although the volume of the formation in different portions of the tract is affected in a general way by subjacent topography and by terracing, its maximum thickness in a given cross-section is doubtless reached along a transverse axis traversing the bay parallel to the fall-line and perhaps three or four miles southeast of it. The average altitude of the summit of the formation here, and indeed everywhere in the vicinity of the fall-line, is, however, materially less than to the eastward, by reason of the depression of the subjacent surface along the inland margin of the Coastal plain; for the topographic trough flanking the fall-line and occupied by the great water lines—the Delaware, the Susquehanna, Chesapeake Bay, the Potomac, etc.—is an expression of geologic structure.

GENESIS.

Were it necessary or desirable it might be demonstrated (1) through legitimate induction from the relations of the individual elements of the formation, (2) through analogy with other rock masses of known subaqueous origin, or (3) through a process of exclusion by which it could be shown that the deposits are not glacial, aeolian, alluvial, or of other subaerial origin, that the formation is subaqueous; but the criteria for genetic discrimination of clastic deposits, particularly, those of superficial character, are now so well established, and moreover the possibilities of erroneous interpretation of the phenomena in this particular case are so limited, that the task would be a fruitless one; and the inference that the mass was formed by subaqueous deposition may be accepted without detailed discussion. This conclusion, it is true, implies, and its integrity demands, the submergence in comparatively recent geologic times of a large part of the tract examined; but the evidence of submergence afforded
by the deposits is corroborated by the indisputable testimony of the terraces in which the region abounds—terraces miles in extent, not carved out of the substratum, but built up of the loams and sands of which the formation consists and evidently coeval in large part with the formation itself.

It is quite manifest that these "terraces of construction" are not subaerial: that they were neither fashioned by rivers, which always leave a record of their wanderings in alluvial sands and gravels and in crescentic depressions, nor accumulated behind barriers now removed; for both structure and configuration oppose either view. There is always a vertical component in the force expressed in fluvial action, and the energy of the action varies with the value of this component; and every alteration in the course of a wandering stream means change in declivity and every change in declivity means modification in competence and variation in deposits. So fluvial deposits are heterogeneous. Moreover, rivers take the paths of least resistance and flow most freely in deep channels; in selecting their courses they avoid elevations and seek depressions which they deepen; the deeper the initial depression the more rapidly is it deepened; and thus fluvial action ever accentuates irregularity of surface. So fluvial plains are multiform. But the force concerned in fashioning these terraces acted horizontally over great distances and with uniform energy for a considerable period, filling depressions, softening contours, and obliterating relief, yet so gently that homogeneity of deposit in the horizontal direction prevails for miles. Only the undulatory but always horizontally acting force of waves is competent to produce so great expanses of uniform surface and constant structure as appear about the head of Chesapeake Bay. It hence appears that they were fashioned by the waves of at least a broad arm of the sea and it is equally apparent that they were fashioned contemporaneously with the deposition of at least the superior division of the formation in question.

Although both terraces and deposits rise to such altitudes as to warrant the conclusion that the entire Coastal plain portion of the tract and the interstream peninsulas to the eastward were completely submerged, the general configuration of the land is such as to indicate that while Chesapeake Bay was greatly deepened and widened by the rise of the waters along its shores, it was practically cut off from the open ocean by the shoals formed by these peninsulas and thus in the behavior of its waters remained essentially a bay. It follows that the deposits are estuarine.

While the finest materials of the formation have not been traced to their original homes by comparative study, sufficient examination has been made of its sand, gravel, pebbles, and small and large boulders to warrant the general statement that the coarsest and most sharply angular materials (i.e., the largest boulders) are
mainly local and sublocal, but derived from the direction of the fall-line; that much of the material of the next arbitrary order of fineness (i.e., small boulders), together with most of the large boulders, was derived from the inland portion of the Piedmont region; that a large proportion of the next finer materials (i.e., pebbles), together with a small proportion of the coarser grades, came from the Paleozoic formations of the Appalachian zone; and that the sand and gravel were derived from all these sources. The materials thus represent the terranes traversed by the Susquehanna; and, since there is no other channel by which they could have been conveyed, it is evident that they have been brought down by that river.

It follows from these and the foregoing premises that the formation represents a subestuarine delta of the Susquehanna, laid down when the tidal waters rose two hundred feet or more above their present level.

The materials constituting the present subestuarine delta, as exhibited in the Fishing Battery boring and represented by the bottom samples collected by the Coast Survey, differ materially from those of the lower division of the formation described: they consist mainly of sandy clay, sand of various degrees of fineness; and fine gravel, with occasional boulders, the maximum size of which has not been determined, but which probably seldom if ever exceeds one or two feet in diameter; and there is total absence, so far as ascertained, of the coarse, cross-stratified sands, the heavy pebble beds, the far-traveled but friable flat slabs, and the enormous boulders of the subjacent deposits. This difference in the deposits is indicative of difference in transporting power of the Susquehanna. Now the boulders of the recent alluvium are ice-borne and dropped from the blocks brought down by the Susquehanna during spring freshets as they melt in the bay; and their maximum size is determined by that of the ice masses transported by the river over the rapids and falls of its lower course. When Chesapeake Bay stood 200 feet higher than now with respect to the land, it is manifest that the rapids and falls of the Susquehanna had no existence, that the current was comparatively gentle, that the ice froze thick over the sluggish stream, and that it was possible for the river to transport ice blocks much larger than those borne on its present turbulent waters. Yet such a change alone is incompetent to explain all the differences in the deposits; for with diminution in declivity of the river would go diminution in fluvial capacity and competence, while the lower portion of the old estuarine formation not only contains numerous rock masses much larger than those of the present alluvium, but is generally made up of coarser materials, and these prove energetic transportation on the part of the river when they were carried into the bay. Moreover, it may be questioned whether the ice formed even on still water in the latitude of the lower Susquehanna River during
the winters of the geologic to-day is of sufficient thickness to transport the larger bowlders found in the formation under consideration. The specific gravity of ice being .92 and that of the average rock forming the bowlders being 2.60, 20 cubic feet of ice are required to float each cubic foot of submerged rock. Therefore the evidently ice-borne quartzite bowlder noted at Turkey Point as 4 by 6 by 7 feet in dimensions, or 168 feet in cubic content, demanded for its transportation from South Mountain a mass of ice which, after traversing not less than 40 miles of rock-bound river channel and 10 miles of open bay, must have been at least 34 by 40 feet in superficial dimensions if two and a half feet thick. Now it is alike improbable that so large an ice-block of so limited thickness could support a concentrated weight of nearly fourteen tons without rupture, or could endure the accidents incident to such a journey; yet greater thickness cannot be assumed under existing winter temperatures in southern Pennsylvania. Again, while the floes of every spring plow the beaches and occasionally produce distortion qualitatively similar to that illustrated in Pl. LXIV, they are not of sufficient volume and weight to produce quantitatively equal effects. Accordingly, the ice-borne blocks of the inferior division of the subestuarine delta about the head of Chesapeake Bay indicate low temperature at the time of their transportation, while the associated gravel and sand beds indicate synchronous intensification of fluvial action; and hence both suggest chronologic equivalence of this formation with the glacial deposits of the headwaters of the Susquehanna.

The fine, calcareous, homogeneous, massive loam with disseminated bowlders and far-traveled slabs, constituting the upper division of the old delta, finds no homologue in the recent alluvium. It is indicative of gentle currents and mud-laden waters bearing occasional ice-blocks, congealed in part among the Appalachian ridges and within the sandstone-floored Cumberland Valley; and the loam itself so closely simulates the rock-flour forming the greater part of the loess of the Mississippi Valley as to suggest that it was precipitated from commingled Gletschermilch and brackish estuarine waters. Accordingly, this division of the deposit appears to represent the latest lingering of a decadent ice-sheet among the northern Appalachians, the western Catskills, and the southern Helderbergs, after the abatement of the greatest glacial floods, after emergence began, but (as attested by the associated terraces) before the resilient rocks of the Chesapeake had regained their former altitude and while yet the ice-burdened land to the northward was so depressed as to diminish the declivity and competence of the southward-flowing rivers.

Although these deposits locally reach thicknesses of a hundred feet or more, although they are spread over a zone not less than twenty
miles wide from east to west at the head of Chesapeake Bay, and although they extend southward along that bay for fifty miles or more, yet, to one familiar with the protean but massy glacial drift, the vast accumulation of laminated clays along the Hudson River and about Lake Champlain, the 200-foot thick beds of loess along the Missouri River, the voluminous lacustral deposits hundreds of feet in thickness and thousands of miles in area in the Bonneville and Lahonten basins, and the great volume of the multiform Quaternary deposits of North America generally, this old delta of a great river is surprisingly small and tells of a surprisingly brief period of deposition.

The delta deposits proper occupy an area of perhaps 20 by 50 miles, and over this area their mean thickness does not exceed twenty feet. The total volume is accordingly 3.8 cubic miles.

Now, the rate at which various rivers mechanically denude their basins and convey the products of denudation into the sea has been computed and, among the best examples, found to range from one-seven-hundred-and-twenty-ninth of a foot in the Po to one-six-thousandth of a foot in the Mississippi. This estimate for the Mississippi is based upon careful measurements by Humphreys and Abbot, and, with some limitations, has been applied by the Geikies, Croll, Reade, and others to the North American continent; but Reade has recently shown that to this must be added the amount of matter removed in chemic solution, which he estimates at 25 per cent. of the mechanical detritus in the Mississippi; and the rate of denudation is thereby decreased to one-forty-five-hundredth of a foot a year. But it is evident that the rate of denudation in the Mississippi Valley is much lower than that of the Susquehanna Valley; for (1) corrosion and transportation are largely functions of declivity in waterways, and the declivity in the latter valley is much greater than in the former; (2) it is during freshets that nearly all the corrosion and transportation of streams is effected (even near the mouth of the Mississippi, as shown by Humphrey's and Abbot's measurements, the transportation of sediment during the "June rise"—which affects the entire upper valley of the stream—is ten times as great as the transportation during the low, autumnal stage), and within the smaller valley freshets are more frequent, more violent, and relatively more extensive than in the larger; and (3) frost and changes in temperature are more efficient agents of denudation in the Susquehanna Valley than in that of the Mississippi. Moreover, the rate of chemic denudation in the latter valley is probably commensurate with that in the former; for A. L. Ewing has shown that, in

1 Text-Book of Geology, A. Geikie, 3d edition, 1885, p. 428.
2 Physics and Hydraulics of the Mississippi River (reprint), 1876, pp. 132-148.
one of the valleys drained by the Susquehanna, limestone solution is now proceeding at the rate of about one-ninth-thousandth of a vertical foot annually. On the other hand, however, the terrains drained by the Susquehanna are the more obdurate. In view of these various considerations it appears probable that the rate of denudation in the Susquehanna Valley approaches more nearly to that determined for the Po, the Ganges, the Rhone, and the Hoang Ho than to that of the Mississippi; and it may be roughly estimated at one-two-thousandth of a foot per annum.

While the deposition of the old delta was in progress, the river maintained a constant freshet stage, as indicated by the character of the deposits, and the rates of corrosion and of deposition were thereby increased; but the increased activity may be supposed balanced by the loss of those materials which were carried beyond the limits of the delta proper and by the loss of area covered by the ice sheet; and the estimated rate of denudation may be accepted as the measure of deposition during the submergence of the head of Chesapeake Bay. The rate of deposition may then be placed at $5280 \times \frac{1}{1000000}$ feet a year per square mile of drainage area; or, since the Susquehanna drainage area is about 27,000 square miles, at .00255 cubic mile annually. At this rate the entire ancient delta represents the deposition of only 1,490 years. This estimate is, of course, rough, and may be two, three, five, or possibly, even ten times too large or too small; but it is sufficient to show that the period of time represented by the gravels and brick clays about the head of Chesapeake Bay was exceedingly short in comparison with those commonly assigned to geologic operations and required to explain partially contemporaneous accumulations in other portions of the country.

The absence of well defined marine deposits in association with the marine terraces (for the stratigraphically connected littoral sands of the coastward peninsulas are of trifling thickness and without consistent structure) and the limited thickness of the terrace materials are alike indicative, also, of the brevity of the period of deposition.

So, to recapitulate, the brick clays and subjacent gravels about the head of Chesapeake Bay represent a subestuarine delta of the Susquehanna River deposited when the Quaternary ice-sheet reached its southernmost extension, contemporaneous in a general way with the glacial deposits of the north; and they indicate coeval but surprisingly brief submergence of the region, reaching at least two hundred and forty feet and continuing some time after the retreat of the ice-sheet commenced.

THE LITTORAL PHASE OF THE FORMATION.

As already indicated, the formation as characteristically developed about the head of Chesapeake Bay merges peripherally into a variable but nevertheless essentially distinct deposit. This phase of
the formation consists of loam, sand, and gravel, separate or combined in varying proportions, predominantly of local or sublocal origin, and quite subordinately erratic. The finer materials comprise (1) débris derived from the immediately adjacent subterranes, and varying locally with it, and (2) sediments indistinguishable from the loamy and sandy portions of the normal phase; while the coarser materials (which include masses reaching 2 inches or more in diameter) consist mainly of well rounded quartzite pebbles, with an unimportant element of angular and worn fragments of Piedmont and Appalachian rocks. In general, the deposit is destitute of regular bedding or other definite structure, though the coarsest materials commonly occur toward or at its base. It forms an irregular mantle, covering practically the whole of the small area of the tract studied not occupied by the normal phase, though it is sometimes absent from eminences and sharply cut valleys. It attains maximum volume in depressions having gentle slopes. Beyond the limits of the tract specially examined it appears to overlie the Coastal plain generally and it is stratigraphically continuous with a series of deposits discriminated in Delaware and denominated "Estuary sands" by Chester. The deposit is evidently littoral and coeval with the deltas of the Susquehanna and other Middle Atlantic slope rivers.

**TAXONOMY.**

The formation as developed about the head of Chesapeake Bay is petrographically homologous with and genetically similar to the ancient deltas of the Patapsco, Potomac, Rappahannock, James, Roanoke, and other Middle Atlantic slope rivers, which have already been studied in some detail and briefly described by the writer; and, since (1) each of these deltas unquestionably represents the product of identical agencies operating throughout a single definitely limited and brief period and since (2) the associated terrace system is continuous from beyond the Susquehanna to beyond the Roanoke, the several deposits are evidently contemporaneous. If the term "formation" be defined as a deposit or series of deposits formed by a definite set of agencies within a definitely bounded area during a definitely limited period, these several deltas and their associated and congeneric littoral deposits combined are entitled to the designation and to a distinctive appellation; and the name already applied to the formation as developed about the national capital has been extended and the entire series of deposits christened the *Columbia formation.*

Upon the grounds of petrographic homology and genetic identity,
as well as upon the ground of stratigraphic continuity, the formation may be correlated with the "Delaware gravels" of Chester and, chronologically, with the "Estuary sands" of the same author; and, since Chester has shown that the Delaware gravels are equivalent to the "Philadelphia brick clay" and "Red gravel" of Lewis combined, it appears evident that the superior division of the Columbia formation is the homologue of the brick clays of the Delaware River and the inferior division of the gravel beds so well developed on the same river. Moreover, since Chester's Estuary sand and Merrill's Gravel drift are petrographic and genetic equivalents of the superficial sands and gravels of the New Jersey peninsula and since the first of these geologists has found that his formation reposes upon clays containing recent shells and none of Pliocene age in eastern Delaware, while the second finds its homologue to contain only recent fossils and to unconformably overlie the latest Tertiary in Long Island, the old Susquehanna delta would appear to be the chronologic equivalent of the "Glass sands," "Preglacial drift," etc. of Cook, and of the "Glassboro gravel" and "Yellow gravel" of Lewis, as well as of the Delaware Estuary sands and the Long Island Gravel drift. Now, as shown by Cook, Merrill, and others, and as recently observed by the writer, this variously designated formation so extensively developed in peninsular New Jersey is in the northern part of its area overlooked by the great terminal moraine and unconformably overlaid by the glacial drift and its derivatives. In like manner the Philadelphia brick clays are unconformably overlaid by the "Trenton gravel" of Lewis, which unquestionably represents the marginal aqueo-glacial deposits of the latest ice-sheet.

It is hence evident that the old Delaware, Susquehanna, and Potomac deltas cannot represent the later of the great ice invasions of the Quaternary already recognized by most American geologists; and it is equally evident, from the stratigraphic relations as well as from the manifest brevity of the period of their deposition, that they cannot represent both invasions. They may accordingly be referred to the earlier epoch of cold and correlated with the inferior bowlder clay of the north.

The relations of the principal deposits of the glacial epoch in the

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2 Ibid., vol. 29, 1885, pp. 49, 41.
7 Geol. New Jersey, 1868, p. 293.
10 Primitive Industry (Abbott), 1881, p. 524.
11 Ibid., p. 528.

7 GEOL——39
Middle Atlantic slope will then be as represented in the accompanying table and ideal section (Fig. 112). This allocation of the Quaternary deposits in the Middle Atlantic slope finds support (1) in the essential unity of the deltas of the Susquehanna, Potomac, and other rivers, in contradistinction from the well marked bipartition of both the glacial deposits of the North and the contemporaneous lacustrine deposits of the West, and (2) in the evident antiquity of the deltas as compared with the drift. The antiquity of the deltas and of the drift is alike measured by stream-corrasion since their deposition; but, while the falls of Niagara have receded only seven miles since the retreat of the last ice-sheet under the most favorable structural conditions for gorge excavation, the falls of the Susquehanna have receded over 20 miles and those of the Potomac 18 miles since the close of the delta epoch, although the terrane in which their gorges had been excavated is among the most obdurate known; and there is corresponding difference in the excavation of the smaller streams—indeed, ceteris paribus, corrasion since the deposition of the deltas must be measured by yards when that of postglacial time within the area covered by the later ice-sheet is measured by feet.

1 Since the table was prepared and the section engraved it has been ascertained that the Wealden clay and Bryn Mawr gravel of Pennsylvania represent the Potomac formation and the Columbia formation, respectively.
### Taxonomy of the Glacial Deposits of the Middle Atlantic Slope

<table>
<thead>
<tr>
<th>Substrata</th>
<th>First Invasion</th>
<th>Second Invasion</th>
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<tbody>
<tr>
<td>Vicinity of Albany</td>
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<tr>
<td><strong>Albany clays</strong></td>
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<td><strong>Bowlder clay</strong></td>
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<tr>
<td>Deposits of earlier ice-sheet and its floods are perhaps preserved locally.</td>
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<tr>
<td>Vicinity of Trenton</td>
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<tr>
<td><strong>Trenton gravels and superjacent clays</strong> (terminal moraine to northward)</td>
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<td><strong>Philadelphia brick clays</strong></td>
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<td><strong>Red gravel</strong></td>
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<tr>
<td><strong>“Wealden” clays</strong></td>
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<td><strong>Bryn Mawr gravel</strong></td>
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<td><strong>Philadelphia gneiss etc.</strong></td>
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<tr>
<td>Vicinity of Philadelphia</td>
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<td><strong>Trenton gravels</strong></td>
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<td><strong>Philadelphia brick clays</strong></td>
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<td><strong>Yellow gravel</strong></td>
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<td><strong>Red gravel</strong></td>
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<td><strong>“Wealden” clays</strong></td>
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<td><strong>Bryn Mawr gravel</strong></td>
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<td><strong>Philadelphia gneiss etc.</strong></td>
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<td>Northern Delaware</td>
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<td><strong>Absent.</strong></td>
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<td><strong>Delaware gravels and estuary sands</strong></td>
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<tr>
<td>Tertiary</td>
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<tr>
<td>Cretaceous</td>
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<td><strong>“Wealden.”</strong></td>
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<td><strong>Gneiss etc.</strong></td>
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<td>Head of Chesapeake Bay</td>
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<td><strong>Columbia clays and gravels</strong></td>
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<td><strong>Greensand, etc.</strong></td>
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<td><strong>Potomac clays.</strong></td>
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<td><strong>Potomac</strong></td>
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<td><strong>Gneiss etc.</strong></td>
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<td>Vicinity of Washington</td>
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<tr>
<td><strong>Columbia clays and gravels</strong></td>
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<td><strong>Potomac</strong></td>
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<tr>
<td><strong>Gneiss etc.</strong></td>
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### Graphic Representation

![Graphic representation of the relations of the glacial deposits of the Middle Atlantic slope](image)

**Note:** The graphic representation shows the distribution of glacial deposits across the Middle Atlantic slope, with varying substrata and deposits associated with each location. The deposits are categorized under their respective invasion periods and geological formations.
In short, the erosion phenomena in the Middle Atlantic slope, like the phenomena of the forest bed in the Mississippi Valley,1 suggest that the period intervening between the two great ice epochs of the Quaternary was longer than that which has elapsed since the final disappearance of the ice. The decided ferrugination and generally thorough lixiviation of the Columbia deposits and the extensive disintegration of the included pebbles and bowlders, in which respects the formation is comparable with the marginal gravels of the older drift sheet in Wisconsin and Illinois, but quite unlike the later drift and its derivatives, are equally indicative of antiquity.

THE SASSAFRAS RIVER GREENSAND.

So far as observed this formation is a nearly homogeneous, massive bed of richly glauconitic sand, with the glauconite diminishing somewhat in abundance toward the base. It is more or less ferruginous, the iron oxidizing on exposure and taking the form either of anastomosing and irregular concretions or of thin, bubble-like crusts, giving a pitted or vesicular aspect to the weathered faces of the cliffs in which it is exposed. Sometimes it is sufficiently ferruginous in certain layers to form ledges projecting from the cliff face, as at the Back Creek section, and on Concretion Reach it abounds toward the base in peculiar ferruginous concretions of large size. In general it is sharply demarcated from the subjacent Potomac clays, but in the Maulden's Mountain section there is indistinct intergradation of the formations, through the intervening bed of pyritous clays. Although careful search was made in numerous localities, no traces of fossils were found in the greensand. Since the deposit is destitute of distinctive bedding it was found impossible to correlate the different exposures stratigraphically, and its thickness is accordingly unknown. There is, however, an exposure of forty or fifty feet of it in the Concretion Reach section, and from the width of the zone of exposure and the dip of the subjacent surface it may be inferred that this represents considerably less than half of its total thickness.

The deposit was noted only along Sassafras River from a short distance above its mouth to Back Creek Neck and on Maulden's Mountain and a few neighboring eminences. The somewhat inconsistent observations upon the base of the deposit along Sassafras River indicate that it reposes upon an unequal surface, but in general has a southeasterly dip of some ten or twenty feet per mile; and its occurrence at an unexpectedly low altitude on Maulden's Mountain suggests that its dip diminishes toward the central and western portion of the tract.

The genesis of the deposit has not been considered, nor has its taxonomic position been finally determined. It is doubtless Cretaceous.

The various clays and sands occurring above the crystalline rocks and beneath the Columbia formation and the greensand may be combined and jointly referred to the Potomac formation as already defined.

The deposits are exceedingly variable. (1) One phase, characteristic of the formation in its southeastern exposures, is that of massive or inconspicuously stratified, black, plastic clay, abounding in carbonaceous matter (either in amorphous condition or in the form of lignitic particles), in lignitized wood, and in iron sulphides, either disseminated or in nodules. At its surface it gives origin to numerous springs of sulphurous or chalybeate water. (2) A second characteristic phase, occurring somewhat farther northward, but below the mouth of Elk River, is sandy clay differing from the last chiefly in its stratification and comparative freedom from carbonaceous matter and the iron sulphides derived therefrom. (3) The most characteristic phase, and that comprising the bulk of the visible deposits, is well exposed on the east side of the head of the bay and occurs also on the north at Poplar Point and at Stump's Point, and on the west in the Swan Point and Swan Doab sections. It is massive or obscurely laminated clay, sometimes arenaceous, snow-white or richly colored—pink, purple, red, and cream, either separately or intermixed—and contains much ferruginous matter which frequently takes the form of iron carbonate, such as is mined in the vicinity of Baltimore. (4) A fourth phase is stratified and sometimes cross-stratified sand, generally with intercalations of clay and occasionally with bands of pebbles. This phase is frequently ferruginous, and the iron is sometimes accumulated in the form of sandstone or pudding-stone. It is well exhibited at Carpenter's Point, Factory Point, and in a few other sections. These various phases, however distinctive they may appear in different sections, intergraduate imperceptibly, and all may sometimes be seen in a single section, e.g., that of Maulden's Mountain or that of Rocky Point.

It was found impossible to correlate the different sections, and, moreover, the base of the formation was not seen. Accordingly, no conclusions whatsoever can be drawn from its stratigraphy as to its thickness, which, as far as observations in this locality indicate, might be anywhere from about one hundred and twenty-five feet (the thickness exposed in Maulden's Mountain) upward. The sole bases for estimating the thickness of the formation within the tract are, indeed, (1) analogy with other regions in which, unfortunately, the stratigraphic data for the estimates are little better than here, and (2) inferences as to the amount of displacement along a line traversing the tract.

Lignitic matter abounds in the Potomac clays and obscure vegetal remains and plant impressions were found in numerous sections;
but the only identifiable fossils discovered were the leaf impressions collected from the Grove Point section. These have been examined by three competent paleobotanists, Newberry, Ward, and Fontaine, all of whom are more or less familiar with the Mesozoic floras of eastern United States, and found to be mainly new forms, whose general facies more closely approaches that of the Raritan floras of New Jersey than that of the lower Potomac flora of Virginia.

The formation is exposed occasionally in natural and artificial excavations in the vicinity of the fall-line, rarely on the west side, more frequently on the north side, and generally on the east side of the rectangular head of Chesapeake Bay. It crops out also in both banks of Northeast River, at and for several miles above the mouth of Elk River, down the east side of the bay so far as observations were extended, and three or four miles up Sassafras River.

Efforts were made to ascertain the former extension of the formation westward, both (1) by examination of the residuary gravels derived from it and (2) by study of the topographic forms indirectly determined by it.

(1) An important and characteristic element of the Potomac formation consists of well rounded quartzite pebbles. Similar pebbles also occur in considerable—but generally less—quantities in the Columbia formation, having evidently been derived from the older deposit; but in the Columbia the pebbles are associated with numerous angular local and sublocal boulders of the Piedmont crystallines, which are exceedingly rare in the Potomac. Thus, in good exposures it is nearly always possible to discriminate the Columbia from the Potomac; but in imperfect exposures the discrimination becomes difficult and sometimes impossible. Unfortunately, the exposures in the elevated northwestern part of the area are imperfect, and efforts to identify the erratic deposits petrographically were sometimes fruitless. The maximum altitude of the pebble-bearing, inferior division of the Columbia deposits was, however, approximately determined on Reservoir Hill. Here a mass of well rounded quartzite pebbles, so largely intermixed with local and sublocal angular blocks as to prove its Quaternary age, was found at an altitude of about two hundred feet, while at greater altitudes on the same eminence, where the conditions for the preservation of such deposits were even better, absolutely no erratic material was found. Moreover, the Quaternary terraces characteristic of this region extend to about the altitude of this deposit on Reservoir Hill, and seldom occur at greater heights. Accordingly, 200 feet may be taken as the maximum altitude of the gravelly member of the Columbia formation, and the erratic materials occurring at higher levels may be regarded as residua of the Potomac formation and evidence of its former westward extension. Now, quartzite pebbles were found on the headwaters of Swan Creek and Wilton Run and northeast of French-
town, up to altitudes of 250 or 300 feet, and some miles west of the known Columbia exposures, and it is hence a legitimate inference, whose value is measured by the weight of negative evidence as to the former extension of the easily eroded Columbia formation over a surface made up of steep slopes, that the Potomac formation originally extended several miles westward of the present fall-line.

(2) It has been shown above that the hydrography of the extreme eastern portion of the Piedmont plain about the head of Chesapeake Bay is of autogenous type and superimposed upon the heterogeneous terrane over which the streams now flow; and, since there is no indication that other Mesozoic or later deposits ever overspread the region and since, moreover, the topography is evidently ancient, it may be assumed that the superimposing terrane was the westernmost margin of the Potomac formation. It would therefore appear that in this latitude the Potomac formation extended as much as from two to five or six miles upon the Piedmont region, but never much more than that.

So discontinuous is the stratification of the Potomac formation in this region and so rarely are definite beds displayed for distances of even a few hundred feet that it is impossible to determine its attitude with any approach to accuracy save by its relation to associated and conformable deposits. Its base was not seen; its summit inclines south-eastwardly ten or twenty feet per mile in the southeastern part of the area, and probably less toward the mouth of Elk River and Maulden's Mountain; and it rises to much less altitudes in the vicinity of the fall-line than on the opposite side of the bay; but whether this depression northwestward be due to inclination of the strata in that direction or to removal of the superior portion by erosion, or to both these causes combined, was not certainly determined. Sensible horizontality of stratification is, however, more common in the northwestern portion of the tract than in the southeastern and suggests diminution or reversal of the prevailing south-eastward dip in that direction.

Observations elsewhere have led to the conclusions that the lower division of the Potomac formation represents the inosculating deltas of the later Mesozoic rivers of the Atlantic coast, together with the associated and congenetic littoral deposits; that it was formed immediately after a sudden submergence and seaward tilting of a deeply corroded surface of crystalline rocks; and that the upper division of the Potomac formation is of like genesis, but deposited perhaps after a retreat and subsequent advance of the sea, and certainly after deposition had diminished the slope of the sea-bottom and consequently the force of waves and littoral currents. The various observations made about the head of Chesapeake Bay are consistent with this

1Since the above was written this inference has been verified by the discovery of several isolated outliers of Potomac gravel three to five miles within the fall-line.
view; and it is worthy of remark that the inferences as to the limited denudation of the marginal deposits of this formation corroborate the previous inference as to high inclination of the shore along which it was laid down.

The lower member of the Potomac formation is regarded by Fontaine, who bases his opinion upon the plant remains, as either late Jurassic or early Cretaceous in age, while the few fossils collected from the upper member in the Grove Point section—and this is the only case in which fossils have been obtained from this division of the formation—correspond with the flora of the Raritan clays more nearly than with that of the lower Potomac, and thus tend to establish its identity with the lowest Cretaceous of New Jersey and the Dakota group of the west. Still, no final opinion has been reached as to the mutual relations of the two members of the Potomac, the relations of the upper to the greensand of Sassafras River, or the relations of any or all of these to the Mesozoic formations of other localities.

THE ARCHEAN (?)

The crystalline rocks of the area examined received but incidental attention. They consist of granites (which are quarried at different points); a coarsely crystalline rock, apparently forming dikes, tentatively called gabbro; various hornblendic and argillaceous schists, frequently intersected by quartz veins, etc. They occur in place only west of the fall-line and at tide-level for perhaps a quarter of a mile southeast of Perryville, on the north side of the Susquehanna. So far as observed they trend in northeasterly-southwesterly directions and are either vertical or highly inclined to the southeast, the dip being seldom as low as 75°. No attempt was made to classify or even to discriminate these rocks.

V. THE DISPLACEMENT.

EVIDENCES OF DISPLACEMENT.

(1) In the portion of the tract lying northwest of the fall line, the streams are far above base-level and are energetically corrading their channels, the corrosion being effected, not only by the wear of sand-laden waters, but by the momentum of currents of sufficient violence to transport bowlders reaching tons in weight and by the impact of these bowlders upon the stream beds. It is demonstrable that all streams flowing upon rocky beds are corrading their channels, and that the energy of the corrosion depends upon their declivity; and so great is the declivity of the Piedmont streams about the head of Chesapeake Bay that corrosion must be progressing there about as rapidly, ceteris paribus, as it ever progressed for considerable periods and areas in any part and during any stage in the geologic
history of the globe; yet, despite the rapid corrosion there, none of the streams (save possibly the Susquehanna at its mouth) has reduced any portion of its course to base-level. Viewed in a general way, the loci of maximum acclivity in the streams flowing from the Piedmont plateau to the Coastal plain coincide closely with the common boundary of these regions. Examining them in detail, however, it is found that the recession of the locus of acclivity varies in each stream with its volume, and, among the tributaries of the Susquehanna, with the volume and the distance below the uppermost fall in that river, i.e., the head of the acclivity. It follows that the Piedmont plateau has been elevated above base-level at a period whose remoteness is measured by the subsequent corrosion of the gorges, but that the elevation is geologically recent, for the corrosion has been effected since the deposition of the Quaternary deltas. Moreover, the elongation of the locus of acclivity in the Susquehanna and its descent directly to tide-level (proving that there has been no recession since the latest elevatory movement) suggest that the elevation is yet in as rapid progress as during any past period; and there is nothing in the phenomena exhibited by any of the streams to oppose this view.

(3) Everywhere southeast of the fall line, on the contrary, the streams are not only at base-level in all except possibly their upper courses, but their tideward portions are drowned. None of these streams are corrading their channels energetically, yet all bear some detritus, and those which originate in the Piedmont plateau are gravel-laden. Such detritus is seldom deposited as alluvium along the fluvial portions of the streams, and consequently must be carried into their estuarine portions, there to form subaqueous deltas, which, however great their volume, however rapidly they may be built up, and however long they may have been in process of building, never reach tide-level; and the absence of alluvium and subaerial deltas proves that the area has been depressed in recent time and suggests that the depression is now progressing.

(3) It has been well shown by Gilbert that when streams are far above base-level and corrading their channels rapidly, their tendency is to assume direct courses and to corrade vertically, thus forming narrow gorges, which, through concomitant weathering and disintegration, tend to become V-shaped in cross-profile; but that, when the stream approaches base-level, wandering is superinduced, vertical corrosion terminates, and lateral corrosion, resulting in the formation of vertical precipices, is inaugurated. In the portion of the Coastal plain here discussed a gradual transition, first from the V-shaped ravine at the source of the stream to the concave-bottomed, alluvium-lined valley in its upper and middle courses, then to the flat-bottomed valley occasionally bounded by precipitous bluffs telling of littoral degradation, and finally to the precipitously bluffed estuarine portion, is well exhibited. Now, in an estuary or arm of the sea in
which the waves are low and the currents weak, if the depth be great and the materials in which it is excavated be obdurate, steepness of the walls may not be indicative either of emergence or of submergence of the land; but, if the depth be limited and the rocks friable and the land undergoing elevation, subaerial decay and the erosion of rain and of rills at the summits of the cliffs may exceed the erosion of the waves at their bases, and at the same time the waves and littoral currents may be unable to keep the bases of the bluffs free of talus, and the tendency will thus be to develop sloping bluffs fringed by littoral and talus deposits; while, if the land be undergoing depression, the action of the waves at the bases of the bluffs may not only keep pace with the weathering at their summits, but the ever-increasing littoral currents may be able to carry away the talus and distribute its materials over the estuary bottom. So steep estuarine cliffs are indicative of progressive depression of the land, and hence about the head of Chesapeake Bay the estuaries themselves prove that the land has been depressed in recent geologic time, and their precipitous cliffs prove that the depression is yet in progress.³

Summarizing, it appears (1) that elevation of the Piedmont region in Post-Quaternary time is proved by the declivity of the streams ¹It is conceivable that the absence of deltas in the estuarine portions of the smaller rivers and the head of the bay — which itself constitutes the estuary of the Susquehanna River — and the precipitous character of the bluffs bounding the estuaries might be due to original great depth of the bay; and such a hypothesis would appear to derive some weight from the thickness of alluvium found at Fishing Battery station. The hypothesis is, however, disproved by the geographic configuration of the bay and confluent estuaries and the topography of the adjacent land. The aspect of the bay and its estuarine affluents, their distribution, and their relations to minor water-ways, all ally them to subaerial drainage systems and suggest that they are drowned rivers. Moreover, the longitudinal profiles of the estuarine valleys above tide-level, which are unmistakably those of river-valleys, are of such character as to suggest that the same profiles, as true river valley profiles, are continued beneath tide-level and beneath the estuarine deposits of each of the confluent streams; and, as already pointed out and illustrated in Fig. 118, the transverse valley-profiles similarly suggest that the estuaries are old fluvial valleys now deeply lined with sediments. No land topography carved out by subaerial erosion can be more characteristic than that of the portion of the Coastal plain now above tide-level; and no one familiar with such topographic forms, seeing the area in question, could for one moment doubt that there is here a partially submerged land topography, i. e., that the estuaries are veritable drowned rivers. Moreover the hypothesis of great original depth is opposed if not disproved by the present subaqueous topography. If the shoreward depth were so great as to explain the absence of taluses along the cliffs, the central depth would surely be greater; but as a matter of fact the bottom of the head of Chesapeake Bay and of the estuaries of Northeast, Elk, and Sassafras Rivers and of Swan, Principio, and Mill Creeks forms a plain comparable in uniformity and extent with the broadest playas of the Great Basin or the salt plains of India. Nowhere does the depth of water exceed 18 feet, and very rarely does it exceed 12 feet; and it is seldom less than 3 feet. The hypothesis of original abysmal depth of the bay and its affluents is therefore untenable.
and by the positions of the loci of maximum declivity and (2) that geologically recent depression of the Coastal plain is proved by the absence of subaerial deltas and alluvial deposits, the profiles of the streams, and the partial submergence of a typical land topography. Moreover, it is forcibly suggested if not established (1) by the character of the loci of declivity in its rivers that the Piedmont region is now in process of elevation and (2) by the absence of deltas and the prevalence of cliffs that the Coastal region is undergoing depression to-day.

POSITION AND CHARACTER OF THE DISPLACEMENT.

The evidence establishing the existence of the displacement is of such character as to indicate that it is coincident with the fall-line, and thus to locate it within narrow limits. Unfortunately, good exposures are rare within these limits, and in consequence the dislocation was not actually observed. Since, however, the unexposed interval of shore between the Potomac clays at Stump's Point on the one hand and the crystalline rocks below Perryville on the other does not exceed perhaps a quarter of a mile, it is evident that it must be either a fracture or an abrupt flexure. The rapid inclination south-eastward of the granitic surface toward its margin suggests the latter character.

GEOGRAPHIC EXTENT OF THE DISPLACEMENT.

The lower Hudson Valley has long been regarded as a line of displacement by different geologists, and the abruptness and height of the escarpment over which fall its tributaries from the west suggest recent movement there by which the Palisades, the western Highlands, and the Catskills have been elevated fully 300 feet; while Lindenkohl and Hilgard have recently shown that the adjacent Coastal plain, there submerged and constituting the Atlantic Ocean bottom, has undergone depression so recently that the old channel of the Hudson yet exists. 1 Lindenkohl has also accumulated (but not yet published) similar evidence of recent depression in Delaware Bay in the form of a subaqueous river channel near the central line of the bay extending far out to sea, locally cut off by the submarine extension of Cape May, which supplements and corroborates the evidence of displacement recorded in a preceding paragraph; and the recently repeated survey of the northeast shore of Delaware Bay by the U. S. Coast and Geodetic Survey shows that the waters are there rapidly gaining upon the land alike by the recession of cliffs and the drowning of marshes. 2 Unpublished observations of the writer indicate that a displacement in the form of either a fault or abrupt

2 These preliminary results of Coast Survey work were obtained through the courtesy of Col. B. A. Colonna, assistant in charge of office, U. S. Coast and Geodetic Survey.
flexure occurs in the Anacostia at Washington, the throw (which is seaward) amounting to seventy-five or eighty feet; and the same series of observations have also shown that at the mouth of Acquia Creek, eighteen or twenty miles north of Fredericksburg, there is a rather abrupt monocline, by which the coastward strata are depressed some twenty or thirty feet within a quarter of a mile. Connecting these observations it would appear that there is a line of dislocation coinciding approximately with the fall-line, extending from about as far south as the Rappahannock River, at least, to some point along the Hudson; that this originates in Virginia as a gentle monocline (apparently represented by slight general tilting still farther to the southward) of small throw; that at Washington it is represented by either an abrupt flexure or fracture; that about the head of Chesapeake Bay it is either a fracture or an abrupt flexure; that in the lower Hudson it is probably a fracture; that everywhere the land side is heaved and the seaward side thrown; and that the throw progressively increases from the Rappahannock to the Hudson.

TOPOGRAPHIC EFFECTS OF THE DISPLACEMENT.

The most conspicuous and important topographic expression of the displacement is the fall-line already described and represented in Pls. LVII and LXVIII and the local configuration connected therewith.1 The partial submergence of the northern extremity of the Coastal plain must also be attributed to the displacement.

It has already been shown in describing the topography and geology of the head of Chesapeake Bay (1) that the present altitudes are less immediately southeast of the Piedmont escarpment than at some distance from it, i.e., that the escarpment forms the steep northwestern and landward side and the Coastal plain the gently sloping southeastern side of a shallow trough, in which the great waterways lie, and (2) that the strata of the Coastal plain appear to be depressed along its extreme northwestern margin, i.e., that the topographic trough is an expression of geologic structure.

Inspection of a map of the Atlantic slope displays the interesting fact that the drainage of the low-lying Coastal plain is not predominantly toward the coast, but rather toward the rivers and bays coinciding with the fall-line. This is well illustrated by the drainage map of the Middle Atlantic region, forming Pl. LVII, upon which the peninsular divides are indicated, and perhaps still better by the stereogram (Pl. LXVIII). From these maps it appears that about one-half of the portion of the Coastal plain lying in New Jersey is drained toward the Delaware River and Delaware Bay; that fully three-fourths of the Delaware-Maryland peninsula is drained into

1 It should be noted in passing that the southern extension of the fall-line appears not to be due to localized displacement, but to unequal degradation of a seawardly tilting plain of unequal obduracy.
CHESAPEAKE Bay; that by far the larger part of the Patuxent-Chesa­
peake peninsula drains into the Patuxent River; that the drainage
of the larger part of the Potomac-Patuxent peninsula finds its way
into the former river; and that there is a prevalence of islands and
irregular channels along the eastern shore of Chesapeake Bay sug­
gesting westward deflection of that water course.

Now, it is scarcely conceivable that such eccentricities of drainage
could have been original, i. e., due in any way to the development
of bars and reef islands parallel with the shore during the emergence
of the area from the ocean. But even if this were possible it is evi­
dent, in view of the submergence of the entire Coastal plain since the
beginning of the Quaternary, that such original hydrography would
have been destroyed had it not coincided with the general slope of
the surface. And indeed, since the emergence of the Coastal plain
was geologically recent, while the drainage is autogenous and ac­
curately coincident with present slopes, it is manifest that the pres­
ent hydrography must be an expression of the general topography —
that the directions of the streams must have been determined to a
great extent by the direction of the slopes of the emerging land. It
is manifest, too, that the continentward tilting of the Coastal plain
is not due to recent corrosion along its inner margin, since all its
streams are depositing there, nor to sedimentation along its outer
margin, since the burden of sediments is laid down toward the fall­
line. Moreover, the stratigraphy about the head of Chesapeake
Bay indicates that the tilting is structural, and the relative rates of
recession of cliffs there and elsewhere in the peninsular area indicate
that while the downward movement affects the entire Coastal plain
in this latitude it culminates in the vicinity of the fall-line.

The sequential connection between the displacement and (1) the
topographic and structural trough coinciding with this line and (2)
the general hydrography of the Middle Atlantic Coastal plain can
scarcely be regarded as incontrovertibly established; yet the phe­
nomena are unquestionably connected in some way.

**THE DATE OF THE DISPLACEMENT.**

The question as to the geologic age of the displacement is involved
in that of its amount, and upon this the determination of the local
thickness of the Potomac formation depends. It is a difficult ques­
tion to answer.

(1) The evidence of the displacement at the head of Chesapeake
Bay, in the Hudson Valley, and at intermediate points attests its re­
cency as emphatically as its occurrence, but affords no means of de­
termining the period of its origin. At Washington one of the lines
of evidence of the dislocation and the measure of its amount are
found in the inequality in altitude of the local phase of the Colum­
bia formation—the Quaternary delta of the Potomac—on opposite
sides of Anacostia River, which tells of a period during which movement has been in progress, but is silent as to the date of its commencement; while at the mouth of Acquia Creek, where the displacement takes the form of a flexure, the nearly horizontal and laterally homogeneous Eocene strata are thrown into a gentle monocline, thereby showing that the displacement has occurred since the close of the Eocene. There is indeed nothing in the relations of the displacement to the strata affected by it to indicate whether or not the whole of the movement has occurred since the period of deposition of the ancient deltas of the Atlantic slope rivers.

(2) As already indicated, the peculiar drainage of the Middle Atlantic Coastal plain appears to have been determined by general topography during the emergence following the deposition of the old deltas; and this drainage suggests that depression of the Coastal plain, culminating then as now near the Piedmont escarpment, was inaugurated at least before the withdrawal of the oceanic waters; and a minimum antiquity is therefore assignable to the displacement.

(3) It has already been shown, too, that about the head of Chesapeake Bay the period of Quaternary submergence was surprisingly short and that the Columbia formation was laid down upon a gullied, ravined, and manifestly subaerially eroded surface; and it might be shown not only that this is true throughout the area of the Columbia formation, but that the Pre-Quaternary surface supported a luxuriant subaerial flora, as attested by its universal ferrugination and, beneath the Potomac delta, by an old soil and the remains of plants and trees in the position in which they grew; and definite conceptions of the Pre-Quaternary topography of the Coastal plain can thus be formed. Moreover, since active Post-Quaternary erosion of the portion of the Piedmont plateau contiguous to the fall-line is confined to the gorges and bluffs of the streams below their loci of acclivity, the Pre-Quaternary topography of the Piedmont region can be definitely restored. Now there is, as shown by Powell, an intimate relation between topography and base level—a relation which is indeed so intimate that the altitude of a stationary tract of country at a given distance from the ocean and of given structure may be inferred from the character and value of its topographic relief; and, if this principle be applied to the mentally restored Coastal and Piedmont regions of Pre-Quaternary time, it will become apparent that they together represent a subaerially eroded plain of essentially equal altitude in its different parts—e.g., such a plain as those between the great water-ways about the junction of the Piedmont crystallines and Coastal plain clastics in southern Virginia and northern North Carolina, into which the hydrographic effect of the Post-Quaternary tilting has not yet extended. So a maximum antiquity for the initiation of the displacement, at and about the head of Chesapeake Bay at least, may be assigned with considerable confidence.
On the whole it appears eminently probable that the displacement was initiated during the epoch of submergence of and rapid deposition upon the Coastal plain by the swollen, ice-fed Quaternary rivers, and that it has continued down to the present; and both submergence and displacement may have been due to the active deposition combined with the weighting of the contiguous country by northern ice.

It should be remembered that the time of the commencement of that stage of the Quaternary period marked by the deposition of the ancient deltas of the Middle Atlantic slope rivers was probably at least twice or thrice as remote as the time of the final withdrawal of the later ice sheet, the subsidence of the waters derived from it, the birth of the faintly scored terraces of New England, and the resumption of its old altitude by the erstwhile ice-burdened land.

**THE AMOUNT OF DISPLACEMENT.**

Since it is impossible to determine the throw along the line of displacement north of Acquia Creek by direct observation, efforts to determine its amount are necessarily based upon (1) inferences from the mentally restored Pre-Quaternary topography, (2) inferences from the period during which displacement has been in progress, and (3) inferences from (a) deformation of the surface and (b) apparent dislocation of strata revealed in natural exposures and artesian borings.

At the mouth of Acquia Creek the flexure per se (which is somewhat difficult to separate from the general seaward tilting of the Eocene and Potomac strata there) amounts to about twenty-five feet. At Washington the minimum displacement, as indicated by the dislocation of the Columbia formation, is seventy-five or eighty feet; but, if movement commenced before deposition of the Columbia formation ceased, as has already been inferred, these figures do not represent its total amount, which, if the rate of movement be assumed uniform since the initiation of Quaternary submergence of the Coastal plain, may be roughly estimated at 100 feet. In the latitude of New York City, Post-Quaternary depression of the now submerged Coastal plain off Long Island and Sandy Hook appears from Lindenkohl's researches to reach some 250 feet; while the elevation of the heaved Highlands in southern New York would appear from the cascades along the west shore of the Hudson to reach 100 or 200 feet. Along the western margin of the Cretaceous formations of New Jersey, at Perth Amboy, Jamesburg, Columbus, and else-

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1 Am. Jour. Sci., 3d series, vol. 29, 1885, p. 476. This is the measure of displacement in that latitude not only since the latest ice advance but since the elevation of the land following the last ice retreat, and, if the displacement was initiated there as early as about the head of Chesapeake Bay, the total amount must be much beyond the estimate here made.
where, artesian borings have disclosed depths of clastic deposits much greater than are found on corresponding portions of the Coastal plain farther southward, and much greater also than outcrops west of the fall-line would indicate, although none of these borings have penetrated the Cretaceous strata and reached the Potomac formation which probably underlies them. Three or four hundred feet is accordingly a reasonable estimate for the displacement in northern New Jersey. At the head of Chesapeake Bay there are absolutely no means of determining the amount of displacement save that derived from the mental restoration of the Pre-Quaternary topography and that afforded by the boring at Fishing Battery station, where an unexpectedly great thickness of alluvium was found; but, if the throw be assumed to increase uniformly from Washington to northern New Jersey, it may be estimated at 150 or 175 feet, which estimate is consistent at the same time with the revelations of the Fishing Battery boring, with the various lines of direct evidence of the dislocation, with the inferences drawn from the ideally restored Pre-Quaternary configuration, and with the various phenomena of different portions of the line of movement.

While these quantitative estimates are uncertain within perhaps a fourth, and possibly even half, of their value, they are the best that can be made in the present state of knowledge; and they indicate with a fair degree of certainty that the displacement commences about Fredericksburg and extends northwardly along the fall-line to the lower Hudson Valley, with a seaward throw progressively increasing from nothing to 300 or 400 or possibly 500 feet. It would appear, too, that with respect to present tide level, there has been approximately equal elevation of the heaved and depression of the thrown areas.

THE RATE OF DISPLACEMENT.

The encroachment of the sea upon the New Jersey coast has long been recognized and has been correctly attributed to concurrent depression of the land by Cook, who estimates the rate of sinking at two feet per century; and although data for a quantitative estimate are wanting, the rate of movement along the inland margin of the Coastal plain is probably still higher. During pre-revolutionary days, Bladensburg, on the Anacostia, and Dumfries, on the Quantico, were ports of entry, and transatlantic shipping found ample accommodations at both places; and during the same early period churches were built near Pohick Creek, Accquia Creek, and Potomac Creek from bricks manufactured in England and, according to reliable tradition, debarked directly opposite the sites of the structures; yet the abandoned ports of entry and the old churches, all of which lie just on the Piedmont side of the line of displacement, are now far beyond

the reach of tide and their water-ways are scarcely navigable by the smallest craft. It is, indeed, a popular impression that this geographic change has resulted from sedimentation in the old estuaries; but this idea is fallacious, as proven by the meager development of alluvium above the crystalline rocks in most of the channels specified.

By reason of the dearth of quantitative data it is impossible to express the annual rate of combined upheaval and downthrow constituting the displacement; but it is possible, through the determination of the geologic antiquity of the displacement, to assign a rough comparative rate for the movement in geologic terms.

Orogeny is probably in as active progress in the Cordilleran region of western America, and particularly in the Great Basin, as in any country. Many of the interior ranges of the basin, as well as the Wasatch and the Sierra Nevada chains by which it is bounded, are now undergoing elevation, as attested by recent fault-scarps; and, since many of these fault-scarps are in the sediments of the great Quaternary Lakes Lahontan and Bonneville, their antiquity is determinate in terms of geologic time. Now, the Post-Quaternary displacement of the lacustral sediments along the fault lines defining the rapidly rising basin ranges generally runs from almost nothing to forty or fifty feet, and probably nowhere reaches one hundred feet. Again, one of the grandest mountain fronts in the world is that of the Wasatch overlooking Great Salt Lake; the youth and the constant growth of this range are attested by its height and its ruggedness, for the high mountains, albeit Tithonus-like, wrinkled and hoary, are the growing mountains; yet the Post-Bonneville movement along the fault line to which the Wasatch Mountains owe their existence, and by which their growth is measured, ranges from only ten or twenty to perhaps fifty feet. So, too, the Post-Lahontan movement along the eastern base of the still more rugged and more rapidly growing Sierras seldom exceeds 50 feet and only in one locality of limited extent (Honey Lake Valley, California) is known to reach one hundred or one hundred and fifty feet.

These Cordilleran examples of Post-Quaternary displacement cannot, it is true, be directly compared with that of the Appalachian fall-line, for they represent the period since the final recession of the latest Quaternary waters, while the amount of the latter is the measure of the period since the initiation of the Quaternary—a time which, as already indicated, is probably twice or thrice as remote; but even after the fullest allowance for the difference in the periods covered by the displacements in west and east, the latter would seem to be fully commensurate with the former.

In brief, if the rate of mountain growth in western America be accepted as a standard for past ages, the present rate of displacement along the fall-line of the Middle Atlantic slope is about as high as...
POSSIBLE CAUSE OF THE DISPLACEMENT.

THE GENERAL HYPOTHESIS.

Of recent years the opinion has been gaining ground among geologists that, in general, particle transference and mass displacement stand to each other as cause and effect, i.e., that the terrestrial crust is in a condition of isostacy and that in consequence depression follows loading and elevation follows unloading. The validity of this doctrine need not be discussed, but its truth and its applicability to the area under consideration may be assumed; and the depression of the Coastal plain and the elevation of the Piedmont region, together with the concomitant development of the displacement, may be attributed primarily to the transference of material from the former region to the latter by hydric action.

THE SPECIAL CONDITIONS.

In extending this hypothesis to the region in question, a difficulty is encountered at the outset, viz, the depression appears to exceed the loading.

Since the terrestrial crust is only slightly mobile, it is manifest that, if depression of a given tract be due solely to sedimentation upon it, the depression can never exceed, but must always lag behind, the sedimentation; and, if sedimentation on different parts of the tract be unequal, the loci of most rapid sedimentation must either be (1) built up above the general level of the tract or (2) so depressed as to deform the subjacent strata, or (3) these effects must be conjoined in a manner determined by the mobility of the tract.

In the inland portion of the Coastal plain there is a zone of indefinite width (which may be taken as 10, 20, or even 50 miles), bounded on one side by the fall-line, to which these axioms are applicable. Within this zone there is rapid deposition and depression is in rapid progress; and the sedimentation is unequal and practically limited to the estuaries, which constitute less than one-twentieth of its area. Now within this zone there is no evidence of local depression beneath the areas of maximum sedimentation or of other deformation indicating a high degree of terrestrial mobility; all the phenomena go to show that the nineteen-twentieths of the tract upon which there is no sedimentation is depressed as rapidly as the one-twentieth upon which sedimentation is in progress; and depression of the entire tract appears to keep pace with sedimentation in the estuaries as proved by the uniformity in character of the alluvium in the head of Chesapeake Bay to depths of 140 feet or more. It might be supposed that this relation is fortuitous were it confined to a more limited area,
but the zone is so extensive and the relation is so constant and consistent as to negative such supposition. So it is evident that within this zone depression is proceeding much more rapidly than sedimentation.

If the assumed tract be so extended as to cover the entire Coastal plain of the Middle Atlantic slope, the apparent discrepancy between supposed cause and observed effect will be greatly diminished, for, as indicated by the inland drainage of the inter-estuarine peninsulas, the landward deflection of the great rivers, the greater altitude of the plain oceanward, the less prevalence of cliffs toward the coast, and the less rapid encroachment of sea upon land in the same direction, depression is less rapid along the coast than toward the fall-line, and, if the entire tract be viewed as a unit, may not be greatly in excess of sedimentation; and, moreover, the zone of most rapid depression is also that of most rapid deposition. Nevertheless, the prime difficulty yet remains: whether the Coastal plain be regarded as a unit or whether any considerable fraction of it be considered separately, the rate of sedimentation upon it is not commensurate with the rate of depression.

But in any discussion of the Coastal plain it must be borne in mind that its geographic delimitation is an accident of altitude and that its geographic boundary is not the true one. Indeed, this low-lying belt of country, as a natural geographic division of the United States, is but the subaerial portion of a vast plain, fully three-fifths of which is submerged beneath the ocean in the Middle Atlantic slope, and which is naturally bounded seaward by a great submarine escarpment seventy-five to one hundred and fifty miles from the coast—a unimembral and remarkably uniform plain of so slight inclination that each foot of change in altitude of the land would shift the shore line an average of half a mile. The essential unity and great uniformity of this plain, its relations to the contiguous Piedmont plateau, and its natural seaward boundary are illustrated in the accompanying stereogram, Pl. LXVIII, from which it will be seen that the limiting submarine escarpment is of such magnitude as to dwarf the mountains and plateaus of the subaerial surface—for it is indeed one of the most striking features of the terrestrial surface, in comparison with which not only the well degraded Appalachian Mountains but the loftiest ranges of the western Cordilleras are pigmies.

The assumed tract may therefore be made to include the entire Coastal plain, from the fall-line to its strongly marked oceanic boundary; when, if depression of the submarine portion be supposed slight or nil, as is suggested by the shoalness of the sea above it, the discrepancy between loading and sinking will disappear and the processes may become commensurate. Yet the prime difficulty in the way of ascribing the displacement to transference of sediment is thereby only transmuted, unless reasons for the unequal geographic
distribution of loading and sinking can be discovered; and this involves inquiry into the mechanism of the displacement.

THE SPECIAL HYPOTHESES.

(1) The ready hypothesis that the displacement is a profound fault of either high normal or reversed hade fails to explain the unequal depression of the Coastal plain and the apparent excess of depression over loading, and, in its simple form, is hence untenable.

(2) There is reason for opining, on theoretic as well as on limited observational grounds, that the hade of faults varies with depth and that at least under certain conditions normal faults originate at great depths and are propagated upward with progressively diminishing hade, while below the couche of origin the fracture gives place to plastic flexure; and the hypothesis that the displacement in question is a profound fault with hade progressively increasing downward appears, at first sight, to explain not only the landward tilting of the Coastal plain, but also the excess of sinking over loading along its inland margin. But unless the radial stresses (due to transference of sediments or other cause) engendering normal faults are accompanied by initial tangential tension, their tendency is demonstrably to produce dragging or upward flexure at the margin of the thrown block, along the fault-surface; and with curvature of the fault-surface such tendency would increase. Manifestly, then, the structural deformation accompanying the development of a fault of this character along the inland margin of the Coastal plain would be (1) gentle landward inclination of the strata at some distance from the fault-line, merging into (2) higher seaward inclination of the strata in its immediate vicinity; and its topographic expression would be an asymmetrically concave trough at an appreciable distance from the fault line. But so far as the observations possible in a débris-burdened region of low relief go, they indicate that the actual deformation of the Coastal plain is a slight landward inclination progressively increasing quite to and culminating at the line of displacement and that its topographic expression is an asymmetric V-shaped trough bounded seaward by a convexly curved surface. Moreover, the inward inclination resulting from displacement along a curved fault-surface would be a function of the curvature of that surface; and while in nature the relation is complicated by so many subordinate factors—the strength, elasticity, and compressibility of the materials fractured, etc.—as to be quantitatively indeterminate in the simplest case, the actual inclination of the Coastal plain in the Middle Atlantic slope would appear to demand so high curvature of the fault surface as greatly to reduce the hade and perhaps render it approximately horizontal in its deepest extension.

If this be the case the movement involves tangential tension, either local or general. Now general tangential tension cannot be postulated without begging the whole question; while local tangential tension cannot be admitted in a rational discussion unless reasons for its existence can be adduced. The validity of the hypothesis is therefore questionable, although it is in partial harmony with the phenomena and with the principles unquestionably involved.

(3) The inferior strata of which the Coastal plain is built unquestionably suffer compression beneath: (1) the marine strata now emerged and beyond the reach of partial flotation, (2) the ever-growing recent deposits, and, probably, (3) the secularly settling superincumbent strata; and this compression must superinduce depression of the surface. But it is improbable that depression due to these causes could so greatly exceed sedimentation as does the actual sinking of the Coastal plain. Again, such compression of the hypogeal strata must vary with the thickness of clastic deposits, with the rate of sedimentation, and with the volume of rock above sea-level; and therefore in the Coastal plain it probably culminates at a distance from the fall-line and thus tends to produce seaward rather than landward inclination of land surface and structure planes. Furthermore, the borings upon which the estimates of the amount of displacement in New Jersey are based suggest that the movement is not confined to the clastic rocks, but extends down into the crystallines. Although this last consideration is at least in a measure balanced by the fact that the displacement is confined to the region in which the clastics reach maximum thickness (as illustrated by the sections in the stereogram of the region, pl. LXVIII), it would appear impossible that simple compressional depression is alone competent to explain the complex phenomena exhibited by the Coastal plain.

(4) The mass of clastic deposits whose surface constitutes the Coastal plain is manifestly in a condition which may be expressed by the term inequipotential, for it consists of a series of seawardly inclined strata resting on a seawardly sloping surface, supported on the landward side by the crystalline substrata and unsupported on the side toward the ocean, in such manner as to render it evident that if the mass is stable the stability depends solely on the excess of cohesion and particle-friction over the gravitative tendency to settle or slip seaward. Since the strata of which the mass is composed are subject to pressure varying with their depth, due to the weight of superincumbent deposits, it is probable that not only compression but attenuation and concomitant elongation of the deeper layers are produced. Now if elongation of the strata occur, it must be in the direction of the unsupported side; but the vertical compression and consequent horizontal elongation of the strata are direct functions of the weight of the superincumbent mass, and must, ceteris paribus, increase toward their unsupported and lower extremity; whence the
maximum depression of the surface resulting from compressional elongation of the strata must culminate in the zone of greatest thickness of deposits. Since, however, such movement is the reverse of that attested by the phenomena already enumerated, and since the discrepancy appears too great to be attributable to sedimentation upon and non-flotation of the terrestrial portion of the Coastal plain, it is evident that the displacement is not due to compressional attenuation and elongation of the strata forming that plain.

(5) Each particle of an inequipotential mass is, like the mass itself, in a condition of inequipotentiality, since it is better supported on one side than on the other; and it is evident that in any readjustment of particles accompanying compression each particle must tend to move in the direction of least resistance, i.e., toward the unsupported side, and thus perhaps induce mass movement in that direction. If, then, the readjustment be deep-seated the superior strata might be carried with the creeping inferior strata upon which they repose, after the manner of ice or névé in a cirque; when, as in the névé-filled cirque, a Bergschrund might be formed between the subterrane and the clastic mass at its inner margin, if the latter were sufficiently rigid, or the marginal clastic strata might progressively sink into the incipient chasm, and thus acquire a structural tilt landward of just such character as the Coastal plain exhibits. It is seriously questionable, however, whether the seaward settling due to such cause in the clastic deposits constituting the Coastal plain can either (1) counterbalance the greater seaward compressional depression or (2) reach such value in the inferior strata as to produce the observed landward inclination of the superior strata.

(6) It is conceivable, if not probable, that the particle readjustment accompanying compression might not be uniformly distributed throughout a considerable thickness of the deposits, and might even be confined to a single definite and deep-seated couche in which the stresses due to inequipotentiality were sufficient to overcome the combined resistances of cohesion and particle-friction. In such case the movement might become a shear along a plane or curvilinear surface analogous to that of a landslide. The behavior of the Middle Atlantic Coastal plain indeed recalls that of landslides in many ways. In both the maximum movement occurs along the emergent surface of displacement corresponding to the Bergschrund of the ice-field; in both there is relative elevation (though absolute depression) at a distance from the Bergschrund; in both the surface is relatively tilted toward the undisturbed portion of the mass; in both the tilting is structural as well as superficial, etc.

At the first blush it may appear extravagant to parallel the slow, orogenic movement of a tract 7,000 or 8,000 square miles in extent, in which the general surface slope is only 1 in 2,500 and the bottom slope (from the Piedmont escarpment to the base of the submarine
escarpment) no more than 1 in 100, with the comparatively rapid movement of a landslide affecting only a fraction of an acre, in which the slope is perhaps as high as 1 in 2; but it is evident that the inequipotentiality of the mass constituting the Coastal plain is of the precise kind relieved by landslides; and, moreover, it might be shown (1) analytically that the stresses and resistances involved in the two cases are qualitatively identical and tend to produce qualitatively similar displacements and (2) empirically that landslides vary so greatly in area while the slopes necessary to produce them diminish so rapidly with increase in area that there is nothing a priori unreasonable in supposing that the miniature displacement in a builder's sand-heap and the great displacement of the Coastal plain represent the extremes of a series, differing greatly in degree but not at all in kind, between which fall the every-day landslide of the hillside and the catastrophic Bergsturz of the mountain-side; and, were this the place for such an investigation, analysis of the mechanics of the former might be made, in a measure, to elucidate the movements of the latter. It may be merely observed in passing that the displacement surface in a landslide, as empirically determined, is, in general, slightly concave upward and roughly conformable to the surface at depths, and that its curvature increases upward until it approaches verticality at its line of emergence—the Bergrand. It may also be observed that, while landslides occur whenever the stresses due to inequipotentiality of the mass affected exceed the resistances resulting from cohesion and particle-friction, their immediate causes are various. Classified empirically by the observed condition of their genesis, they are separable into the following categories, viz:

1. Landslides due to degradation, developed when erosion attacks the foot of the slope, and thus effects the removal of support.
2. Landslides due to deposition, developed when instability of the mass is superinduced through loading by deposition upon it of sediment or talus.
3. Landslides due to alteration, developed when the consistency of the mass is affected by disintegration, permeation of water, or other causes of diminished cohesion or friction.
4. Compound landslides, developed by various combinations of the preceding conditions.

Now, if the movement of the Coastal plain be analogous to a landslide it will obviously fall in the second of these categories, since (1) the velocity of the Gulf Stream is inadequate to corrade the submarine escarpment and since (2) the current alteration of the clastic deposits of the plain probably tends to decrease rather than to increase their mobility.

But in addition to the serious question as to the quantitative sufficiency of inequipotentiality in the Coastal plain deposits to produce mass movement—a question which cannot be satisfactorily discussed in existing ignorance of the effects of great pressure upon solids—
this hypothesis is open to the objections which beset the hypothesis of seaward settling: It is uncertain (1) whether such movement would counterbalance the vertical compression of the shoreward strata, or (2) whether, under the hypothesis, the observed depression along the fall line would not (a) involve greater seaward movement and geographic deformation of the continent than has actually occurred or (b) imply a steeper slope for the plane of movement than that of either the Coastal plain strata or the crystalline surface upon which they repose; and like all hypotheses in which the displacement is ascribed to movement confined to the clastic Coastal plain deposits, it fails to explain the probable extension of the displacement into the crystalline subterrane in New Jersey.

(7) The crystalline rocks along the Piedmont margin have generally, if not universally, a high seaward dip, often approaching verticality, and a trend nearly parallel with the fall-line, and it is probable that this stratigraphic attitude continues to profound depths, perhaps with progressively diminishing inclination of the strata. If such be the case it is conceivable (and the same is true in a measure whatever the stratigraphic attitude) that compressional readjustment of particles and concomitant seaward settling may extend to the crystalline strata, when the most serious objections to the third hypothesis will disappear. This view, however, like the last, encounters an additional objection, found in the fact that the displacement diminishes and finally dies out with the southward attenuation of the clastic deposits, as illustrated in the stereogram of the Middle Atlantic slope.

(8) The marginal attitude of the Piedmont crystallines is such as to suggest that the great displacement of the Middle Atlantic slope may be a profound fault of curved surface, either coinciding with a structural plane in these rocks or extending to several planes, in accordance with the principle enunciated by Becker, in such manner as to simulate flexure when propagated upward into little disturbed and continuous superjacent strata and to approach horizontality at some depth beneath the land surface; in which case, and particularly if the inference be valid that the hade of normal faults commonly increases downward until the fracture gives place to plastic flexure, the movement may relieve the stresses due to, and at the same time find its raison d'être in, the inequipotentiality of the Coastal plain. Moreover, since any movement tending to relieve inequipotentiality in slightly clastic materials must develop subordinate stresses in its vicinity, it is conceivable that such faulting might be accompanied by extensively distributed particle readjustment, and consequent settling of the clastic portions and perhaps of the crys-

talline portions of the mass, together with some compressional at-
tenuation and elongation of the strata and depression of the surface.
A composite movement of this character appears not only to explain
the diverse phenomena of the displacement, but to find an adequate
cause in the physical condition of the region in which it occurs.

RÉSUMÉ.

Summarizing the leading pertinent considerations, it appears (1)
that the true boundaries of the Middle Atlantic Coastal plain are the
fall-line and the great submarine escarpment; (2) that the character
of the downthrow of this plain is such as to produce superficial and
structural landward tilting, culminating at the fall-line; (3) that the
entire plain is undergoing loading by deposition of sediment, which
attains a maximum near its inland margin; (4) that along the inland
margin of the plain depression is far in excess of sedimentation, al-
though the processes are more nearly and perhaps quite commen-
surate if the entire plain is regarded as a unit; (5) that it is uncertain
whether or not the displacement extends to the crystalline subter-
rane, for the Virginia phenomena indicate that it does not so extend,
while those of New Jersey indicate that it does; (6) that the mass of
clastic deposits constituting the Coastal plain, together, possibly,
with the crystalline subterrane, are in a condition of inequipoten-
tiality; (7) that the congeries of phenomena of the great displace-
ment are inexplicable save on the assumption either (a) that the en-
tire region is affected by tangential tension or (b) that the vertical
displacement is combined with some lateral movement; (8) that the
assumption of general tangential tension is inconsistent with the
orographic phenomena of the contiguous land areas; and (9) that
the local tangential tension (or equivalent lateral movement) is such
as the inequipotentiality of the mass tends to produce.

The several special hypotheses may be assembled for review as:
The hypotheses of—
(1) Simple faulting.
(2) Faulting along a curved surface.
(3) Compressional depression.
(4) Compressional attenuation and elongation of hypogeal strata.
(5) Settling of the clastic deposits, due to inequipotentiality.
(6) Sliding of the clastic deposits, due to inequipotentiality.
(7) Settling of clastics and crystallines, due to inequipotentiality.
(8) Faulting along a curved surface, combined with inequipotential sliding and
settling of clastics and crystallines.

Inspecting these hypotheses in connection with the conditions of
the problem, it appears at once that the first is untenable; that the
second consists fairly with the phenomena, and upon certain postu-
lates has strong elements of probability; that the third involves per-
tinent considerations, but is alone incompetent; that the same is true
of the fourth; that the fifth, like the second, is in harmony with
many of the phenomena and has elements of probability without irrelevant postulates; that the sixth is in even closer accord with the phenomena and principles and appears to embody a true and perhaps adequate cause; that the seventh is free from the most serious objections to the possibly valid fifth hypothesis; and that the eighth, which combines the plausible second and still more plausible sixth hypotheses, as well as the probable elements of the others, is not only consistent at the same time with the assemblage of phenomena and with established principles, but appears to afford a complete raison d'être for the displacement.

Briefly, the region is in an inequipotential condition, and the displacement is of precisely such character as the stresses arising from inequipotentiality combined with current sedimentation tend to produce; but it is impossible to demonstrate the quantitative sufficiency of these stresses, for, although the inequipotentiality might be evaluated, the resistances opposed by cohesion and particle friction cannot be determined with present limited knowledge of the behavior of solids under such pressures as obtain at even inconsiderable depths beneath the terrestrial surface.

VI. THE GENERAL SECTION.

The taxonomic and stratigraphic relations of the rock masses developed about the head of Chesapeake Bay are exhibited in the following scheme:

| CENOZOIC QUATERNARY | | MESOZOIC CRETACEOUS (?) | | ARCHÆAN (?) |
|---------------------|-----------------|--------------------------|-----------------|
| Alluvium            | Unconformity    | Sassafros River green-sand | Unconformity   |
| (above tide at least) | Columbia ......... | Varicolored clays | Potomac ............... |
| Brick clays         | Transition Gravels, | Unconformity (?) | Kaolinic sandstones, |
| Littoral sands and gravel | Unconformity |                           |                 |
|                      |                 |                           | Piedmont crystallines |

Subaërial alluvium attains only an exceedingly limited development in the tract; for in the northwestern portion the streams are energetically corrodng their channels, while in the southeastern portion depression is proceeding pari passu with deposition. The head of the bay and its affluent estuaries are, however, alluvium-lined to depths probably commensurate with the complementary relief of the land. The surface southeast of the Piedmont escarpment, too, is commonly
covered by a thin stratum of indefinite structure, consisting in part of aeolian sand and dust, in part of talus-like debris derived from contiguous elevations, and in part of local materials modified by weathering and rearranged by the beating of storms and by rainborn rills, the whole constituting the soil and subsoil of much of the tract.

The Columbia formation exhibits two distinct phases within the tract studied: (1) The predominant phase comprises (a) a generally massive loam or brick clay, with sparsely distributed pebbles and rare boulders, graduating into (b) a heavy bed of coarse, stratified sand and gravel, abounding in local and erratic boulders and pebbles. The two members combined represent a subestuarine delta deposited by the Susquehanna River during the initial episode of the Quaternary, when the sea rose over two hundred feet above present tide-level and the climate was colder than now. The deposits attenuate radially from a medial and maximum thickness of probably one hundred and twenty-five or one hundred and fifty feet to perhaps ten feet, and peripherally merge into the second phase of the formation. (2) The locally subordinate phase is a heterogeneous and variable sheet of loam, sand, and gravel largely made up of local debris, and consists of littoral deposits and sediments laid down concurrently with the more massy delta. Its thickness within the tract specifically examined probably nowhere exceeds ten feet; and it has been removed by Post-Quaternary degradation from the higher eminences, the steeper slopes, and some valleys. The two phases of the Columbia formation combined occupy nearly all the land area of that portion of the tract southeast of the Piedmont escarpment; and the delta doubtless completely floors the estuaries beneath the Post-Quaternary alluvium and there attains maximum thickness.

Beyond the limits of the tract lying about the head of the bay the locally subordinate phase becomes predominant and the formation overspreads almost the entire Coastal plain, at least north of the thirty-sixth parallel, reaching its greatest development in the ancient deltas, now deeply graven by erosion, always found where the great rivers embouch upon the plain. Although the volume of the formation is inconsiderable, it represents a critical and interesting stage in the geologic development of the continent and affords at the same time a record of the orogenic movements by which the structure of the inner margin of the Coastal plain has everywhere been affected and a physical means of correlating the later Tertiary episodes of the south with the Quaternary vicissitudes of the north.

The Sassafras River greensand is found only in the extreme southeastern portion of the tract as a continuous stratum; but its outliers, frequently in the form of insulated, wave-worn eminences, rounded in plan and profile, occur as far west as Elk Neck. It is a massive and nearly homogeneous bed of glauconitic sand, probably seventy-five or one hundred feet thick, dipping southeastward perhaps twenty
feet per mile. It undoubtedly belongs to the long-recognized but ill-defined series of Cretaceous deposits passing through Maryland and Delaware and perhaps extending into New Jersey.

The Potomac formation comprises two members, viz: (1) varicolored plastic clays with occasional intercalations of sand, and (2) a characteristic, irregularly bedded, and porous kaolinitic sand or arkose, interspersed with pockets and lenticular sheets of quartzitic gravel and of plastic clay. The superior member occurs immediately beneath the greensand and the Columbia formation throughout the greater portion of the tract. Its upper surface is, probably, as extensively and deeply graven by erosion as the present land surface of the region. Its base was not seen; and, while it is apparent that its inland margin is deeply crenulate and possible that considerable marginal outliers are insulated by Pre-Quaternary channels, the observations indicate that it is an essentially continuous and uniform stratum southeast of a line passing through Carpenter's Point and Fishing Battery Station, with a maximum thickness of perhaps two hundred feet. The exposures of the inferior member are confined to the area between that line and the Piedmont escarpment. The outcropping surface of this member is as deeply corraded as that of the superior one, and, since neither base nor summit was seen, its indubitably variable thickness is indeterminate by direct observation; but a variety of indirect observations indicate that the thickness is some two hundred and fifty feet.

The Potomac formation is typically exposed on the river from which it takes its name between Washington and the mouth of Aquia Creek, where its divisions are found to be unconformable. So far as known empirically, it is the basal deposit of the series of Coastal plain clastics and overlaps the eastern margin of the crystallines, save where the superincumbent Mesozoic and Cenozoic formations outstretch and conceal it, from Philadelphia to Weldon; while still farther southward it probably reappears in corresponding stratigraphic position as the homologous and presumptively identical Tuscaloosa formation. The superior division appears to be either equivalent to or older than the Raritan clays of New Jersey, the eastern time-equivalent of the Dakota; while the inferior is probably an earlier deposit of the Cretaceous period than any hitherto discriminated in this country, though it is possibly Jurassic.1 About the head of Chesapeake Bay the formation is confined to the Coastal plain, and study of its residuary gravels and of the topography of the Piedmont plateau justifies the inference that it never extended

1 Since this was written, Fontaine has completed his examination of the rich flora of the Potomac, on the basis of which he and Ward are disposed to regard the formation as either early Cretaceous or late Jurassic, and Marsh has found it to yield dinosaurian remains of Jurassic type. Cf. Am. Jour. Sci., 3d series, vol. 35, 1888, pp. 89-94; ibid., pp. 130-143; ibid., vol. 36, 1888, pp. 119-131.
more than a dozen miles beyond its present inland limits in this latitude, although in Virginia its outliers are occasionally found far out upon the Piedmont zone.\(^1\)

The Piedmont crystallines comprise a variety of granites, gneisses, greenstones, schists, etc., trending northeast-southwest in nearly vertical attitude, and apparently intersected by one or more eruptive dikes.

The structure of the tract is affected by a displacement (either fracture or abrupt flexure) of perhaps 175 feet, coinciding approximately with the Piedmont escarpment, which extends with progressively increasing throw from latitude 38° at least to New York, which originated with the commencement of the Quaternary refrigeration and yet continues, and by which the Piedmont area is heaved and the Coastal plain is thrown.

The general section thus interpreted forms the accompanying Fig. 113.

**VII. THE QUATERNARY HISTORY RECORDED IN THE COLUMBIA FORMATION.**

The leading events indicated by the Columbia and associated deposits and by the complementary degradation may be summarily stated as follows:

The Pre-Columbia degradation, as interpreted from the topography, indicates stable geography, differing little from that of to-day, for a considerable period; and there is nothing in the deposits, the mineral accumulations, or the scant vegetal remains preserved at the base of the formation, to indicate that the Pre-Columbia climate was variable or materially different from that of to-day.

The Columbia formation in its several aspects is indicative of (1) climatal refrigeration, unquestionably coeval with the first invasion of Quaternary ice; (2) partially synchronous and partially subsequent submergence, reaching several hundreds of feet, which, although brief, lasted until after amelioration of the climate began; (3) emergence of and resumption of its old or a somewhat greater altitude by the land; and (4) the initiation of a displacement by which the Coastal plain was depressed.

The Post-Columbia degradation is indicative of a long period of uniform climate and stable geography, save for the progressive displacement, interrupted (in the north only) by the second ice invasion and concomitant temporary submergence.

The Trenton gravels and the associated deposits are indicative of temporary climatal refrigeration and contemporaneous or immediately subsequent submergence of the land in the northern portion of

\(^1\) Additional outliers have recently been found in Maryland, Pennsylvania, Delaware, and New Jersey, in such positions as to verify this inference.
the Coastal plain, coeval with the second advance of the Quaternary ice-sheet, and, perhaps, accelerated displacement.
(1) From the far less volume of the Trenton gravels than of the evidently homotaxial Columbia formation, (2) from the less extent of the marginal gravels of the later than of the earlier drift-sheet, and (3) from the far less depression of the imperfectly mobile terrestrial crust accompanying the second ice advance (if the depression of the land be attributed to the weighting by ice) it would appear that the earlier period of submergence was by far the longer. Cook, Upham, Chamberlin, Lewis, and others have, however, shown that in the eastern United States the later ice-sheet extended as far southward as the earlier: and, accordingly, the inference deduced by Gilbert from the phenomena of Lake Bonneville, that the Quaternary comprised two periods of refrigeration of which the earlier was the longer and the later the more intense, would seem to apply as well in the Atlantic slope as in the Great Basin. It is noteworthy, however, that Gilbert's generalization as to the brevity of the interglacial period is inapplicable in the east, for the time measured by the deposition of the Columbia formation is surprisingly short, while that indicated by Post-Columbia and Pre-Trenton degradation is surprisingly long.

Briefly, the Columbia formation and associated phenomena record a history of the great continental and climatal changes of the Middle Atlantic slope since some indeterminate date in Tertiary time, in which the principal episodes are: (1) uniform climate and stable geography; (2) brief climatal refrigeration and considerable submergence; (3) a long period of uniform climate and generally stable geography, together with progressive displacement; (4) much briefer refrigeration and slight submergence affecting only the northern portion of the area; and (5) a considerable period of uniform climate and essentially stable geography.

Qualitatively interpreted, these vicissitudes may be represented graphically as in Fig. 114.1

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2 This history has recently been supplemented by the recognition of an antecedent alteration in base-level extending throughout the Middle Atlantic slope. Cf. Am. Jour. Sci. 3d series, vol. 33, 1888, p. 496.
As already intimated, the original and immediate purpose of the investigation was to ascertain the probable artesian water supply obtainable at or near tide level at Fishing Battery station, five miles south of Havre de Grace, Md.; and only such collateral studies were undertaken as promised to elucidate the central question.

It was evident at the outset that the possibility of strong artesian flow at the place specified depended (1) upon the presence of a porous stratum with a natural outcrop forming an adequate catchment basin at a considerable altitude above tide, confined beneath a superjacent impervious stratum, and (2) upon the substantial integrity and continuity of the porous stratum, despite the observed channeling of its surface by erosion and the possible interception of its mass by the suspected displacement; and it was also evident that the purity or impurity of the water would depend upon the absence or presence of free salts and unstable chemic compounds in the water-bearing stratum. After the first hasty inspection of the region it became apparent, too, that there is no more than a single porous stratum possibly present and so conditioned as to afford an adequate supply of pure water, viz, the inferior division of the Potomac formation; and accordingly the investigation at once resolved itself into: (1) search for the Potomac sandstone; (2) observation of its structure, attitude, and physical and chemic constitution; (3) estimate of the area and altitude of its outcrop; (4) examination of the superjacent confining stratum; (5) determination of the thickness and subsurface extent of the sandstone; and (6) study of the displacement and its effects upon the sandstone and the confining stratum.

(1) After considerable search the Potomac sandstone was found in a number of localities in the vicinity of the Piedmont escarpment (whose position determines and is indicated by that of the railways traversing the tract), viz, in the woods at Gravel Spring, in an inconspicuous exposure in the bank of Swan Creek at the head of its estuarine portion, at Stump's Point, at Wild Duck Bluff, and at the Factory.

(2) The sandstone observed at these outcrops was found to exhibit the features by which it is characterized in the type locality of the formation where it is noted as a source of abundant and pure water, i. e., it is a somewhat porous and thoroughly lixiviated aggregation of predominantly angular quartzic and quartzitic sand grains, feldspathic and micaceous flakes, etc. In structure it was found to be

---

1The requisite and qualifying conditions of artesian wells have been set forth at length by Chamberlin (Fifth Ann. Rept. U. S. Geol. Survey, for 1883-'84, 1885, pp. 131-173).
irregularly stratified, frequently cross bedded, and interspersed with extensive though discontinuous sheets of coarse gravel and pebbles; and, although so inconstant in structure that its attitude is not certainly determinate, the stratum appears to incline slightly southeastward. So, at this stage of the investigation, it became manifest that there is a water-bearing stratum in the region of such physical and chemieal constitution and stratigraphic attitude as to afford pure artesian water at the desired point, provided it is not intercepted by displacement and the confining stratum and catchment basin are adequate.

(3) The determination of the area and the altitude of the outcrop of the porous stratum demanded (1) investigation of its petrographic relations, in the course of which it was discovered that it unconformably overlies the Piedmont crystallines of the tract and is in turn overlaid (perhaps unconformably) by the impervious plastic clays forming the upper division of the Potomac formation, and (2) a general geographic study of the tract. These and collateral studies resulted in the discovery that the area of outcrop affords an adequate catchment basin for a moderate water supply, but that its altitude is so slight as to render flowage doubtful unless other conditions are peculiarly favorable.

(4) One of the most essential of these conditions is that found in the confining stratum; and hence it became necessary to ascertain the physical constitution and geographic extent of the impervious bed of clay constituting the upper division of the Potomac formation, and to determine, also, whether its surface has been so deeply corraded as to suggest that its continuity is materially broken by ancient water-ways. This involved minute examination of the Potomac clay, as developed throughout the tract, and the determination of the stratigraphic relations of the two divisions of the formation on all sides of the head of the bay. The extended investigation thus inaugurated led to the conclusions (1) that the physical condition of the clay is such as to render it a perfect confining stratum, and (2) that, although its surface is deeply graven and its margins scalloped by erosion, the bed is essentially continuous; but (3) that, while the clay occurs on the west side of the head of the bay at Swan Point, White Bluff, and elsewhere, its extent is too limited to imply strong flowage at Fishing Battery station; and, moreover, (4) that it probably has been cut through by erosion within the profound though now deeply lined channel constituting the bay.

These conclusions, in turn, led to a general study of the old Susquehanna delta, already known to overlie the Potomac sandstone in its westernmost exposures, made for the purpose of ascertaining (1) whether it probably lines the head of the bay and the affluent estuaries and (2) whether, if so, it would afford an impervious confining stratum. This study led directly to the determination of the char-
acter and extent and indirectly to the elucidation of the genesis of the ancient delta and the coeval littoral deposits, together constituting the Columbia formation. The immediate conclusions derived from this line of investigation were (1) that the Columbia formation unquestionably underlies the head of the bay everywhere except along the shores and doubtless exists in considerable thickness beneath Fishing Battery station and (2) that it would afford a confining stratum inferior to the Potomac clays, but perhaps sufficient. Incidentally, it was inferred that this formation would oppose and add materially to the cost of boring. The more remote results of the investigation are incorporated in the preceding pages.

(3) It was naturally inferred that the flowage from the Potomac sandstone would vary, ceteris paribus, with its thickness. Moreover, the reasonable certainty that the Potomac clays have been removed by erosion from beneath Fishing Battery station raised the inquiry whether the Potomac sandstone has been similarly removed from the channel now occupied by the head of the bay, and it hence became doubly important to ascertain its thickness. Now, since neither summit nor base of the sandstone could be found anywhere within the tract and since it was found impossible to estimate its volume by means of analogy with other regions in which, unfortunately, the opportunities for observation are little better than here, the determination was exceedingly difficult. It was evident, however, from its attitude and stratigraphic relations, that its thickness is a function of its extension upon the Piedmont region; and an exhaustive analytic study of the topography of that part of the tract was accordingly made, with the results, among others, of developing a topographic taxonomy probably extensively applicable and of determining roughly the original extent of the Potomac sandstone. The more immediate and practical results of this analytic study were the inferences (1) that the Potomac sandstone is of such thickness as to imply its existence beneath the Piedmont crystallines at Fishing Battery station but (2) that its thickness is so limited as to render it uncertain whether it is intercepted by the supposed displacement. The first of these inferences involves and its value is dependent upon an assumption as to the amount of Pre-Quaternary erosion within the bay. This assumption is not gratuitous, but is based on finely drawn inferences from the ideally restored Pre-Quaternary topography, which in this brief summary cannot be set forth at such length as to be intelligible.

Empiric determination of the subsurface extent of the Potomac sandstone was found impracticable, since it occurs above tide level in but a limited portion of the tract; but analogy with the type and other localities warranted the inference that it underlies the vari-colored clays and greensand everywhere southeast of the line passing through the mouth of Swan Creek and Carpenter's Point.
(6) The most delicate collateral line of investigation was that relating to the displacement; for, while the existence and value of faults and flexures can readily be ascertained in montane or plateau regions in which the structure is clearly revealed, it is difficult to diagnose a completely concealed displacement in a region of rarely exposed rocks in which, moreover, the structure is inconstant. There is indeed no decisive evidence of displacement save that afforded (1) by the present behavior of streams and (2) by the interpretation of the elusive and little understood topographic features recording the behavior of the streams of earlier epochs; and accordingly thorough studies of the hydrography and surface-relief were instituted. These studies resulted directly in establishing the validity of the inference that a considerable displacement has affected the region and in proving that it is still in progress and, indirectly, in showing that the most conspicuous hydrographic and geographic features of the Middle Atlantic slope have probably been produced by the displacement.

It remained to ascertain (1) whether the displacement is probably an abrupt fracture, cutting off a part or the whole of the Potomac sandstone, or a flexure so gentle as not to interrupt its continuity, and (2) whether the amount of displacement is such as to intercept the stratum. In order to solve the first of these questions, the investigation was extended beyond the limits of the tract specifically studied, and the outcome of this branch of the investigation was the conclusion that the displacement is either a fracture or a sharp flexure and that the interception of the stratum probably depends upon the amount rather than upon the character of the displacement. Now, the physical difficulties in the way of ascertaining the amount of displacement empirically are insurmountable, and it became necessary to base estimates of amount mainly (1) on inferences as to the date of initiation and the rate of movement and (2) on inferences from the ideally restored Pre-Quaternary topography. The determination of the date of the initiation of movement involved a chronologic taxonomy of the Columbia and correlative formations, and the determination of its rate led to some consideration of orogenic movements in other regions and of erosion and deposition as geologic chronometers; while the ideal restoration of the Pre-Quaternary topography involved extensive topographic study and extension of the analysis of topographic forms throughout the entire tract. The immediate outcome of this collateral study was the inference that the amount of displacement is considerably less than the thickness of the Potomac sandstone, which is consequently only partially intercepted.

Finally, since the data for some of the conclusions appeared insecure and possibly inadequate, it was thought desirable to bring the various lines of investigation relating to the displacement together, in order to ascertain whether by their convergence and blending into
a symmetric whole they appeared to mutually sustain each other, and thus corroborate the individual conclusions; and for this reason, as well as because the question is an important one in geologic science, some discussion of the possible cause of the displacement was undertaken. Little of practical moment grew out of this part of the study except the confidence which comes from familiarity with all phases of a problem; but, if the tentative conclusion that the displacement is attributable to inequipotentiality of the Coastal plain deposits be sustained, an important advance will have been made in that portion of orology dealing with direct displacement and consequent corrugation, tufefaction, metamorphism, etc.

The scientific results of the many-sided investigation thus determined are recorded in preceding sections of this paper. The immediate and practical results of the work are embraced in the following conclusions:

1. The Potomac sandstone probably occurs beneath Fishing Battery station.

2. Its physical condition, attitude, confining stratum, and catchment basin are apparently such as to afford a moderate supply of pure water.

3. The sandstone is probably overlaid by the Columbia formation at Fishing Battery station, and the inferior division of this formation is doubtless there of such constitution as to involve considerable labor and expense in its penetration.

4. In view of the imperfection of the confining stratum and of the limited head, it is doubtful whether water reached in the Potomac sandstone would flow, though it would probably rise nearly or quite to the surface.

5. In brief, the favorable probabilities are such as to warrant the risk of boring provided it can be done at small cost, but not such as to warrant costly operations; while the unfavorable probabilities are such that a successful issue cannot be confidently predicted.

THE GENERAL APPLICATION.

Probably nowhere in the world is the intimate relation between natural structure and cultural development better exemplified than in the Middle Atlantic slope. The earliest settlements were coastal; as the pioneers penetrated the wilderness and the population increased the St. Augstines and Jamestownes were neglected or abandoned and new settlements clustered about the head of navigation in the different rivers; with the differentiation of industries and the waxing of thrift the water power afforded by the rivers at their falls just above the head of tide, was utilized, and the settlements located there grew and multiplied; at the shoals between the torrential and fluvial portions of the rivers, fording, ferriage, and bridging were found practicable, and the routes of travel, following those of the
aborigines, were diverted thither; and thus the towns and cities and
the main routes of travel between north and south came to be lo­
cated on that continuous line of falls in the Atlantic slope rivers
which extends from the Hudson in New York to the Altamaha in
Georgia.  This relation between urban culture and the fall-line in
the eastern United States has long been recognized; and as long ago
as 1817 Maclure pointed out, 1 and in 1868 Cope showed more specif­
ically, that the fall-line is also an important line of geologic structure.

Throughout the Middle Atlantic slope the fall-line is the common
boundary of the Potomac crystallines and the Cenozoic and Mes­
ozoic formations of the Coastal plain; and the cities of Trenton, Phila­
delphia, Wilmington, Havre de Grace, Baltimore, Washington, Al­
exandria, Fredericksburg, Richmond, Petersburg, and Weldon, as
well as many intermediate towns, are located upon it.  In all of these
cities and towns the artesian well question has long been mooted and
is of growing importance.  Moreover, everywhere east of the fall­
line, the terrane consists of clastic deposits abounding in free salts
and unstable compounds, that frequently impregnate the water of
wells, springs, and streams; and so the artesian well problem is im­
portant throughout the Coastal plain.  Now, along the fall-line, as
well as throughout the Coastal plain generally, the geologic struc­
ture is so uniform and consistent that the solution of the artesian
water problem in any one locality will apply with limited modifica­
tion in the various other localities.

The principal cities of the middle Atlantic slope are located on the
larger rivers; and all of these rivers have ancient deltas so closely
similar that, from Philadelphia southward, the petrographic descrip­
tion of one will apply to each of the others.  The preceding descrip­
tion of the Quaternary delta of the Susquehanna will therefore facili­
tate the discrimination of the delta deposits of the other rivers.
So, too, the littoral phase of the Columbia formation is not only strat­
igraphically continuous but petrographically similar throughout its
area, and its aspect 1 is described with sufficient fulness about the
head of Chesapeake Bay to permit its identification anywhere upon
the Coastal plain.  In like manner the subsurface and especially the
subestuarine extent of the Columbia formation, as well as its suffi­
ciency as a confining stratum, may be inferred from analogy with the
tract described.

Throughout the Coastal plain, and especially near its inland mar­
gin, the Potomac sandstone is the only deposit so constituted and
conditioned as to afford ample supplies of pure water.  Now, this
sandstone is petrographically similar throughout its extent, and its
description at the head of Chesapeake Bay is so generally applicable

1 Observations on the Geology of the United States of America, 1817, pp. 33, 34;
also 99 et seq.
that it can everywhere be discriminated thereby; and the area of the catchment basins afforded by it locally can be readily determined by any person of average intelligence. So, too, the impervious confining stratum, the upper division of the Potomac formation, found at the head of Chesapeake Bay, occurs generally throughout the Coastal plain beneath the fossiliferous Tertiary deposits, and can readily be identified by the amateur or by the practical man from the preceding descriptions and illustrations. It is true that the Potomac clays attenuate southward and disappear about the Rappahannock River; but they are replaced by the impervious marls and clays of the Eocene and by a heavy bed of varicolored clays, probably Pliocene in age, though distinguishable from the Potomac only with difficulty, typically developed on and named from the Appomattox River.

Finally, the seaward inclination of the strata constituting the Coastal plain is so uniform that the approximate depth of the water-bearing sandstone anywhere near the inland margin of that plain may be inferred from its ascertained attitude and depth at the head of Chesapeake Bay.

Thus, although no attempt has been made to specifically solve the artesian well problem at any point along the fall-line or over the Coastal plain save at Fishing Battery station, it is believed that a general result of the investigation herein described is the approximate solution of that problem for an extensive region in which the subject is of prime importance, in such terms that it may be readily applied by practical men without special geologic training.
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