DEPARTMENT OF THE INTERIOR
Hubert Work, Secretary

U. S. GEOLOGICAL SURVEY
George Otis Smith, Director

PROFESSIONAL PAPER 132

SHORTER CONTRIBUTIONS TO GENERAL GEOLOGY

1923-1924

W. C. MENDENHALL, CHIEF GEOLOGIST

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[The letters in parentheses preceding the titles are those used to designate the papers for advance publication.]

ILLUSTRATIONS

SHORTER CONTRIBUTIONS TO GENERAL GEOLOGY 1923–1924.

ROCK FORMATIONS IN THE COLORADO PLATEAU OF SOUTHEASTERN UTAH AND NORTHERN ARIZONA.

By C. R. Longwell, H. D. Miser, R. C. Moore, Kirk Bryan, and Sidney Paige.

NATURE AND PURPOSE OF THE INVESTIGATION.

The field work of which this report is a record was done in the summer and fall of 1921 by members of the United States Geological Survey. A project to build a large storage dam at Lees Ferry, on Colorado River in northern Arizona, called for a detailed topographic survey of the area covered by the project, for the purpose of determining the capacity of the reservoir. This work was undertaken by the United States Geological Survey in cooperation with the Southern California Edison Co. Three surveying parties were sent to the field, each accompanied by a geologist, whose specific duty was to study and report on the rock formations within the area to be flooded.

One topographic party, under A. T. Fowler, which started at Lees Ferry and worked upstream in Arizona, was accompanied by Kirk Bryan. Another party, under K. W. Trimble, which started near Bluff and worked down the San Juan and thence down the Colorado, was accompanied by H. D. Miser. The third party, under W. R. Chenoweth, worked from Fremont River to the Waterpocket Fold and then returned to Green River, Utah, and traversed Cataract Canyon during the period of low water. C. R. Longwell was with this party until September, when his place was taken by Sidney Paige. Mr. Paige, in company with the Kolb brothers, E. C. La Rue, and Henry Rauch, left the Chenoweth party after Cataract Canyon had been surveyed and rowed down the Colorado to the mouth of the San Juan, where they were joined by Mr. Miser. Then they took a hurried trip by boat down the Colorado to Lees Ferry, making a few short stops and visiting the famous Rainbow Bridge.

Thus the geology of the canyons of Colorado and San Juan rivers and of the lower parts of tributary canyons was examined continuously, and reconnaissance work was done in the country back from the rivers. At the same time a fourth party, under R. C. Moore, was mapping parts of Kane, Garfield, and Wayne counties, Utah, to determine whether oil might be found there.

The present paper includes brief descriptions of the rocks of the regions traversed, detailed geologic sections, and columnar sections measured not only by the geologists who accompanied these parties but by other geologists who have worked in the same regions or in adjoining regions. The positions of the columnar sections measured and many of the other sections are shown on Figure 1.

PREVIOUS WORK.

The first geologic work done in the area here considered was that recorded in the report of the Macomb expedition of 1859 by J. S. Newberry,[1] who examined the Mesozoic formations near Bluff. Next followed J. W. Powell's historic explorations in 1869 to 1872, which contributed some geologic information, although their most valuable results were geographic.[2] G. K. Gilbert's work in 1875 and 1876 was necessarily of a reconnaissance nature, but it showed powers of observation and interpretation that have aroused the admiration of later workers who have used his report [3] as a guide.

[1] Newberry, J. S., Geological report, in Report of the exploring expedition from Santa Fe, N. Mex., to the junction of the Grand and Green rivers of the Great Colorado of the West, in 1859, under the command of Capt. J. N. Macomb, pp. 101-109, 1876.

[2] Powell, J. W., Exploration of the Colorado River of the West, 1875.

[3] Gilbert, G. K., Report on the geology of the Henry Mountains, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1880.

W. H. Holmes contributed information on the San Juan district,[4] in a report on field work that was in part contemporaneous with that done by Gilbert farther north and west. The classic reports of Gilbert and Holmes served all practical needs for a knowledge of this sparsely settled region until oil was discovered at Goodridge in 1908. H. E. Gregory [5] and E. G. Woodruff [6] made reports on the geology of the oil field, and Gregory later, in his reports on the Navajo country,[7] described the geology of the region on the south side of the San Juan. The most recent papers of direct interest in the present connection are those by W. B. Emery,[8] C. L. Dake,[9] Dorsey Hager,[10] C. T. Lupton,[11] and R. C. Moore.[12] Numerous papers on adjacent areas, herein referred to, have been of great assistance in making correlations.

TOPOGRAPHY.

The area considered in this report is part of a large arid region that is sparsely settled and difficult of access. It is a typical portion of the Colorado Plateau, characterized by canyons, cliffs, mesas, and buttes. The general plateau surface, averaging between 5,000 and 6,000 feet in altitude, appears fairly regular and continuous in a panoramic view; but Colorado River and its tributaries have cut hundreds of feet below the general level, and Navajo Mountain and the Henry Mountains project conspicuously above it, attaining maximum altitudes of about 11,000 feet. The Henry Mountains are classic as the type locality of the igneous intrusive masses known as laccoliths. Northwest of these mountains are the so-called High Plateaus, lofty forest-clad tablelands with gently irregular surface topography and precipitous borders, which have an average altitude of more than 9,000 feet.

Alternating sedimentary formations of varying resistance exert a strong topographic control. Heavy sandstone and limestone units form vertical cliffs or level mesa tops; shales produce slopes or local areas of badlands. Stream courses cut into sandstone or limestone are confined in narrow, steep-walled canyons; but at horizons of thick shales the valleys are wide, with vertical outer walls made by the overlying sandstones. Typical cross sections of the larger streams show prominent structural terraces or benches, which mark abrupt changes in the character of the rocks.

SEDIMENTARY ROCKS.

GENERAL FEATURES.

The nakedness of the surface rocks and their deep dissection give an excellent opportunity for detailed study, and when the entire region has been systematically surveyed there should be few important problems of correlation left unsolved. But in spite of the apparent simplicity of the geology it is not safe to attempt correlation of widely separated sections without knowledge of the intervening areas, however thorough the study of the sections may have been. Errors have already resulted from such attempts, and a certain degree of confusion now exists as to the exact stratigraphic succession and the proper terminology. Many of the formations are of continental origin, and some have yielded no determinable fossils. Certain of these formations have lithologic characteristics that are remarkably persistent over wide areas; but in many sections two or more formations are strikingly similar in general appearance, and members that are of only local distribution may be confused with formations that are considered the most trustworthy as guides to correlation. In correlating these deceptive formations, therefore, it is desirable to measure sections as close together as possible, and continuous tracing in the field is the most satisfactory method. The rocks are essentially horizontal or dip gently, except for local strong flexures, and the present writers found it possible to follow certain guide horizons essentially without interruption.

The rocks range in age from Pennsylvanian to Tertiary, but the Tertiary formations were not studied in detail. Triassic and Jurassic rocks are the most widely distributed forma-

[4] Holmes, W. H., Geological report on the San Juan district: U. S. Geog. and Geol. Survey Terr. Ninth Ann. Rept., for 1875, pp. 237-276, 1877.

[5] Gregory, H. E., The San Juan oil field, Utah: U. S. Geol. Survey Bull. 431, pp. 11-25, 1911.

[6] Woodruff, E. G., Geology of the San Juan oil field, Utah: U. S. Geol. Survey Bull. 471, pp. 76-104, 1912.

[7] Gregory, H. E., The Navajo country: U. S. Geol. Survey Water-Supply Paper 380, 1916; Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, 1917.

[8] Emery, W. B., The Green River Desert section, Utah: Am. Jour. Sci., 4th ser., vol. 46, pp. 551-577, 1918.

[9] Dake, C. L., The pre-Moenkopi unconformity of the Colorado Plateau: Jour. Geology, vol. 27, pp. 61-74, 1920; Horizon of the marine Jurassic of Utah: Jour. Geology, vol. 27, pp. 634-646, 1919.

[10] Hager, Dorsey, Oil possibilities of the Holbrook area in northeast Arizona, 1921. A private publication.

[11] Lupton, C. T., Geology and coal resources of Castle Valley, Utah: U. S. Geol. Survey Bull. 628, 1916.

[12] Moore, R. C., On the stratigraphy of northeastern Arizona: Am. Assoc. Petroleum Geologists Bull., vol. 6, No. 1, pp. 47-49, 1922. Discusses paper by Hager cited above.

tions on the surface, and they are largely of continental origin. Bright colors prevail, making the region a "painted desert" of great scenic interest. In Utah the older formations are revealed in a few broad anticlines, notably in Cataract Canyon and in the San Juan oil field; and in the adjoining part of Arizona they appear in Marble Canyon.

Besides the laccoliths of igneous rocks in the Henry Mountains there are a few igneous dikes and volcanic necks at other places in the part of the Colorado Plateau under discussion. In the High Plateaus, west of the Henry Mountains, there are large areas of extrusive igneous rocks. None of these igneous rocks are here described.

The section exposed in the walls of the Grand Canyon, which adjoins Marble Canyon, is probably better known than any other in the Colorado Plateau, and it is taken as a standard in correlating Paleozoic formations in the region. This section has been studied in great detail by L. F. Noble, and he has recently proposed some changes in the stratigraphic subdivision and the terminology to be used.[13] (See Fig. 1 and Pl. I.)

[13] Noble, L. F., in Schuchert, Charles, On the Carboniferous of the Grand Canyon of Arizona: Am. Jour. Sci., 4th ser., vol. 45, pp. 347-362, 1918. Noble, L. F., Paleozoic formations of the Grand Canyon at the Bass trail: U. S. Geol. Survey Prof. Paper 131, pp. 23-73, 1922.

His usage is indicated below, in comparison with the older usage, with a view to making clearer the discussion of Paleozoic formations here presented.

Older usage.		Noble's usage.	
Kaibab limestone		Kaibab limestone	(Permian).
Coconino sandstone		Coconino sandstone	
Supai formation	Upper	Hermit shale	
		Unconformity.	
	Lower	Supai formation (Pennsylvanian and Permian?).	
Redwall limestone	Upper		
		Unconformity (?).	
	Lower	Redwall limestone (Mississippian).	
Unconformity.		Unconformity.	
Pre-Carboniferous formations.		Pre-Carboniferous formations.	

In thus redefining the Supai and Redwall formations Noble has definitely referred the Hermit shale to the Permian on the basis of plant remains first discovered by Schuchert and identified by David White. No fossils have been found in the thick red sandstone at the top of the Supai formation as redefined, and this member may therefore belong either in the Permian or in the Pennsylvanian.

The rock formations studied in southeastern Utah and the adjoining part of Arizona are indicated in the following table:

Rock formations in southeastern Utah and the adjoining part of Arizona.

Age.	Formation.	Character.	Thickness (feet).	Remarks.
Tertiary (Eocene).	Wasatch (?) formation.	Calcareous sandstone, shale, and limestone; pink, white, and varicolored, evenly stratified, soft; composes highest plateaus; crops out in cliffs and forms slopes.	2,000	
		Unconformity		
Upper Cretaceous.	Masuk sandstone.	Yellowish-gray massive sandstone with some sandy shale; grades without break into formation below; a prominent cliff-forming division.	300-500	
	"Masuk shale."	Gray to drab sandy shale containing some thin beds of yellow sandstone.	500-1,000+	
	Blue Gate sandstone.	Yellow to brown irregularly bedded medium to massive sandstone; contains lignite beds up to 4 feet in thickness; forms prominent escarpments.	230-1,000	

Rock formations in southeastern Utah and the adjoining part of Arizona—Continued.

Age.	Formation.	Character.	Thickness (feet).	Remarks.
Upper Cretaceous.	"Blue Gate shale."	Bluish-drab argillaceous to sandy shale; very uniform in color and texture; forms slopes and badlands; thickness, 1,100–1,200 feet.	2,115–2,250	
	Tununk sandstone.	Yellowish medium to massive irregularly bedded sandstone; contains lignite; forms escarpments and hogbacks; thickness, 60–100 feet.		
	"Tununk shale."	Bluish-drab sandy shale grading to fossiliferous sandstone at base; shale contains abundant *Gryphaea newberryi* and other fossils; thickness, 900–1,000 feet.		
	Dakota (?) sandstone.	Yellow to nearly white sandstone; conglomeratic in part; irregularly bedded; contains lignite locally.	0–100	
		Unconformity		
Cretaceous (?) (Lower Cretaceous ?).	McElmo formation.	Maroon to light bluish-gray sandy banded shale; conglomerate; and coarse gritty maroon, yellow, and gray irregularly bedded sandstone; forms escarpments.	125–565	
		Unconformity		
Jurassic.	Varicolored sandstones and shales.	Very massive soft light creamy-white, tan, and orange-brown cross-bedded sandstone; grades into very sandy shale; weathers readily in rounded slopes and forms abundant dune sand.	170–1,430	Navajo sandstone of Emery. Included by Lupton in McElmo formation.
	Gypsiferous shales and sandstones.	Pink to red and bluish sandy shale, gypsum in beds up to 5 feet thick, and massive white sandstone; forms badlands; 50–300 feet. Shale, sandstone, and siliceous dark-maroon and light bluish-green limestone; forms distinct escarpment; 30–55 feet.	45–450	Todilto (?) formation of Emery. Horizon of marine Jurassic. Included in McElmo formation by Lupton.
	Navajo sandstone.	Light creamy-yellow, white, pinkish, and buff, highly cross-bedded, very massive calcareous sandstone; weathers in high cliffs and innumerable cones, towers, and domes; forms caves, alcoves, and natural bridges.	500–1,800	Gregory's usage. Included in Wingate sandstone by Emery.
	Todilto (?) formation.	Maroon coarse-grained cross-bedded sandstone; conglomerate; blue-gray hard dense limestone; maroon and brown shale. All in thin irregular beds.	125–249	Gregory's usage. Included in Wingate sandstone by Emery.

Rock formations in southeastern Utah and the adjoining part of Arizona—Continued.

Age.	Formation.	Character.	Thickness (feet).	Remarks.
Jurassic.	Wingate sandstone.	Reddish-brown very massive sandstone; prominently jointed; outcropping commonly in a single vertical cliff resembling a palisade. Cross-bedded but not so prominently as Navajo sandstone.	250–500	Gregory's usage. Included in Wingate sandstone by Emery.
		—Unconformity—		
Upper Triassic.	Chinle formation.	Thick variegated calcareous shales or "marls," fine-grained sandstones, cherty limestones, and conglomeratic limestone. Sandstone most abundant near top of formation.	300–1,000	
Upper (?) Triassic.	Shinarump conglomerate.	Light-gray to yellow coarse-grained to conglomeratic sandstone, very irregularly bedded and variable in thickness; grades locally into bluish sandy shale; contains silicified wood; forms prominent bench in topography.	0–220	
		—Unconformity—		
Lower Triassic.	Moenkopi formation.	Chocolate-brown to yellowish shale and sandstone, containing locally in upper portion very thin hard limestones. The shale very sandy and grading into shaly sandstones; the sandstone ranging from thin-bedded platy to thick massive beds. Ripple-marked. Contains DeChelly (?) sandstone lentil in middle portion; thickness, 0–200 feet.	304–920	Directly overlies Coconino sandstone where Kaibab limestone is absent.
		—Unconformity—		
	Kaibab limestone.	White to yellowish massive more or less dolomitic limestone; in part cherty; lower part increasingly sandy and grading into subjacent sandstone without sharp change. Fossiliferous in part.	0–250	Not continuous.
Permian.	Coconino sandstone.	White to tan massive calcareous saccharoidal hard to friable sandstone. In Circle Cliffs not differentiated from Supai (?) formation.	300–1,000	
	Supai (?) formation.	Red to light-yellow shale and sandstone.	380	Possibly Hermit shale.
		—Unconformity—		
Pennsylvanian.	Goodridge formation.	Bluish fine-grained dense, medium to massively bedded limestone; red and grayish-white sandstone, in part petroliferous; red and dark-gray sandy shales. Limestone predominates in lower part of section, sandstone and shale in upper part.	1,582	

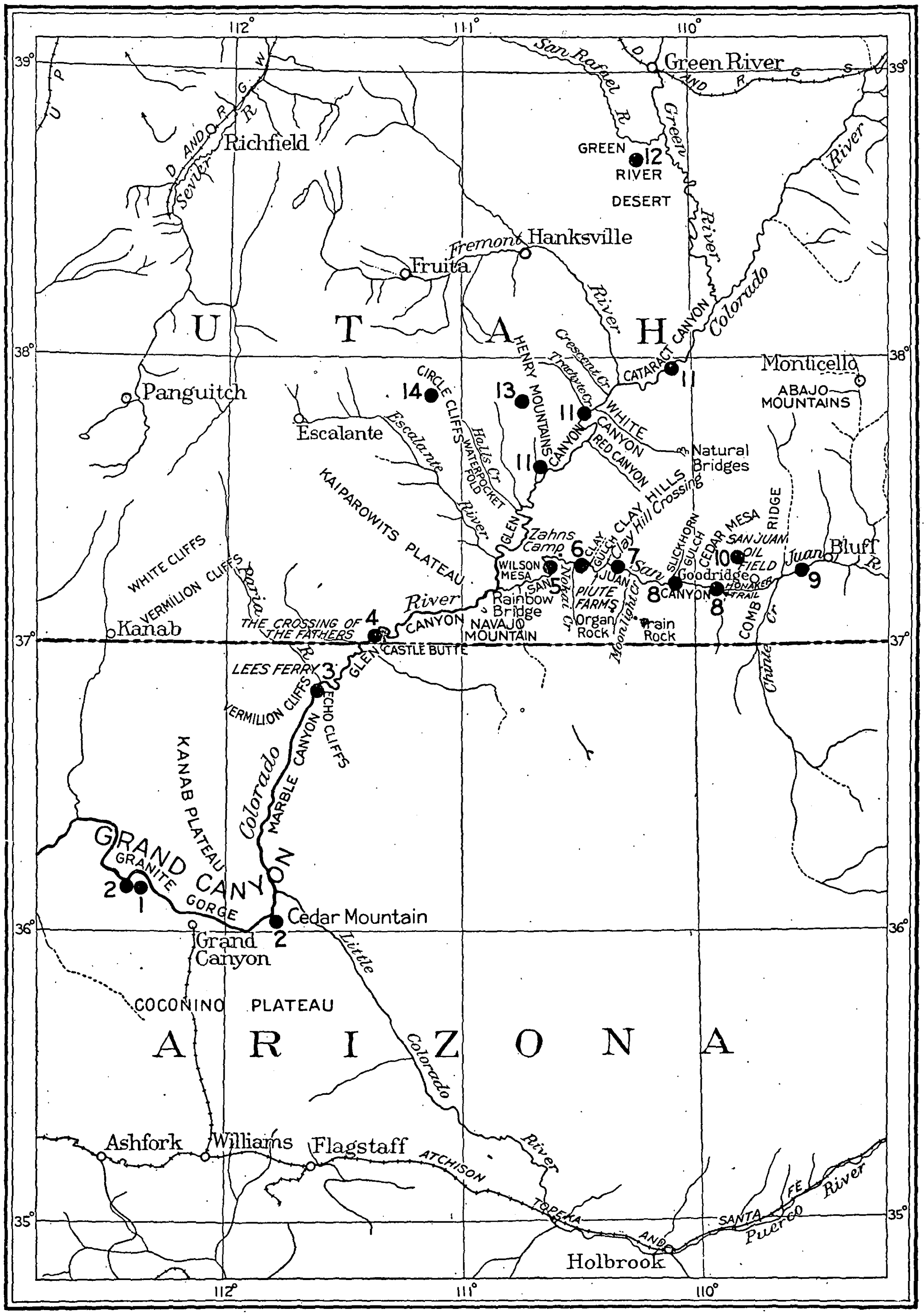
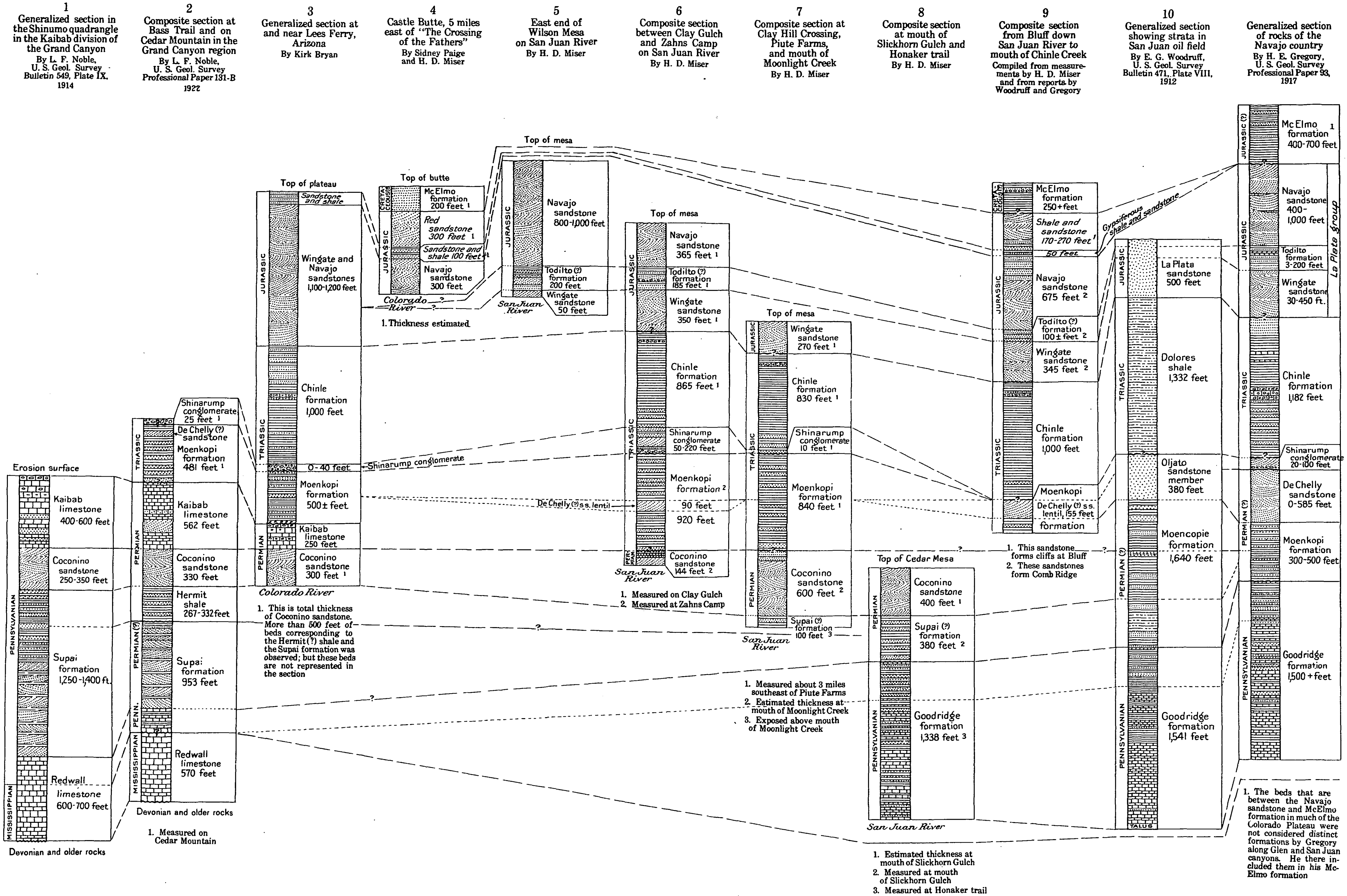
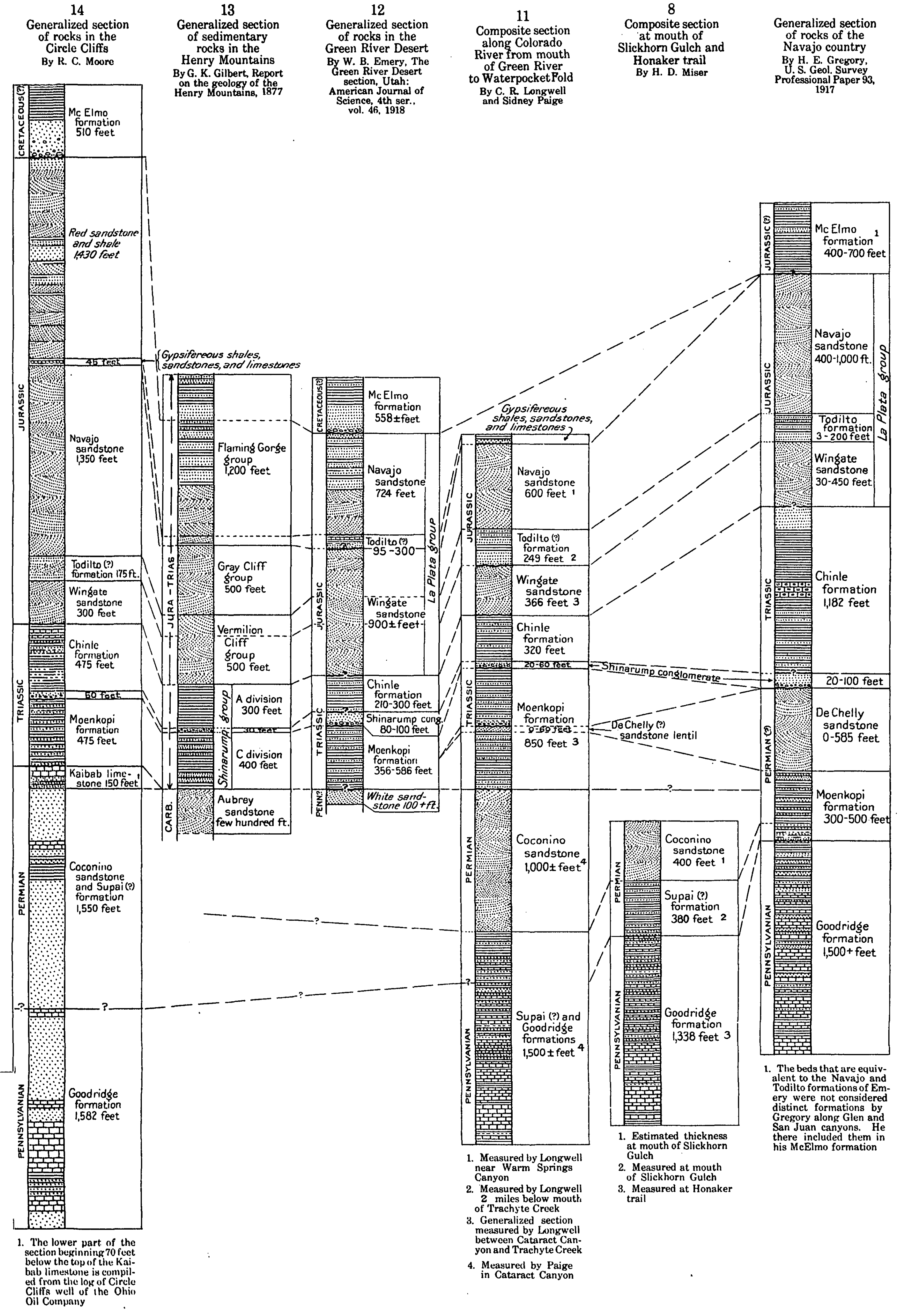


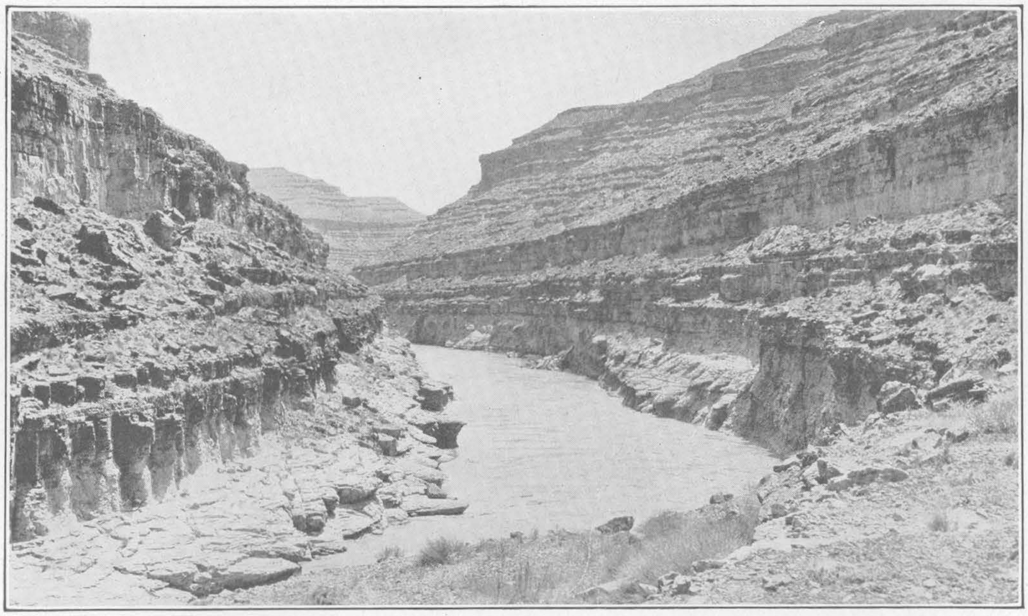
FIGURE 1.—Index map of parts of Utah and Arizona showing location of columnar sections (numbered dots) given in Plates I and II. Nos. 1 to 10 are given in Plate I; Nos. 11 to 14 in Plate II.



GENERALIZED COLUMNAR SECTIONS OF THE PALEOZOIC AND MESOZOIC ROCKS OF NORTHERN ARIZONA AND SOUTHEASTERN UTAH

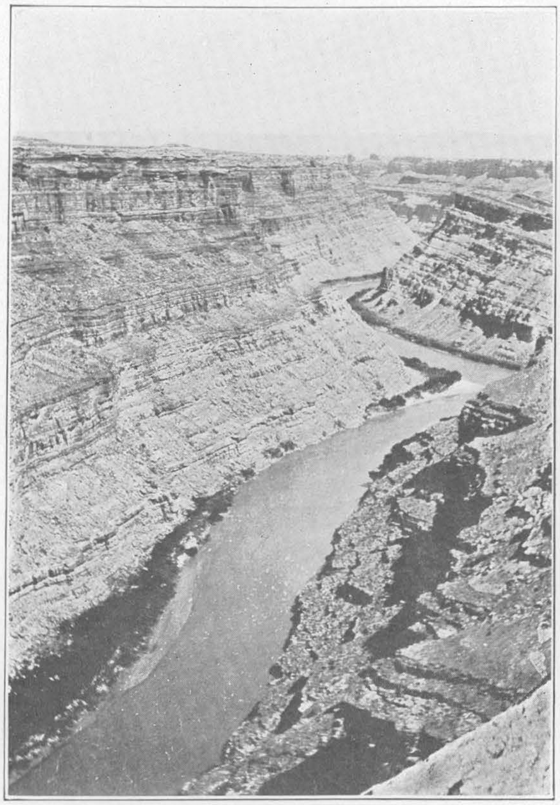


GENERALIZED COLUMNAR SECTIONS OF THE PALEOZOIC AND MESOZOIC ROCKS OF SOUTHEASTERN UTAH



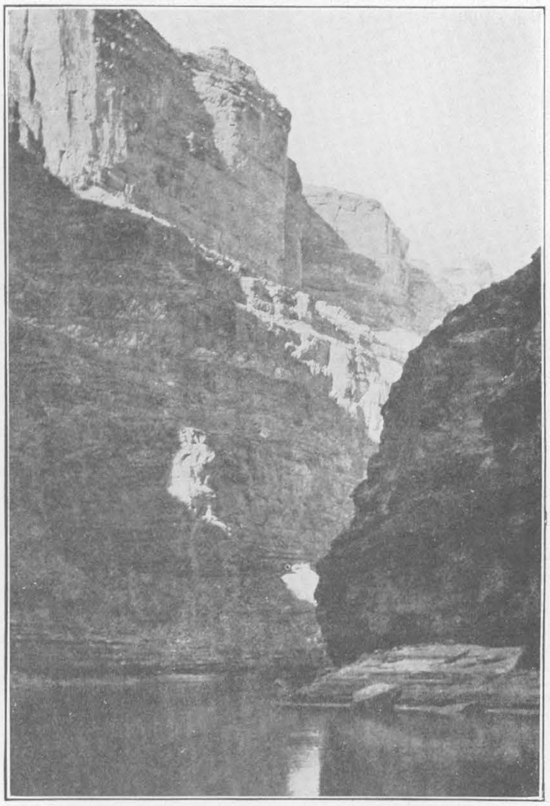
A. VIEW LOOKING DOWN SAN JUAN CANYON, UTAH, AT A POINT 9 MILES BY STREAM ABOVE HONAKER TRAIL.

Canyon has been cut in Goodridge formation. Photograph by Robert N. Allen.



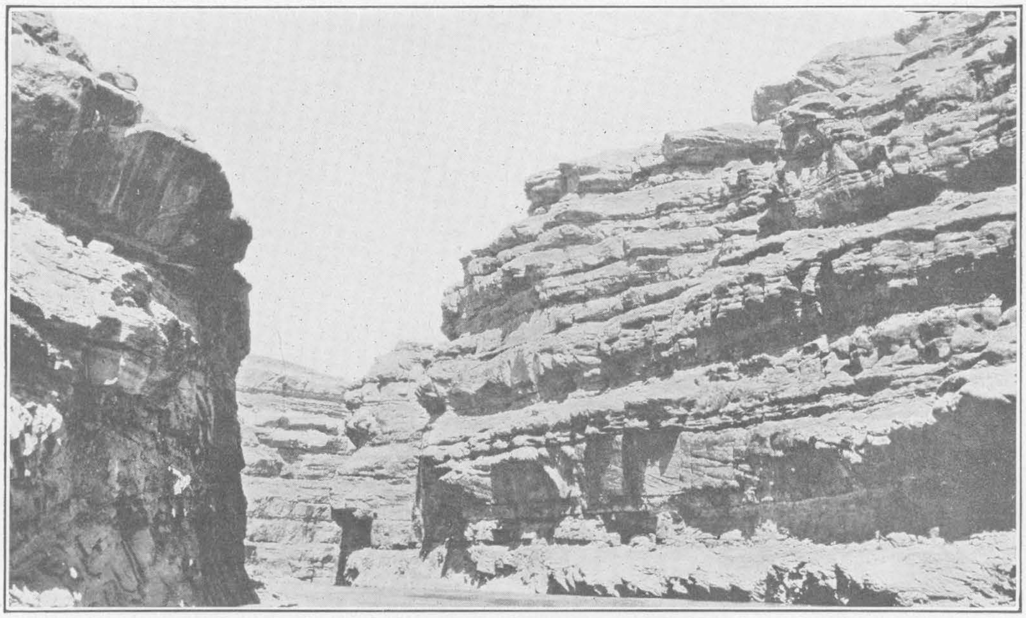
B. VIEW LOOKING DOWN GREEN RIVER TOWARD ITS JUNCTION WITH COLORADO RIVER, UTAH.

Canyon cut in Goodridge formation. Photograph by Sidney Paige.



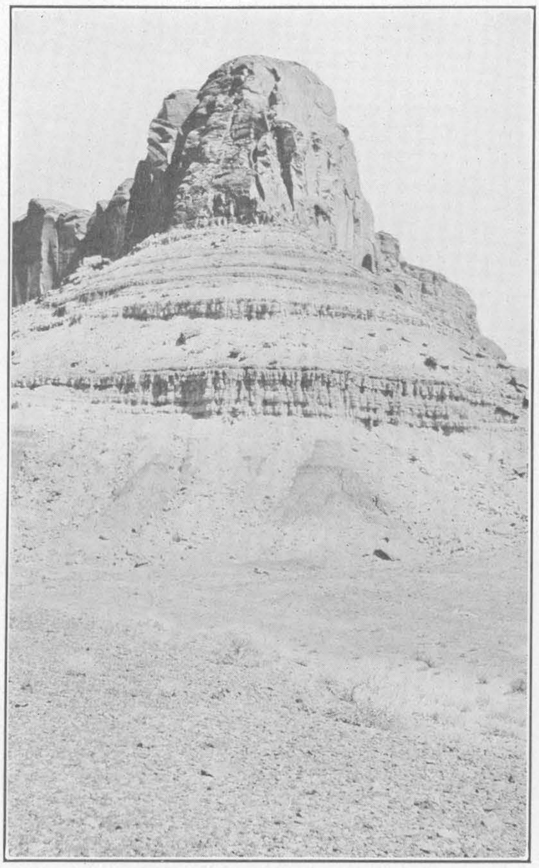
C. VIEW IN CATARACT CANYON OF THE COLORADO, UTAH.

Goodridge formation forms lower part of canyon walls and Coconino sandstone the upper part. These two formations are probably separated by beds that are equivalent to the Supai (?) formation of the San Juan Canyon. Photograph by Sidney Paige.



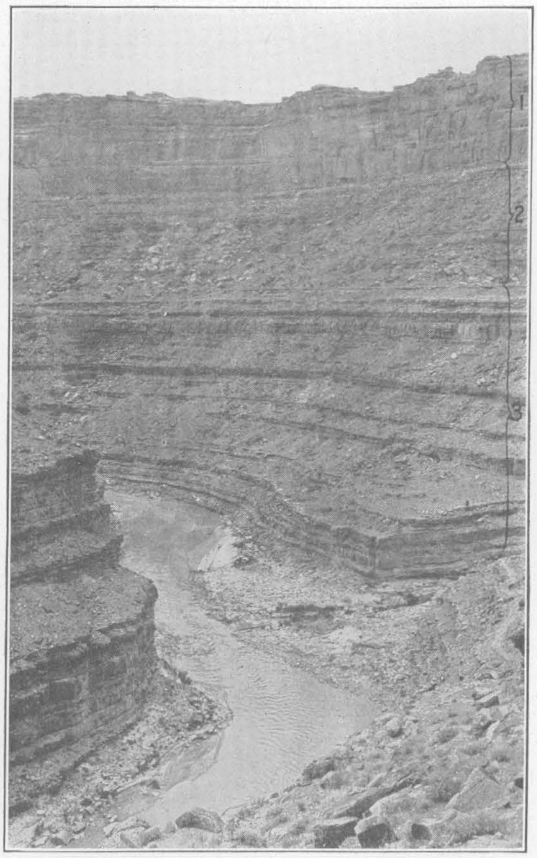
A. VIEW LOOKING DOWN SAN JUAN CANYON, UTAH, AT A POINT BETWEEN CLAY HILL CROSSING AND THE MOUTH OF MOONLIGHT CREEK.

Coconino sandstone forms canyon walls. Photograph by H. D. Miser.



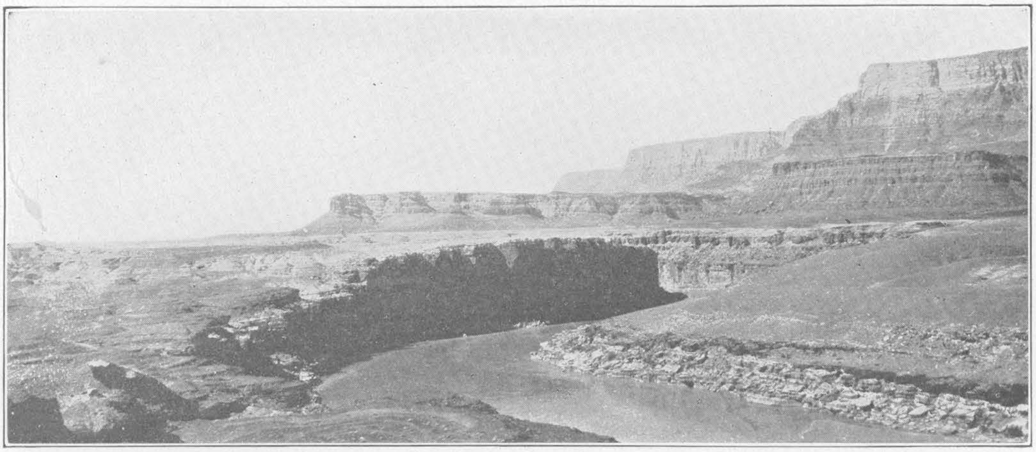
B. VIEW NEAR COLORADO RIVER 2 MILES BELOW MOUTH OF TRACHYTE CREEK, UTAH.

Showing Chinle formation, about 320 feet thick, capped by Wingate sandstone. Part of wide bench in foreground is on Shinarump conglomerate. Photograph by C. R. Longwell.



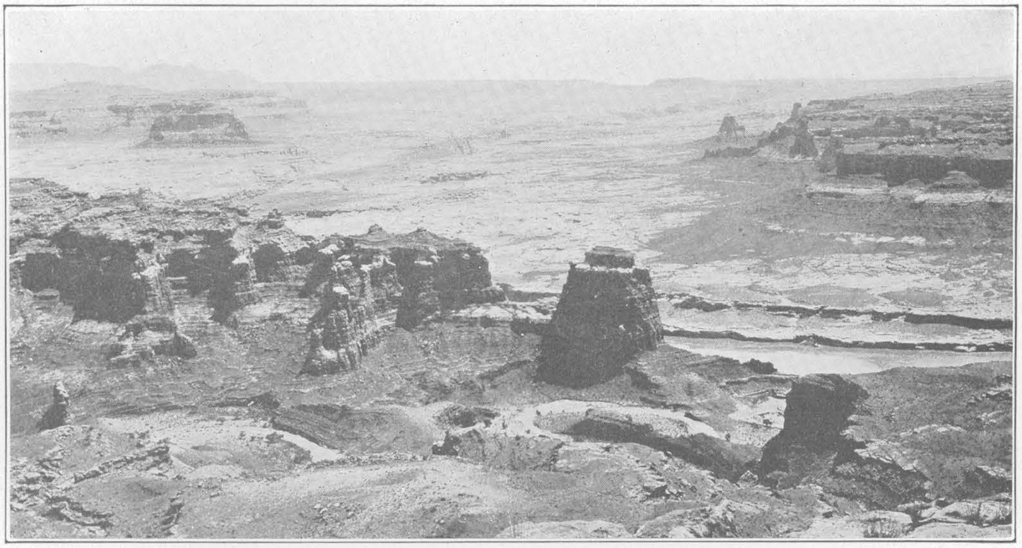
C. VIEW LOOKING DOWN SAN JUAN CANYON AT THE MOUTH OF SLICKHORN GULCH, UTAH.

1, Coconino sandstone; 2, Supai (?) formation; 3, Goodridge formation. The rapid is produced by a boulder bar at the mouth of Slickhorn Gulch. Photograph by Robert N. Allen.



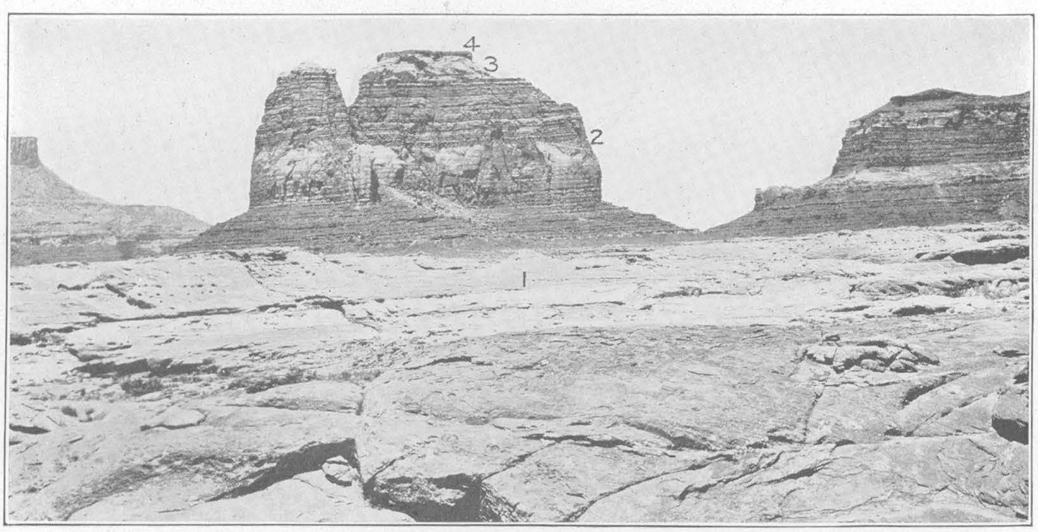
A. VIEW LOOKING SOUTHWEST DOWN HEAD OF MARBLE CANYON FROM POINT NEAR LEES FERRY, ARIZ.

Platform in foreground is underlain by Kaibab limestone; next higher platform reveals the Moenkopi formation and is capped by Shinarump conglomerate; the high Vermilion Cliffs, to the right, are formed by Wingate and Navajo sandstones. Chinle formation is exposed on steep slope below Vermilion Cliffs. Photograph by Kirk Bryan.



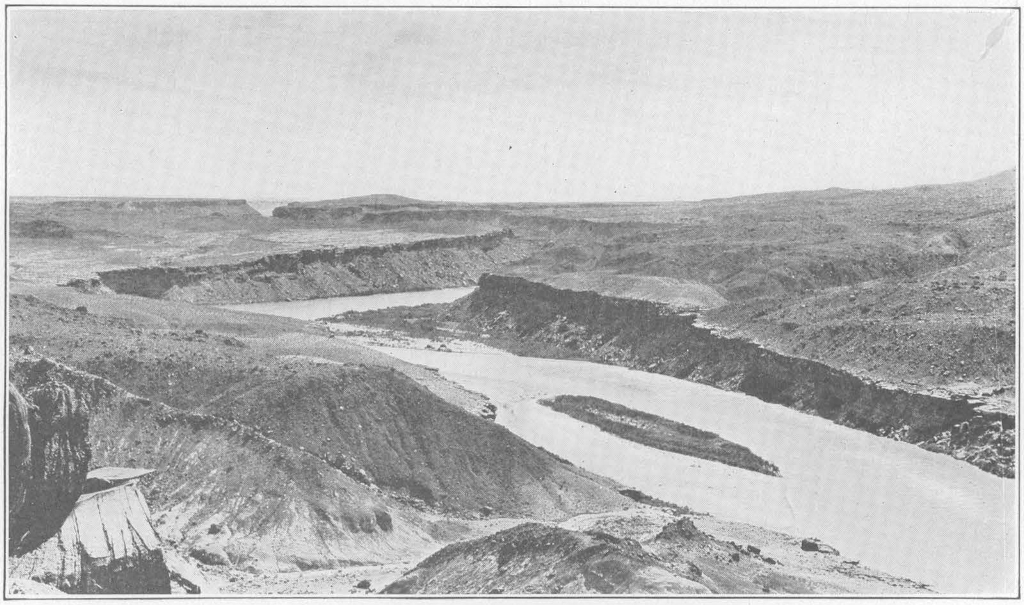
B. VIEW LOOKING UP COLORADO RIVER FROM A HIGH POINT NEAR THE MOUTH OF CRESCENT CREEK, UTAH.

Crescent Creek in foreground. The Colorado is deeply incised in the Coconino sandstone, which forms the light-colored platform. Moenkopi formation in the foreground is stripped from this platform. Photograph by C. R. Longwell.



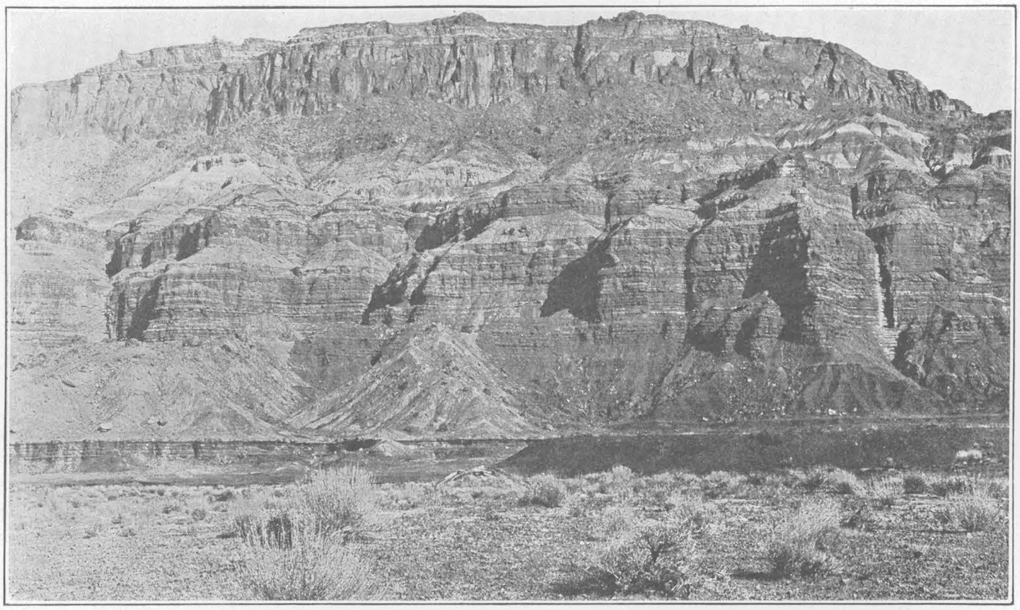
C. EROSION REMNANTS STANDING ON PLATFORM OF COCONINO SANDSTONE NEAR MOUTH OF FREMONT RIVER, UTAH.

1, Coconino sandstone; 2, lower member of Moenkopi formation; 3, De Chelly (?) sandstone lentil of Moenkopi formation; 4, conglomerate at base of upper member of Moenkopi formation. Photograph by C. R. Longwell.



A. VIEW LOOKING UP SAN JUAN CANYON FROM POINT NEAR MOUTH OF CLAY GULCH, UTAH.

Platform is underlain by Shinarump conglomerate, but in foreground terrace gravels and landslide material rest on Shinarump. Moenkopi formation is exposed in lower part of canyon walls. Photograph by Robert N. Allen.



B. VIEW LOOKING WEST TOWARD HIGH MESA AT CLAY HILL CROSSING ON SAN JUAN RIVER, UTAH.

Coconino sandstone underlies level foreground; Moenkopi formation, next above, weathers with fluted edges; De Chelly (?) sandstone lentil of Moenkopi is absent; Chinle forms steep badland slope with dark and light bands; Wingate, Todilto (?), and Navajo formations form cliffs at top of mesa. Shinarump conglomerate is absent. Photograph by Robert N. Allen.

CARBONIFEROUS SYSTEM.

Goodridge formation.—The Goodridge formation, which has been described by Woodruff,[14] is best exposed at the type locality on the Honaker trail in San Juan Canyon near Goodridge, where the canyon has been carved into it to a depth of 1,338 feet without revealing the base. It is of marine origin and consists of sandstone, sandy shale, and cherty limestone, with gray limestone predominating in the lower 500 feet and sandstone and shale in the upper portion. (See Pls. III, *A*, and IV, *C*.) Red is the most common color of the beds in the upper 700 feet. The base of the formation is nowhere exposed, and therefore its relation to older rocks is not known. A less complete section of the formation—about 1,000 feet—is exposed in another anticline east of Goodridge. About 1,500 feet of it is exposed in Cataract Canyon on the Colorado. (See Pls. II, III, *B* and *C*.) A deep well drilled in the Circle Cliffs by the Ohio Oil Co. penetrated in its lower part 1,582 feet of white sandstone and limestone that may represent the Goodridge formation.

Fossils are abundant and are distributed throughout the type section from a horizon near the base to the top. G. H. Girty, who has studied the faunas, makes the following statement:

The Goodridge formation, as described by Woodruff,[14] comprises two widely different faunas. The lower fauna, which contains almost no true Mollusca, changes abruptly, at bed No. 55 of his published section, to one that contains almost nothing else. The base of the bed as measured by Miser is 314 to 324 feet below the top of the formation. The character of the change suggests that it may not be as significant as the degree of the change might indicate.

The two sections that naturally invite comparison with the Goodridge are the San Juan section, Colorado, to the east, and the Grand Canyon section, to the west. [See Pl. I.] As I suggested in 1912, the general faunal resemblances would tend to correlate the upper part of the Goodridge with the Rico formation in the San Juan region and with the upper part of the Redwall limestone [old usage of Redwall] in the Grand Canyon region. On the same grounds the lower part of the Goodridge would be correlated with the Hermosa formation of the San Juan, which underlies the Rico. In the Grand Canyon section, however, the lower part of the Goodridge has no equivalent that can at present be recognized, but it is closely related faunally to the Magdalena limestone of New Mexico.

Developments of the last ten years have brought about an assignment of the Rico formation to the Permian (?), while the upper part of the old Redwall limestone is referred to the Pennsylvanian and now included in the Supai formation. It is evident that the upper part of the Goodridge can not be correlated with both these formations and yet these assignments be correct. An error evidently exists, but it can not at present be located. The correlations here adopted seem the natural ones, and it is thought better to continue them for the present and to leave adjustments of age determinations to a future day and more satisfactory evidence.

At present, therefore, the upper part of the Goodridge can not be assigned with assurance to any epoch, but the greater part of the formation is certainly Pennsylvanian. It is evident from Mr. Girty's remarks that any attempt to match the Goodridge with a part of the standard Grand Canyon section must be considered as tentative only. This fact should be borne in mind in connection with the columnar sections (Pls. I, II) offered in this paper.

Sandstone and limestone beds of the Goodridge formation supply the oil in the San Juan field, as noted by Gregory and Woodruff. Some of these oil-bearing beds are near the top of the formation, but others are much deeper, the lowest being 1,300 feet below the top. Oil seeps occur at several places along the bottom of the San Juan Canyon. The largest extends for 1¼ miles above the mouth of Slickhorn Gulch, and the oil at this locality comes from westward-dipping beds along and near a fault about 520 feet below the top of the Goodridge.

Supai (?) formation.—The Goodridge formation in the San Juan region and in Cataract Canyon is overlain by red sandy shale and shaly sandstone. (See Pl. III, *C*.) Gregory notes that no definite unconformity is recognized at the top of the Goodridge,[16] but there appears to be a transition to the red beds above through limestone conglomerate that may represent a gradual change from marine to continental conditions. At the mouth of Slickhorn Gulch, on the west side of the San Juan oil field, these higher red beds are 380 feet thick. (See Pl. IV, *C*.) In view of their lithologic character and their position immediately beneath the Coconino sandstone, a possible correlation with Noble's Hermit shale is suggested; but in the absence of fossils the beds are correlated doubtfully with the upper part of Noble's Supai formation, which has a much wider known distribution than the Hermit shale. Woodruff and Gregory referred these red beds to the lower part of the Moenkopi formation, which is now recognized as Triassic. (See Pls. I and II.)

[14] Woodruff, E. G., op. cit., pp. 80–85.

[16] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, p. 21, 1917.

In the head of Marble Canyon about 500 feet of red shale and sandstone containing beds of blue limestone in their lower part were observed beneath the Coconino sandstone. The highest of these beds may be equivalent to Noble's Hermit shale, but the lowest are probably equivalent to his Supai formation.

Coconino sandstone.—The Coconino sandstone has yielded no determinable fossils, but it is recognized in southern Utah by criteria other than its peculiar lithologic character. In Marble Canyon, southwest of Lees Ferry, Ariz., the sandstone is present in its normal position beneath the Kaibab limestone, which in turn is unconformably overlain by the Lower Triassic Moenkopi beds. In Circle Cliffs the same relations are seen but the Kaibab is much thinner than at Lees Ferry and localities farther west. In and about Cataract Canyon and on the San Juan the Kaibab is absent and the Moenkopi rests unconformably on a thick sandstone that has all the characteristics of the Coconino. Gilbert recognized this relation near Cataract Canyon and referred to the sandstone as the "Upper Aubrey sandstone," the name used at that time for the Coconino in the Grand Canyon. (See Pls. I, II, IV, *C*, and V, *B* and *C*.)

The sandstone here called Coconino has been traced by B. S. Butler,[17] F. L. Hess,[18] H. E. Gregory,[18] C. R. Longwell, and H. D. Miser practically the entire distance from Cataract Canyon to the San Juan oil field by way of White Canyon. The three large natural bridges in White Canyon are stated by Hess and Gregory to have been formed in this sandstone. On the San Juan the Coconino is exposed in a small area on the crest of an anticline at Zahns Camp, but farther upstream it is exposed over large areas, being the surface formation in the part of Moonlight Valley in which Train and Organ rocks are situated and also in the broad dissected plateau between the Clay Hills and the San Juan oil field. (See Pl. IV, *A* and *C*.) The eastern part of the plateau is known as Cedar Mesa. Woodruff[19] states that eastward from Cedar Mesa the sandstone grades completely into red sandy shale on the southeast side of the oil field. This shale and the equivalent sandstone were included by Woodruff[20] and Gregory[21] in their Moenkopi formation. (See Pls. I and II.)

The sandstone is massive and highly cross-bedded, and its color is creamy white, though on Cedar Mesa much of it is tan. The grains are fine to medium in size, and as a rule the cement of calcium carbonate is sufficient to make the rock fairly firm, although in places it is friable. The greatest thickness observed is in Cataract Canyon, where it measures nearly 1,000 feet. In the Circle Cliffs only the top of the formation can be seen, but the deep well mentioned above penetrates white sandstone hundreds of feet thick immediately beneath the Kaibab and then passes through beds that are probably the equivalent of the Supai (?) formation. The Coconino, as well as most of the supposed Supai there, consists of white sandstone, so that these two formations can not be separated in the well log. Their combined thickness is 1,550 feet. Near the mouth of Moonlight Creek on the San Juan the thickness of the Coconino is about 600 feet; at the mouth of Slickhorn Gulch, also on the San Juan, it is about 400 feet; at Lees Ferry it is 300 feet; in the Grand Canyon it ranges from 250 to 350 feet; and to the west it gradually decreases,[22] the formation losing its identity in southern Nevada.[23] Thus it is evident that the sandstone thickens consistently toward the northeast in the area of its known distribution.

Kaibab limestone.—Typical Kaibab limestone consisting of white and yellow dolomite and limestone with numerous chert nodules is present in the Circle Cliffs, but its thickness is only 150 feet, as compared with 250 feet at Lees Ferry, 400 to 600 feet in the Grand Canyon,[24] and 1,000 feet in northwestern Arizona and southwestern Utah.[25] (See Pl. V, *A*.) It is not found in Cataract Canyon, in the Henry Mountains,[26] or along San Juan River. (See Pls. I and II.) Thus it appears to thin progressively toward the northeast, with the thickening

[17] Butler, B. S., The ore deposits of Utah: U. S. Geol. Survey Prof. Paper 111, pp 619–620, 1920.

[18] Oral communication.

[19] Woodruff, E. G., op. cit., p. 86.

[20] Woodruff, E. G., op. cit., pp. 86–87.

[21] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, pp. 29–30, 1917.

[22] Reeside, J. B., and Bassler, Harvey, Stratigraphic sections in southwestern Utah and northwestern Arizona: U. S. Geol. Survey Prof. Paper 129, pp. 57–58, 1922.

[23] Longwell, C. R., Geology of the Muddy Mountains, Nev., with a section to the Grand Wash Cliffs in western Arizona: Am. Jour. Sci., 5th ser., vol. 1, p. 47, 1921.

[24] Noble, L. F., The Shinumo quadrangle, Grand Canyon district, Ariz.: U. S. Geol. Survey Bull. 549, p. 70, 1914.

[25] Reeside, J. B., and Bassler, Harvey, op. cit., pp. 69–76.

[26] Gilbert, G. K., Geology of the Henry Mountains, p. 4, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1880.

of the Coconino sandstone in this direction, suggesting lateral gradation of the limestone into the sandstone at the top of the Coconino. It is probable, however, that a large part of the thinning is due to beveling during the erosion interval recorded by the unconformity at the base of the Triassic. This problem is of considerable interest, especially to the paleogeographer, for under the first interpretation the Kaibab shore line certainly lay at no great distance east of the Circle Cliffs, whereas the alternate explanation permits a much greater extension of the Kaibab sea eastward. Study of the Kaibab faunas gives weight to the suggestion that pre-Triassic erosion beveled progressively eastward, for the fauna found in the Circle Cliffs is of the "normal Kaibab" type[27] and not the upper "*Bellerophon* limestone" fauna. Therefore it is probable that the Kaibab present in the Circle Cliffs is lower stratigraphically than the top of the Kaibab in the Grand Canyon and the "*Bellerophon* bed" in the Park City formation of the Uinta country.

EROSION INTERVAL.

A significant unconformity separates the Paleozoic and Mesozoic sections. There is no perceptible divergence between beds, but an unmistakable surface of erosion lies beneath the Moenkopi formation wherever it has been studied in Arizona, Utah, and Nevada. The unconformity is particularly well shown near Cataract Canyon and about the mouth of Fremont River, where the top of the Coconino sandstone forms wide structural platforms. Recent erosion has stripped away the soft Triassic sediments, and the more resistant Coconino preserves large areas of the pre-Triassic erosion surface almost unchanged, with patches of the basal conglomerate of the Moenkopi still adherering to it here and there in the shallow valleys and rounded divides. Farther back from the main streams recent canyons are cut through the contact, revealing it as a distinct wavy line, overlain by conglomerate in which all the pebbles are of sandstone.

TRIASSIC SYSTEM.

Moenkopi formation.—The Moenkopi formation, of Lower Triassic age, comprises thick beds of shale and sandstone that lie unconformably on the Permian rocks and are at most places unconformably overlain by the distinctive Shinarump conglomerate. As thus defined the Moenkopi consists of several members, which vary considerably in character and thickness from one locality to another. The total thickness ranges from 304 feet in the Circle Cliffs to 920 feet south of the Henry Mountains and along San Juan River. No marine fossils have been reported from the formation in southern Utah, but the lower beds exhibit a regularity and a uniformity of texture that suggest deposition in a large body of water. Farther west and southwest, in Arizona, southern Nevada, and southwestern Utah, the lower part of the formation is clearly of marine origin but the upper part is unmistakably of continental origin.

Along the San Juan the Moenkopi consists principally of red sandy shale and earthy sandstone, with a little gypsum. (See Pl. VI, *B*.) South and southwest of Piute Farms, on the river, a thin bed of cream-colored sandstone is found near the middle of the formation, and this layer thickens gradually toward the south, developing into a massive cross-bedded member which in Train Rock has an estimated thickness of about 200 feet. This sandstone is apparently the same as the sandstone in southeastern Utah called De Chelly by Gregory. He treated the De Chelly as a separate formation, because in most of the region he studied south of the San Juan he found it above Moenkopi shales and immediately underneath the Shinarump conglomerate. He also found that the "Oljato sandstone" of Woodruff is made up of the De Chelly and the Shinarump. (See Pl. I.) The De Chelly sandstone, according to Gregory, is present on the east side of the San Juan oil field, where it is red and thins out toward the north. He also states that the Shinarump conglomerate, wherever it is present on the east side of the oil field, rests on the De Chelly sandstone. It appears probable, therefore, that the upper shales of the Moenkopi were entirely removed in part of the Navajo country by pre-Shinarump erosion. An alternate hypothesis might be that these upper shales are replaced toward the south by the thickening of the De Chelly sandstone.

The sandstone that is here tentatively correlated with the typical De Chelly sandstone of northeastern Arizona disappears entirely near

[27] See Reeside, J. B., and Bassler, Harvey, op. cit., pp. 66–67.

Piute Farms and Clay Hill Crossing on the San Juan, and it was not recognized in sections for 25 miles north of Clay Hill Crossing.

Along Colorado River below Cataract Canyon the Moenkopi again shows three distinct divisions. The lower division, about 400 feet thick, consists of red and maroon sandstone and sandy shale in regular beds, with a gray conglomerate layer at the base. Shaly beds predominate near the bottom of the section, forming a slope that steepens upward and merges into a cliff made of the more resistant red sandstone. In most sections this cliff is capped with a layer of cross-bedded gray or cream-colored sandstone, ranging in thickness from a few inches to 60 feet. On account of its persistence and its striking contrast with the underlying red beds this member forms an excellent horizon marker. Its stratigraphic position and lithologic character suggest its correlation with the De Chelly (?) lentil on the San Juan.

The upper division of the Moenkopi along this portion of the Colorado consists chiefly of chocolate-colored, red, and gray shale and sandstone ranging in thickness from 350 to nearly 400 feet. Thin-bedded sandstone predominates in the lower part, and the proportion of sandy shale increases upward. The division as a whole has a weak topographic expression, forming a concave slope below the Shinarump cliff. Thin flaggy sandstone layers with strong ripple marks and current marks recur at short intervals in the section. Lenticular layers of cross-bedded sandstone 15 feet in maximum thickness are also common and form the roofs of many old cliff dwellings that are built in reentrants at horizons of shale. All the sandstone beds show evidence of strong fluviatile action, and the shales were probably deposited on flood plains or in shallow temporary lakes. A persistent layer of conglomerate, from a few inches to 25 feet thick, forms the base of the upper division and fills erosion channels in the De Chelly (?) sandstone. This distinct erosional unconformity within the Moenkopi is seen in all sections along Colorado River and its tributaries from Cataract Canyon to Red Canyon, where the gradual westward dip carries the formation below the surface. (See Pls. V and VII, *A*.)

Near Lees Ferry, Ariz., the Moenkopi consists of about 500 feet of red sandy shale and thin-bedded sandstone with seams of gypsum, but 50 miles to the south it has numerous thick beds of red and buff sandstone. Near Jacobs Pools, 25 miles west of Lees Ferry, 12 feet of greenish-yellow sandy shale and 12 feet of yellow sandy and gypseous limestone occur at the top of the formation.

In the Circle Cliffs the Moenkopi consists of 475 feet of chocolate-colored and yellow shale and sandstone with a few thin beds of hard limestone near the top. No gypsum was seen in the formation in this area or along the Colorado, but secondary veins of gypsum traverse the Moenkopi shales near Fruita, in Wayne County, Utah. Only a little gypsum occurs in the Moenkopi of the San Juan region and near Lees Ferry, and the general scarcity of the mineral in the entire region under discussion is noteworthy in view of the high content of primary and secondary gypsum found in both the marine and continental phases of the Lower Triassic in Arizona, southern Nevada, and southwestern Utah.

From the foregoing account and from the columnar sections (Nos. 6 to 9 on Pl. I) it is apparent that the Moenkopi of Woodruff and Gregory in the San Juan region includes not only the typical or true Moenkopi but also the Coconino sandstone and the Supai (?) formation.

Shinarump conglomerate.—The remarkable persistence of the Shinarump conglomerate has excited the wonder of geologists who have studied Triassic sections in different parts of the Colorado Plateau. Within the area under discussion it is generally present at the base of the Upper Triassic, lying on the eroded upper surface of the Moenkopi formation. It is a massive unit of coarse cross-bedded sandstone, in which are interspersed lenses of conglomerate that contain small rounded pebbles of chert, quartzite, and silicified wood. Silicified logs are abundant, and many plant impressions were seen on bedding surfaces. The average thickness of the unit is probably less than 50 feet, but it fills depressions in the underlying beds and at some localities attains a thickness of more than 200 feet. Near the mouth of Nokai Creek on the San Juan the thickness is 220 feet.

The position of the Shinarump conglomerate between two thick shaly formations gives it a strong topographic expression on the sides of valleys, the edge forming a prominent cliff in front of a stripped bench and above a pronounced slope. (See Pls. IV, *B*; V, *A*; VI, *A*; and VII.) The formation is made still more conspicuous in many sections by its dark color on exposed edges; for although the fresh sandstone is ordinarily gray, it appears to acquire an especially dark coat of desert varnish with long exposure. This characteristic is so pronounced that the Shinarump is often referred to as "the black layer" by prospectors and others along the Colorado. Deposits of carnotite in the formation have been mined at several localities.

The exact conditions under which the Shinarump was deposited have been the subject of much discussion, and no conclusion appears to be generally accepted. Whatever the conditions were, it is evident that they must have been almost uniform over a very wide region, for in its essential characteristics the formation differs little in all the sections studied in Utah, Arizona, and Nevada. The uniformity extends even to its thickness, for the total section rarely exceeds 200 feet, and this maximum applies to very small areas. The lenticular and cross-bedded structure indicates the action of shifting streams with fluctuating volume, and the uniformly small thickness evidently indicates a nearly even surface with slight elevation. It is not probable that the region was a desert, for the abundance of silicified wood found in all sections testifies to a climate suitable for the growth of large trees.

Chinle formation.—The Shinarump is believed to be the "basal conglomerate" of the Upper Triassic, for the finer sediments of the Chinle formation in this region follow without any apparent break. Thick beds of marly shale, gray, pink, lavender, yellow, and variegated, form the most conspicuous part of the Chinle. Fine-grained sandstone, cherty limestone, and a few conglomeratic beds are intercalated with the shale. Large silicified logs are found in sandstone layers at several horizons, and there are other indications that the entire deposit is of continental origin. Along the San Juan the thickness ranges from 800 to 1,000 feet, and at Lees Ferry it is about 1,000 feet thick, but it is much thinner to the north, averaging 300 feet along the Colorado above the Waterpocket Fold and 450 feet west of the Waterpocket Fold. This thinning may be due in part to pre-Jurassic erosion, for an erosional unconformity at the top of the Chinle is generally recognized, especially in the northern localities, although it does not appear to be profound.

Wherever the Chinle is exposed over areas of considerable size it gives rise to badland topography. Along the sides of valleys it forms long slopes, broken by low steps at horizons of sandstone or limestone layers. (See Pls. IV, *B;* V, *A;* VI, *B;* VII; and VIII, *B*.)

Limestone is found in the upper part of the formation in beds that range from a few inches to 2 feet in thickness, intercalated with limy shales. The limestone is dense and hard and contains an abundance of chert in nodules or lenses. Layers of intraformational limestone conglomerate are not uncommon. In most places the limestone beds are thin and are limited to a section not exceeding 30 feet in thickness, but at a few localities the individual layers average nearly 2 feet in thickness and make up fully half of a section 50 or 60 feet thick. Sandstone increases in amount toward the top of the formation.

JURASSIC SYSTEM.

General features.—Red, brown, tan, and gray sandstones of Jurassic age form the most prominent outcrops in the area under consideration. The units were traced almost continuously, and their relations for this portion of the plateau were determined without question. There still exists some degree of doubt as to the proper terminology to be applied in the Jurassic section, however, and the reasons for this uncertainty will be discussed briefly.

In the eastern part of the Navajo country Gregory recognized three Jurassic formations,[28] which he thought were equivalent to the La Plata sandstone of southwestern Colorado. For the lowest unit he adopted Dutton's term Wingate sandstone, considering it identical with the section in the Zuni Plateau,[29] to which this name had been applied, and he called the upper formation the Navajo sandstone. In western New Mexico and eastern Arizona these two thick, cross-bedded formations are separated by beds of hard limestone and limy shale, at no place aggregating a

[28] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, pp. 52-59, 1917.

[29] Dutton, C. E., Mount Taylor and the Zuni Plateau: U. S. Geol. Survey Sixth Ann. Rept., pp. 136-137, 1885.

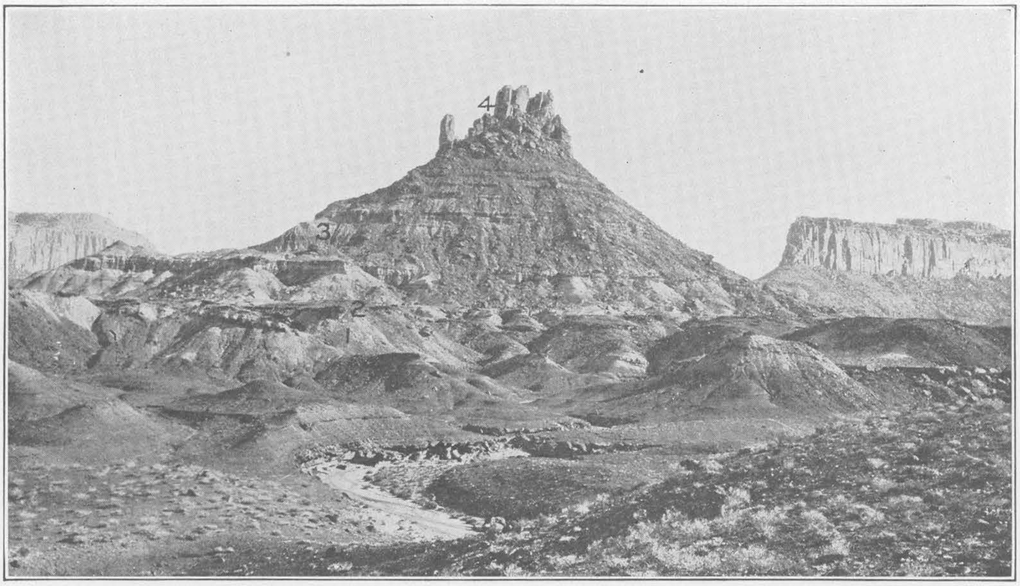
thickness of more than a few feet, but so persistent that they were recognized as a distinct unit and named the Todilto formation, from Todilto Park, N. Mex. In his reconnaissance survey Gregory was not able to trace the Todilto continuously to the west, but along the San Juan and in the vicinity of Navajo Mountain he recognized a distinct threefold division that appeared to correspond to the three formations observed farther east. The middle unit along the San Juan contains more sandstone than the typical Todilto, but limestone and limy shale are present at numerous places, and the sandstone formations above and below appear to be identical with the Navajo and Wingate of western New Mexico. Accordingly, Gregory applied the name Todilto to the middle unit tentatively, realizing that the correlation was not certain but only very probable.[30] His Wingate and Navajo of the western Navajo country correspond respectively to Powell's Vermilion Cliff and White Cliff sandstones in the region north of the Grand Canyon and Marble Canyon, but no intervening formation is recognized in that region.

Emery worked with Gregory in the eastern part of the Navajo country and later made a survey of the Green River Desert, east of the San Rafael Swell, where he recognized three distinct Jurassic formations and applied to them Gregory's names Wingate, Todilto (?), and Navajo.[31] The Todilto (?) of Emery contains fossils and is known to be at the horizon of the marine Jurassic. He noted an apparent threefold division of his Wingate in different sections, the middle member consisting of thin-bedded sandstone and shale; but the height of these thin beds above the base of the Wingate varies at different localities, and therefore he believed that the beds were lenticular and did not represent a constant horizon. Later work, however, indicates that the beds occur at a definite horizon and that the variation in height above the base of the Wingate merely represents a variation in thickness of that formation, perhaps due in part to the unconformity at the top of the Chinle. The thin-bedded unit was traced by Mr. Moore along the San Rafael Swell and the Waterpocket Fold, and other contributors to this report followed the beds continuously in other parts of the region, tracing them to the San Juan and to Rainbow Bridge and other localities where the beds form the unit correlated with the Todilto by Gregory. (See Pl. II.) It appears, therefore, that Gregory's usage has priority and should be retained for the present. It remains for future field work to determine the exact horizon of the Todilto at the type locality. If Gregory's tentative correlation along the San Juan should prove to be correct, then his terminology should be kept permanently and new names should be given to the formations designated Todilto (?) and Navajo by Emery. If the type Todilto is found to be at the horizon of the marine Jurassic, then Emery's tentative usage of the name will be established; but in that case his use of the names Wingate and Navajo should be reconsidered, for it appears that the name Navajo might well be retained for the sandstone that is typically exposed in Navajo Canyon and at Navajo Mountain, and the series of thin beds beneath it (Gregory's Todilto of the San Juan) deserves a new formation name.

In the following descriptions the three names are used in Gregory's sense, with the reservation suggested above regarding the Todilto. Emery's Todilto (?) will be referred to as "gypsiferous shales and sandstones" and his Navajo will be designated "varicolored sandstones and shales." Gregory, during field work since the publication of his reports on the Navajo country, has recognized these two units but has applied only temporary field names to them.

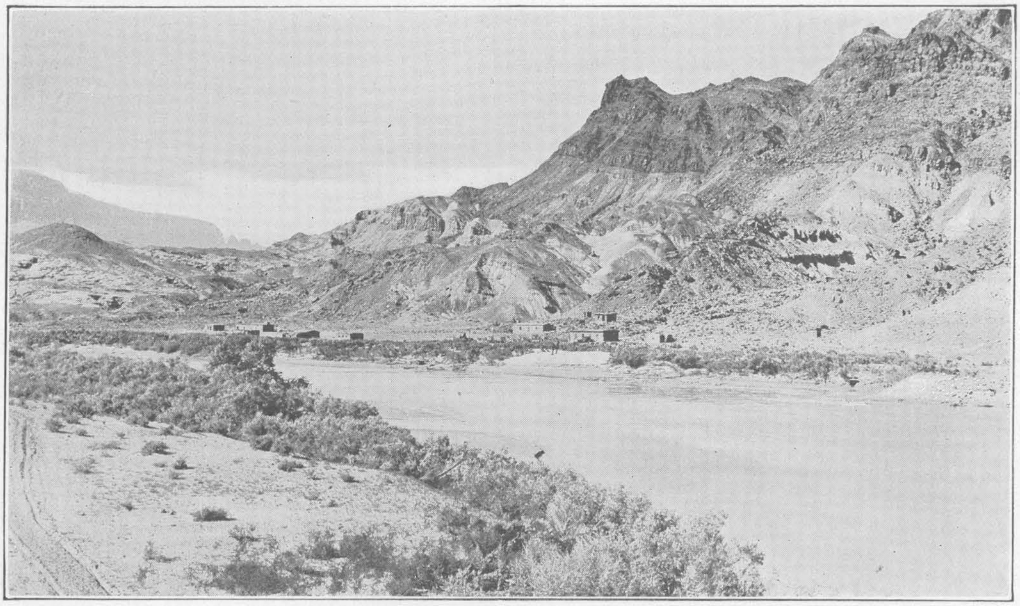
Wingate sandstone.—The Wingate sandstone is the most conspicuous cliff-maker in the region. (See Pls. IV, *B*; V, *A*; VI, *B*; VII, *A*; and VIII.) It is from 250 to 500 feet thick, and commonly the greater part of the total thickness appears as a single massive unit, which is cut by vertical joints and presents an impassable wall at the top of Chinle slopes. In some sections the lowermost beds are lenticular, in part conglomeratic, and apparently fill slight depressions in Chinle shale. These lower beds are obviously waterlaid. The massive, cliff-making portion, which averages about 300 feet in thickness, has indistinct and discontinuous bedding and is cross-bedded on a large scale. These structural characteristics,

[30] Gregory, H. E., op. cit., pp. 55–56.
[31] Emery, W. B., The Green River Desert section, Utah: Am. Jour. Sci., 4th ser., vol. 46, pp. 551–577, 1918.



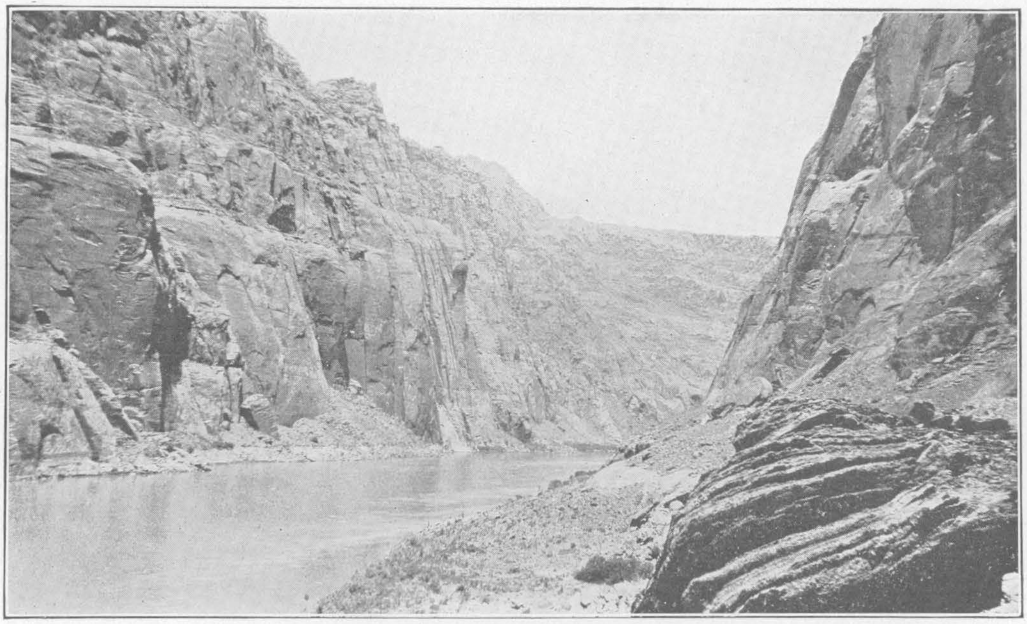
A. CASTLE BUTTE, NEAR MOUTH OF RED CANYON, UTAH.

1, Shale of upper member of Moenkopi formation; 2, Shinarump conglomerate; 3, Chinle formation; 4, Wingate sandstone. Photograph by C. R. Longwell.



B. VIEW LOOKING NORTH ACROSS COLORADO RIVER AT LEES FERRY, ARIZ.

Small rounded knoll to left stands on Shinarump conglomerate, which dips east. All the higher beds to the right form entire thickness of Chinle formation. Vermilion Cliffs in left background. Photograph by Robert N. Allen.

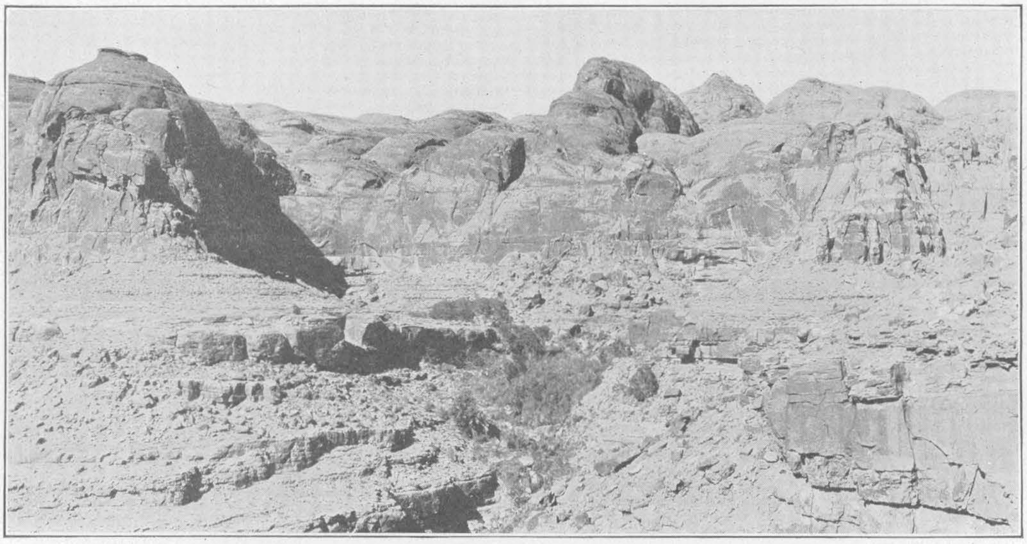


A. VIEW LOOKING NORTHWEST UP COLORADO RIVER TOWARD PROPOSED DAM SITE NEAR LEES FERRY, ARIZ.

Canyon walls are formed by Wingate and Navajo sandstones. Todilto (?) formation is apparently absent. Photograph by Kirk Bryan.

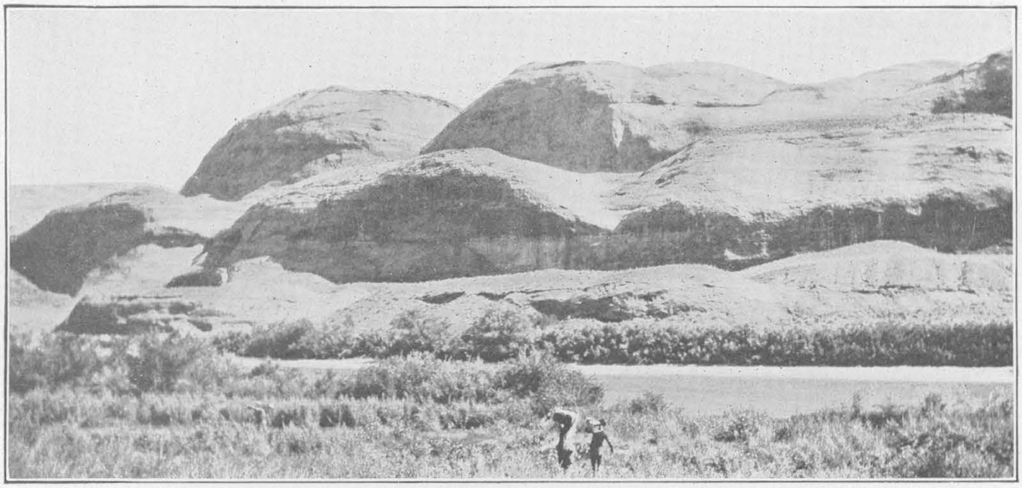
B. VIEW FROM POINT HALF A MILE SOUTH OF SPENCER CAMP, LOOKING SOUTH DOWN SAN JUAN CANYON TOWARD NAVAJO MOUNTAIN, UTAH.

Canyon has been cut in Navajo, Todilto (?), Wingate, and Chinle formations. Photograph by Robert N. Allen.



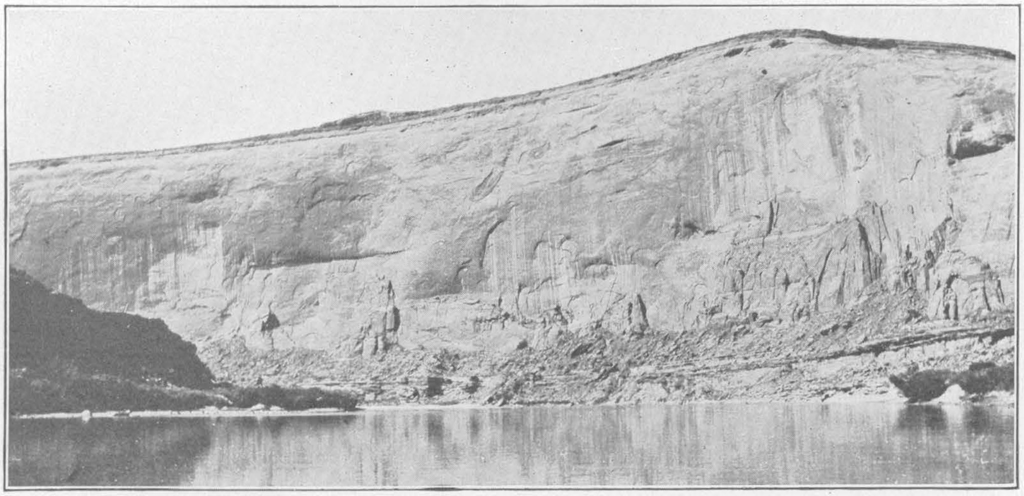
A. VIEW LOOKING NORTHEAST TOWARD WILSON MESA FROM POINT ON WILSON CREEK NEAR SAN JUAN CANYON, UTAH.

Showing bare domes and "mosques" of Navajo sandstone. Todilto (?) formation underlies platform in foreground. Photograph by Robert N. Allen.



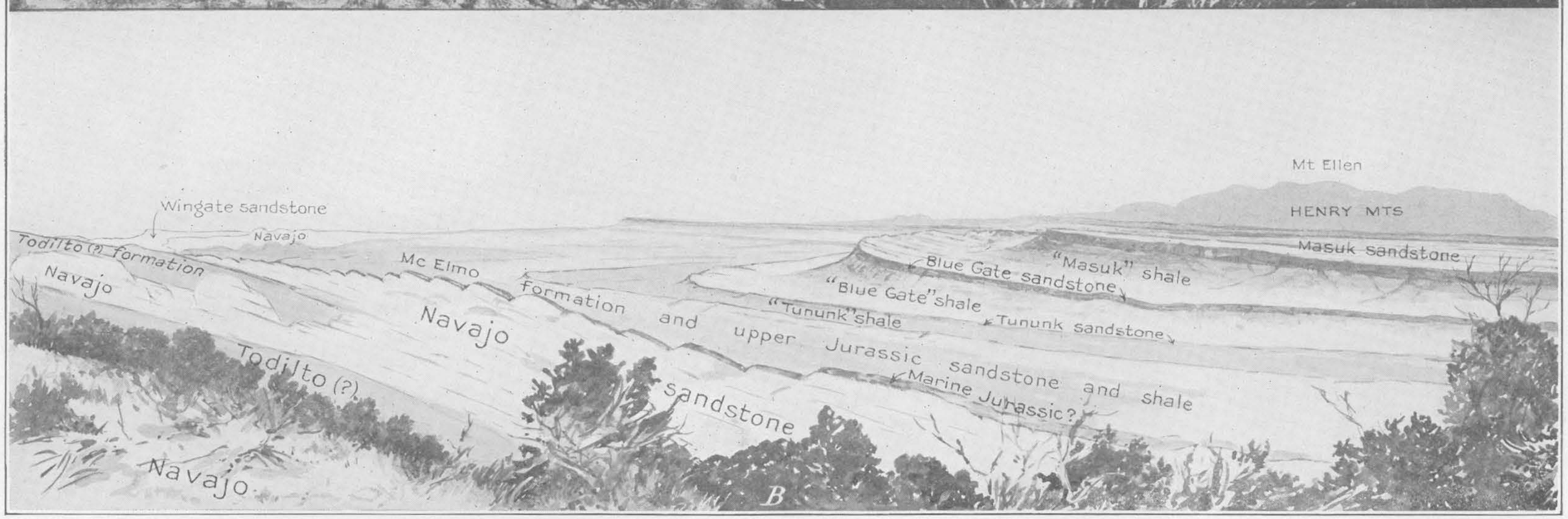
B. VIEW LOOKING ACROSS COLORADO RIVER OPPOSITE SMITHS FORK, UTAH.

Showing colossal domes of Navajo sandstone. Photograph by Sidney Paige.



C. SHEER CLIFF OF NAVAJO SANDSTONE AT WARM SPRING CREEK ON COLORADO RIVER, UTAH.

Photograph by Sidney Paige.



VIEW OF WATERPOCKET FOLD AND CRETACEOUS PLATEAUS BETWEEN THE CIRCLE CLIFFS AND THE HENRY MOUNTAINS, UTAH, AND SKETCH SHOWING THE SURFACE DISTRIBUTION OF THE ROCK FORMATIONS.

Photograph by R. C. Moore.

as well as the universal fineness and roundness of grain, suggest an eolian origin for this principal member. The only fossils reported from the formation are a few dinosaur tracks observed by Mr. Miser on surfaces of the lower lenticular beds at a locality several miles above the mouth of San Juan River.

The color of the sandstone on exposed surfaces gives the cliffs a striking appearance even in a "painted desert"; but the color is reddish brown rather than vermilion as suggested by the old formation name. On unweathered surfaces the rock is typically buff-colored, the darker shade ordinarily seen on cliffs resulting from weathering.

This sandstone forms the Vermilion Cliffs in western Kane County, Utah. Together with the overlying Todilto (?) formation it corresponds in age to Gilbert's Vermilion Cliff group in the Henry Mountains.[32] But the massive sandstones of the Vermilion Cliffs near Lees Ferry, Ariz., and of the Echo Cliffs are made up not only of the Wingate sandstone but of the Navajo sandstone; the Todilto (?) formation has not been recognized and is apparently absent there.

Todilto (?) formation.—The character of deposits in the formation tentatively correlated with the Todilto varies considerably both vertically and horizontally; but the formation is sharply distinguished from the underlying and overlying sandstones by comparative thinness of beds and by undoubted evidence of deposition in water. Measured sections of the formation in the region under discussion range from 125 to 249 feet in thickness. Layers of flinty limestone and of calcareous shale are present in most localities, except perhaps to the north and west, but everywhere sandstone makes up the greater part of the thickness. The lower part is commonly very lenticular and contains considerable conglomerate with small sandstone pebbles. These beds, as well as others higher in the formation, were probably deposited by streams with rapid, shifting currents. The layers of shale and limestone are found for the most part in the middle and upper portions. The shale forms a zone of weakness that commonly causes the overlying Navajo sandstone to retreat behind the Wingate cliffs, leaving benches floored by the lower resistant sandstone of the Todilto (?). (See Pls. VIII, *B*, and IX, *A*.) The limestone beds are lenticular and range from a few inches to 2 feet in thickness. The material is dense, hard, and cherty and is probably of fresh-water origin.

In some sections the transition from the massive Wingate to the thinner beds above appears to be gradual, but at many localities along the Colorado a distinct erosional unconformity separates the two formations, lenticular fluviatile beds filling valleys on the surface of the Wingate. In a cliff the lower sandstones of the Todilto (?) are readily distinguished from the light-colored Wingate by their dark-maroon or reddish-brown color. At higher horizons the Todilto (?) beds vary in color through shades of brown, tan, and lavender. The limestone layers are usually gray.

Navajo sandstone.—Many of the picturesque and grotesque erosion forms common in southern Utah and northern Arizona are carved in the Navajo sandstone of Gregory, which is essentially equivalent to Gilbert's "Gray Cliff group" and to Powell's White Cliffs sandstone. It is exposed over large areas along the Colorado and the San Juan, in the Waterpocket Fold and the Circle Cliffs, and farther west in south-central Utah and forms great tracts of almost impassable badlands, in which domes, "mosques," and "minarets" are common features. (See Pls. VI, *B*; VIII, and IX.) Caves, alcoves, and arches are conspicuous in cliffs of this sandstone, and it forms a number of natural bridges, notably the Rainbow and Owl bridges, near Navajo Mountain.

The thickness varies between wide limits, reaching a reported maximum of 1,800 feet in western Kane County, Utah, and a minimum of about 500 feet south of the Henry Mountains. Along the Colorado and the San Juan the thickness is commonly from 600 to 800 feet, but a few sections measure 1,000 feet. From the Waterpocket Fold westward the thickness is generally above 1,000 feet. There is also a marked change in color from east to west. From the Waterpocket Fold westward a large part of the formation is commonly gray or creamy white, whereas in the region south of the Henry Mountains, around Navajo Mountain, at Lees Ferry, and in Comb Ridge the sandstone is typically tan or buff.

This sandstone is frequently cited as a typical eolian deposit. Cross-bedding of the

[32] Gilbert, G. K., Report on the geology of the Henry Mountains, pp. 5–7, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1880.

"tangential" type and on a very large scale characterizes the greater part of the formation, and the laminae of the cross-bedded structure show the abrupt and repeated truncation so commonly seen in "living" sand dunes. True bedding planes are present but not distinct, so that the entire formation stands in some cliffs with the appearance of a single massive layer. Beds of compact limestone from 2 to 5 feet thick lie at several horizons but chiefly in the upper half of the formation. These beds extend laterally from a few hundred feet to half a mile and probably represent deposition in shallow pans or basins. In view of the general high porosity of the sandstone, it would seem that these deposits required a high ground-water level, at least locally.

Gypsiferous shales and sandstones.—The series of beds here designated gypsiferous shales and sandstones is exposed at Bluff, in the Henry Mountains, and farther north, between Kaiparowits Plateau and Escalante River and along the Colorado below the mouth of the San Juan almost to Lees Ferry. (See Pl. X, *A*.) It is also found west of the Kaiparowits Plateau at several localities, notably in western Kane County, Utah, where it is apparently represented by about 100 feet of bluish-gray marl with considerable gypsum. In typical sections the beds consist of gypsiferous shale intercalated with layers of sandstone and some limestone, with an average total thickness of about 75 feet. In 1918 W. B. Emery[33] studied these beds in the Green River Desert and reported the occurrence of marine Jurassic fossils in some of the limestone layers. This fossiliferous series had been noted previously by Gilbert[34] and by Lupton.[35] In some sections there are indications of an unconformity between these beds and the underlying Navajo sandstone.

The beds deserve a formation name, but it appears best to postpone assigning a definite name until the Todilto problem, discussed above, has been finally solved by further field work.

Varicolored sandstones and shales.—The thick series of beds here termed varicolored sandstones and shales includes the greater portion of the rocks in Gilbert's "Flaming Gorge group." These beds reach a maximum thickness of approximately 1,430 feet in the Waterpocket Fold. (See Pl. X, *A*.) Along Colorado River between the mouth of the San Juan and the Crossing of the Fathers the series appears to have a thickness as great as 500 feet, and near Bluff it is from 170 to 270 feet thick. Complete and partial sections are exposed at many localities south and west of the Henry Mountains and northeast of the Kaiparowits Plateau. The series contains a massive cross-bedded sandstone member, tan, red, and gray, which has some resemblance to the typical Navajo sandstone. Other parts of the section consist of thin-bedded sandstone, much of it shaly. East of the Waterpocket Fold the predominant colors are red and tan, but in western Kane County, where the stratigraphic position of the series is occupied chiefly by sandy shale, many of the beds are gray and bluish gray.

Emery considers that this series of beds, as well as those at the horizon of the marine Jurassic, corresponds to the La Plata sandstone of Cross. Gregory limits the La Plata group to his Wingate, Todilto, and Navajo formations.

McELMO FORMATION (CRETACEOUS?).

The McElmo formation, of Cretaceous (?) age, is exposed near Bluff, where it consists of gray, red, and green shale and thin beds of sandstone with two heavy conglomeratic layers, making an incomplete section several hundred feet thick. At places these conglomerates contain carnotite deposits. Along the Colorado below the San Juan partial sections of the formation are made up chiefly of a massive cliff-making greenish-gray sandstone, in part conglomeratic. In western Kane County the McElmo appears to be represented by a coarse conglomerate of undetermined thickness.

CRETACEOUS SYSTEM.

Rocks of known Cretaceous age, all probably belonging to the Upper Cretaceous series, are represented in southern Utah by exposures in the vicinity of the Henry Mountains, along the southern border of the High Plateaus in western Garfield and Kane counties, and in a southeastward projection, of which Kaiparowits Plateau is the chief part, extending into eastern Kane County. (See Pl. X, *A* and *B*.)

[33] Op. cit., pp. 568–569.
[34] Gilbert, G. K., Geology of the Henry Mountains, p. 6, 1880.
[35] Lupton, C. T., U. S. Geol. Survey Bull. 628, p. 24, 1916.

The total thickness of the Cretaceous section in this region is about 3,500 feet. The rocks consist of alternating divisions of bluish-drab shale and yellowish-brown sandstone, the former appearing in slopes and badlands, the latter in more or less prominent escarpments and hogback ridges. They are divisible into seven distinct units, the basal one of which is doubtfully correlated with the Dakota sandstone. To the rocks above this basal sandstone Gilbert applied the following local names, in ascending order: Tununk shale, Tununk sandstone, Blue Gate shale, Blue Gate sandstone, Masuk shale, and Masuk sandstone. These names were derived from geographic features in the Henry Mountains. As duplication of names is contrary to the practice of the United States Geological Survey, only Gilbert's names for the sandstones have been adopted, and in this report his names for the shales will be used in quotation marks, because of the doubt regarding the relations of this whole succession of sandstone and shale to named units to the north and east. In the present state of knowledge Mr. Moore tentatively correlates the "Tununk shale," Tununk sandstone, and "Blue Gate shale" with the Mancos shale of southwestern Colorado and east-central Utah. The Blue Gate sandstone he tentatively correlates with the Mesaverde formation, the "Masuk shale" with the Lewis shale, and the Masuk sandstone with the so-called "Laramie" sandstone of southwestern Colorado. Some geologists, however, believe that the whole succession corresponds to the Mancos shale.

Dakota (?) sandstone.—As in most of the Cretaceous sections of the Rocky Mountain and Plateau region, there is present in southern Utah a basal sandstone and conglomerate which appears to be homotaxially equivalent to the Dakota sandstone. This sandstone attains a thickness of 100 feet in the escarpment of Kaiparowits Plateau, but in the Henry Mountains district it is much thinner and in places is absent. It evidently overlies the beds beneath it unconformably, for the upper surface of the McElmo is somewhat uneven, the thickness of the upper division of the McElmo is variable, and at one place a slight fold in the McElmo strata was found to have been truncated before the deposition of the sandstone. To these evidences may be added the conglomeratic character of the formation. The color of the Dakota (?) sandstone is yellowish brown to white. The bedding is irregular. Locally thin beds of lignite are present.

"Tununk shale."—The formation above the Dakota (?) sandstone consists of bluish-drab argillaceous and in part sandy shale, called "Tununk shale" by Gilbert. The shale is 900 to 1,000 feet thick in exposures east of the Waterpocket Fold. It is very sandy and grades at the base into extremely fossiliferous brown sandstone. The shale is also fossiliferous, containing especially large numbers of *Gryphaea newberryi*.

Tununk sandstone.—The sandstone overlying the shale just described was called Tununk sandstone by Gilbert. It has a maximum observed thickness of about 100 feet. It is well developed in the vicinity of the Henry Mountains and appears to be present in the Kaiparowits Plateau but was not found southwest of Table Cliff Plateau in western Garfield County. It is light yellowish brown, is irregularly bedded, and locally contains some lignite.

"Blue Gate shale."—Overlying the Tununk sandstone is a shale formation 1,100 to 1,200 feet thick, which resembles the "Tununk shale" in texture and color but lacks the numerous fossils that are characteristic of the "Tununk." To this shale Gilbert applied the name "Blue Gate shale."

Blue Gate sandstone.—A prominent creamy-yellow to light-brown massive and irregularly bedded sandstone succeeds conformably the shale just described. Its thickness in the Henry Mountains, where it was named the Blue Gate sandstone by Gilbert,[36] is 250 to 500 feet, but in the Kaiparowits Plateau and west of Escalante the thickness of this formation is at least 1,000 feet. The sandstone contains lignite, which locally is of very good grade and reaches a thickness of 4 feet west of Mount Ellen. No fossils were obtained from this sandstone, but Lee [37] has suggested that it is comparable with the Mesaverde. It is extremely improbable that this sandstone could represent the Ferron sandstone of Castle

[36] Gilbert, G. K., op. cit., p. 4.

[37] Lee, W. T., Relation of the Cretaceous formations to the Rocky Mountains in Colorado and New Mexico: U. S. Geol. Survey Prof. Paper 95, p. 50, 1915.

Valley, as suggested by Lupton.[38] The Ferron occurs about 600 feet above the base of the Mancos as there identified and is overlain by 3,000 feet of Mancos shale, whereas this sandstone is 2,200 feet above the base of the Mancos and, as seen in the Henry Mountains, is succeeded by only a few hundred feet of shale. The Cretaceous section of southern Utah appears to be intermediate in character between those of southwestern Colorado, northwestern New Mexico, and northern Arizona and those of central and northern Utah.

"*Masuk shale.*"—Above the Blue Gate sandstone is a light-drab, very sandy shale, which in the Henry Mountains area has a thickness of 500 to 700 feet and to which Gilbert applied the name "Masuk shale." Below Table Cliff Plateau, in western Garfield County, the thickness of this shale is undetermined but is probably more than 1,000 feet. The upper part of the shale contains thin beds and lenses of brown sandstone and appears to grade without break into the overlying formation, the Masuk sandstone.

Masuk sandstone.—The uppermost Cretaceous formation in the region is a massive yellowish-gray sandstone, which east of the Circle Cliffs appears in a prominent table-land bounded by high, sheer cliffs. Its thickness is about 300 feet according to measurements made at its west margin, but Gilbert [39] reports a thickness of 500 feet.

TERTIARY SYSTEM.

In the High Plateaus are found exposures of the youngest stratified rocks of the region, comprising pink, lavender, white, and varicolored limestones, sandstones, and shales of Eocene age. These rocks, which in Garfield and Kane counties have been referred to the Wasatch formation, appear in vertical cliffs and in the fantastically carved, brilliantly tinted walls of canyons that head along the margins of the plateaus. The thickness of the Tertiary sequence in this region is about 2,000 feet. Much of it, especially toward the north, is buried beneath a great accumulation of extrusive igneous rocks.

The Tertiary beds rest with very great unconformity on the Mesozoic rocks, the unconformity being angular as well as erosional. The base of the Tertiary is found in contact successively with all the formations from the highest Cretaceous to the Navajo sandstone, and much of the Navajo was in places removed before Eocene sedimentation. It therefore appears that an important deformative movement, in which such structural features as the Waterpocket Fold, the Circle Cliffs dome, and the gentle flexures south of Table Cliff Plateau were formed, followed Cretaceous deposition, and that before the deposition of the Tertiary strata began this deformed rock series had been planed off by erosion to a nearly level surface, a denudation involving the removal in places of rock strata some thousands of feet in thickness.

LOCAL SECTIONS.

General section of rocks near Lees Ferry, Ariz.

[Measured by Kirk Bryan.]

	Feet.
Brown thin-bedded sandstone and shale, which are probably the equivalent of the beds of marine Jurassic farther north	(?)
Navajo and Wingate sandstones: Massive tangentially cross-bedded red to buff sandstone. No parting visible at the center, but upper half has lenses of dense gray limestone 6 inches to 3 feet thick at intervals, and near the top nodules of limonite the size of peas are common. In the Vermilion Cliffs the upper half is distinctly lighter in color. The Todilto (?) formation is apparently absent	1, 100–1, 200
Chinle formation: Blue, green, and red shale; white, gray, purple, and red sandstone; and cherty limestone. Upper part consists of heavy-bedded sandstone and red shale; lower part contains fossil wood	1, 000±
Shinarump conglomerate: Gray conglomerate with lenses of sandstone and shale; much fossil wood	0–40
Unconformity.	
Moenkopi formation: Red sandy shale and thin-bedded sandstone with seams of gypsum. In places has beds of red and gray sandstone 2 to 6 feet thick, and in one locality 12 feet of gypsiferous limestone at the top. Base, generally, 1 to 10 feet of chert conglomerate	500±
Unconformity.	
Kaibab limestone: Yellow limestone with numerous more or less rounded nodules of chert	250
Coconino sandstone: Gray cross-bedded massive sandstone	300
Unconformity (?).	
Hermit (?) shale: Red shale and sandstone; Unconformity (?) (not observed); Supai formation: Red shale with beds of blue limestone. } (observed)	500±

[38] Lupton, C. T., Geology and coal resources of the Castle Valley, Utah: U. S. Geol. Survey Bull. 628, p. 32, 1916.

[39] Gilbert, G. K., op. cit., p. 4.

Section about 3 miles southeast of Piute Farms on San Juan River.

[Measured by H. D. Miser.]

	Feet.
Wingate sandstone:	
Massive cross-bedded tan sandstone forming sheer cliff; cut by numerous vertical joints; face of cliff is stained dark brown	270
Coarse brown sandstone with pebbles of shale and sandstone up to 2 inches in diameter	4
Chinle formation: Green and pink marly clay with beds of mottled pink and gray compact limestone as much as 4 feet thick in upper part. Some of the limestone is conglomerate. Pebbles in conglomerate are limestone. Pink and gray flint on slope may have been derived from weathering of limestone. Some parts of clay contain irregular concretions of calcareous earthy material	830
Shinarump conglomerate: Massive gray sandstone	10
Moenkopi formation:	
Chocolate-colored shale with some green shale in upper half; light chocolate-colored shale with some thick beds of brown fine-grained sandstone in lower half	340
Brick-red sandy shale and earthy sandstone in beds of uniform thickness. The De Chelly (?) sandstone is absent at this place but wedges in farther south near the top of this part of the formation	500
Moenkopi or Coconino: "Transition beds" like those described in section at Zahns Camp.	
Coconino sandstone.	

Section at Zahns Camp on San Juan River.

[Measured by H. D. Miser.]

	Feet.
Chinle formation: Variegated marly shale.	
Shinarump conglomerate: Massive gray pebbly sandstone; forms cliff	50
Moenkopi formation:	
Chocolate-brown sandy shale with a smaller amount of brown shaly and platy sandstone; forms steep slope	325
Brick-red sandy shale and earthy sandstone in even-bedded layers	55
Cream-colored cross-bedded massive sandstone; De Chelly (?) sandstone lentil	90
Brick-red sandy shale and a smaller amount of red earthy sandstone in even-bedded layers	450
Total thickness of Moenkopi formation	920
Moenkopi or Coconino ("transition beds"):	
Heavy gray sandstone	5
Brown sandy shale and brown shaly sandstone. A bed of gray limestone 1 foot or more thick near top	45
Massive gray sandstone	6
Brown sandy shale	5
Massive gray sandstone	4
Brown sandy shale and brown earthy sandstone. Contains one or two thin beds of gray limestone	24
Total thickness of "transition beds"	89
Coconino sandstone: Massive cross-bedded cream-colored sandstone. Two beds of brown sandy shale aggregating 3 feet near the top. Exposure of sandstone extends down to San Juan River	55

Section on San Juan River north of Spencer Camp.

[Measured by H. D. Miser.)

	Feet.
Navajo sandstone: Cream-colored to yellow massive cross-bedded sandstone	200+
Todilto (?) formation:	
Brown fine-grained shaly sandstone with lavender cast	170
Lenses of conglomerate as much as several feet thick; conglomerate composed of sandstone pebbles in sandy matrix	
Lavender, brown, and buff fine-grained sandstone in comparatively thin layers	50
Total thickness of Todilto (?) formation	220
Wingate sandstone: Buff fine-grained cross-bedded sandstone; no conglomerate at base	330
Chinle formation: Variegated marly shale; concealed almost everywhere by landslides. Formation extends to river, and base is not exposed	510

Section on north side of San Juan River just above its junction with the Colorado.

[Measured by H. D. Miser.]

	Feet.
Navajo sandstone:	
Gray thin-bedded very fine grained limestone; forms flat top of small mesa	4½
Buff massive cross-bedded sandstone	310
Todilto (?) formation: Dark and light brown sandstone in comparatively thin beds	200
Wingate sandstone: Buff sandstone to water's edge of San Juan River	10+

Section on Colorado River near the mouth of Fremont River.

[Measured by C. R. Longwell. The canyons of Colorado and Fremont rivers are cut in the Coconino sandstone. Above the canyons there is a wide stripped bench on the Coconino, with scattered buttes of the Moenkopi formation.]

	Feet.
Moenkopi formation:	
Conglomerate at base of upper member of formation. Contains angular pebbles of chert, with maximum length of 2 inches, also a few fragments of silicified wood. Firmly cemented by calcium carbonate	15
Unconformity.	
Gray sandstone, medium to coarse, strongly cross-bedded throughout. Conspicuous by contrast with red sandstone below. De Chelly (?) lentil	40
Regular beds (a few with cross laminae) of red to maroon sandstone, averaging several feet in thickness, of fine, uniform grain. A few shaly layers, forming narrow benches in cliff.	158
Heavy bed of cross-bedded pink to tan sandstone; persistent, good horizon marker; fine uniform grain	28
Heavy bed of reddish-brown sandstone, grading into gray at the base	6

	Feet.
Moenkopi formation—Continued.	
Fine-grained maroon and red sandstone and sandy shale in regular beds from 6 to 30 inches thick; form steep interrupted slope	115
Red sandy shale, with some layers of cross-bedded fine-grained sandstone; forms slope; muscovite abundant	45
Massive white to gray sandstone, with medium grain	2
Gritty shale and fine-grained sandstone, red to light brown	22
Incomplete thickness of Moenkopi formation	431
Unconformity.	
Coconino sandstone: Gray and tan sandstone, of fine to medium grain, in massive beds and with cross-bedding on large scale. Forms walls of Narrow Canyon and Dirty Devil Canyon. Base not exposed.	

Section on Colorado River near mouth of Crescent Creek ("North Wash").

[Measured by C. R. Longwell.]

	Feet.
Wingate sandstone forms a sheer cliff at least 300 feet high, at top of the steep slope on which the Chinle formation is exposed	300+
Chinle formation:	
Regular beds of pink sandstone, 6 inches to 2 feet thick	12
Coarse sandstone, pink to tan, cross-bedded	25
Gritty shale and fine-grained sandstone, in thin layers	10
Gray calcareous sandstone	1
Pink sandstone in thin beds	27
Massive layer of gray to buff sandstone	6
Calcareous shale in massive layers, containing more or less grit, with a few intercalated thin layers of fine-grained sandstone	155
Heavy bed of dense gray limestone, with chert lenses and nodules	4
Pink calcareous shale	24
Alternating layers of gray limestone and pinkish shale. Limestone layers average 2 feet in thickness and are dense, with abundance of chert	27
Gray, lavender, and yellow shale, banded, with a few thin sandy layers	102
Total thickness of Chinle formation	393
Shinarump conglomerate: Massive coarse-grained, cross-bedded sandstone, with lenses of conglomerate; contains abundance of silicified wood	35
Unconformity.	
Moenkopi formation:	
Lavender, pink, and greenish shale, with a few sandstone layers; green layers prominent near top	72
Gray and yellow sandy shale and fine-grained sandstone	6
Bright-red clay shale	22
Gray, lavender, and yellow shale, with a few bands of dense gray limestone	60
Moenkopi formation—Continued.	
Red and pink sandy shale and fine-grained sandstone	70
Fine-grained cross-bedded red to pink sandstone	2
Alternating layers of gray sandstone and red shale; shale papery, sandstone ripple marked	17
Alternating layers of red and brown sandstone and sandy shale; sandstone layers have current and ripple marks, also a few rain prints; partings of brown paper shale	55
Single bed of massive cross-bedded light-brown sandstone	22
Alternating layers of red and brown sandstone and sandy shale; sandstone layers have current and ripple marks, also a few rain prints	65
Alternating thin beds of gray sandstone, with very thin partings of brown shale	6
Light-brown conglomeratic sandstone	2
Alternating thin beds of gray sandstone, with very thin partings of brown shale	2
Light-brown conglomeratic sandstone	2
Alternating thin beds of gray sandstone, with very thin partings of brown shale	4
Light-brown conglomeratic sandstone	3
Alternating thin beds of gray sandstone, with very thin partings of brown shale	9
Massive gray cross-bedded sandstone	3
Alternating thin beds of sandstone and shale, yellow, red, brown, and lavender	9
Firmly cemented conglomerate with angular pebbles of chert and hard sandstone; fragments of lustrous coal and of silicified wood also occur as pebbles	10
Total thickness of upper member of Moenkopi formation	441
Unconformity.	
Massive gray sandstone, with marked cross-bedding, loosely cemented with calcium carbonate. De Chelly (?) sandstone lentil	35
Typical red and maroon beds of lower member.	

Section on Colorado River below mouth of Crescent Creek.

[Measured by C. R. Longwell.]

	Feet.
Navajo sandstone: Tan and buff sandstone, cross-bedded on large scale. The sandstone of this locality is an isolated remnant capping a high point	300
Todilto (?) formation:	
Alternating regular beds of calcareous sandstone and gritty shale, with a few layers of limestone conglomerate. Two of the sandstone layers are cross-bedded and tan. Other beds are pink, gray, and lavender. Form long slope	77
Thin layers of red and maroon sandstone, cross-bedded	60
Light-brown and gray cross-bedded sandstone; friable, forming slope; contains hard, concretionary nodules	22
Total thickness of Todilto (?) formation	159

	Feet.
Unconformity (?).	
Wingate sandstone:	
Tan and light-brown cross-bedded sandstone, forming cliff	85
Conglomerate, with pebbles and boulders of sandstone as much as 2 feet in diameter, also pebbles of red clay; calcareous cement	0–4
Massive cross-bedded sandstone, forming almost unbroken cliff. Tan on fresh surfaces, reddish brown on weathered face	280
Total thickness of Wingate sandstone	369
Chinle formation: Forms a long slope below the cliff of the Wingate sandstone.	

Section on Colorado River near mouth of Trachyte Creek.

[Measured by C. R. Longwell.]

	Feet.
Shinarump conglomerate: Coarse-grained gray conglomeratic sandstone, with abundance of silicified wood. Forms low cliff, with shelf above	5–15
Unconformity.	
Moenkopi formation:	
Alternating layers of gray sandstone and greenish shale	5
Lavender, gray, and pink calcareous shale	25
Fine-grained brown sandstone	3
Gray "marl," sandy near base	55
Gray cross-bedded sandstone	3
Greenish-gray and pink shale, paper-thin	4
Bright-red clay shale	5
Yellow, lavender, pink, and gray "marly" shale, in thick beds	60
Alternating chocolate-colored shale and gray to brown sandstone, in thin layers. Ripple marks abundant	60
Massive brown sandstone with strong current marks	2
Alternating chocolate-colored shale and gray to brown sandstone	8
Massive sandstone	2
Chocolate-colored sandy shale	6
Massive cross-bedded sandstone	2
Gray sandstone and chocolate-colored shale, in alternating thin layers	4
Massive gray to brown cross-bedded sandstone	8
Alternating chocolate-colored shale and gray to brown sandstone, with strong ripple marks	22
Light-brown cross-bedded sandstone	5
Chocolate-colored sandy shale	10
Thick layers of sandstone, with thin partings of chocolate-colored shale	11
Alternating gray sandstone and chocolate-colored shale	18
Heavy layers of cross-bedded current-marked sandstone, with thin shale partings; sandstone gray to brown, shale dark chocolate-colored	12
Brown fine-grained sandstone, with thin lamination	6
Heavy layers of pink cross-bedded sandstone, with shale partings	16
Alternating gray sandstone and brown shale; abundant ripple and current marks	22

	Feet.
Moenkopi formation—Continued.	
Fine-grained sandstone with shaly lamination	9
Firmly cemented conglomerate containing angular pebbles of chert and hard sandstone	2
Total thickness of upper member of Moenkopi formation	385
Unconformity.	
De Chelly (?) sandstone lentil (gray to pink cross-bedded sandstone)	20
Typical red beds of the lower member.	

Section on north side of Twomile Canyon, directly east of Mount Holmes, in the Henry Mountains.

[Measured by C. R. Longwell.]

	Feet
Navajo sandstone: Massive tan sandstone, capping a rounded hill	250
Todilto (?) formation:	
Massive fine-grained cross-bedded lavender and gray sandstone	18
Purple and gray shale; forms slope	10
Massive cross-bedded brown sandstone, medium to coarse	9
Red and brown sandy calcareous shale with thin layers of dense gray limestone; forms slope	40
Brown and gray heavy-bedded sandstone with calcareous cement	27
Pink sandy shale; forms slope	14
Gray sandstone and pink sandy shale in alternating beds	11
Reddish-brown and gray medium to fine grained sandstone in heavy layers, some with cross-bedding. Calcareous cement. Layers of unequal resistance, forming steep slope. All beds lenticular; a few lenses conglomeratic	120
Total thickness of Todilto (?) formation	249
Unconformity.	
Wingate sandstone: Tan to reddish-brown sandstone, chiefly in unbroken cliff. Large-scale cross-bedding	366
Unconformity (?).	
Chinle formation:	
Alternating layers of hard fine-grained sandstone and pink sandy shale	14
Pink shale, with a few layers of gray sandstone	22
Gray conglomeratic sandstone, with small pebbles of chert and hard sandstone	2
Heavy bed of fine-grained pink sandstone, loosely cemented	8
Varicolored calcareous shale, with a few sandstone layers	40
Cross-bedded gray sandstone, conglomeratic at base; contains silicified logs	6
Pink and yellow calcareous shale, sandy near top	17
Hard gray limestone, containing chert nodules	2
Lenticular layers of gray sandstone with partings of shale	10
Pink and yellow gritty shale	20

Chinle formation—Continued.	Feet.
Gray and lavender "marl" beds, jointed	34
Cross-bedded gray and lavender sandstone	15
Massive fine-grained sandstone, rich with calcium carbonate and containing cherty nodules	6
Brick-red gritty shale, with layers of gray sandstone	28
Pink and gray calcareous shale or "marl," appearing massive	80
Gray and purplish sandy shale in thin beds	16
Total thickness of Chinle formation	320
Shinarump conglomerate: Coarse conglomeratic massive and cross-bedded sandstone with lenses of conglomerate; abundance of silicified logs; plain impressions of plants on bedding surfaces. Forms vertical cliff	60–120
Unconformity.	
Moenkopi formation: Greenish shale immediately below unconformity. Forms slope.	

Section of Chinle formation at north end of prominent Wingate-capped outlier west of South Fork of Silver Falls Creek, in the Circle Cliffs.

[Measured by R. C. Moore.]

	Feet.
Wingate sandstone: Reddish-brown fine-grained cross-bedded, very massive sandstone, forming single vertical wall; prominently jointed; basal few feet horizontally bedded in thin layers, with ripple marks measuring about 6 inches from crest to crest; thickness estimated	250
Chinle formation:	
Soft limestone, lavender mottled with light greenish blue, weathering in very irregular fragments; partly covered with débris; upper part oxidized and stained to dark purple beneath Wingate sandstone and along joints	5
Light-bluish conglomerate, mostly rather fine-grained; pebbles consist almost entirely of limestone like the associated limestones of the Chinle formation, but there are some flint, quartz, and ironstone pebbles as much as 1½ inches in diameter; upper part grades into very coarse limestone grit, with lines and lenses of fine conglomerate; very massive; crops out in prominent bench	28
Soft shaly limestone, light greenish blue and lavender, mottled; contains locally harder limestone in beds 6 to 10 inches thick which project; this division weathers in a slope	70
Very hard dense fine-grained limestone, light bluish in lower part with mottling of lavender, massive and uniform; locally contains calcite crystals; except for lower part, which is somewhat softer, this bed forms prominent cliff, which in places overhangs	5
Light-blue hard calcareous shale; forms landslide slope	15
Argillaceous limestone, impure, mottled light greenish blue and lavender; weathers in small angular fragments but forms at outcrop a massive vertical ledge; grades upward and downward into hard calcareous shale	3

Chinle formation—Continued.	Feet.
Light-blue hard calcareous shale; forms slope	14½
Hard dense nodular limestone, mottled light greenish blue and lavender; weathers in small irregular-shaped fragments; grades imperceptibly into shale above and below; forms bench	8
Hard calcareous light-blue shale, forming slope.	38
Light-bluish shaly soft, very micaceous sandstone, grading into sandy shale	59½
Light-bluish to brown limestone conglomerate, containing pebbles of limestone and chert 3 inches or less in diameter; grades into coarse limy sandstone	2½
Yellowish-brown hard sandy shale grading to ash-gray and lavender shale	53
Grayish-blue to lavender calcareous, highly micaceous sandstone, grading upward into soft massive cross-bedded sandstone; lower part weathers in thin platy fragments	35½
Purple shale, grading upward into yellow and blue shale; sandy, especially in lower part; contains abundant mica; weathers in rounded slopes	13
Brownish-gray thinly laminated to platy sandstone, weathering dark brown; lower part locally conglomerate, containing pebbles of ironstone and jasper as much as 1 inch in diameter	5–6
Sandy shale; upper part weathers to shades of lavender and purple; lower part darker; the proportion of sand increases toward the top; contains satin spar, crystals of gypsum, and mammillary concretions of ironstone with crystalline calcite; weathers in rounded slopes	91½
Brown thin-bedded flaggy sandstone, grading laterally to burnt sienna slaggy ironstone, containing nodules of limonite; this bed forms a bench that weathers irregularly in crumbly fragments	2
Hard calcareous sandy shale, light greenish blue predominant in variegated coloring; weathers in rounded badland slopes	25
Total thickness of Chinle formation	474
Shinarump conglomerate: Grayish-brown irregularly bedded massive sandstone, showing thin cross lamination; some of the weathered surfaces are dark brown or black on account of a surface deposit of iron oxide; contains bluish sandy shale in middle part	85
Moenkopi formation.	

Section of Kaibab limestone west of The Peaks, in the Circle Cliffs.

[Measured by R. C. Moore.]

Moenkopi formation.	
Kaibab limestone:	Feet.
Yellow dolomitic limestone in massive evenly bedded ledges; weathers in large angular blocks pitted by solution; part contains numerous dendrites of manganese oxide and concretions of a mineral resembling wad; contains fossils; forms resistant cap of prominent bench	37

	Feet.
Kiabab limestone—Continued.	
Light-yellow soft dolomitic massive limestone, filled with angular fragments of chert; weathers in smooth slope; exposed	15
Soft light creamy-yellow thin to medium bedded limestone; weathers in slope; partly concealed	37
White very sandy limestone, rounded sand grains scattered rather evenly; more lime than sand; weathers in thick ledges	34
White medium to coarse grained massive sandstone; rounded quartz grains in a lime matrix	19
White very sandy limestone, rounded sand grains scattered rather evenly; more lime than sand; weathers in thick ledges; forms bench	21
Total thickness of Kaibab limestone	163
Coconino (?) sandstone: White medium to coarse grained moderately soft massive sandstone; rounded quartz grains in a lime matrix; breaks into irregular blocks on weathering; exposed	73

Section of lower beds in front of Kaiparowits Plateau, south of Tenmile Spring, about 15 miles southeast of Escalante, in middle part of sec. 4, T. 37 S., R. 4 E.

[Measured by R. C. Moore.]

	Feet.
"Tununk shale": Bluish sandy shale, grading downward into soft fossiliferous sandstone	400+
Dakota (?) sandstone: Conglomeratic buff to almost white coarse to medium grained sandstone, containing lenses of conglomerate with pebbles as much as 3 inches in diameter; irregularly cross-bedded; forms cliff and prominent bench	90
McElmo formation:	
Red and light-brown sandy shale, interbedded with sandstone of similar color; forms slope partly concealed	55
Light-brown and yellow fine-grained sandstone, cross-bedded in part; occurs in massive layers and forms bench	70
Total thickness of McElmo formation	125
"Varicolored shales and sandstones":	
Red and gray shale and sandstone, interbedded; mostly covered	12
Red, gray, and drab sandstone and shale, in thin alternating beds; considerable variation in color and texture	60
Yellow and buff soft, very massive sandstone; weathers in smooth round slopes, locally with caves and shallow depressions at outcrop	300+
Partial thickness of "varicolored shales and sandstones"	372

Section on Halls Creek about 8 miles above its mouth.

[Measured by R. C. Moore.]

	Feet.
McElmo formation: Reddish-brown and light greenish-gray massive hard, irregularly bedded conglomeratic sandstone; forms prominent escarpment; thickness reduced by erosion	76
"Varicolored shales and sandstones":	
Thin-bedded red sandstone	123
Tan-brown massive soft cross-bedded sandstone, weathering in smooth rounded slopes, partly covered	850
Total thickness of "varicolored shales and sandstones"	973
"Gypsiferous shales and sandstones":	
Light-red and greenish sandy shale; contains beds of white sandstone and gypsum	90
Maroon shale and hard fine-grained quartzitic sandstone; forms escarpment	50
Total thickness of "gypsiferous shales and sandstones"	140
Navajo sandstone: White medium-grained very massive cross-bedded sanstone; forms prominent ridge	600+

Section across Waterpocket Fold near southwest corner of T. 32 S., R. 8 E., at Bitter Creek divide, head of Halls Creek.

[Measured by R. C. Moore.]

	Feet.
Masuk sandstone: Light-yellow massive sandstone, weathering yellowish brown; forms very prominent escarpment; in lower part grades into medium-bedded sandstone	297
"Masuk shale": Yellowish-brown to drab sandy shale; upper part contains beds and lenses of soft sandstone; forms slope beneath escarpment of sandstone above	700
Blue Gate sandstone: Yellow to light-brown medium to massively bedded sandstone forming precipitous cliff; locally contains lignite	230
"Blue Gate shale": Bluish-drab sandy shale, very uniform in color and texture; upper part grades into soft shaly sandstone	1,200
Tununk sandstone: Yellowish-brown medium to massively bedded sandstone	50–75
"Tununk shale": Bluish-drab sandy shale, uniform in color and texture; includes very fossiliferous thin yellow sandstone at base	975
Dakota (?) sandstone: Light-yellow soft irregularly bedded sandstone, grading upward into sandy shale; contains two thin beds of impure lignite 9 and 20 inches thick	15
McElmo formation:	
Grayish-blue, maroon, and purple banded soft sandy shale, weathering in valleys and badlands	415

McElmo formation—Continued.	Feet.
Grayish-white to light bluish-green conglomerate and sandstone; contains pebbles as much as 2 inches in diameter; consists in part of thick beds and lenses of coarse conglomerate and in part of coarse gritty very irregularly bedded sandstone	150
Total thickness of McElmo formation	563
"Varicolored shales and sandstones":	
Red and gray banded sandy shale grading to soft thin-bedded sandstone	90
Tan-brown massive soft cross-bedded sandstone, weathering in smooth rounded surfaces	260
Reddish-brown and bluish-gray very soft shaly sandstone, weathering readily, forming valley; partly covered	470
Tan-brown massive soft cross-bedded fine-grained sandstone, weathering in smooth rounded surfaces	340
Total thickness of "varicolored shales and sandstones"	1, 160
"Gypsiferous shales and sandstones:"	
Light-red and bluish-gray shale and sandstone; gray to white sandstone in alternating beds; contains several beds of bluish to white gypsum as much as 3 feet thick; the gypsum occurs also in numerous thin veins	400
Dark to light red sandy shale, containing two beds of very hard reddish and light green mottled dense siliceous massive and flaggy limestone that forms escarpments	50
Total thickness of "gypsiferous shales and sandstones"	450
Navajo sandstone: White to very light cream-colored sandstone, locally stained light orange-red in middle and lower parts; capped by bed of coffee-brown sandstone, 10 feet, and light tan, highly cross-bedded sandstone, 8 feet. Very massive, highly cross-bedded on large scale; the cross-beds are etched in relief by weathering; crops out in high, prominent "reef" whose surface is marked by numerous conical tepees, mosques, and rounded domes	1, 400
Todilto (?) formation: Dark-red to maroon cross-bedded sandstone, medium to coarse grained, thin to medium bedded; some beds hard, others soft; bedding very irregular; locally contains soft maroon sandy shale; thickness in part estimated.	160
Wingate sandstone: Red very massive hard fine-grained sandstone, of uniform color and texture, cross-bedded but bedding not prominent, much jointed; crops out as single ledge making a vertical cliff or palisade	340
Chinle formation:	
Light-bluish hard calcareous shale, mottled with lavender; upper part stained purple; weathers in rough angular blocks; forms slope	48

Chinle formation—Continued.	Feet.
Massive light greenish-blue limestone conglomerate, composed of pebbles of limestone, quartz, jasper, and sand in a lime matrix	2
Alternating beds of light bluish-green limestone and shale, mottled with lavender; the shale is hard and calcareous, forms slopes, and grades without demarcation into limestones that are nodular, hard, and massive and form projecting ledges	146
Sandy shale and sandstone, yellowish brown, yellow, dark brown, blue, purple, and ash-gray, dark tones predominating; sandstone in part soft and massive, in part hard, dense, cross-bedded, and forming projecting ledges, locally conglomeratic	304
Total thickness of Chinle formation	500
Shinarump conglomerate: Hard very massive, irregularly bedded light bluish-gray to white sandstone, weathering yellowish white locally; forms prominent escarpment; at this place thickness ranges from 40 to 110 feet within a short distance, average	60
Moenkopi formation: Thin to medium-bedded ripple-marked micaceous sandstone; weathers in slopes and projecting ledges; base not exposed	250+

Section of Shinarump conglomerate and upper part of Moenkopi formation on west side of Circle Cliffs between Horse Creek and the Peaks.

[Measured by R. C. Moore.]

Shinarump conglomerate:	Feet.
Light-gray coarse-grained very massive sandstone, forming almost unbroken vertical-faced escarpment; weathers in large angular blocks	30–60
Massive cross-bedded light bluish-gray sandstone, mottled and streaked along irregular joints with purple; grades upward without demarcation into sandy limestone; weathers in single massive bed softer than overlying sandstone and therefore forming a reentrant in the cliff; upper surface uneven	16
Moenkopi formation:	
Chocolate-brown very sandy shale, grading into shaly sandstone; more calcareous above.	7
Chocolate-brown thin-bedded ripple-marked and cross-laminated sandstone	3
Chocolate-brown very micaceous sandy shale, grading into thin shaly sandstone	5
Chocolate-brown hard shaly to platy sandstone; forms slight projecting ledge	1
Brown sandy shale, grading into thin shaly sandstone; weathers as slope	8
Chocolate-brown hard platy sandstone, forming a ledge	1
Chocolate-brown sandy shale, grading into shaly sandstone	22½

Moenkopi formation—Continued.	Feet.
Chocolate-brown thin-bedded ripple-marked laminated sandstone, locally weathering massive and forming a prominent projecting ledge	5
Chocolate-brown sandy micaceous shale with thin seams and beds of soft sandstone; in upper part contains thin beds of shaly sandstone	46½
Light greenish-gray platy fine-grained micaceous sandstone, with large asymmetrical ripple marks; produces a slight bench	⅓
Chocolate-brown sandy micaceous shale, containing abundant thin beds of shaly sandstone which weathers in thin chips and platy slabs; weathers in gentle rounded slope	27
Brown very micaceous ripple-marked sandstone, with thin light-gray bands, platy with thin shale beds between harder layers; top layer very hard and slabby	2½
Chocolate-brown sandy shale, with thin yellow and brown sandstone beds that make slight benches	56
Light-yellow very massive hard sandstone; forms projecting wall	50
Light-yellow massive sandstone, weathering in thin plates; grades into shaly sandstone; forms bench	12
Chocolate-brown sandy micaceous shale	40
Light-yellow massive sandstone; locally stained red on outcrop; grades locally into shaly or thin-bedded sandstone; forms prominent bench	160
Yellow very shaly sandstone, grading to sandy shale	5
Yellow calcareous micaceous sandstone, massive but thinly laminated, with ripple bedding; grades to shaly sandstone	4
Partial thickness of Moenkopi formation	456

(Top of Kaibab limestone 25 to 40 feet below.)

Section of Moenkopi formation in canyon north of The Peaks, northwest of Wagonbox Mesa, in the Circle Cliffs.

[Measured by R. C. Moore.]

	Feet.
Shinarump conglomerate: Gray medium to fine grained massive sandstone, weathering yellowish in part, locally conglomeratic; weathers in large angular blocks; outcrop forms prominent cliff	50–150
Moenkopi formation:	
Maroon sandy shale grading into yellow shale in upper 15 feet, with many paper-thin sandstone layers	50
Yellow fine-grained soft sandstone; weathers rather shaly	3
Maroon shale with thin shaly sandstone	39
Buff, brown, and gray fine-grained sandstone, in layers 1 to 4 inches thick	8
Yellowish-brown sandy shale	26
Pink to maroon sandstone, thin bedded, with a few massive layers as thick as 16 inches at intervals; interbedded with very sandy shale; upper part yellow-brown	48
Fine-grained hard gray and light-pink sandstone, weathering brown and light gray; weathers in beds 2 to 12 inches thick, but in fresh exposures beds appear very massive; upper part more reddish than lower; ordinarily well exposed	42
Red sandstone, with thin sandy shale interbedded, medium to massive bedding	31
Very thin bedded platy light-brown and yellow to pink sandstone, weathering reddish brown; abundant ripple marks; grades locally into shale; forms slopes	36
Pink to red sandy shale, containing thin beds of platy sandstone; weathers in slopes	21
Total thickness of Moenkopi formation	304
Kaibab limestone: Deep-yellow to buff very hard fine-grained dense dolomitic limestone, in massive beds 3 to 6 feet thick; weathers in large angular blocks; forms prominent bench; exposed thickness	20

A NEW FAUNA FROM THE COLORADO GROUP OF SOUTHERN MONTANA.

By John B. Reeside, Jr.

INTRODUCTION.

This paper describes a small but interesting fauna collected in 1921 by W. T. Thom, jr., Gail F. Moulton, T. W. Stanton, and K. C. Heald in the Crow Indian Reservation in southern Montana. The locality is in sec. 36, T. 6 S., R. 32 E., Big Horn County, and is 2 miles east of the Soap Creek oil field.

The stratigraphic section in the Soap Creek oil field was described briefly by Thom and Moulton in a press notice issued by the United States Geological Survey December 5, 1921, entitled "The Soap Creek oil field, Crow Indian Reservation, Mont." It was described also in a later and more general paper.[1] The youngest beds present near the oil field belong to the Niobrara formation, but in the adjacent parts of the Crow Reservation to the east and north higher formations are present and are in part included in the section given below. The part of the section from the Cloverly formation to the Niobrara formation, inclusive, is derived from the publications mentioned above and from data kindly supplied by Mr. Thom. The thicknesses given for the Eagle sandstone and the Telegraph Creek formation apply especially to the vicinity of Pryor Creek, some 30 miles north of the Soap Creek oil field. The included lists of fossils are based on the writer's determinations.

Partial section of formations exposed in the Crow Indian Reservation, Mont.

	Feet.
Eagle sandstone	200–250

Sandstones and some shales; at base the massive Virgelle sandstone member. This formation contains *Scaphites hippocrepis* (Dekay), *Scaphites* n. sp. aff. *S. aquisgranensis* Schlueter, *Inoceramus* aff. *I. lobatus* Goldfuss, *Placenticeras syrtale* (Morton), *Placenticeras meeki* Boehm, *Placenticeras planum* Hyatt, *Baculites ovatus* Say, *Baculites asper* Morton, *Baculites* n. sp. aff. *B. anceps* Lamarck, and many other fossils.

	Feet.
Telegraph Creek formation	320–350

Sandstones and shales. This group of beds contains at places in the upper part a fauna like that of the Eagle sandstone, but in the lower beds it contains *Uintacrinus* sp., *Marsupites* sp. (identified by Frank Springer), *Inoceramus deformis* Meek var., *Ostrea* cf. *O. congesta* Conrad, *Baculites* sp., *Puzosia* (*Latidorsella*) n. sp., and *Scaphites* n. sp. aff. *S. geinitzi* D'Orbigny.

Niobrara formation (top formation of Colorado group)	400

Bluish calcareous shale in upper and lower parts; dark shale in middle. In the upper part it contains *Uintacrinus socialis* Grinnell (identified by Frank Springer), *Yoldia* sp., *Inoceramus*, large thick-shelled species, *Ostrea congesta* Conrad, *Lunatia concinna* (Hall and Meek), *Tessarolax* cf. *T. hitzi* White, *Baculites* sp., *Scaphites vermiformis* Meek and Hayden, and fish scales. In the middle part it contains *Inoceramus* aff. *I. lamarcki* Parkinson, *Inoceramus umbonatus* Meek and Hayden, *Inoceramus*, large thick-shelled species, *Pteria* aff. *P. nebrascensis* (Evans and Shumard), *Anatina* aff. *A. subgracilis* (Whitfield), *Veniella goniophora* Meek, *Cardium* n. sp., *Fusus* sp., *Voluderma* sp., *Baculites* aff. *B. anceps* Lamarck, *Baculites asper* Morton, *Scaphites vermiformis* Meek and Hayden. In the lower part it contains *Inoceramus*, large thick-shelled species, *Ostrea congesta* Conrad, and the basal bed, a zone of large yellow concretions, contains *Yoldia* sp., *Nemodon* sp., *Barbatia* n. sp., *Inoceramus fragilis* (Hall and Meek)?, *Inoceramus* (*Actinoceramus*) n. sp., *Veniella goniophora* Meek, *Callista tenuis* (Hall and Meek), *Corbula* cf. *C. nematophora* Meek, *Dentalium* sp., *Gyrodes* aff. *G. petrosa* (Morton), *Turritella* aff. *T. whitei* Stanton, *Anchura* sp., *Nautilus* sp., *Baculites* sp., and *Scaphites vermiformis* Meek and Hayden.

Carlile shale	425

This formation may be divided into a number of units as follows:

Dark shale with whitish septarian nodules containing *Inoceramus labiatus* (Schlotheim), *Veniella goniophora* Meek, *Corbula* aff. *C. nematophora* Meek, *Pseudomelania?* sp., *Fusus* sp., *Prionocyclus wyomingensis* Meek. Thickness 50 feet.

Zone of large yellowish sandstone concretions. Thickness 5 feet.

Dark shale. Thickness 35 feet.

Shale with thin hard rusty red concretions and layers containing *Inoceramus fragilis* Hall and

[1] Thom, W. T., jr., Oil and gas prospects in and near the Crow Indian Reservation, Mont.: U. S. Geol. Survey Bull. 736, pp. 35-53, 1922 (Bull. 736-B)

	Feet.
Meek, *Inoceramus* cf. *I. lamarcki* Parkinson, *Veniella* sp., *Volutoderma?* sp., *Baculites gracilis* Shumard, *Scaphites warreni* Meek and Hayden, *Prionotropis* aff. *P. woolgari* (Mantell). Thickness 30 feet.	
Dark shale. Thickness 60 feet.	
Bluish calcareous shale containing in its lower part the fauna described in this paper. Thickness 100 feet.	
Dark shale and bentonite. Thickness 145 feet.	
Frontier formation	410
Chiefly dark shale with bentonite but with a zone of thin coarse sandstones near the top. Shark teeth the only fossils observed.	
Mowry shale	200–300
Hard bluish-white shale with layers of hard dark shale. Contains abundant fish remains but few other fossils.	
Thermopolis shale	550–800
Dark marine shale with streaks and lenses of light-colored sandstone containing *Inoceramus labiatus* (Schlotheim), *Pteria* aff. *P. nebrascensis* (Meek and Hayden), *Ostrea* sp., *Entolium* sp., *Modiola* n. sp., *Gyrodes* aff. *G. depressa* Meek, fish and turtle remains. Middle part of formation of dark clay and bentonite; lower part of dark marine shale.	
Cloverly formation	320–425
An upper member of sandy shale and thin-bedded rusty sandstone that may represent the Dakota sandstone of Upper Cretaceous age.	
A middle member consisting of variegated shale where exposed along the Big Horn Mountains and containing *Unio* sp. and *Viviparus?* sp. and a basal member of thick coarse-grained conglomeratic sandstone. These divisions may represent the Fuson shale and Lakota sandstone, of Lower Cretaceous age.	

THE FAUNA AND ITS RELATIONS.

The collection described in this paper contains five species of ammonites referred to three genera, two species of *Inoceramus*, an ostreid, and a gastropod.

The species are as follows:

Vascoceras thomi Reeside, n. sp.
Vascoceras moultoni Reeside, n. sp.
Vascoceras stantoni Reeside, n. sp.
Vascoceras sp. undeterminable.
Pseudotissotia (Choffaticeras) sp.?
Helicoceras pariense White?
Inoceramus labiatus (Schlotheim).
Inoceramus sp. undetermined.
Ostrea or Exogyra sp.
Gastropod, undetermined.

This fauna is known from only this one locality in the Western Interior province of North America, and consequently its correlation must rest in large part on its position with relation to other faunal zones in the same stratigraphic section and in the adjacent region. It is therefore of interest to consider some of the faunal zones recognizable in the Cretaceous deposits of this province.

A series of more or less widespread and more or less distinctly defined faunal zones have long been recognized in the Cretaceous deposits of the Western Interior. The lowest zone to be considered here is well characterized only in the southern part of the province, where it contains *Exogyra columbella* Meek and *Gryphaea newberryi* Stanton as its guide fossils. This zone includes the Graneros shale of the central Great Plains, the basal part of the Mancos shale of New Mexico, Colorado, and Utah, and the Thermopolis shale of the north. At many places, especially in the north, it is nearly barren of fossils, and those present are not sufficiently restricted to serve as guide fossils.

Above this zone occurs a zone with an abundance of *Inoceramus labiatus* (Schlotheim). In the central Great Plains region this zone is contained in the Greenhorn limestone, and very few other fossils than the guide fossil have been found in it. In western Colorado and the adjacent region it is well marked in the lower part of the Mancos shale. It occurs in southern and central Wyoming in the Frontier formation and in northern Montana in the lower part of the Colorado shale.

Above this zone of *Inoceramus labiatus* lies a zone which contains as its more prominent and restricted species *Scaphites warreni* Meek and Hayden, several species each of *Prionotropis*, and *Prionocyclus*, *Inoceramus fragilis* Hall and Meek, *Inoceramus dimidius* White, and *Ostrea lugubris* Conrad. It very rarely contains *Inoceramus labiatus* (Schlotheim). This zone is perhaps the most sharply defined and most widely recognized of the series. It comprises the entire Carlile shale of the central Great Plains and Black Hills regions, part of the Mancos shale of western Colorado and adjacent regions, the Carlile shale of Wyoming, and part of the Colorado formation of Montana.

Above the zone of *Scaphites warreni* comes a zone which contains *Uintacrinus socialis* Grinnell, *Inoceramus umbonatus* Meek and Hayden, *Inoceramus deformis* Meek, and, especially in the north, *Scaphites ventricosus* Meek and Hayden and *Scaphites vermiformis* Meek and Hayden. A very abundant and locally restricted form of this zone is *Ostrea congesta*

Conrad. *Inoceramus labiatus* is reported in the literature as occurring here also, but it has not been found in numerous recent collections, and its earlier assignment to the fauna of this zone is very probably due to the erroneous reference of local exposures of the Greenhorn limestone to the Niobrara formation in Nebraska, Kansas, and elsewhere prior to Darton's work in that region. In this zone falls the Niobrara formation of the Great Plains region, part of the Mancos shale of western Colorado and the adjacent regions, the Niobrara formation of Wyoming, and the upper part of the Colorado shale of northern Montana.

Above this zone of *Uintacrinus* and *Scaphites vermiformis* comes a zone containing *Scaphites hippocrepis* (DeKay), *Scaphites* n. sp. aff. *S. aquisgranensis* Schlueter, *Placenticeras syrtale* (Morton) and its allies, *Placenticeras planum* Hyatt, and *Inoceramus* aff. *I. lobatus* Goldfuss. In New Mexico this zone has yielded also *Mortoniceras* aff. *M. delawarense* (Morton). In Montana and in southwestern Colorado and adjacent parts of New Mexico there is a subzone at the base of this zone which lacks *Scaphites hippocrepis* and *Scaphites* aff. *S. aquisgranensis* but which contains *Scaphites* n. sp. aff. *S. geinitzi* D'Orbigny as its most distinctive form. The zone of *Scaphites hippocrepis* is represented by the Eagle sandstone and Telegraph Creek formation of southern Montana, part of the Cody shale of northern Wyoming, part of the Steele shale of central and southern Wyoming, and the upper part of the Mancos shale of southwestern Colorado and adjacent New Mexico. Presumably the basal part of the Pierre shale of the central Great Plains and Black Hills regions represents this zone, though the distinctive species have not been found in it except in northeastern New Mexico. Above the zone of *Scaphites hippocrepis* other faunal zones may be recognized but will not be described in this paper.

The stratigraphic section at the Soap Creek oil field and in the adjacent country, as shown in the section given on page 25, has afforded enough paleontologic data to determine the relative position of the fossils described in this paper. The beds containing the fauna include the highest bed in which *Inoceramus labiatus* occurs abundantly and lie immediately beneath beds with the characteristic fauna of the zone of *Scaphites warreni*. They are therefore to be correlated with at least the upper part of the Greenhorn limestone of the central Great Plains, though the occurrence of *Inoceramus labiatus* in beds some 800 feet lower in the section raises a doubt whether the beds containing *Vascoceras* represent all of the Greenhorn limestone as developed at such localities as those in eastern Colorado, where the Greenhorn limestone contains the only beds in which *Inoceramus labiatus* occurs, is only about 50 feet thick, and is separated from the Dakota sandstone by scarcely 200 feet of Graneros shale. It is possible that the relatively great thickness of Graneros shale present in the Black Hills region beneath the Greenhorn limestone is due entirely to greater deposition of material to form the shale without an appreciably greater lapse of time and that the Greenhorn limestone, which does not change much in thickness over the whole region, represents approximately the same time interval everywhere. If so, the beds containing *Vascoceras* may represent all the time interval of the Greenhorn limestone and its equivalents in various parts of the Western Interior. In central Montana the Mosby sandstone member of the Warm Spring shale [2] occupies a position in the section similar to that of the beds containing *Vascoceras*. Inasmuch as the faunas of the two units have in common only *Inoceramus labiatus* they do not help in determining the relations between them. Perhaps the only suggestion offered is the occurrence of *Metoicoceras whitei* Hyatt in the Mosby sandstone. This species is most abundant in and most characteristic of the lower part of the Colorado group in southern Utah and in New Mexico and may indicate that the conditions which permitted the northward extension of *Vascoceras* as far as southern Montana were the same as those which permitted *Metoicoceras* to reach central Montana and that the Mosby sandstone and the beds containing *Vascoceras* represent the same time.

The only other occurrence of *Vascoceras* in North America is that at Cerro del Macho, in the State of Coahuila, Mexico, described by Böse.[3] Here the associated fossils are more numerous, though none of the species seem to be identical with those from Montana, except *Inoceramus labiatus*. Böse has given a good summary

[2] U. S. Geol. Survey Bull. 736, p. 172, 1922 (Bull. 736-F).

[3] Böse, Emil, On a new ammonite fauna of the lower Turonian of Mexico: Texas Univ. Bull. 1856, pp. 173-257, 1918.

of the distribution of the *Vascoceras* fauna and of its composition in all its principal occurrences. The fauna in its fullest and most typical development contains species of the ammonite genera *Fagesia, Vascoceras, Mammites, Pseudaspidoceras, Neolobites, Pseudotissotia, Hoplitoides*, and *Thomasites*. It is the Salmurian fauna of the European geologists and is widely distributed in the Mediterranean region. It occurs in the lower and middle Turonian of Portugal; the lower Turonian of Algeria, Tunis, and Egypt; the Turonian of the southern Sahara region; and in Brazil, Colombia, Peru, and Mexico. Faunas more or less related though not yet reported to contain *Vascoceras* occur in the Turonian of southern France, in India, and in Japan.

A comparison of the faunal succession in the Western Interior province with that in western Europe suggests the following correlations:

Western Interior.	Europe.
Zone of *Scaphites hippocrepis*	Lower Campanian. Upper Santonian.
Zone of *Uintacrinus, Inoceramus umbonatus*, and *Scaphites vermiformis*.	Lower Santonian. Coniacian.
Zone of *Scaphites warreni*	Upper Turonian.
Zone of *Inoceramus labiatus* (*Vascoceras* at top in Montana)	Lower Turonian.

Apparently the present occurrence of *Vascoceras* would agree with the accepted assignment of the other known occurrences to the lower Turonian. It might be middle Turonian, if such a unit were recognized, but scarcely younger.

DESCRIPTIONS OF SPECIES.

Genus VASCOCERAS Choffat.

Choffat's original description[4] is in part as follows:

Genus formed by shells more or less thick, sometimes globular, with ventral region rounded, ornamented in youth by ribs giving rise to tubercles on the flanks and to tubercles or elongated swellings on each side of the siphon. With some rare exceptions (*Vascoceras subconciliatum*), these lines of tubercles disappear in the adult stage, those of the umbilical border persisting longer, and the ventral region, or even all the visible part of the shell, is without ornamentation.

The length of the living chamber is from one-half to three-fourths of a whorl.

The suture shows two broad, rounded, weakly incised saddles, the third saddle much less important than it would be if the decrease were regular. The lobes are broad and divided by small saddles, in general not incised. From the position of these saddles the first lobe may be considered as divided into two or three parts. The second lobe is either simple or divided into two. [Translated.]

Choffat proposed four sections of the genus—(*a*) monotuberculate forms with wide umbilicus, (*b*) subglobular forms with rounded umbilical border, (*c*) globular forms with angular or subangular umbilical border, (*d*) multituberculate forms.

Pervinquière[5] later discussed *Vascoceras*, modifying somewhat Choffat's original description. Pervinquière's description is as follows:

Shell more or less thick, sometimes globular, with ventral region rounded, ornamented, in youth, by ribs bearing umbilical tubercles and marginal tubercles; these tubercles become less distinct in the adult stage (the umbilical tubercles remain distinct longer) and even disappear completely except on one group. There is never a median ventral tubercle. Living chamber measuring three-fourths of a whorl or even more. * * * Suture including two broad, rounded, little incised saddles; the third much smaller. Lobes broad and divided by small unincised saddles. [Translated.]

Pervinquière recognizes only three sections of the genus:

1. Group of *V. gamai* and of *V. douvillei-durandi*. Monotuberculate forms with wide umbilicus in the first species and more restricted in the second. There is every intermediate form between the two, as regards both general form and the greater or lesser rounding of the umbilical shoulder.
2. Group of *V. harttiformis*. Globular forms, with the umbilicus generally narrow, the umbilical shoulder more or less angular.
3. Group of *V. subconciliatum*. Multituberculate forms, departing notably from the preceding and approaching *Mammites* and the extreme forms of *Acanthoceras*.

Pervinquière points out that *Vascoceras* differs from the nearly related genus *Fagesia* Pervinquière in general form, in the much earlier disappearance of the ribs and tubercles, and especially in the suture. The suture of *Fagesia* has four slender lateral saddles, rounded in the upper part and trifid in subdivision; three lateral lobes, of which the first is profoundly bifid, the second less so, and the third pointed. Pervinquière adds, however, that some forms of *Vascoceras* are difficult to distinguish from *Fagesia*.

[4] Choffat, Paul, Les ammonées du Bellasien, des couches à *Neolobites vibrayeanus*, du Turonien, et du Sénonien: Faune crétacique du Portugal, vol. 1, ser. 2, p. 53, 1898.

[5] Pervinquière, Léon, Études de paléontologie tunisienne, pt. 1, Céphalopodes des terrains secondaires, pp. 331-332, 1907.

The specimens in hand from Montana are a bit confusing in their relations. The general form, except perhaps for the width of the umbilicus, would permit an assignment to *Fagesia*, and the proportions and degree of incision of the suture fit those of *Fagesia* better than those of *Vascoceras*. Moreover, the umbilical tubercles are prominent, and there are traces of the ventral ribs in even the largest specimens. The younger whorls, however, show distinctly the umbilical and ventral tubercles of *Vascoceras*, the umbilicus is wider than shown in most of the figured specimens of *Fagesia*, and the suture in every specimen examined shows a pointed first and second lateral lobe, not bifid. The writer therefore assigns the specimens to *Vascoceras* rather than to *Fagesia* and further would place the first two of the species here described under Pervinquière's section 1 and the third under section 2.

Vascoceras thomi Reeside n. sp.

Plate XI, figures 1–2; Plate XII, figures 1–2; Plate XIII, figures 1–2; Plate XIV, figures 1–2; Plate XV, figures 1–7; Plate XVI, figures 1–6.

Shell stout, coronate. Earlier whorls not well shown in the type specimen except for the umbilical part, but apparently stout. Whorls above 115-millimeter diameter have a moderately depressed, oval cross section. Living chamber in type occupies three-fourths of a whorl and is apparently incomplete. Maximum diameter of type 165 millimeters. Umbilicus deep but fairly wide—about one-half the diameter of the shell in width. Umbilical shoulders rounded but well defined.

Sculpture of earlier whorls of type specimen seen only in the umbilicus, where it consists of large blunt conical nodes, seven to the whorl. On the last whorl of the type faint coarse ribs connect the umbilical nodes and a faint flattening on the venter seems to correspond to the space between the marginal nodes of the younger stages.

The suture shows a fairly broad ventral lobe and four lateral lobes and saddles, only moderately incised. The first lateral lobe is bluntly pointed, and the first lateral saddle is trifid.

A very large specimen (see Pl. XIII, figs. 1–2; Pl. XIV, figs. 1–2) assigned to this species has a maximum diameter of 260 millimeters and is apparently almost complete. The inner whorls are poorly preserved. The living chamber occupies three-fourths of a whorl; the aperture is not preserved. The suture of this specimen has wider saddles than those of the suture of the type but is otherwise like it. The umbilical nodes and obscure ventral ribs persist to the end of the specimen.

A small specimen assigned to this species (see Pl. XV, figs. 1–7) shows the sculpture and form of the stages following that at the diameter of 25 millimeters. The whorls to a diameter of about 40 millimeters are as high as wide and have strong rounded ribs that begin at the umbilical nodes, pass with a slight forward curve to the margin of the venter, where they form an elongated, poorly defined node, and then continue unbroken across the venter. Two or three ribs start from each umbilical node, and there are some intercalated ribs. On the half whorl from the diameter of 25 millimeters to the diameter of 40 millimeters there are four umbilical nodes and 15 ventral ribs. Above the diameter of 40 millimeters the ribs are less and less distinct on the venter, and at the diameter of 75 millimeters there are only indistinct folds. The umbilical nodes, however, remain large and blunt. The suture is much like that of the type.

A fourth specimen (see Pl. XVI, figs. 1–6), about the size of that just described, is assigned with some doubt to this species. The sculpture is much weaker than on the specimen just described and less than one would expect to find on the type at the same size. The cross section of the whorl is somewhat more depressed, and the suture is more incised. The specimen is closer to *V. thomi* than to the other species described in this paper and is therefore attached to it.

Vascoceras thomi may be recognized by its well-rounded venter and relatively high whorls. It differs from *V. moultoni* Reeside in possessing more elevated whorls and in sutural details; from *V. stantoni* Reeside in its much more elevated whorls and less angular umbilical shoulder It suggests somewhat *V. silvanense* Choffat [6] but is apparently a much larger species and has a wider umbilicus and a different suture. It also suggests *V. adonense* Choffat [7]

[6] Choffat, Paul, Les ammonées du Bellasien, des couches à *Neolobite vibrayeanus* du Turonien, et du Sénonien: Faune crétacique du Portugal, vol. 1, ser. 2, p. 57, pl. 8, fig. 5; pl. 21, fig. 9, 1898.

[7] Idem, p. 59, pl. fig. 9, 3; pl. 21, fig. 12.

but differs in the retention of the tubercles, in the form of the umbilicus, and in suture.

Vascoceras moultoni Reeside, n. sp.

Plate XVII, figures 1–2; Plate XVIII, figures 1–2.

Shell stout, coronate. Earliest stage seen in the single specimen available is at diameter of 80 millimeters. Whorl has broad, depressed-oval cross section. Width of umbilicus more than half the diameter of the shell. Umbilical shoulder bluntly rounded. Living chamber and aperture unknown.

Sculpture of the visible whorls consists chiefly of large blunt conical nodes on the umbilical shoulders; umbilical wall smooth; venter smooth except for ill-defined broad, low ribs connecting the nodes.

Suture little incised; the lobes long and slender, the saddles rather broad and open; first lateral lobe pointed; first lateral saddle trifid.

Vascoceras moultoni may be recognized by the depressed-oval form of the cross section of the whorl and the relatively simple suture. It has a broader, more depressed whorl and simpler suture than *V. thomi* Reeside and a rounded rather than a subangular umbilical shoulder as in *V. stantoni* Reeside. It resembles some of the forms assigned in the literature to *V. douvillei* Choffat but is distinct from all of them in the persistence of the umbilical tubercles and in the suture.

Vascoceras stantoni Reeside, n. sp.

Plate XIX, figures 1–2; Plate XX, figures 1–3; Plate XXI, figures 1–3.

Shell stout, coronate. Earliest stage seen, at diameter of 35 millimeters, has whorl with depressed-ovate cross section. The form of the cross section changes little to the stage at diameter of 100 millimeters but thereafter becomes a broad pentagon. Width of umbilicus about half the diameter of the shell; umbilical shoulders subangular. Type entirely septate.

Sculpture of the whorl at diameter of 35 millimeters consists of coarse rounded ribs starting in pairs from a high conical umbilical node, passing to the margin of the venter, where they form blunt elongated nodes, and then continuing unbroken across the venter. There are four umbilical nodes and perhaps 10 ventral ribs on the half whorl succeeding the diameter of 35 millimeters. At the diameter of 70 millimeters, a whorl later, the whorl is smooth except for the umbilical nodes, and it remains so in all the later stages seen.

The suture shows four lateral lobes and saddles, moderately incised. The first lateral lobe is pointed, and the first lateral saddle trifid.

Two other specimens assigned to this species show a much later stage of growth than the type. The better preserved though less complete specimen (see Pl. XXI, figs. 1–3) would have measured about 275 millimeters in diameter. It has the same form of the whorl as the type and preserves even at so late a stage the umbilical tubercles and traces of the ventral ribs. The suture of this specimen was not seen.

Vascoceras stantoni may be recognized by its broad whorls with depressed pentagonal cross section and subangular umbilical shoulders. In the early stages it is not greatly different from *V. thomi* Reeside except that the ribs are finer, but in the later stages it departs sharply from that species in the form of the whorl. It differs from *V. moultoni* Reeside in its subangular umbilical shoulders and in sutural details. It is perhaps closest to *V. harttiformis* Choffat[8] in its general form but differs in the persistence of the umbilical nodes, in the greater width of the umbilicus, and in the suture.

Vascoceras sp.

Plate XX, figure 4.

The young stages of these American species of *Vascoceras* seem to be missing in most of the specimens in hand. One rather poorly preserved mold shows the exterior of younger whorls than any of the other specimens and is therefore figured.

Genus PSEUDOTISSOTIA Peron.

Subgenus CHOFFATICERAS Hyatt.

Pseudotissotia (Choffaticeras) sp.?

Plate XII, figures 3–6.

A single small specimen of an ammonite with sharp venter was obtained in cleaning the

[8] Choffat, Paul, op. cit., p. 53, pl. 12, fig. 3; pl. 13, figs. 3–6; pl. 21, figs. 22–24, 1898.

umbilicus of one of the large specimens of *Vascoceras*. This small specimen is nearly complete, preserving three-fourths of the last whorl unseptate, although only 13 millimeters in greatest diameter. The shell is very much compressed, discoid. The flanks of the whorls curve evenly from the umbilicus to the ventral keel. The umbilicus is moderately wide, about one-fourth the diameter of the shell, and the umbilical margin is rounded. The entire shell is smooth, without any trace of ribs or nodes. The suture is well preserved and very simple. It shows a very broad ventral lobe, a broad first lateral saddle with two incipient marginal lobes, a broad first lateral lobe with a suggestion of an incipient marginal lobe on the outer side, a simple second lateral saddle and lobe, and one auxiliary saddle and lobe.

The generic assignment of this little ammonite is uncertain. On the basis of Hyatt's figures of the sutures of young *Metengonoceras* and *Coelopoceras* [9] it could scarcely belong to those genera of sharp-ventered ammonites, both of which are known to occur in the Colorado group of the Interior province of North America. Of other genera its suture appears to be proportioned more like that of *Pseudotissotia* than of any other genus, and it is therefore tentatively assigned to *Pseudotissotia* and to the subgenus *Choffaticeras* because it shows no trace of ventrolateral keels or nodes.

[9] Hyatt, Alpheus, Pseudoceratites of the Cretaceous: U. S. Geol. Survey Mon. 44, pl. 10, figs. 10-12; pl. 27, fig. 13, 1903.

Helicoceras pariense White?

Plate XX, figures 5-6.

A single fragment of a small cephalopod that appears to have had an open coil in a single plane was uncovered in preparing the type of *Vascoceras thomi*. It suggests very strongly young *Helicoceras pariense* White,[10] though the specimen is insufficient to warrant an unquestioned assignment to that species. The suture is not visible, but the form and sculpture agree closely with those of the specimen figured by Stanton.

Hyatt [11] referred *Helicoceras pariense* White to his genus *Exiteloceras*, but the writer prefers to use the more general name here.

Inoceramus labiatus (Schlotheim).

Plate XIV, figures 3-5.

A number of specimens of this widespread species accompany the other fossils of the collection. They are mostly of small size but do not depart in any way from typical shells from other localities.

Inoceramus sp.

Plate XIV, figure 6.

A single small specimen of a relatively coarse-ribbed, transversely elongated species of *Inoceramus* is contained in the collection. It resembles in some respects several different species but is hardly sufficient for certain identification.

[10] Stanton, T. W., The Colorado formation and its invertebrate fauna: U. S. Geol. Survey Bull. 106, p. 164, pl. 35, figs. 2-4, 1893.

[11] Hyatt, Alpheus, The phylogeny of an acquired characteristic: Am. Philos. Soc. Proc., vol. 32, p. 577, 1894.

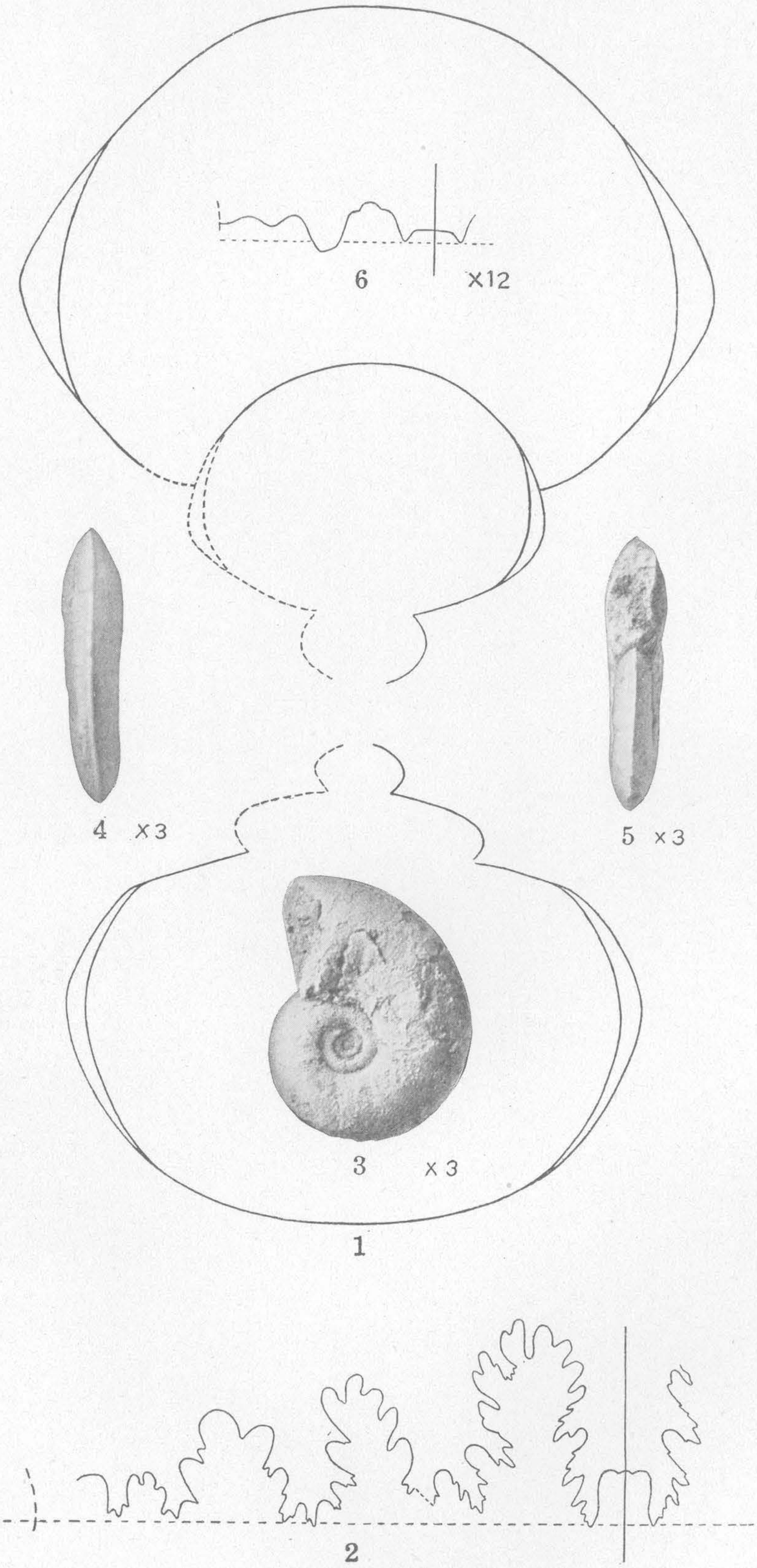
PLATES XI-XXI.

1

2

FOSSILS FROM THE COLORADO GROUP OF SOUTHERN MONTANA.

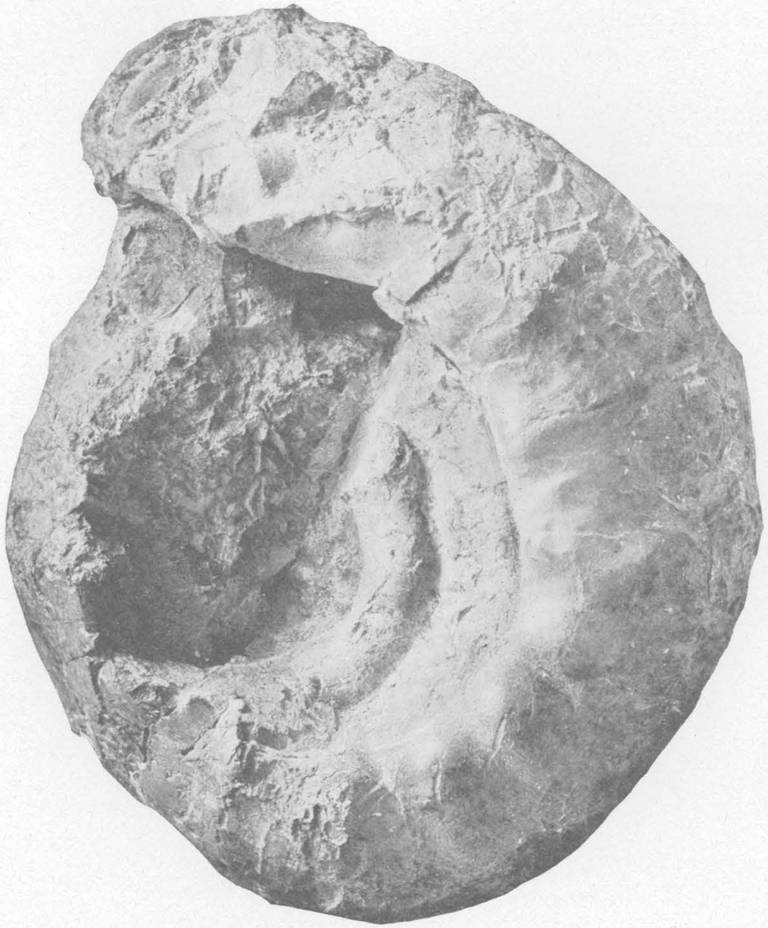
Vascoceras thomi Reeside, n. sp. Type specimen (U. S. Nat. Mus. catalog No. 32535). **1,** Side view; **2,** rear view.



FOSSILS FROM THE COLORADO GROUP OF SOUTHERN MONTANA.

1-2. *Vascoceras thomi* Reeside, n. sp. Type specimen (U. S. Nat. Mus. catalog No. 32535). **1,** Cross section at diameter of 165 millimeters; **2,** suture at diameter of 100 millimeters.

3-6. *Pseudotissotia* (*Choffaticeras*) sp.? **3,** Side view; **4,** rear view; **5,** front view; **6,** suture. (U. S. Nat. Mus. catalog No. 32541.)

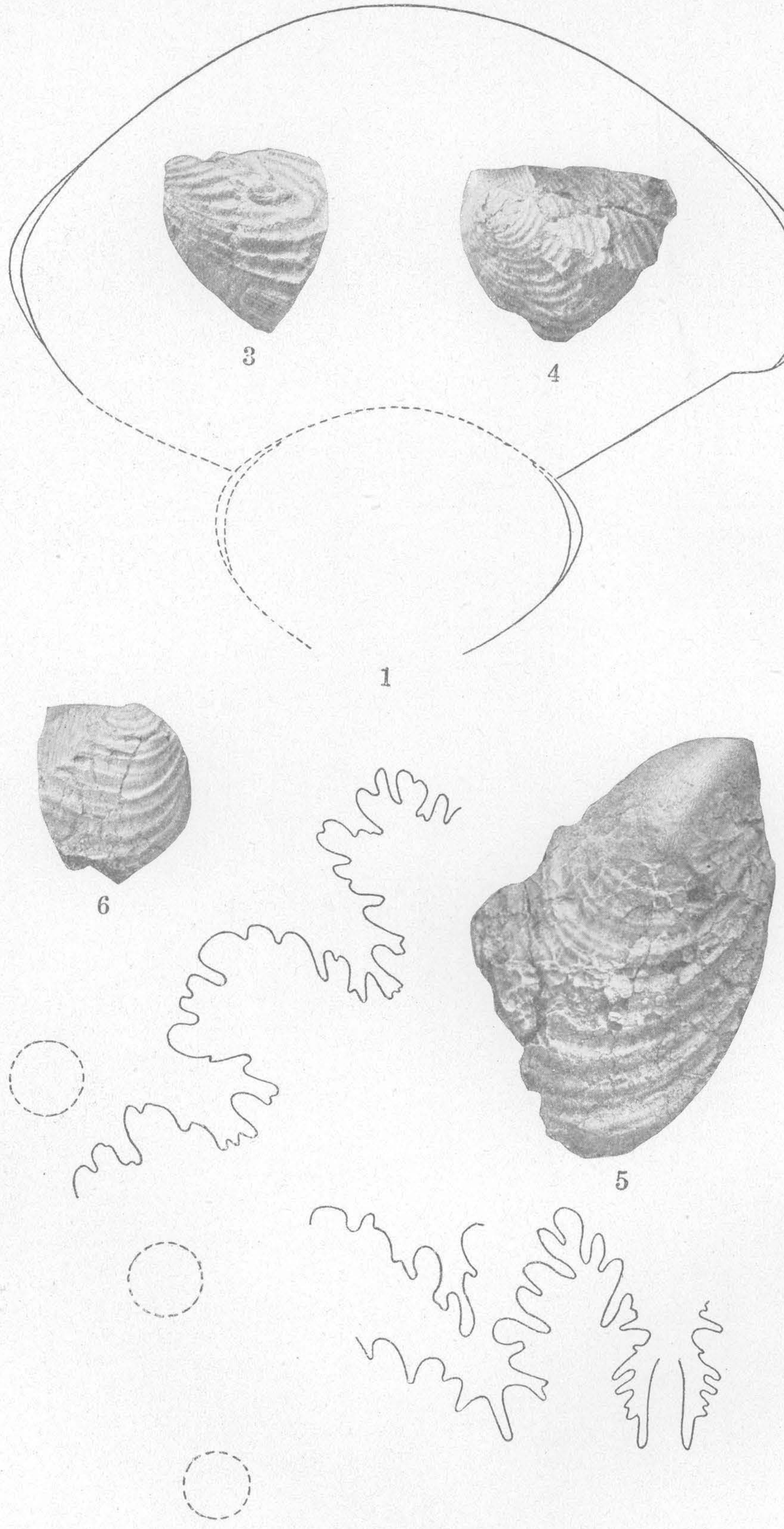


1 × ½

2 × ½

FOSSILS FROM THE COLORADO GROUP OF SOUTHERN MONTANA.

Vascoceras thomi Reeside, n. sp. **1,** Side view; **2,** rear view. (U. S. Nat. Mus. catalog No. 32536.)

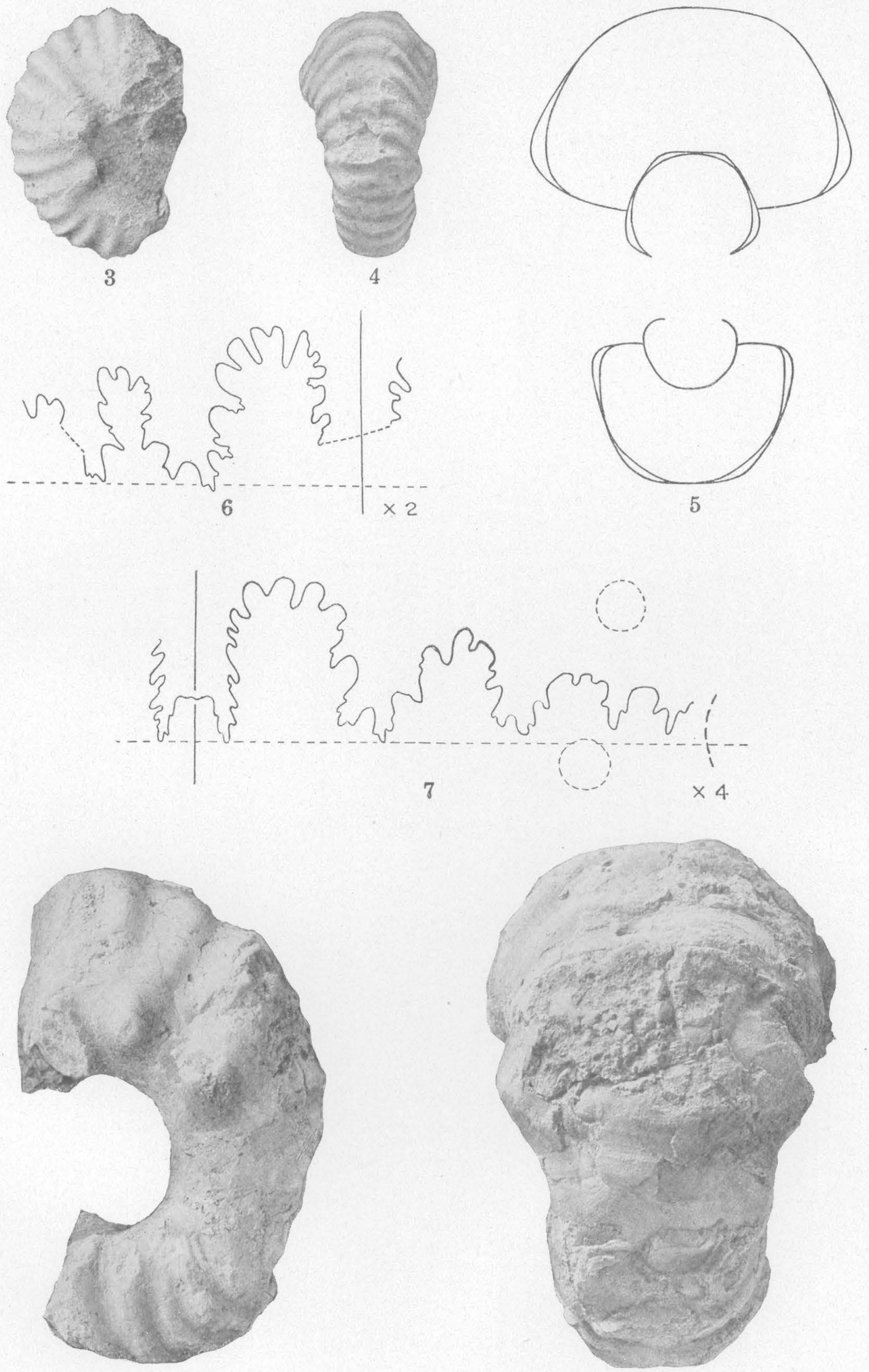


FOSSILS FROM THE COLORADO GROUP OF SOUTHERN MONTANA.

1-2. *Vascoceras thomi* Reeside, n. sp. **1,** Cross section of whorl at diameter of 200 millimeters; **2,** parts of three sutures at diameter of 150 millimeters of specimen shown on Plate XIII. (U. S. Nat. Mus. catalog No. 32536.)

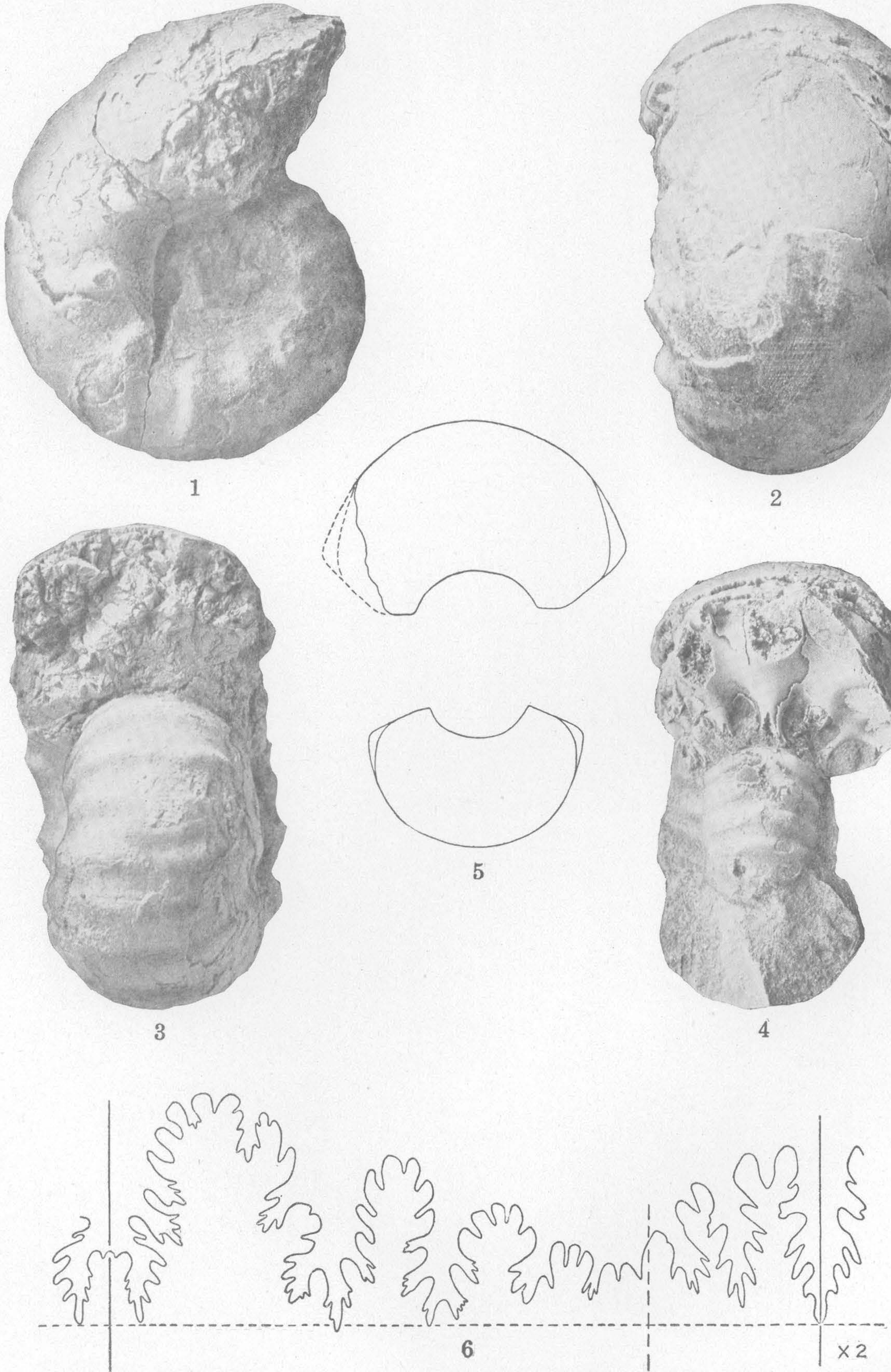
3-5. *Inoceramus labiatus* (Schlotheim). (U. S. Nat. Mus. catalog Nos. 32540 and 32543.)

6. *Inoceramus* sp. (U. S. Nat. Mus. catalog No. 32542.)



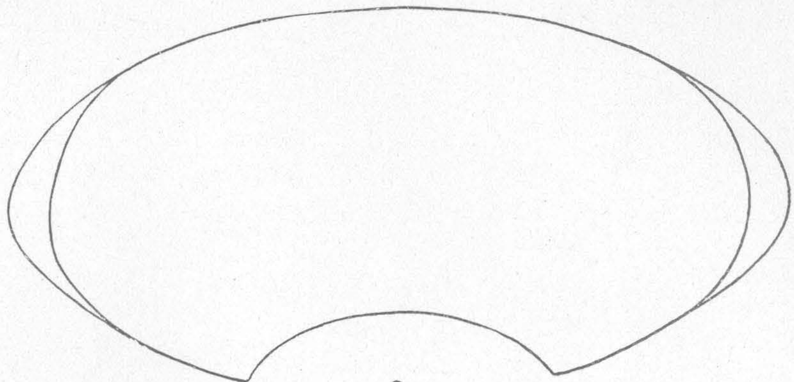
FOSSILS FROM THE COLORADO GROUP OF SOUTHERN MONTANA.

Vascoceras thomi Reeside, n. sp. **1,** Side view of outer whorl; **2,** rear view of outer whorl; **3,** side view of inner whorl; **4,** rear view of inner whorl; **5,** cross section at diameter of 75 millimeters; **6,** suture at diameter of 55 millimeters; **7,** suture at diameter of 30 millimeters. (U. S. Nat. Mus. catalog No. 32536.)



FOSSILS FROM THE COLORADO GROUP OF SOUTHERN MONTANA.

Vascoceras thomi Reeside, n. sp. **1–3,** Entire specimen; **1,** side view; **2,** rear view; **3,** front view; **4,** rear view with part of outer whorl removed; **5,** cross section at diameter o170 millimeters; **6,** suture at diameter of 60 millimeters. (U. S. Nat. Mus. catalog No. 32536.)

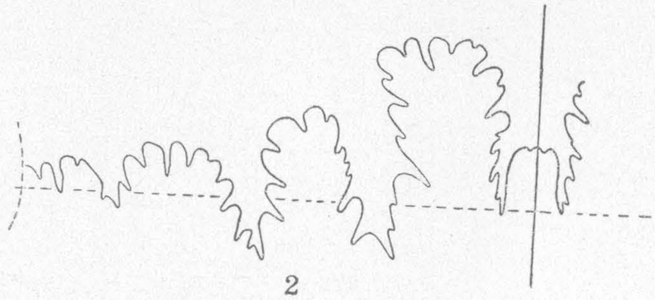


2

1

FOSSILS FROM THE COLORADO GROUP OF SOUTHERN MONTANA.

Vascoceras moultoni Reeside, n. sp. Type specimen (U. S. Nat. Mus. catalog No. 32537). 1, Side view; 2, rear view.



2

1

FOSSILS FROM THE COLORADO GROUP OF SOUTHERN MONTANA.

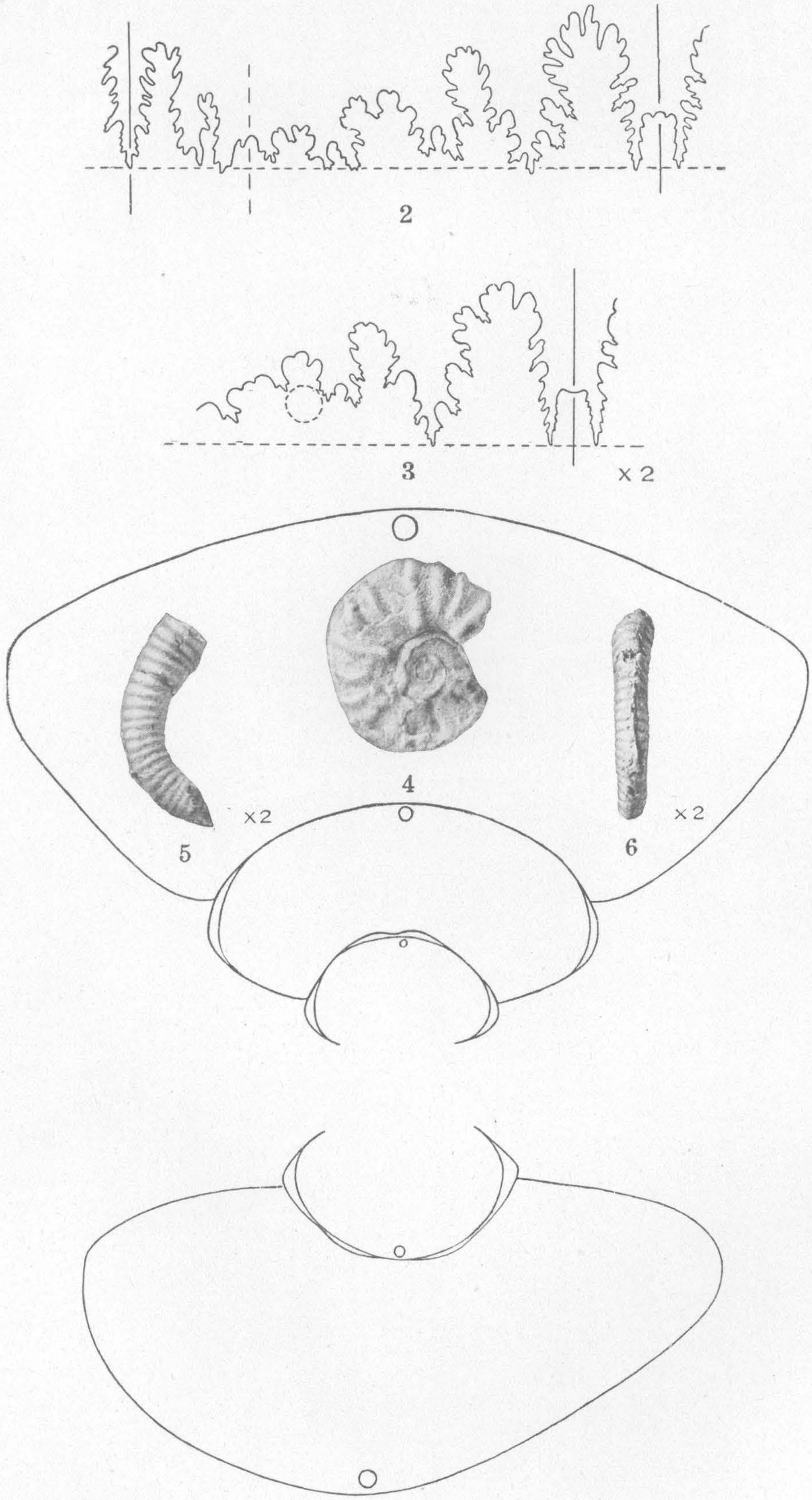
Vascoceras moultoni Reeside, n. sp. Type specimen (U. S. Nat. Mus. catalog No. 32537). **1,** Cross section of whorl at diameter of 150 millimeters; **2,** suture at diameter of 110 millimeters.

1

2

FOSSILS FROM THE COLORADO GROUP OF SOUTHERN MONTANA.

Vascoceras stantoni Reeside, n. sp. Type specimen (U. S. Nat. Mus. catalog No. 32532). **1,** Side view of whole specimen; **2,** front view with part of outer whorl removed.

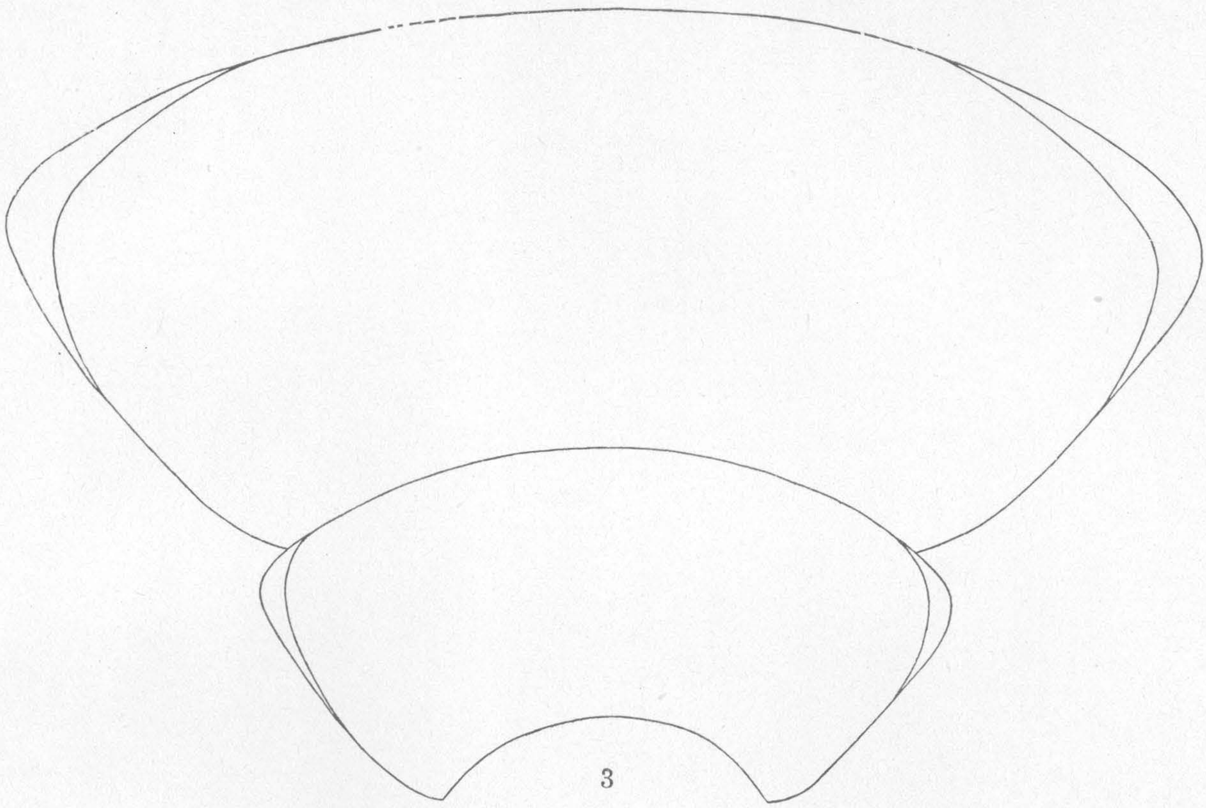


FOSSILS FROM THE COLORADO GROUP OF SOUTHERN MONTANA.

1–3. *Vascoceras stantoni* Reeside, n. sp. Type specimen (U. S. Nat. Mus. catalog No. 32532). **1,** Cross section at diameter of 150 millimeters; **2,** suture at diameter of 90 millimeters; **3,** suture at diameter of 40 millimeters.

4. *Vascoceras* sp. Side view of squeeze showing young whorls. (U. S. Nat. Mus. catalog No. 32538.)

5–6. *Helicoceras pariense* White? **5,** Side view; **6,** rear view. (U. S. Nat. Mus. catalog No. 32539.)



3

2 × ½

1 × ½

FOSSILS FROM THE COLORADO GROUP OF SOUTHERN MONTANA.

Vascoceras stantoni Reeside, n. sp. **1,** Side view; **2,** rear view; **3,** cross section, slightly reduced, at diameter of 240 millimeters. (U. S. Nat. Mus. catalog No. 32533.)

NOTES ON THE GEOLOGY OF GREEN RIVER VALLEY BETWEEN GREEN RIVER, WYOMING, AND GREEN RIVER, UTAH.

By John B. Reeside, Jr.

INTRODUCTION.

During July, August, and part of September, 1922, I had the privilege of accompanying a party sent out jointly by the Utah Power & Light Co. and the United States Geological Survey to gather such data as were still needed to complete a study of the power resources of Green River between Green River, Wyo., and Green River, Utah. The chief deficiency to be supplied was a continuous topographic map of the valley in sufficient detail to permit calculation of the storage capacity of any reservoir site that might be used, the stream gradient, and similar features. Maps on a satisfactory scale of a number of isolated stretches of the river had already been made by public or private agencies, and it was necessary to verify them and connect them on a uniform datum. Inasmuch as it was deemed unlikely that a dam higher than 300 feet would be constructed anywhere on the part of the river to be examined, a plane 300 feet above the water surface was made the upper limit of mapping. Over such parts of the valley as had been mapped already the progress of the party was naturally very rapid, and even where no mapping had previously been done, the 300-foot limit set upon the work and the usual narrowness of the valley combined to reduce the extent of the area to be mapped, so that the speed maintained was relatively high. Under this condition of rapid movement it was seldom possible to make more than the most cursory examination of the rocks, though occasionally circumstances permitted more or less detailed observation. The notes here recorded are therefore mostly of a rather generalized character, but as they pertain in part to localities that are difficult of access and not often visited by geologists, and that are at the same time classic in the history of American geology, I venture to to record them for whatever value they may have to other geologists.

GEOLOGIC NOTES.

Green River, Wyo., to the mouth of Henrys Fork.—Most of the part of Green River valley lying between Green River, Wyo., and Henrys Fork is cut in rocks assigned to the Green River formation (lower Eocene). This formation includes a lower division of whitish, gray, and greenish fissile shale, light-colored limestone, and sandstone and an upper division of massive, irregularly bedded brown sandstone with some sandy limestone and shale—the "Tower sandstone" and "plant beds" of Powell.[1] Over much of the way the "Tower sandstone" caps the bluffs along the river, and the gray mass of shaly beds beneath it forms steep slopes. The dips of the beds are low, usually so low that they are not apparent to the eye.

As the mouth of Henrys Fork is approached the influence of the Uinta uplift shows in the appearance of an appreciable northward dip. About 6 miles above the mouth of Henrys Fork this dip increases very much, and the river, running nearly across the strike of the beds, quickly passes out of the Green River formation into the beds mapped by Schultz [2] as Wasatch formation (lower Eocene). These beds consist of white to brown sandstone, gray shale, and red shale and are said to contain some coal.

From the Wasatch exposures the river passes through beds that dip 40°–50° N. and have been assigned by Schultz [2] to the Lewis

[1] Powell, J. W., Report on the geology of the eastern portion of the Uinta Mountains, pp. 40, 45, U. S. Geol. and Geog. Survey Terr., 1876.

[2] Schultz, A. R., Oil possibilities in and around Baxter Basin, in the Rock Springs uplift, Sweetwater County, Wyo.: U. S. Geol. Survey Bull. 702, pl. 1, fig. 3, 1920.

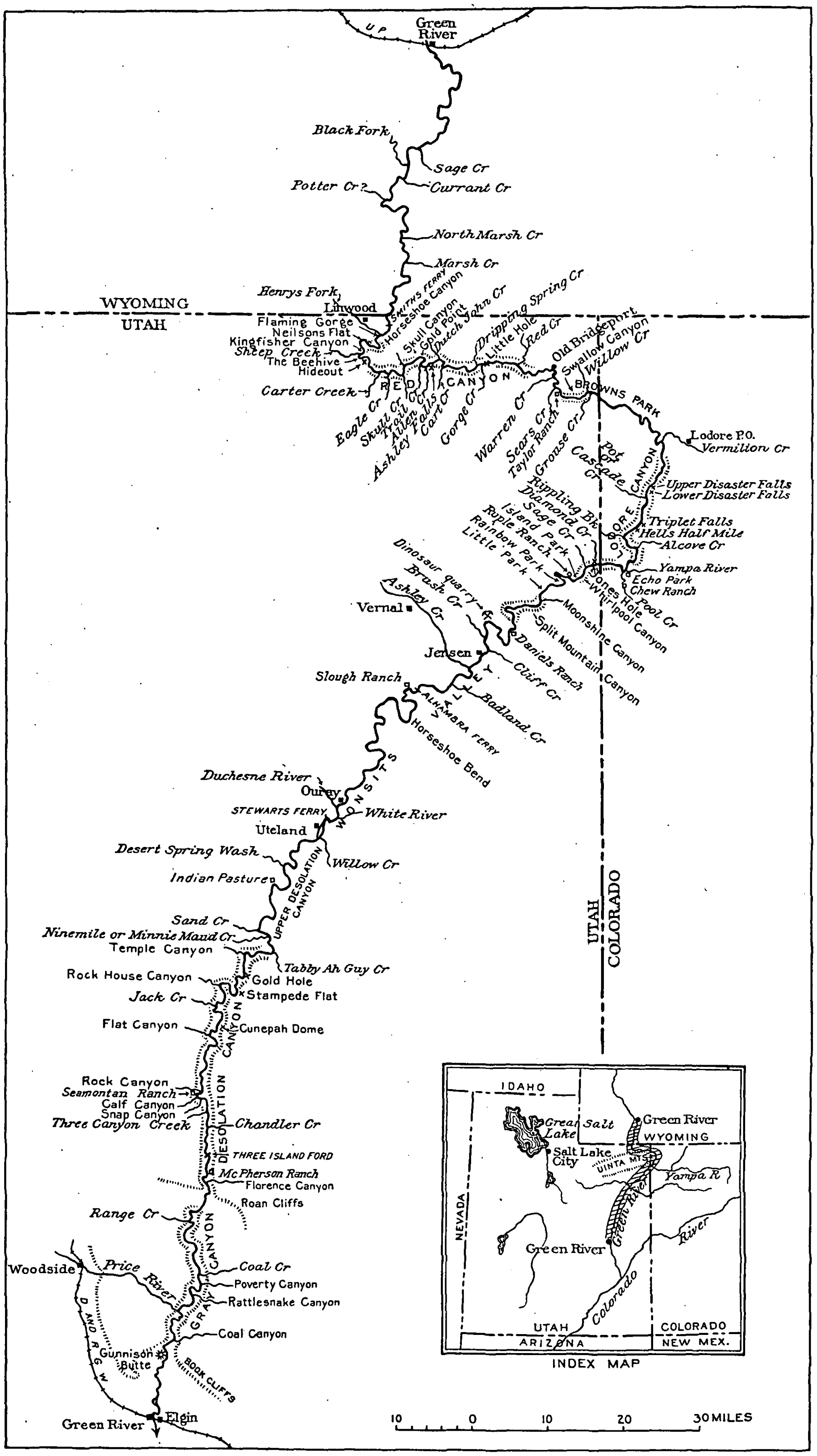


FIGURE 2.—Sketch map of Green River between Green River, Wyo., and Green River, Utah.

shale, Mesaverde formation, and Hilliard shale (all Upper Cretaceous). These beds are not very well exposed immediately adjacent to the river, and I had no opportunity to study the exposures lying at some distance from the river bank. The Hilliard shale, viewed from a distance of perhaps a mile, appears to be a normal dark-gray marine shale such as one would expect to find in this region. Near the mouth of Henrys Fork the dip is nearly vertical.

Boars Tusk ridge.—The north flank of the Boars Tusk, a sharp ridge running southeastward from the river just below the mouth of Henrys Fork, shows at the base the sandstone assigned by Schultz [2] to the Frontier formation; above it, topographically, the beds assigned to the Aspen shale (Upper Cretaceous), the Beckwith formation (Jurassic and Cretaceous?), the Twin Creek limestone (Jurassic), and the Nugget sandstone (Jurassic). The south slope shows the red beds assigned by the same author [2] to the Ankareh shale (Triassic?), Thaynes (?) formation (Lower Triassic), and Woodside shale (Lower Triassic). The dip is nearly vertical in the Frontier and Aspen formations, is overturned to the northeast in the lower Beckwith and Twin Creek, and appears to be nearly vertical in the basal sandstone of the Nugget and the underlying red beds. Schultz [3] gives the thickness of the formations here as follows: Frontier formation, 125 feet; Aspen shale, 135 feet; Beckwith formation, 850 feet; [4] Twin Creek limestone, 140 feet; Nugget sandstone, 1,000 feet; [5] Ankareh shale, 300 feet; Thaynes (?) formation, 290 feet; and Woodside shale, 500 feet.

The Frontier formation here, as understood by the writer, consists of a massive brown coarse-grained cross-bedded quartzose sandstone with some thin included lenses of carbonaceous shale and, as nearly as can be determined, is about 100 feet thick. The Aspen shale is a blue-white porcelaneous platy shale containing an abundance of imprints of fish scales. It is the lithologic equivalent of the Mowry shale of the region to the east and north in Colorado and Wyoming. The thickness

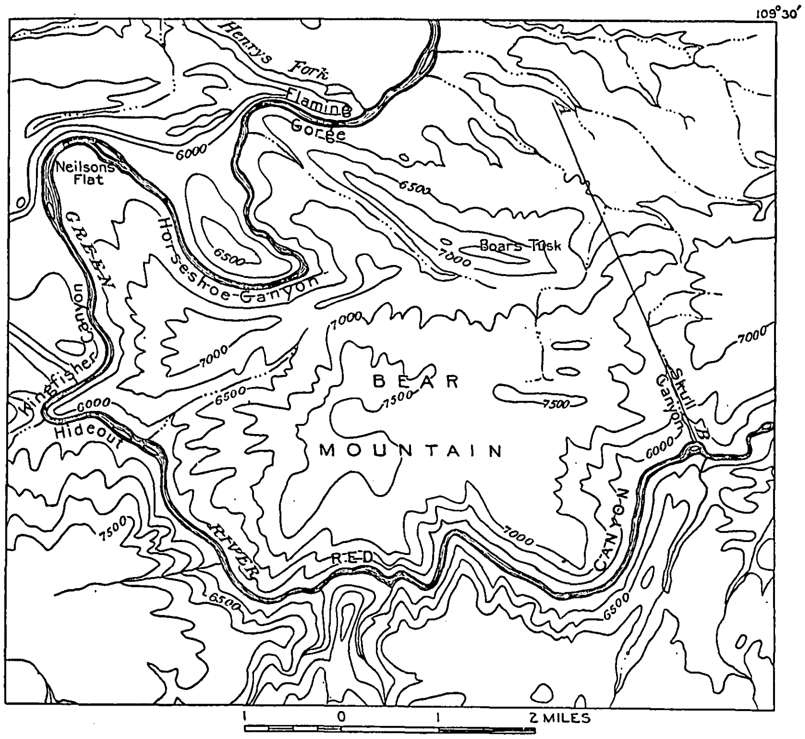


FIGURE 3.—Map showing Green River between the mouth of Henrys Fork and the mouth of Skull Canyon, Daggett County, Utah. Shows also location of section presented in Figure 5 (line *A–B*). Adapted in part from Marsh Peak topographic map.

[2] Schultz, A. R., Oil possibilities in and around Baxter Basin, in the Rock Springs uplift, Sweetwater County, Wyo.: U. S. Geol. Survey Bull. 702, pl. 1, fig. 3, 1920.

[3] Schultz, A. R., op. cit., table opposite p. 36, pp. 73–78, and fig. 3.

[4] In the table opposite p. 36 and in fig. 3 Schultz gives this thickness as 1,500 feet, but on p. 76 it is given as 850 feet, which I believe to be correct.

[5] In the table opposite p. 36 and in fig. 3 Schultz gives this thickness as 1,600 feet, but on p. 78 it is given as 1,000 feet, which I believe to be correct.

seemed to be about 225 feet, but the exposures are not entirely satisfactory, and it is possible that part of the interval should go into the Frontier formation. Immediately above the Aspen shale in the slope, but below it, in stratigraphic position, is a coarse brown conglomeratic sandstone. This sandstone is the topmost member of the Beckwith formation of Schultz, but from its lithologic constitution and its position it would be called the Cloverly formation in Wyoming or the Dakota sandstone at many other localities in the Rocky Mountain region. The pebbles in the conglomeratic parts are mostly of white and gray chert and are as much as an inch in diameter. The thickness of the sandstone is 150 feet.

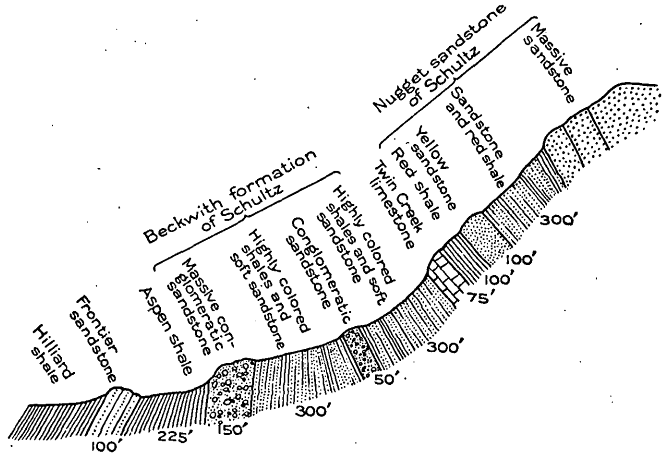


FIGURE 4.—Section of north slope of Boars Tusk ridge, Daggett County, Utah.

Above the sandstone in the slope, but below it stratigraphically, lies a mass of highly colored, variegated shale and soft sandstone about 300 feet thick, which strongly resembles the Morrison formation of eastern Colorado and central Wyoming. These beds form a slope and at most places are not well exposed. The next higher bed in the slope is a second conglomeratic sandstone 50 feet thick, above which more colored shale and soft sandstone, about 300 feet thick and not very well exposed at most places, constitute the basal member of Schultz's Beckwith formation. Above the colored shale last mentioned (below it stratigraphically) lie gray limestone and gray calcareous shale. Some of the limestone layers are fairly massive, but most of them are thin and platy. *Rhynchonella gnathopora* Meek and *Ostrea strigilecula* White were noted, but the beds would undoubtedly yield many more species on careful search. This calcareous unit is the Twin Creek limestone of Schultz and is about 75 feet thick. Above the Twin Creek beds in the slope lie red shale 100 feet thick, then a yellow sandstone about 100 feet thick, then about 300 feet of beds that are not well exposed but seem to consist largely of sandstone interbedded with layers of red shale, all of which together with the overlying sandstone were referred to the Nugget sandstone by Schultz. Above these beds and constituting the comb of the ridge is the massive white, brown, or reddish sandstone forming the base of the Nugget. (See figs. 4 and 7.)

I did not examine the Nugget sandstone and older beds in Boars Tusk ridge with any care and made few notes on them. The basal member of the Nugget sandstone is a thick, massive cross-bedded sandstone that resembles both the sandstone in the lower part of the Sundance formation in Wyoming and the Jurassic sandstone of southern Utah. The red beds were not well exposed in the only place where I crossed them—the gap between Skull Canyon and the drainage north of the ridge. At this locality the red beds are cut off below by the great Uinta fault, which extends for miles along the northern edge of the Uinta Mountain uplift. The beds on the south side of the fault are the much older beds described below as the "Uinta formation," the formations normally occurring between the red beds and the "Uinta formation" having been displaced by the fault. (See fig. 5.)

It seems hardly possible that the Frontier formation, the Aspen shale, and the uppermost part of the Beckwith formation of Schultz are the exact equivalents of the Frontier, Mowry, Thermopolis, and Cloverly formations in Wyoming, but the similarity of lithologic succession is striking. That the beds in the Beckwith formation of Schultz that resemble the Morrison formation are equivalent to that formation is placed beyond doubt by the occurrence of a large fauna of Morrison dinosaurs in beds at the same stratigraphic position near Jensen, Utah. The Twin Creek limestone of Schultz is beyond question equivalent to the upper, calcareous zone of the Sundance formation of central Wyoming. These calcareous beds with the beds below them, down probably to the base of the Nugget sandstone, I consider to represent the interval usually included in the Sundance formation in central Wyoming.

Flaming Gorge, Horseshoe Canyon, Neilsons Flat, and Kingfisher Canyon.—In Flaming Gorge the conspicuous rocks are the rim of Nugget sandstone and the slopes of red beds (Ankareh, Thaynes (?), and Woodside formations of Schultz). At the lower end of the gorge the river passes across the trough marking the outcrop of the rather soft and unresistant upper part of the Park City formation (Permian and Pennsylvanian) into the box canyon cut in the lower part of the Park City formation and the Weber sandstone (Pennsylvanian) and named by Powell Horseshoe Canyon. From Horseshoe Canyon the river passes back into the trough of Park City beds, where a low area near the river is known as Neilsons Flat. From Neilsons Flat the river passes into a second box canyon cut in Weber sandstone and named by Powell Kingfisher Canyon. Kingfisher Canyon is cut off at its lower end by the Uinta fault mentioned above, though here the surface trace of the fault has passed over into older beds and the Weber sandstone lies in contact with the "Uinta formation." (See fig. 3.)

The area including the localities just mentioned is a geologic unit, and the geographic divisions are made by sharp turns in the river. The Nugget sandstone forms a cliff running northeastward and lying to the north and northwest of the area. Beneath it the Ankareh shale of Schultz is composed of dark salmon-red sandstone and shale with a minor proportion of yellowish beds. The upper part of the formation appears to contain softer rock and forms a slope, but the lower part is harder and forms a bench. The formation is bounded at the base by a very irregular, wavy surface of erosion that I take to be the unconformity noted by Schultz.[6] The beds next below the unconformity are darker in color—a brick-red—and weather differently, their surface having a sort of network sculpturing due to small regularly arranged cavities, whereas the surface of the upper beds is fairly smooth. The lower beds are nearly all sandstone and are clearly the Thaynes (?) formation of Schultz. The typical Thaynes formation,[7] near Park City, is essentially a calcareous formation with gray limestone and sandstone, but there is nothing of the sort to be seen here. Beneath the cliff of Thaynes (?) formation lies a long slope underlain by light brick-red sandy shale and soft sandstone and broken near the base by some harder layers that form small benches and by some gray layers interbedded with the red. This unit is evidently the Woodside shale of Schultz and corresponds in a general way to the description of the typical Woodside shale near Park City.[8]

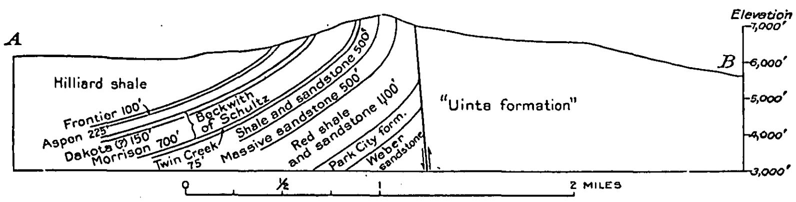


FIGURE 5.—Cross section of ridge east of Boars Tusk ridge, Daggett County, Utah. See Figure 3 for location.

Schultz gives the thickness of the formations as follows: Ankareh, 300 feet; Thaynes, 290 feet; Woodside, 500 feet. I did not make any measurements but believe these figures to be about right. (See fig. 6.)

Boutwell[9] gives the thickness of the Ankareh formation at its typical locality near Park City as over 1,150 feet, the Thaynes formation as 1,290 feet, and the Woodside shale as 1,090 feet. If the beds assigned to these formations near Green River are really equivalent to the typical divisions near Park City, the differences between them and the typical development as described by Boutwell must be ascribed to some such change in passing eastward from Park City as occurs in southern Utah in the Moenkopi formation, also of Tri-

[6] Schultz, A. R. Oil possibilities in and around Baxter Basin, in the Rock Springs uplift, Sweetwater County, Wyo.: U. S. Geol. Survey Bull. 702, tables opposite pp. 24 and 36, 1920.

[7] Boutwell, J. M., Geology and ore deposits of the Park City district, Utah: U. S. Geol. Survey Prof. Paper 77, pp. 55-88, 1912.

[8] Idem, pp. 52-54.

[9] Idem, pp. 52, 56, 58.

assic age.[10] The Moenkopi formation thins eastward, and the proportion of limestone to noncalcareous beds decreases rapidly in the same direction. The Ankareh formation suggests, in its position beneath the Nugget and its unconformable relation to the underlying beds, the Jelm formation [11] of southern Wyoming, which lies beneath the basal Sundance sandstone and is unconformable on the underlying Chugwater red beds. The Chugwater beds are in turn much like the combined Thaynes (?) and Woodside formations of Green River valley.

The Park City formation lies beneath the Woodside shale and is only indistinctly separated from it. It is described by Schultz [12] as calcareous. It stands in cliffs along the river at most places where it is exposed. Schultz gives the thickness along Green River as 1,600 feet.

Hideout and Red Canyon.—Hideout is a rather open area between Kingfisher Canyon and Red Canyon. It is perhaps a mile in length measured along the river and affords relatively easy access to the river on either bank. Red Canyon may be considered to extend down the river from Hideout to a point several miles below Red Creek, though it might equally well be considered to end at or above Red Creek. The height and inclination of the canyon walls varies very much—so much, in fact, that perhaps the only uniform character is the constituent rock, the mass of dark-red to red-brown sediments called by Powell [13] the "Uinta group" and by most later geologists the "Uinta quartzite" or "Uinta formation," though by King and Emmons mistakenly identified as Weber sandstone. The name Uinta is more correctly applied to the very much later Tertiary formation that occurs in the Uinta Basin, to the south of the mountains, but as no other acceptable name has been given to the older unit the name "Uinta formation" will be used with quotation marks for it in the present description.

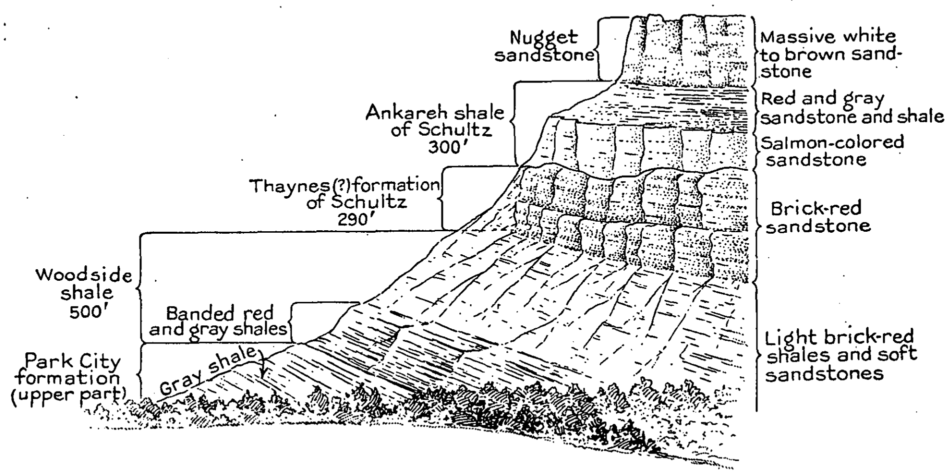


FIGURE 6.—Diagrammatic sketch of bluff northwest of Neilsons Flat, Daggett County, Utah.

containing near Flaming Gorge in the upper part a gray calcareous shale or shaly limestone 200 feet thick, underlain by a massive cherty limestone 25 feet thick, a phosphate-bearing shale, with chert nodules, 40 to 50 feet thick, and a basal member of massive limestone 100 feet thick resting unconformably on the Weber sandstone. These subdivisions are recognizable without difficulty and maintain very nearly the thicknesses given.

The Weber sandstone is a very massive, resistant brown sandstone, probably in part

The "Uinta formation," the only one exposed in Red Canyon, is a succession of deep-red to maroon resistant sandstone and conglomerate, with lesser amounts of hard red shale. The sandstone is usually dense and is

[10] Reeside, J. B., jr., and Bassler, Harvey, Stratigraphic sections in southwestern Utah and northwestern Arizona: U. S. Geol. Survey Prof. Paper 129, pp. 59-61, 1922.

[11] Knight, C. W., Age and origin of the red beds of southeastern Wyoming (abstract): Geol. Soc. America Bull., vol. 28, p. 168, 1917.

[12] Schultz, A. R., A geologic reconnaissance of the Uinta Mountains, northern Utah: U. S. Geol. Survey Bull. 690, p. 52, 1918; Oil possibilities in and around Baxter Basin, in the Rock Springs uplift, Sweetwater County, Wyo.: U. S. Geol. Survey Bull. 702, tables opposite pp. 24 and 36, 1920.

[13] Powell, J. W., Report on the geology of the eastern portion of the Uinta Mountains, pp. 41, 61, 141, U. S. Geol. and Geog. Survey Terr., 1876.

in places changed to a true quartzite in which individual grains are not easily distinguished; locally the color is a deep brown. The shale at some places is greenish. The beds in the upper part of Red Canyon contain more shaly beds proportionately than those in the part farther downstream, though there are some massive beds throughout its length. The canyon walls at many places are débris-covered slopes; at others, cliffs of bare rock. Powell gives the thickness of the "Uinta group" as more than 12,000 feet, and most later writers quote his figures. I had no opportunity to estimate or measure the thickness, but it is certainly very great.

No fossils have been recorded from the "Uinta formation," and it has been assigned by various writers to the Devonian, Carboniferous, Cambrian, and pre-Cambrian. I can add nothing regarding the age of the formation except that search at many places for features that would aid in fixing the age revealed only obscure trails, mud cracks, and raindrop impressions, of no especial value for this purpose.

Browns Park and Swallow Canyon.—The open valley between Red Canyon and Lodore Canyon, called Browns Park, affords few good exposures near the river, and as it had already been mapped the party's passage through it was too rapid even to see much of those. One exposure of soft dove-gray shale or clay not far below the upper end of the park is probably late river-terrace material, though as far as lithology goes it might equally well be of Tertiary age. Other exposures of brown sandstone are probably part of the late Tertiary Browns Park formation.[14] Swallow Canyon, on the south side of Browns Park, is a relatively shallow canyon cut through the "Uinta formation" by a 4-mile loop of the river which abruptly leaves the soft valley deposits to plunge into the hard sandstone beds and as abruptly returns to the valley.

Lodore Canyon.—From Browns Park the stream passes again into exposures of "Uinta formation" in the deep, narrow course of Lodore Canyon. These exposures differ in no essential respect from those in Red Canyon. The formation has perhaps fewer soft layers, and the walls stand at high angles with but little débris upon them. For the first 12 miles of the canyon, approximately, no rocks except this formation are visible. Then there appears at the top of the canyon walls the first of the post-"Uinta" formations, the Lodore group of Powell.[15] This gradually descends down stream until at a point near the mouth of Alcove Creek it reaches river level. Above the Lodore "group," or Lodore formation, as it would now be called, appear the beds designated by Powell "Redwall group," "Lower Aubrey group," and "Upper Aubrey group."[16] These divisions probably correspond closely to the Mississippian limestone, Pennsylvanian limestone, and combined Weber sandstone and Park City formation of Schultz.[17]

The Lodore formation, as I interpreted it, contains a flaggy basal sandstone of salmon color that is sharply separated from the underlying "Uinta formation" by an unconformity representing an erosion interval.[18] This basal sandstone is overlain by a succession of variegated red, purplish, and green sandy shales and thin sandstones. Possibly there are some thin limestone beds at the top that should also be included in the Lodore formation, though I tentatively put all the limestones into the next higher unit. The shale unit is softer than the underlying beds and the succeeding Carboniferous limestone and makes a marked slope. The basal sandstone is about 150 feet thick and the shale unit about 300 feet thick. Powell gives 460 feet as the thickness of his Lodore "group," and the round figure of 500 feet is cited by most later writers. No fossils have been recorded from the Lodore formation but it is supposed by recent writers to be Cambrian, both from its position in the section and its resemblance to beds in the Tonto group of the Grand Canyon. The Carboniferous fossils noted by Powell on page 56 of the report cited were very probably out of place.

The beds designated by Powell "Redwall group" and "Lower Aubrey group" include in the lower part much massive cream-colored to brown cherty limestone very similar to the Madison limestone (lower Mississippian) of

[14] Powell, J. W., op. cit., pp. 40, 44, 168.

[15] Powell, J. W., op. cit., pp. 41, 56, 147.

[16] Idem., pp. 41, 54-55, 147-149.

[17] Schultz, A. R., Oil possibilities in and around Baxter Basin, in the Rock Springs uplift, Sweetwater County, Wyo.: U. S. Geol. Survey Bull. 702, table opposite p. 36, 1920.

[18] Powell, J. W., op. cit., pp. 144-145.

central Wyoming; and in the upper part a succession of red, pink, and purplish shale and sandstone and gray and pinkish limestone, all in relatively thin layers and as a mass much like the beds commonly assigned to the Amsden formation (Pennsylvanian and upper Mississippian) in central Wyoming. I estimate the thickness of the upper and lower divisions as 1,000 to 1,200 feet each.

Above the beds of Powell's "Lower Aubrey group" comes the Weber sandstone, here as in Horseshoe and Kingfisher canyons a very massive, much cross - bedded yellow - brown quartzose sandstone that rises in sheer unbroken walls for hundreds of feet.

At the extreme lower end of Lodore Canyon, just at the edge of Echo Park, a fault, visible on the right bank of the river and striking in a direction somewhat east of north, brings the lower part of Powell's "Redwall group" into contact with the extreme top of his "Lower Aubrey group." The extension of this same fault southward is clear in Mitten Park and the basin of Pool Creek. (See below.)

Echo Park, Pool Creek, and Mitten Park.—Green River, on leaving Lodore Canyon, follows for some miles a course shaped like a narrow U with the open end to the north. The east limb of this U receives Yampa River from the east, and the bend receives Pool Creek from the south. The narrow open bottom adjacent to the mouths of these streams is Echo Park or Pat's Hole. Farther downstream, at the top of the west limb of the U, another small open bottom is known as Mitten Park. From Mitten Park the river passes abruptly into Whirlpool Canyon.

Echo Park is walled in by sheer cliffs of Weber sandstone, which likewise forms Steamboat Rock, the great mass that fills the area in the center of the U. The lower course of Pool Creek is a narrow box canyon, likewise in the Weber sandstone, though in about 2 miles the creek bed rises above it, through the Park City beds, and runs upon red beds. These red beds lie in a small basin bordered on the west by the fault mentioned above and possibly by another on the south. The Woodside shale appears to be much as on the north side of the mountains, and the Thaynes (?) about the same except for the occurrence of some heavy beds of brown sandstone. I believe that the supposed Ankareh and later beds have been removed here by erosion.

In Mitten Park the rocks are tilted to a high angle in proximity to the fault and are even overturned. The downthrow is on the east and the upthrow on the west, bringing above the river level several hundred feet of the upper part of the "Uinta formation."

I made no estimate of thicknesses in this region, though the Weber sandstone is certainly in excess of 1,000 feet.

Whirlpool Canyon.—At the upper end of Whirlpool Canyon the uppermost several hundred feet of the "Uinta formation" appears west of the fault described above. The normal succession of formations appears above it—Lodore formation, "Redwall group," and "Lower Aubrey group." The Lodore formation has about the same constitution and thickness as in Lodore Canyon; likewise the lower Madison-like part of Powell's divisions and the upper Amsden-like part. The irregular contact of the Lodore formation on the "Uinta formation" is especially well shown. The formations dip downstream, and at the lower end of the canyon the Weber sandstone appears. It is bent sharply downward and cut off by a fault, which runs about parallel to that of the upper end, with the downthrow on the west and the upthrow on the east.[19] Whirlpool Canyon therefore seems to cross an uplifted fault block, with the Mitten Park fault on the east and the Island Park fault on the west.

Island Park.—The area along the river between Whirlpool Canyon and Split Mountain Canyon is divided by the local residents and on some maps into three small parks. These are merely large bottoms separated by low ridges and are called, in order downstream, Island Park, Rainbow Park, and Little Park. The rocks of this area, often called as a whole Island Park, lie in an unsymmetrical syncline with axis plunging a little south of east and with the eastern tip truncated by the fault at the eastern edge of Island Park. The formations present extend from the Weber sandstone to the Hilliard shale, inclusive. The character of the rocks is best shown in the following section:

[19] See Schultz, A. R., A geologic reconnaissance of the Uinta Mountains, northern Utah: U. S. Geol. Survey Bull. 690, pl. 5, 1918.

Section measured in Island Park.

[See also fig. 7.]

Measured northwest of Rainbow Park.

	Feet.
Hilliard shale.	
Frontier formation of Schultz:	
Sandstone, massive, gray to yellow	35
Shale, yellow, sandy	33
Sandstone, massive, gray to yellow	40
Shale, yellow to gray, in part sandy	130
Aspen shale of Schultz: Shale, hard, platy, bluish-white, with abundant fish scales. Exactly like Mowry shale in Wyoming	80
Beckwith formation of Schultz:	
Sandstone, massive, brown to gray, coarse, containing few lenses of pebbles the size of wheat. (Where measured the upper part of this unit is in almost direct contact with Aspen shale, but along the strike the upper 50 feet changes to very dark shale)	75
Shale, brown to dark gray, with some thin beds of brown sandstone. Not as dark as might be expected at this horizon	38
Sandstone, coarse, brown to gray. No pebbles seen	8
Shale, variegated purple, green, gray; sandstone, soft, whitish; and sandstone, brown, hard. Contain bone fragments and gastroliths at a number of horizons. Beds change rapidly both vertically and horizontally. Possibly some of the basal beds may belong to the underlying marine Jurassic, but they did not furnish clear evidence of marine origin. Thickness calculated from topographic data	700

Measured 1 mile west of Ruple ranch.

	Feet.
Twin Creek formation of Schultz:	
Shale, greenish gray, with layers of platy argillaceous sandstone and some lenses of soft yellow sandstone. Not sharply separated from overlying unit. Sandstone layer 10 feet above base contains *Rhynchonella gnathophora* Meek, *Ostrea* sp. undetermined, *Tancredia warrenana* Meek and Hayden, *Trapezium?* sp	40
Sandstone, blocky, light brown, fine-grained; contains *Rhynchonella*, *Ostrea*, and other fossils very poorly preserved	3
Sandstone, soft, gray-white, cream-colored to yellow, argillaceous; at most places weathers back like shale, at others stands out as ledges; contains lenses of greenish shale. No fossils seen	85
Shale, greenish gray, with thin layers of sandy brownish limestone and nodules of dense blue limestone. Contains *Cidaris?* sp., bryozoan, *Parallelodon?* n. sp., *Pinna* sp., *Eumicrotis curta* (Hall), *Ostrea strigilecula* White, *Cardinia?* n. sp., *Trigonia quadrangularis* Hall and Whitfield, *Camptonectes platessiformis* White, *Modiola pertenuis* Meek and Hayden, *Pleuromya newtoni* Whitfield, *Astarte packardi* White, *Tancredia? inornata* Meek and Hayden, *Dosinia jurassica* Whitfield, *Quenstedticeras? hoveyi* Reeside, *Cardioceras* cf. *C. cordiforme* (Meek and Hayden), *Cardioceras* sp., *Belemnites densus* Meek and Hayden	50
Nugget sandstone of Schultz:	
Sandstone, platy, gray to cream-colored, with thin shale layers. Grades into overlying beds	15
Sandstone, massive, cream-colored, cross-bedded	20
Sandstone, platy, gray, interleaved with thin layers of green, gray, and purple shale. The lower part contains clay-pellet conglomerates, and the base is a sinuous line. Probably no unconformity of much magnitude, as both these beds and the underlying beds are shallow-water deposits.	
Sandstone, massive, cream-colored to brown, cross-bedded, in a single bed. Cross-bedding seems to be of the current type	75

Measured in Little Park.

	Feet.
Shale, brick-red with some gray streaks	200
Sandstone, gray to yellow, locally salmon-colored, cross-bedded, very massive	560
Sandstone and shale, alternating in thin beds, red and white	14
Ankareh shale of Schultz:	
Shale, sandy, red with some white streaks and gray layers	50
Sandstone, salmon-colored, massive, medium grained	15
Shale and soft sandstone, mostly brick-red	160
Grit, coarse, white, yellow, and pink, with lenses of pebbles of quartz and chert 1 inch or less in diameter; basal part has pebbles as much as 2 inches in diameter	30
Unconformity.	
Thaynes (?) and Woodside formations of Schultz:	
Shale and sandstone, brick-red, without any prominent subdivisions; estimated at	1,000
Park City formation.	

Split Mountain Canyon.—The rocks exposed in Split Mountain Canyon (sometimes locally called Black Mountain Canyon) form a sharp unsymmetrical anticline whose axis runs about due west. The river enters the canyon at right angles to the strike of the rocks on the north limb but on reaching the axis of the fold runs parallel to it for about 5 miles, then at right angles to the strike across the south limb. The upper end of the canyon is in Weber sandstone, but the dip is steep and soon brings up the upper part of the "Lower Aubrey group" of Powell (Amsden-like beds) and in places along the axis Powell's "Redwall group" (Madison-like beds). On the south limb the reverse succession is present, and the canyon ends at the top of the Weber sandstone.

Wonsits Valley.—The name Wonsits Valley was applied by Powell [20] to the region extending from the lower end of Split Mountain Canyon to the mouth of Duchesne River. It is here extended arbitrarily southwestward to include the valley as far as the mouth of Willow Creek.

Immediately following the Weber sandstone at the lower end of Split Mountain Canyon comes a succession of red beds, Nugget sandstone, etc., nearly identical with that in Island Park. These beds dip very steeply but are not as well exposed near the river as in Island Park. Owing to the steep dip the river passes through the older beds in a short distance and then runs upon the Cretaceous a considerable distance, but the exposures are rather poor because of the abundance of river-terrace material. Along this part of the river a number of attempts have been made to exploit the river terraces for placer gold, but they have not yet been wholly successful.

At a point about 6 miles above Jensen the river approaches closely the outcrops of the pre-Cretaceous rocks. Near this point the Carnegie Museum of Pittsburgh, Pa., has for years been taking dinosaur remains from a quarry in beds of Morrison age. A stratigraphic section in the neighborhood of the quarry is as follows:

Section measured at Carnegie Museum dinosaur quarry, above Jensen.

[See also fig. 7.]

	Feet.
River-terrace materials, underlain by Hilliard shale.	
Frontier formation of Schultz:	
Sandstone, fairly coarse, gray to brown, cross-bedded	22
Shale, yellow, sandy, with thin layers of gray sandstone	158
Aspen shale of Schultz:	
Shale, bluish gray, hard, platy; contains many fish scales	50
Shale, yellowish, sandy	37
Beckwith formation of Schultz:	
Sandstone, gray to brown, locally weathering pink, coarse, conglomeratic, cross-bedded	35
Shale, rusty brown and drab	27
Sandstone, gray to brown, in thin beds	10
Shale, rusty brown and drab	37
Sandstone, ripple-marked, coarse, cross-bedded, brown to gray; rusty in places. This bed seems to be variable in thickness and may even be absent a short distance to the west	37
Beckwith formation of Schultz—Continued.	
Shale, gray, violet, and greenish, with lenses of greenish argillaceous sandstone, grit, and conglomerate that weather to a chocolate-brown; highly variable unit	279
Sandstone, greenish, conglomeratic; weathers brown. Horizon of dinosaur quarry	10
Shales and sandstone, variegated; like second unit above	506
Twin Creek formation of Schultz:	
Sandstone, fine grained, fissile, beautifully ripple marked and rain pitted, greenish gray, with considerable interbedded shale. Some layers contain *Ostrea* sp	40
Sandstone, platy, ripple marked, gray, fine grained; contains *Rhynchonella gnathophora* Meek and *Tancredia warrenana* Meek and Hayden	2
Shale, greenish gray, with some platy sandstone of same color	65
Sandstone, brown, limy; contains *Ostrea strigilecula*	1
Shale, dark gray, almost black, containing dense blue limestone in concretions	42
Limestone, gray, coarse, sandy; contains *Eumicrotis curta* (Hall), *Ostrea strigilecula* White, *Camptonectes platessiformis* White, *Astarte packardi* White, *Tancredia? inornata* Meek and Hayden, *Tancredia* sp., *Dosinia jurassica* Whitfield?, *Cardioceras russelli* Reeside, *Cardioceras hyatti* Reeside, *Cardioceras cordiforme* Meek and Hayden, *Cardioceras* aff. *C. wyomingense* Reeside, *Cardioceras* sp	1
Shale, greenish gray, with limestone in nodules and containing *Ostrea strigilecula* White and *Eumicrotis curta* (Hall)	27
Nugget sandstone of Schultz:	
Sandstone, very massive, cross-bedded, medium grained, yellow to gray	91
Shale and platy sandstone, yellow to gray	12
Sandstone, massive, gray to yellow, cross-bedded, medium grained	120
Shale, variegated, gray and brick-red	107
Sandstone, very massive, yellow to gray; forms here an impassable ridge; must be some hundreds of feet thick.	

For a short distance below the dinosaur quarry there are very good exposures of Hilliard shale close to the river, but over much of the way to Jensen the exposures are poor. The rocks lie in a syncline plunging to the west, as shown by Gale [21] and Schultz.[22] An anticline, also plunging westward and with its axis passing close to Jensen, brings up Frontier sandstone just east of the town. Downstream from Jensen the river passes through higher and higher beds. About 6 miles southwest of Jensen sandstone and shale containing

[20] Powell, J. W., Map of Green River from the Union Pacific Railroad to the mouth of White River, 1873; Exploration of the Colorado River of the West and its tributaries, explored in 1869, 1870, 1871, and 1872, p. 44, 1875.

[21] Gale, H. S., Coal fields of northwestern Colorado and northeastern Utah: U. S. Geol. Survey Bull. 415, pl. 21, 1910.

[22] Schultz, A. R., A geologic reconnaissance of the Uinta Mountains, northern Utah: U. S. Geol. Survey Bull. 690, pl. 5, 1916.

many red beds appear. These beds are relatively soft and lack the hard sandstones present in the Wasatch. I take them to be the Tertiary beds assigned to the Bridger formation (middle and upper Eocene) and dip northward. From that point on to a locality some distance above Ouray only these red beds are visible, but at this locality gray beds appear at river level and the red element is less striking.

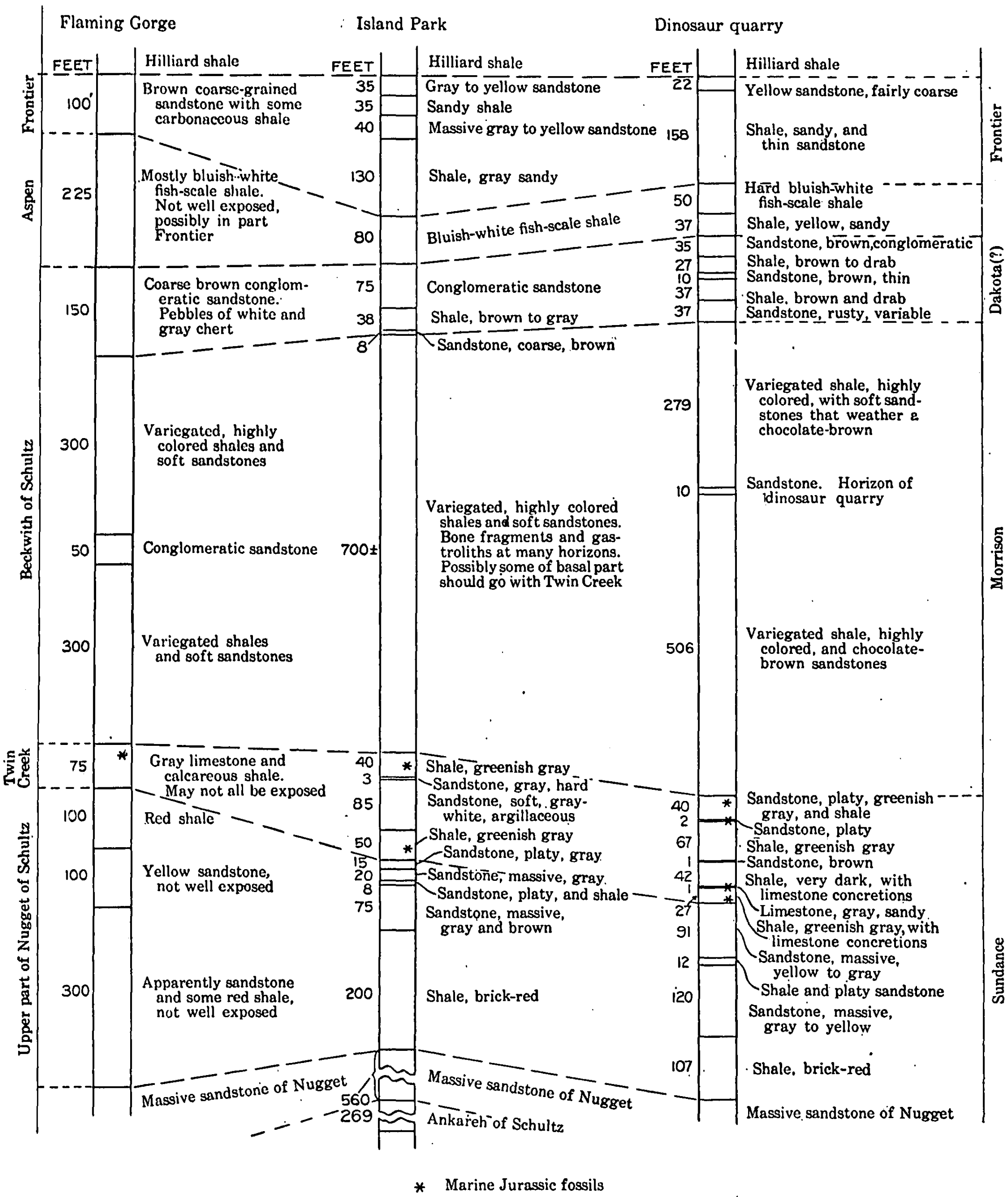


FIGURE 7.—Diagram showing correlation of sections near Flaming Gorge, Daggett County, and in Island Park and near the Carnegie Museum dinosaur quarry, Uinta County, Utah.

Uinta formation (upper Eocene). This is the real Uinta formation. These beds have a south dip at their northern edge. Farther downstream they lie practically flat, but about at the neck of Horseshoe Bend they begin to

Upper Desolation Canyon.—The name Desolation Canyon was applied by Powell [23] to the stretch of valley from a point somewhere in the

[23] Powell, J. W., Exploration of the Colorado River of the West and its tributaries, explored in 1869, 1870, 1871, and 1872, pp. 46-50, 1875.

neighborhood of Indian Pasture downstream to the Roan Cliffs. For the present description the stretch of valley between Willow Creek and Minnie Maud Creek is taken arbitrarily as Upper Desolation Canyon, though it is much less a canyon than a sharply limited valley, and the valley below it to the Roan Cliffs is taken as Desolation Canyon proper.

Near the mouth of Willow Creek much sandstone is present in short lenses. The shale between and around the sandstone lenses is of a sort of mauve color, and the sandstones themselves a coffee-brown. The whole mass has a purple tone when seen in the distance. Near the mouth of Desert Spring Wash the purple beds are replaced in part by gray and yellowish beds. The dip is low, but the replacement is thought to be due to the rising of older beds to river level. A few miles below Desert Spring Wash the walls of the valley are all of gray and yellowish beds of unmistakable Green River aspect. Sandstone is present but only in short lenses, and the bulk of the rock is shale. At Indian Pasture the shaly beds are very conspicuous and the slopes look as if all shale. The change from the purple beds to the gray beds appears to mark the change from the Bridger and Uinta formations to the Green River formation. There seems to be no break. I did not estimate the thickness of the purple-red beds.

Winchester [24] places the base of the Bridger beds some distance above Desert Spring Wash—in fact, beyond the area covered by his map—but he must have had some such distinction in mind as that stated above. The zone of rich oil shale appears at river level about 3 miles above the mouth of Minnie Maud Creek, according to Winchester, and is mapped by him along the walls of the canyon for many miles below, rising southward until high up on the walls it turns to the east and west somewhere near Chandler Creek.

Desolation Canyon.—Desolation Canyon is here considered to extend from Minnie Maud Creek to the Roan Cliffs below the McPherson ranch.

Near Minnie Maud Creek the walls of the canyon appear to be largely shale, gray to yellowish, with only a minor amount of sandstone, but downstream some miles near Tabby Ah Guy Canyon, much more sandstone appears—fine grained, yellow to brown, platy. The sandstone layers in weathered faces are often masked by débris but in clean vertical faces are very evident. Some of the sandstone has probably come in by lateral change from shale, some of it by rising above river level. Near Temple Canyon the lowest beds are nearly all sandstone, yellow and rusty brown, with a minor amount of maroon and greenish-gray shale. Above these sandy beds the shaly gray Green River beds like those of Minnie Maud Canyon appear, but they are so high on the canyon wall that, considering the low dip, it is very unlikely that they could have simply risen. I believe that there has been some lateral change in lithology.

Near the mouth of Jack Creek the rocks for perhaps 1,000 feet above the river are brown sandstone with a minor amount of red and greenish shale. Above these beds are oolitic cream-colored limestone and light shale and sandstone, such as are present in the more typical Green River beds. How much, if any, of the mass of brown sandstone and colored shale are Green River formation and how much Wasatch formation I am unable to say.

Down near the river level at Jack Creek some striking deep-red beds appear. Downstream these red beds near the river become progressively thicker, and there is a fairly sharp plane of division between them and the overlying mass of brown sandstone and colored shale. The distinction is not ideally sharp, as some red coloring occurs in the rocks above, and there is no evidence of any break in sedimentation. The top of the marked red series might well be considered the top of the Wasatch formation, though here, as has been noted at other places in the region by various observers, the position of the boundary between the Wasatch and Green River formations offers ground for wide difference of opinion. These reddish beds make up more and more of the canyon walls downstream until they finally include practically all the rock visible from the river. Near Three Canyon Creek there is much conglomerate of small chert pebbles in the fallen blocks along the

[24] Winchester, D. E., Oil shale of the Uinta Basin, northeastern Utah: U. S. Geol. Survey Bull. 691, pl. 12, 1919.

river, though I did not see the rock in place. Just below the McPherson ranch at river level appear gray shale, thin brown sandstone, and dark fresh-water limestone crowded with *Viviparus, Unio,* and other fossils. Beneath these beds are gray shale with streaks of red and then plain gray shale and brown sandstone. I supposed the red and gray shales associated with the fresh-water limestone to be the base of the Wasatch and the gray shale and brown sandstone beneath them to be the Mesaverde formation of the region. The outcrop of the red beds turns away from the river here to form the Roan Cliffs, and Gray Canyon begins.

Gray Canyon.—Gray Canyon is cut in a succession of alternating massive brown sandstone and gray shale—the Mesaverde formation of the region. Coal beds are present in the lower part of this series, but I did not have time to locate any definitely. There is little change in character of the rocks above the end of the canyon, where the outcrops of the sandstones turn off to the east and west to form the Book Cliffs, and the river runs through lowlands of Mancos shale.

COMPARISON OF THE LITHOLOGIC SUCCESSION IN GREEN RIVER VALLEY, SOUTHWESTERN UTAH, AND CENTRAL WYOMING.

The lithologic succession in Green River valley affords an interesting comparison with that of southwestern Utah and that of central Wyoming. In general, the information available would not justify a statement that the units compared are strictly chronologic equivalents, for in the greater parts of the respective stratigraphic columns close paleontologic correlations are not possible. A similarity in the succession of lithologic units may be pointed out, however. The thicknesses of the individual lithologic units compared with one another may differ greatly, owing to differences in the length of the time interval represented by the units compared or to differences in the contemporaneous rate of deposition in the respective areas or to both causes at once.

It has seemed the best method to make such a comparison by arranging the names in current use in three vertical columns with horizontal lines including the units compared and with such comment as may be made appended as notes.

Comparison of the series of lithologic units recognized in Green River valley with those in southwestern Utah and central Wyoming.

Age.	Southwestern Utah.	Green River valley.	Central Wyoming.	Note.
Tertiary (Eocene).	Pink Cliff series of Dutton.	Uinta formation. Bridger formation.	Uinta formation. Bridger formation.	(a)
		Green River formation.	Wasatch formation. / Wind River formation.	
		Wasatch formation.		
		"Post-Laramie" formation.	Fort Union formation.	(b)
Tertiary?		"Laramie" formation.	Lance formation.	
Cretaceous.	Shales and sandstones variously named.[e]	Lewis shale.	Lewis shale.	(c)
		Mesaverde formation.	Mesaverde formation.	(d)
		Hilliard shale.	Steele shale. Niobrara formation. Carlile shale.	
		Frontier formation of Schultz.	Frontier formation.	(f)
		Aspen shale of Schultz.	Mowry shale. Thermopolis shale.	(g)

(See footnotes on pp. 48, 49.)

Comparison of the series of lithologic units recognized in Green River valley with those in southwestern Utah and central Wyoming—Continued.

Age.	Southwestern Utah.		Green River valley.		Central Wyoming.	Note.
Cretaceous. Cretaceous?	Sandstone. Variegated shale.		Beckwith formation of Schultz.	Dakota(?) formation. Morrison formation.	Cloverly formation. Morrison formation.	(*h*)
Jurassic.	Marine Upper Jurassic.		Twin Creek limestone of Schultz.		Sundance formation.	(*i*)
	White Cliff sandstone. Vermilion Cliff sandstone.		Nugget sandstone of Schultz.			
Triassic.	Chinle formation. Shinarump conglomerate.		Ankareh shale of Schultz.		Jelm formation.	(*j*)
	Moenkopi formation.		Thaynes(?) formation of Schultz. Woodside shale of Schultz.		Chugwater formation.	(*k*)
Permian.	Kaibab limestone. Coconino sandstone. Hermit shale.		Park City formation.		Phosphoria formation.	(*l*)
Pennsylvanian.	Supai formation.				Absent(?).	
			Weber sandstone.		Tensleep sandstone.	(*m*)
			Pennsylvanian limestone.		Amsden formation.	(*n*)
Mississippian.	Redwall limestone.		Mississippian limestone.		Madison limestone.	
Cambrian.	Tonto group.	Muav limestone.	Lodore formation.	(?)	Gallatin limestone.	(*o*)
		Bright Angel shale.		Shale.	Gros Ventre shale.	
		Tapeats sandstone.		Sandstone.	Flathead quartzite.	
Pre-Cambrian.	Pre-Cambrian.		"Uinta formation."		Pre-Cambrian.	(*p*)

a The exact equivalent in time of the Pink Cliff series of Dutton is uncertain, but it probably represents some part of the Wasatch formation with possibly some later beds. The Green River formation and the Wind River have little in common except stratigraphic position; it is also probable that the Wasatch and Wind River formations are in part contemporary.

b The "post-Laramie" formation and the Fort Union formation, besides having a similar stratigraphic position, contain the Fort Union flora. The "Laramie" formation contains the Laramie flora and the Lance formation the Fort Union flora and are supposed on that ground to differ in age. Beds older than Dutton's Pink Cliff series and younger than Cretaceous are not known in southwestern Utah.

c The Lewis shale is a somewhat doubtful unit on Green River. There is no well-defined shale unit between the Wasatch beds of the Roan Cliffs and the Mesaverde formation of the Book Cliffs, south of the Uinta Mountains, that could be called Lewis shale. North of the mountains such a unit is mentioned by Gale (U. S. Geol. Survey Bull. 341, p. 310, 1909), and by Schultz (U. S. Geol. Survey Bull. 702, fig. 3, 1920), but no description is given. A correlation of the Lewis shale of the Green River region with that of central Wyoming, and of either with the typical Lewis shale in southwestern Colorado is simply a loose grouping of large shale units of upper Montana age and does not imply identity in time of deposition.

[d] It is not known that the Mesaverde formation of the Book Cliffs occupies the same time interval as the Mesaverde formation north of the Uinta Mountains, nor that either is the same as the Mesaverde formation of central Wyoming or of the typical region in southwestern Colorado. This name, like Lewis, has been loosely used and is made to apply practically to any coal-bearing formation within the Montana group.

[e] The Upper Cretaceous deposits of southern Utah are variable in constitution and have been classified differently by different geologists. Much still remains to be learned, and I do not venture to make detailed correlations. There are beds that in a loose way might be called Frontier, others that might be called Mesaverde, and still others that may require other names.

[f] The Frontier formation of the Green River region is a thin sandstone unit very low in the Colorado group. It can hardly be really the same as the much thicker Frontier formation of other areas except under the loose application of the name to any sandy unit in the lower part of the Colorado group.

[g] The Aspen shale on Green River has exactly the lithologic character of the Mowry shale of Wyoming but is very thin and rests almost directly on the preceding sandstone (Dakota?) without any suggestion of an intervening shale like the Thermopolis shale.

[h] The Beckwith formation as delimited by Schultz on Green River contains as its upper member a conglomeratic sandstone that would certainly be mapped as Cloverly formation in Wyoming or Dakota sandstone in Colorado. Whether it is equivalent only to the Dakota sandstone proper or contains also, like the Cloverly formation, beds of probable Lower Cretaceous age, can not be determined in the absence of fossils. The Beckwith beneath this upper sandstone contains three members which together seem to me to be the Morrison formation of Colorado and Wyoming. Schultz offers two different correlations for his Beckwith formation. In one (U. S. Geol. Survey Bull. 702, tables opposite pp. 36 and 82, 1920) he indicates that the Dakota sandstone and Cloverly formation are both probably absent and that the Beckwith formation is all Morrison in age. In the second (idem, pp. 75-77) he expresses the belief that the upper sandstone is equivalent to the Dakota sandstone of some regions and upper Cloverly of others, that the upper shale and middle conglomerate are equivalent to the middle and lower parts of the Cloverly formation, and that the lower shale alone is Morrison. The position of the dinosaur fauna near Jensen and the lithology of the Cloverly formation, so far as I know it, are both against the correlation of the two middle members with the Cloverly formation. It seems also very doubtful to me whether the Beckwith formation of the Green River region is really comparable to the beds to which the name Beckwith is applied farther west in Utah and in Idaho.

[i] W. T. Lee, in a paper now awaiting publication, has adduced abundant evidence to indicate that the Sundance formation of Wyoming, as usually defined, contains in the lower part the equivalent of the Nugget sandstone of the Green River region and of the thick Jurassic sandstone unit of southern Utah believed to include the White Cliff and Vermilion Cliff sandstones. Some writers on Wyoming stratigraphy have included the sandstone in the upper part of the Chugwater formation, but its structural relations ally it more with the overlying than the underlying beds. The Twin Creek limestone of the Green River region is the lithologic and faunal equivalent of the calcareous beds in the upper part of the Sundance. It is very likely that the Twin Creek formation of the Green River region is equivalent to only a small part of the beds to which the name was originally applied. No evidence of any other marine Jurassic formation than the Sundance was observed on Green River.

[j] The correlation suggested by stratigraphic position and structural relations between the Shinarump and Chinle formations, the Ankareh shale of Schultz, and the Jelm formation is largely conjectural. All three are separated from the preceding beds by an unconformity. The Shinarump is regarded as probably Upper Triassic; the Chinle and Jelm contain vertebrate remains of Upper Triassic age; the Ankareh formation in the typical region contains in the lower part marine invertebrates of Lower Triassic age. Whether the Ankareh formation of the Green River region is the same as the typical Ankareh may well be questioned.

[k] A correlation of the Moenkopi formation and the Woodside and Thaynes (?) formations of the Green River valley rests on the assumption that the latter beds are really the equivalent of the marine Lower Triassic formations of the same names that occur in the western Uinta region. It seems to me that the assumption is very probably valid, at least in a broad sense, even though continuous tracing between the two regions is not possible. The relation of the Chugwater formation to those just named is more doubtful, though the presence of a marine limestone in the upper part of the Chugwater is difficult to account for except as an eastward extension of the marine Lower Triassic strata. Another point of difference is that the Moenkopi formation is unconformable on the preceding beds, whereas the Woodside and Chugwater formations appear to be conformable.

[l] The equivalence of the Kaibab limestone, Coconino sandstone, and Hermit shale on the one hand and the Park City formation on the other is not supported by direct evidence. The Coconino and Hermit are placed in the Permian on the basis of fossil plants in the Hermit formation and an unconformity beneath it. The Kaibab limestone has a marine fauna of Permian age, and so has the Park City formation, in its upper (Phosphoria) part, but there are very few species in common. It is possible that the upper (Phosphoria) part of the Park City formation may be entirely later than the Kaibab limestone, though still Permian, as the Kaibab is followed by an unconformity and the upper part of the Park City is

believed to be conformable with the succeeding beds. An unconformity is known in places in southeastern Idaho at the base of the Phosphoria formation.

m The Tensleep sandstone, Weber sandstone, and Supai formation are somewhat variable sandy formations that in some phases are very much alike and in others quite different. They are assigned to the late Pennsylvanian (Supai, possibly also including Permian) and probably do not differ greatly in age.

n The Redwall limestone, as originally defined from its occurence in northern Arizona, contained beds of both Pennsylvanian and Mississippian age, but in recent classifications the Pennsylvanian part has been added to the Supai formation. In southern Utah a considerable thickness of calcareous strata beneath the sandy beds assigned to the Supai formation contains Pennsylvanian fossils. It is possible also that there are in Green River valley beds of upper Mississippian age, which in Wyoming in places occur in the lower part of the Amsden formation and above the Madison limestone (lower Mississippian).

o There is no specific evidence for correlating the Lodore formation with either the Tonto group or the Flathead, Gros Ventre, and Gallatin formations of central Wyoming. All three have a sandstone at the base followed by shales, the gross lithologic features of which are similar. If there is any limestone in the upper part of the Lodore formation, its analogy to the Tonto and Deadwood would be complete. In the field I considered any limestone beds to belong to the overlying Carboniferous, but I may have been mistaken.

p There is no specific evidence to show that the "Uinta formation" is Cambrian nor that it is pre-Cambrian.

THE EVOLUTION AND DISINTEGRATION OF MATTER.

By Frank Wigglesworth Clarke.

INTRODUCTION.

In any attempt to study the evolution of matter it is necessary to begin with its simplest known forms, the so-called chemical elements. During a great part of the nineteenth century many philosophical chemists held a vague belief that these elements were not distinct entities but manifestations of one primal substance—the protyle, as it is sometimes called. Other chemists, more conservative, looked askance at all such speculations and held fast to what they regarded as established facts. To them an element was something distinct from other kinds of matter, a substance which could neither be decomposed nor transmuted into anything else. This belief, however, was based entirely upon negative evidence—the inadequacy of our existing resources to produce such sweeping changes. Many important facts were ignored, and especially the fact that the elements are connected by very intimate relations, such as are best shown in the periodic law of Mendeléef, who, from gaps in his table of atomic weights, predicted the existence of three unknown metals, which have since been discovered. For these metals, scandium, gallium, and germanium, he foretold not only their atomic weights but also their most characteristic physical properties and the sort of compounds that each one would form. His prophecies have been verified in every essential particular. One obvious conclusion was soon drawn from Mendeléef's "law," although he was too cautious to admit it, namely, that the chemical elements must have had some community of origin. The philosophical speculations as to their nature were fully justified.

In 1873 I ventured to publish the suggestion that the evolution of planets from nebulae was accompanied by an evolution of the chemical elements.[1] The validity of the nebular hypothesis was assumed, and the progressive chemical complexity of the heavenly bodies gave my argument its plausibility. The nebulae are chemically simple, the hotter stars more complex, the cooler stars and the Sun still more so, and the solid Earth the most complicated of all. The evidence for this statement was found in the spectroscopic researches of Huggins and Secchi, which seemed to me to be conclusive, although defective in one respect: instead of helium in the nebulae they reported nitrogen, for helium was yet to be discovered. This defect, however, did not invalidate my conclusions, which were promptly denounced as heretical but which have since been accepted as quite orthodox. Nearly a year later Lockyer[2] put forth an analogous suggestion, based upon evidence of the same sort but starting from the other end. That is, he assumed that in the hotter stars the elements were dissociated, and his suggestion was received with a good deal of favor. As to the origin of the dissociated elements he had nothing to say. That the elements are really decomposable was the substance of his suggestion, which he followed up in detail in his later publications.

With the discovery of radioactivity by Becquerel and of radium by Madame Curie a new era in chemistry began. It was at once found that at least some of the elements were really unstable; and the evolution of helium from radium, discovered by Ramsay and Soddy, made the evidence complete. A derivation of one element from another had actually been observed.

These discoveries opened a new field of research; and it was soon found that the elements at the top of the atomic-weight scale, namely, uranium and thorium, are spontaneously but slowly decaying, yielding more than thirty new substances which differ widely in

[1] Clarke, F. W., Evolution and the spectroscope: Pop. Sci. Monthly, January, 1873.

[2] Lockyer, J. N., Roy. Soc. Proc., vol. 21, p. 513; paper dated Nov. 20, 1873.

stability. To each one a half-life period is assigned, some of them measured in thousands of years, others in fractions of a second. Among these substances are two new varieties of lead—one derived from uranium, the other from thorium—which chemically are not distinguishable from ordinary or normal lead except by differences in their atomic weight and their specific gravity. The lead from thorium has an atomic weight about a unit higher and that from uranium about a unit lower than the atomic weight of normal lead. To this class of facts I shall recur later, as evidence in support of my arguments. That chemical elements can decay is the essential fact to be remembered.

That the chemical elements were formed by a process of evolution from the simplest forms of matter can hardly be doubted now, but the process is not yet ended. They were developed at high temperatures; but when a certain stage was reached in the cooling mass they began to combine with one another to form the new class of substances which are known as compounds. These substances obviously represent an advanced degree of complexity, with corresponding instability; and with varying conditions both combination and decomposition, such as are reproducible by human agencies, constantly occur. By this extension of the evolutionary process the solid Earth was built up, but in principle the process is the same throughout. From the formation of the first elements to the chemical changes now taking place upon the Earth there is no real interruption. One line of progress has been followed until a maximum of natural complexity and instability is reached in the organic compounds that form the basis of all physical life, whether vegetable or animal. The same fundamental matter, governed by the same fundamental laws, appears from beginning to end of the evolutionary process.

THE EVOLUTION OF THE CHEMICAL ELEMENTS.

In any attempt to discuss the evolution of the chemical elements we have for guidance some facts and many analogies. That the most complex elements are unstable we have already seen, and it is suspected that all the others follow the same rule. Potassium and rubidium are feebly radioactive, a property which is an evidence of instability, and other confirmatory evidence will be cited later. Stability, however, is a relative term, and a substance that is stable under certain conditions becomes unstable under others. The prime factors that determine external stability are temperature, pressure, and chemical environment. For example, some compounds that are stable in anhydrous surroundings are decomposed in presence of water. Calcium carbonate, under ordinary conditions, is divided at high temperatures into carbon dioxide and lime, but heated in a steel bomb it not only remains undecomposed but may even be melted, to form upon cooling a crystalline marble. Examples like this might be multiplied indefinitely. As a rule stability diminishes with increasing temperature but is favored by increased pressure. We may also assume that the more symmetrical an atom or compound is the more stable it is likely to be.

Now, to return to our main problem, was the evolution of the elements a regular progression, such as might be represented by a smooth curve or a straight line; or was it irregular and quite independent of their order in the scale of atomic weights? To answer this question we must try to imagine what happened in the development of the larger masses, the nebulae and the stars. On this subject there is a plausible hypothesis which has been favored by many astronomers—namely, that the nebula at first was relatively cool, that the temperature gradually rose to that of the hottest stars and then regularly declined to that of the end product of the series, the solid planet. A gaseous mass, contracting under the influence of gravitation, became warmer; at its center, where the pressure was greatest, the increasing condensation generated still higher degrees of temperature, until a luminous nucleus was formed. As condensation went on with increasing intensities of pressure, the temperature continued to rise until the heat generated by compression was less than that lost by radiation into space, when cooling began. Although this hypothesis, in its crude form, is not universally accepted, it nevertheless gives a fair conception of that part of the evidence with which we are now concerned. The process of evolution from cool to hot and then to cool again is fairly outlined. The nucleus of the original nebula has its modern representative in the Sun.

In all the foregoing discussion it has been tacitly assumed that the nebula from which the solar system was developed was similar in all essential respects to the planetary nebulae. The latter, as shown by their spectra, consist mainly of hydrogen, helium, and nebulium, with slight traces in some of them of carbon, nitrogen, and perhaps other elements. Nebulium is known only from its lines in the spectrum, and its atomic weight has been estimated by Fabry and Buisson as 2.7, placing it between hydrogen and helium. In any further study of relations between the atomic weights of the elements, nebulium must be taken into account, and perhaps also coronium, so called from its lines in the spectrum of the solar corona. From its position in the corona it is assumed to be lighter than hydrogen and so would seem to be an even more primitive element. That possibility can not be considered here; we must limit ourselves to the conditions actually seen in the nebulae. No assumption is made as to the possible ancestry of the nebular elements; they are the visible beginnings.

Passing from the nebulae to the stars and finally to the planets, the course of evolution has been one of uninterrupted gradations. There are no sharp lines of demarcation between one class and another. As for the elements their evolution has been admirably summarized by Campbell[3] in his lectures on the evolution of the stars. Without literal quotation and accepting the Harvard classification of the stars, I may briefly outline Campbell's summary as follows: After the gaseous nebulae there are first the blue stars of classes A and B. In class B, known as the helium stars, the hydrogen and helium lines are conspicuous, and in their later stages silicon, oxygen, and nitrogen are represented by a few absorption lines. In class A the hydrogen lines are the most prominent, and helium has nearly disappeared. Lines of magnesium and calcium are also conspicuous, and those of iron and titanium are beginning to appear.

In the spectra of stars of class F, the bluish-yellow stars, the metallic lines increase rapidly in prominence; and in those of the yellow stars of class G they appear in great number. Hydrogen is much less conspicuous. In the spectra of the reddish-yellow stars of class K, which are weak in violet light, the metallic lines are more evident, and still more in those of the red stars of class M, in which the spectra also show absorption bands attributed to titanium oxide. In the spectra of the very red stars of class N the violet end of the spectrum is almost entirely lacking, the metallic absorption is very strong, and bands representing carbon oxides are conspicuous.

Such, in brief, was the probable course of elemental evolution in the passage from a gaseous nebula to the coolest and oldest stars. It is not necessary for my purpose to go more into detail on this phase of my subject. The literature relative to solar and stellar spectra is very extensive and is steadily increasing in volume. It involves many questions that I can not attempt to consider, even if I felt myself competent to do so. That the evolution of the elements has actually taken place seems to be established, and I must limit myself to some of the chemical problems that are suggested by it.

Now, it is easy to see that in the process of evolution from nebula to Sun an orderly development of the elements could hardly have been possible. With changing pressure, changing temperature, and changing environment all the conditions required for a regular progression according to the order of the atomic weights were lacking. In the hotter stars only the simplest and most stable elements were formed, and these in the greatest abundance. We have already seen that magnesium, calcium, titanium, and iron were among the earliest to appear, and that the others, between helium (atomic weight 4) and iron, either came later or were developed at first in much smaller quantities. As cooling went on more and more elements were generated, and in the Sun all the possible elements are presumably present, although only about half of them have been actually detected. It is conceivable that elements of different degrees of stability may have been formed simultaneously, one in that part of the cooling mass where the temperature and pressure were highest, another farther away from the center, under less rigorous conditions. This suggestion, however, is something which can not be proved. If the three

[3] Campbell, W. W., Pop. Sci. Monthly, vol. 87, p. 209, 1915; Sci. Monthly, vol. 1, pp. 1, 177, 238, 1915.

nebular elements were the raw material from which the other elements were built, their relative amounts must have been continually changing, so that as each new element appeared a new environment was established for all that followed. At some time early in the course of evolution nebulium seems to have vanished, for its lines do not appear in the spectrum of any true star. Was it completely absorbed in building other elements? The question is easy to ask but very difficult to answer.

That the cooling of a star made the formation of the less stable elements possible has already been assumed. But was the rate of cooling uniform, or was it subject to fluctuations? To answer this question we must bear in mind the clear distinction between atoms and molecules, for here the elements as we know them differ widely. Some molecules, like those of zinc, cadmium, mercury, and the inert gases of the helium group, are monatomic. Hydrogen, nitrogen, oxygen, chlorine, bromine, and iodine are diatomic. Phosphorus and arsenic are tetratomic, and so on. For most of the elements we lack the positive information which we have for those just named. In ordinary chemical reactions the complex molecules are easily decomposed, and at high temperatures also decomposition is possible. The molecule of iodine, for example, is dissociated into its atoms at about 1,700° C., a temperature much lower than that of even the coolest stars. In the hotter stars all the elements present are probably in the atomic state, a considerable fall of temperature must take place before even diatomic molecules can be formed, and they may be regarded as a very primitive order of compounds. In the Sun and the cooler stars compounds in the ordinary sense of the term begin to appear and certain obvious consequences follow.

Whenever two or more free atoms unite to form a chemical compound heat is given out; and in most such unions, as in the formation of water from its elements, condensation has also its thermal value. I must here emphasize my use of the expression "free atoms," for they alone exist in the hotter stars. Such unions are rarely recognized in laboratory experiments, which deal not with direct combinations but nearly always with reactions. The heat of a reaction, which is usually called the heat of formation of a compound, is really the algebraic sum of three or more terms, some of which are positive and some negative. A reaction may be endothermic when the minus terms are in excess, as in the formation of hydriodic acid from its elements. Here the decomposition of the hydrogen and iodine molecules precedes the union of the momentarily free atoms.

In the evolution of the elements we have, then, first the formation of individual atoms, and as cooling goes on their union into diatomic and polyatomic molecules becomes possible. Heat is given out, and the rate of cooling must be somewhat retarded. Whether the retardation is great or small it is impossible to say; but some increase of temperature, even if it is very slight, may fairly be assumed. In short, the rate at which a star cools is in all probability subject to fluctuations, which may influence the development of the more complex and less stable elements. When compounds, as we understand them, begin to be formed, the heating effect is likely to be relatively larger. The cooling of our Sun is almost certainly subject to this sort of retardation, and so its existence as a heat-giving luminary may be considerably prolonged. Heat of chemical origin, with its attendant condensations, must be taken into account in any serious attempt to discover the sources of solar energy. The formation of molecular from atomic hydrogen would alone give out a vast amount of heat, about 82,000 calories per gram-molecule. The supposed formation of helium from hydrogen need not be considered. The helium of the Sun is probably primordial.

So far we have considered only the astronomical evidence relative to evolution, but that evidence is purely qualitative. For quantitative data we must study the so-called atomic weights and their relations, chemical and physical, with one another. The atomic weights, it must be remembered, are not absolute quantities, for no single atom has ever been directly weighed. They are really the expression of ratios, one element being assumed as a standard, with which the others can be compared, by methods that are so well known that it is not necessary to explain them here. These very elementary considerations are cited now because they are so familiar that they are often unconsciously ignored. If we think of the atomic weights as the combining numbers of the elements—that is, the proportions in which each one unites with others—it may be easier to avoid confusion of ideas.

At least three different standards of atomic weight have actually been in use. In the Berzelian system the atomic weight of oxygen was taken as 100, but that led to figures so large for most of the elements that they were difficult to remember and inconvenient to use. The system was therefore abandoned, and the atomic weight of the lightest element, hydrogen, was assumed as unity, a much more natural and satisfactory plan than that of Berzelius. The hydrogen unit, $H = 1$, was in general acceptance until about 30 years ago, and it is still regarded favorably by many chemists. The only objection to it, at least until recently, was that very few of the atomic weights appeared as whole numbers, and the fractional parts were somewhat annoying. There was therefore a tendency among practical chemists to round the figures off to the nearest integers, for in many kinds of analytical work greater accuracy was not required.

On the hydrogen scale the atomic weight of oxygen is 15.876, or nearly 16, a figure which is the basis of the system of atomic weights now generally used. With $O = 16$ a considerable number of other atomic weights become close approximations to whole numbers and therefore more convenient to handle. That is the principal reason why the oxygen standard has been so commonly accepted by chemists. This reason would be more valid if determinations of atomic weight had been made by direct comparison with oxygen, whereas as a matter of fact comparatively few such determinations have been at all satisfactory. With some exceptions, by far the larger number of the best modern determinations have been indirect, with silver, chlorine, and bromine as intermediaries. This indirection, however, does not imply inaccuracy. The actual measurements are those of ratios. To discuss this subject in detail would take me too far from my main theme.

We have already seen that hydrogen and helium are the two oldest elements of which we have any direct experimental knowledge. They also have the lowest atomic weight and are therefore the simplest. The astronomical and chemical lines of evidence are in complete harmony. Nebulium may be left temporarily out of account. Hydrogen and helium, then, are the two elements with which to begin any detailed study of elemental evolution. The atomic weight of hydrogen, 1.0078, is the starting point, with helium next in order. From these elements all other forms of matter may have been derived. There is much evidence in favor of this suggestion, although anything like absolute proof is lacking and perhaps unattainable.

Of the mechanism of the processes by which the elements were built up we have no positive knowledge. It is, however, in the highest degree probable that they were formed under extremely high temperatures and pressures, such as we can not hope to reproduce experimentally. That the evolution of the elements was accompanied by a progressive condensation is evident; and it is also clear that the contraction from the primal highly attenuated nebula to the solid planet was something enormous—so great that we can form no definite conception of its magnitude.

The two most promising lines of quantitative attack upon the problem of elementary evolution are as follows: One begins with a study of the numerical relations between the atomic weights of the elements, and the other with attempts to determine the structure of the atoms. I cite these in their historical order, which is not necessarily the one of greatest importance. The atomic theory was still in its infancy when in 1815 Prout suggested that all the atomic weights were whole numbers, based upon hydrogen as unity. Hydrogen, then, was the primordial element from which all others were derived. As most of the early determinations of atomic weight were rather crude and many of them close to integers, Prout's hypothesis was quite plausible. As the determinations became more exact it was found that few atomic weights were integral and that many of them differed widely from whole numbers. Prout's hypothesis was therefore set aside, although it has recently been revived upon a different foundation.

Since the time of Prout numberless attempts have been made to trace relationships between the atomic weights, but only a few of them were of any scientific value. The subject was a favorite one for a certain class of speculators, who generally started with preconceived opinions as to what atoms ought to be. Some interesting partial relations were pointed out by competent investigators, but the first advance of general significance was the reconstruction of the entire scheme of atomic weights by Cannizzaro, which brought it into harmony with the law of Avogadro. In this new system the old chemical equivalent of oxygen, O = 8, became O = 16, the present standard of value. Definite relations between the atomic weights now began to appear which previously were unsuspected, and these found expression in the "periodic law" of Mendeléef and the Lothar Meyer curve of atomic volumes. In both generalizations the starting point was the same, and the atomic weights were arranged in the order of increasing magnitude, from hydrogen up to uranium; or, as we can say now, the order of their atomic numbers, an expression which has become significant only within very recent years.

The periodic law, or periodic classification of the elements, is given in the following table. The atomic numbers precede the symbols of the elements, and the atomic weights are given below them. A different placing of the rare-earth metals will be considered later.

Periodic table of the elements.

[The upper numerals in the headings indicate natural groups; the lower numerals (arabic) indicate valencies. The rare-earth elements are inclosed within a thick line.]

0 0	I +1	II +2	III +3	IV +4	V −3–5	VI −2–6	VII −1–7	VIII ([a])
	1 H 1.008							
2 He 4.00	**3** Li 6.9	**4** Gl 9.1	**5** B 10.8	**6** C 12.00	**7** N 14.01	**8** O 16.00	**9** F 19.00	
10 Ne 20.2	**11** Na 23.00	**12** Mg 24.32	**13** Al 26.96	**14** Si 28.07	**15** P 31.04	**16** S 32.06	**17** Cl 35.46	
18 A 39.9	**19** K 39.1	**20** Ca 40.07	**21** Sc 45.1	**22** Ti 48.1	**23** V 51.0	**24** Cr 52.0	**25** Mn 54.93	**26** Fe **27** Co **28** Ni 55.85 58.97 58.68
	29 Cu 63.57	**30** Zn 65.37	**31** Ga 70.1	**32** Ge 72.5	**33** As 74.96	**34** Se 79.2	**35** Br 79.92	
36 Kr 82.92	**37** Rb 85.45	**38** Sr 87.83	**39** Y 89.33	**40** Zr 90.6	**41** Cb 93.5	**42** Mo 96.0	**43** —	**44** Ru **45** Rh **46** Pd 101.7 102.9 106.7
	47 Ag 107.88	**48** Cd 112.40	**49** In 114.8	**50** Sn 118.7	**51** Sb 121.7	**52** Te 127.5	**53** I 126.92	
54 Xe 130.2	**55** Cs 132.81	**56** Ba 137.37	**57** La 139.0	**58** Ce 140.25				
	59 Pr 140.6, **60** Nd 144.3, **61** —, **62** Sm 150.4, **63** Eu 152.0, **64** Gd 157.3, **65** Tb 159.2							
	66 Ds 162.5, **67** Ho 163.5, **68** Er 167.7, **69** Tu 168.5, **70** Yb 173.5, **71** Lu 175, **72** —				**73** Ta 181.5	**74** W 184.0	**75** —	**76** Os **77** Ir **78** Pt 190.9 193.1 195.2
	79 Au 197.2	**80** Hg 200.6	**81** Tl 204.0	**82** Pb 207.2	**83** Bi 209.0	**84** [b]	**85** —	
86 Rn 222.0	**87** —	**88** Ra 226.0	**89** [c]	**90** Th 232.15	**91** [d]	**92** U 238.2		

[a] Valencies diverse. [b] Polonium? [c] Actinium? [d] Protoactinium?

The significance of the foregoing table, of which there are many variants, is evident at a glance. The elements in each vertical column are closely allied, forming the natural groups with which all chemists are familiar. The alkaline metals, the series calcium, strontium, and barium, the carbon group, and the halogens are examples of this regularity. In other words, similar elements appear at regular intervals and occupy similar places. If we follow any horizontal line of the table from left to right we find a progressive change of valency, and in both directions we find a systematic variation of properties. Broadly stated, the properties of the elements, chemical and physical, are periodic functions of their atomic weights; and this is the most general expression of the periodic law. At certain points in the table gaps are left, and these are believed to correspond to undiscovered elements. For three of the spaces that were vacant when Mendeléef announced the law he made specific predictions, which, as has already been stated, were verified by the discovery of scandium, gallium, and germanium. Radium and the inert gases, much more recently discovered, all fall into their proper places in the table and give additional emphasis to its validity. Place No. 72 is undoubtedly to be filled by the recently discovered element termed hafnium or celtium, two names which are at present in controversy. The names assigned to Nos. 84, 89, and 91 are provisional only and may not be sustained. The elements corresponding to Nos. 43, 61, 75, 85, and 87 are as yet unknown, although their properties can be predicted with a close approach to certainty.

The periodic table is also very suggestive as regards the chemical relations and modes of occurrence of the elements in nature. In the first place, the members of the same elementary group have similar properties, form similar compounds, and give similar reactions, and because of these conditions they are commonly found in more or less close association. Thus the platinum metals are seldom found apart from one another; chlorine, bromine, and iodine occur under very similar conditions; selenium is found in native sulphur; cadmium is extracted from ores of zinc; and so on through a long list of regularities. The group relations govern many of the associations that are actually observed, although they are modified by the conditions that influence chemical union. Even here, however, regularities are still apparent. In combination unlike elements seek one another, and yet there appears to be a preference for neighbors of approximately equivalent mass. For example, silicon follows aluminum in the scale of atomic weights, and in the crust of the earth silicates of aluminum are far the most abundant minerals. An even more striking example is furnished by the series oxygen, sulphur, selenium, and tellurium. Oxidized compounds of many elements are found in the mineral kingdom, but most of them are compounds of metals of low atomic weight. Above manganese, sulphides are abundant; but selenium and tellurium are more often united with the heavier metals silver, mercury, lead, or bismuth, and tellurium with gold. The elements of high atomic weight seem to seek one another, a tendency which is indicated in many directions, even though it may not be stated in the form of a precise law. The general rule is evident, but its full significance is not so clear.

One phase of the periodic law, equally suggestive with the preceding table, is shown in Lothar Meyer's curve of atomic volumes. When these volumes are plotted against the atomic weights they give a curve that consists of a series of undulations or waves of considerable amplitude. On these waves similar elements occupy similar positions—the alkaline metals at the crests, the heavier metals in the depressions, and the other elements in orderly arrangement between these extremes. The regularities are very striking and continue as far as the elements of the rare-earth group above cerium, where the waves flatten out, until at tantalum the curve becomes normal again. Similar curves can be drawn for other physical properties of the elements, with similar results. Richards,[4] for example, has superimposed upon the curve of atomic volumes curves representing compressibilities, coefficients of cubical expansion, and the reciprocals of the melting points. All four curves are similar in type and show the same periodicity. They are somewhat ragged, but nevertheless they tell the same story. The irregularities are due partly to defective data and partly to the fact that the physical constants were not

[4] Richards, T. W., Am. Chem. Soc. Jour., vol. 37, p. 1649, 1915.

determined under strictly equivalent conditions. The atomic volumes, which are the ratios between the atomic weights and the specific gravities of the solid elements, are especially in need of revision. The specific gravities of some elements were determined at temperatures relatively near their melting points, those of others at temperatures 1,000 or more degrees below them. It is possible that if all could be determined at points near the absolute zero, or, as an alternative, at points just below the temperature of fusion, a smoother curve might be given.

The curve of atomic volumes, as given in Plate XXII, is reproduced, with the author's permission, from Professor A. W. Stewart's volume "Some physico-chemical themes" (London, 1922). In one respect it is likely to be misleading. The atomic volumes are calculated from the atomic weights, not from the atomic numbers.

In the region of the rare-earth metals, between cerium and tantalum, the regular evolution of the elements seems to have been interrupted, so that a systematic periodicity is no longer evident. These metals all resemble one another very closely and form compounds of similar type. Their normal oxides are all of the form R_2O_3, their chlorides are RCl_3, and so on, and they are therefore to be considered trivalent. Cerium, however, which is a member of this group, also forms a dioxide, and it is therefore possibly quadrivalent, although most of its compounds are of the trivalent type. The earlier elements of the group, which appear in the periodic scheme—namely, scandium, yttrium, and lanthanum—are all normal.

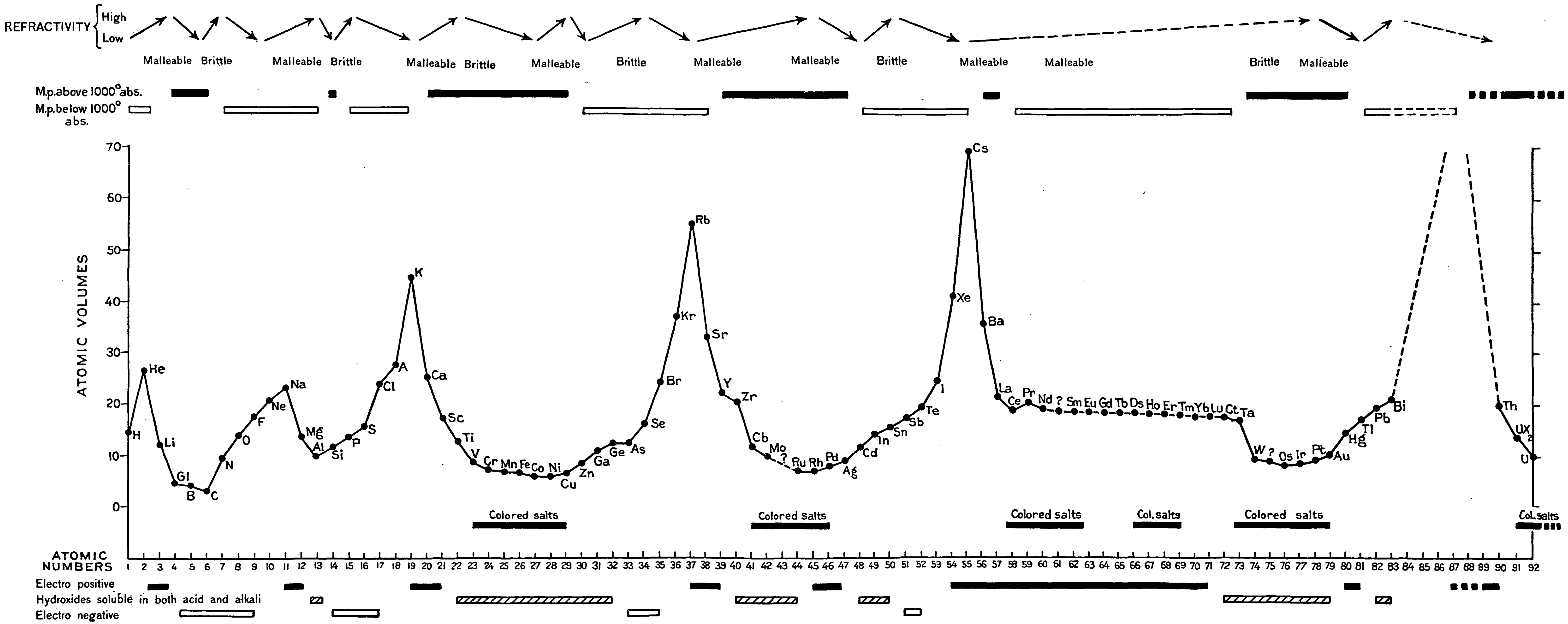
Furthermore, the rare earths occur in nature under similar conditions, they are almost everywhere intimately associated, they are difficult to separate, and their oxides are not easily reducible to metals. These very intimate relations need to be explained, and the curious flattening of the Lothar Meyer curve in the part of the atomic-weight scale which the rare-earth metals occupy gives us a clue to their mode of origin. It is evident that they must have been formed under very similar conditions, which changed but slightly as the atomic weights increased. In other words, the conditions were nearly constant, but not quite, for with absolute constancy there would have been only one element generated instead of at least a dozen.

The two preceding paragraphs lead at once to a very simple hypothesis. In the course of evolution from the hottest to the coolest stars there was probably a period of undeterminable duration when the rate of cooling and condensation was in some unknown way retarded, so that the conditions became nearly uniform. During this period, which was followed by one of increased activity, the elements of the rare-earth group were formed. This hypothesis gives a rational explanation of the known facts concerning these elements and is therefore, despite its speculative feature, legitimate. If it is sound, then the elements of the rare-earth series should appear in the periodic table as prolonging the trivalent group, and not be scattered under other groups to which they can not possibly belong.[5]

One more curiously suggestive relation connecting three distinct groups of elements deserves consideration here. The halogens, F, Cl, Br, I, are strongly electronegative; the alkaline metals, Li, Na, K, Rb, Cs, are strongly electropositive; and these two groups are separated by the inert gases, He, Ne, A, Kr, Xe. So we have the following triads: F, Ne, Na; Cl, A, K; Br, Kr, Rb; I, Xe, Cs. The atomic weights in each triad are consecutive. Another probable triad is incomplete; only He and Li are known. One more electronegative element is needed here, which should be a gas of greater chemical activity than fluorine and of lower atomic weight. Is nebulium, with atomic weight near 2.7, the missing member? If so its chemical activity might account for the nonappearance of its lines in the stellar spectra. Was it used in building other elements? That question I have asked already, but it is not yet answered. Here we enter the realm of pure speculation, the foundations of which are insecure. Speculation is of value only in so far as it is suggestive. The intervention of the inert gases between two groups of great chemical activity is well established, but I must leave its explanation to physicists and mathematicians.

Although the periodic classification of the elements is now thoroughly established, there

[5] In this mode of placing the rare-earth metals, I find that I have been anticipated by Dr. C. Renz (Zeitschr. anorg. allgem. Chemie, vol. 122, p. 143, 1922). My interpretation of the scheme is, I think, new.



THE CURVE OF ATOMIC VOLUMES.

are certain details of it that remain to be adequately investigated. The numerical relations between the atomic weights can not at present be discussed with any approach to finality. The problem is complicated by frequent changes—for example, within the last two or three years the atomic weight of scandium has been raised from 44 to 45, that of bismuth from 208 to 209, and that of antimony from 120.2 to 121.77. Recent investigations relative to "isotopes" have thrown doubt upon the definiteness of the atomic weights as they have been actually determined; and until that question is settled experimentally the true numerical relations must remain uncertain. The theoretical atomic weights will be considered later.[6]

Now, using the word in its chemical sense, let us ask: What is an atom? Here many loose reasoners have gone astray and have assumed that because atoms have been found to be decomposable, the atomic theory is overthrown. They seem to regard the etymological meaning of the word as having ultimate significance, but etymology is an unsafe guide in the discussion of scientific problems. The technical significance of a word may be quite unrelated to its etymological history. What, for instance, does the word "chloroform" mean? According to etymology, a green ant!

In brief, the chemical atoms are now known to be complex, ranging from the comparatively simple hydrogen up to the highly complicated and unstable uranium. Each atom is supposed to consist of an electropositive nucleus, attended by one or many electrons of opposite sign. In the hydrogen atom there is one "planetary" electron, in helium two, and so on regularly up to 92 in uranium, at the present summit of the atomic-weight scale. These electrons are also supposed to be, above a certain small number near the beginning of the scale, arranged in rings or perhaps concentric shells around the nuclei. Whether they are revolving about the nuclei, like planets around the Sun, or are relatively at rest is an open question. Models that show the structure of atoms have been constructed, but they are not in complete agreement. The prevalent opinion regards each atom as resembling a miniature solar system, and the term "planetary electrons" is used to distinguish those around the nucleus from some which have found place within it. The mass of an atom is almost entirely concentrated in the nucleus, for it is known that the weight of a single electron is only about $\frac{1}{1800}$ of that of an atom of hydrogen, or 0.00054 on the ordinary scale of atomic weights.

On this foundation Rutherford[7] has erected his scheme of elementary evolution, starting with the hydrogen atom. The nucleus, or "proton," and the single electron are taken as the two fundamental constituents of all matter, whether element or compound, and these units are purely electrical. Prout's hypothesis has come to life again, but in a highly modified form.

The next important step in the study of atomic structure was taken by Moseley,[8] who from measurements of the X-ray spectra of the elements discovered relations which proved that "there is in the atom a fundamental quantity which increases by regular steps as we pass from one element to the next"—that is, the next in the ascending scale of atomic weight—and that "this quantity can only be the charge on the central positive nucleus." That charge increases with increasing atomic weight and so follows the order of the elements upward, or in other words the order of the atomic numbers H 1, He 2, Li 3 . . . Ca 20, Zn 30, and so on up to U 92. These numbers are now regarded by many physicists as of more fundamental importance than the atomic weights from which they were first derived. In the series of atomic numbers, just as in the periodic law, there are gaps that represent undiscovered elements. There is no place in the scheme, however, for nebulium or coronium. The atomic numbers may have to be revised.

Now, without rejecting Moseley's "law," we must admit that the experimental evidence for it is incomplete. The region of the metals of the rare earths needs to be investigated, so as to determine whether their atoms carry electrical charges in the order demanded by the law. Does their anomalous character show itself here? The curious relations of the inert

[6] For a very complete history of the periodic law, see Venable, F. P., The periodic law, Easton, Pa., 1896—a valuable contribution to the history of chemistry.

[7] Rutherford, Sir Ernest, Nature, vol. 110, p. 182, 1922.

[8] Moseley, H. G. J., Philos. Mag., 6th ser., vol. 26, p. 1024, 1913; vol. 27, p. 703, 1914.

gases, which have already been pointed out, also need explanation. The periodic variations in the physical properties of the elements also seem to require adjustment to the law. The difficulties thus suggested may be more apparent than real, but they should not be ignored.

The question has often been asked whether the atomic weights of the elements are definite constants, or merely statistical averages of slightly differing values? The actual determinations were made on masses of material containing millions of atoms, which may or may not be exactly alike but are tacitly assumed to be so. To state the problem in different form, what are the elements as we really know them?

In a remarkable series of experiments Aston [9] has obtained evidence, which he regards as proof, of the complexity of the atomic weights as determined by chemical methods. Powerful positive rays in a magnetic field were driven upon a number of elements, which then gave on photographic plates what he calls their "mass spectra." These spectra show lines corresponding to whole-number atomic weights, which, with some exceptions, represent not the accepted values but some higher and some lower. The new lines, as interpreted by Aston, are due to "isotopes," and the elements yielding them are regarded as mixtures. The subject of isotopes I shall take up in the final section of this paper, where it properly belongs. A few elements gave mass spectra of single lines, which nearly agreed with the accepted atomic weights, and these Aston defines as "simple elements."

From the evidence furnished by the mass spectra Aston concludes that all the true atomic weights, including the isotopes but excepting hydrogen, are whole numbers. This rule he regards as fundamental, although it is based on O = 16 as the standard of values. But this standard was originally adopted as a matter of convenience and had at first no theoretical foundation. It seems, therefore, as if its importance is overrated. Nevertheless we may assume the validity of the rule and see how nearly the atomic weights of some of the "simple elements" conform to it. That is, How far do the real atomic weights diverge from the theoretical whole numbers? The figures are given in the following table:

	Atomic weight.		Divergence, 1 part in—
	Found.	Theoretical.	
Glucinum	9.018	9.0	500
Nitrogen	14.008	14.0	1,750
Aluminum	26.963	27.0	730
Phosphorus	31.04	31.0	773
Sulphur	32.06	32.0	540
Arsenic	74.96	75.0	1,875
Iodine	126.92	127.0	1,588
Caesium	132.81	133.0	700

These divergences are too large to be ascribable to experimental errors. The poorest of the atomic-weight determinations cited above is probably correct within 1 part in 3,000, and that of nitrogen is trustworthy, I think, within 1 part in 10,000. I base my opinion on a careful study of the methods by which each value was determined and especially on their concordance.

That the real and the ideal rarely coincide is well shown in the preceding table, and I venture to cite two well-known examples of such disagreement. Avogadro's law, that equal volumes of gases under equal conditions contain equal numbers of molecules is rigorously applicable only to ideally perfect gases. To the real gases with which we have to deal the law applies approximately and is subject to correction by the two small constants discovered by Van der Waals. The law of electrolytic dissociation is true only for infinitely dilute solutions, and solutions of that kind do not come within our experience. Under working conditions it may be nearly true. Now, if the whole-number rule for the atomic weights is theoretically sound, a supposition which is not yet proved, we may have to assume a distinction between perfect and imperfect elements, and for that assumption there is some justification. Uranium, as we know it, has been slowly decomposing for millions of years, and the uranium that remains is partly decayed. The atomic weight of the normal element as it was before decay began is quite unknown. Thorium offers a similar example, and it is furthermore very doubtful whether any thorium exists that is quite free from ionium of certainly lower atomic weight. In short, the

[9] Aston, F. W., Isotopes, London, 1922. In this volume Aston gives a complete summary of his own researches, together with much material relative to Rutherford's work, Moseley's law, the periodic system, and related subjects.

radioactive elements are probably all imperfect in the same way. Are any other elements defective? That we can not say, unless we attempt to define a perfect element. Such an element should be absolutely stable and therefore undecomposable, and only the primal protyle would satisfy these conditions. Hydrogen is the simplest known form of matter, but is there nothing simpler? We do not know.

In Rutherford's scheme of elementary evolution he uses the hydrogen nucleus with its single electron as a primary unit, and helium, with four protons and two electrons, as a secondary unit. From hydrogen and helium nuclei and electrons the complex nuclei of all the other atoms are supposed to be built up. A system similar to this has been developed by Harkins,[10] who assumes another hypothetical unit of mass 3, composed of three protons and two electrons. This new unit may be equivalent to nebulium, but that is by no means certain. The system, however, works well and brings out some interesting relations between the atomic weights, which may be partly real and partly coincidental. Rutherford seems to neglect nebulium, and neither he nor Harkins takes into account coronium, of unknown atomic weight. Its possible importance, however, ought not to be ignored. Coronium surely exists and must play some part in the evolution of matter. In Nicholson's scheme of elemental evolution[11] coronium, nebulium, and a hypothetical protofluorine are utilized and given atomic weights. That of coronium is assumed to be a little more than half that of hydrogen.

So far the views of Rutherford and Harkins are in essential harmony with the astronomical evidence. Hydrogen and helium are two primary units from which other elements were developed, but in the electrical theory an assumption is made to which an alternative hypothesis is possible. The helium nucleus is supposed to be built up from four hydrogen nuclei or protons. But He=4, and H=1.0078; so that 4H is really 4.0312, or slightly less if the loss of two electrons is deducted. A loss of mass in forming helium is therefore assumed and is explained by an electromagnetic theory of "packing." For this explanation, which is not very clear, I must refer to the publications of Rutherford and Aston already cited.

Suppose now that helium instead of being a quasi polymer of hydrogen is really an independent entity of mass 4. This supposition may not be in complete agreement with the electrical theory of matter as that is now formulated, but it is sustained by some evidence. Hydrogen is chemically active, helium is inert, and it is not easy to see how four atoms of the one could coalesce to form an atom of the other. In the nebulae the two elements appear to be widely separated, with no suggestion of any other relation between them than that of a possible common ancestor. Furthermore, the alpha ray of radioactive transformations is an atom of helium, which shows no sign of further decomposition. A priori the new hypothesis is just as plausible as the other, although neither is completely proved. That the alleged loss of mass is not a necessary assumption seems to be clear. In the formation of compounds there is no indication of any "packing effect," although there may be very great condensation.

It is in the highest degree probable that hydrogen and helium are two fundamental elements in the evolution of matter. But nebulium should be considered with them as having some part, if only a subordinate one, in the evolutionary system. From the position of its lines in the spectrum of the great nebula of Orion, Fabry and Buisson, by interferometer measurements, found its atomic weight to be 2.7, or almost exactly $2\frac{2}{3}$. Now, the atomic weights of several other elements, taken as whole numbers, are even multiples of this figure and also of the atomic weight of helium.

From a much larger list I select the following atomic weights for comparison with that of nebulium and with one another; Helium, 4; oxygen, 16; magnesium, 24; sulphur, 32; calcium, 40; titanium, 48; iron, 56. Five of these elements, it will be remembered, are those which appear earliest in the hotter stars. Now, with nebulium (Nm) $= 2\frac{2}{3}$, the comparison is as follows:

3 Nm= 8=2He
6 Nm=16=4He=O
9 Nm=24=6He
12 Nm=32=8He=2 O
15 Nm=40=10He
18 Nm=48=12He=3 O
21 Nm=56=14He

[10] Harkins, W. D., Phys. Rev., 2d ser., vol. 15, pp. 73, 141, 1920.

[11] Nicholson, J. W., Philos. Mag., 6th ser., vol. 22, p. 864, 1911. Coronium and nebulium are also taken into account by Rydberg (Jour. chim. phys., vol. 12, p. 585, 1914).

Regarded superficially the foregoing figures are very suggestive, but they must not be taken too seriously. They may, perhaps, express approximate relations, and they show that nebulium deserves consideration in any scheme of atom building. It is, however, an unruly element, for it disturbs the order of atomic numbers, and its atomic weight is not integral. The latter irregularity is not serious, for five of the elements in the table have atomic weights that diverge appreciably from whole numbers. Whether the divergences indicate mixtures of isotopes remains to be seen. The table as it stands is an excellent example of the ease with which the theorist can find relations between the atomic weights if he is only allowed to take a few little liberties with the facts.

Two other sets of figures approximating atomic weights are worth citing here. Whole numbers are assumed, and the symbols represent the atomic weights:

$$Fe=2Si=4N=8Li=14He$$
$$Mo=2Ti=3S=4Mg=6O=8C=24He$$

These relations are very striking, but have they any real significance relative to the evolution of the elements? If we were to arrange 92 integers, taken at random between the atomic weights of hydrogen and uranium, and as nearly as possible equally spaced, should we not be likely to find many numerical relations between them? In short, is not the problem of the atomic weights something more than a mere numerical exercise? This question, I think, needs no answer. If many of the chemical atomic weights are merely "statistical averages" of two or more isotopic values, any attempt to discover exact mathematical relations between them will surely be futile.

Since the discovery of radioactivity atomic genealogists, if I may call them so, have been extremely busy. Their contributions to the literature of the subject are very numerous, and I can not undertake to summarize them here. Some of their publications are worthless, and some are extremely valuable, but nearly all are more or less one-sided, for they lay undue stress upon mathematical or physical or chemical data, and each writer ventures little out of his own special field. Not until all lines of evidence have been brought into convergence can the problem of elementary evolution be solved. The workers in different fields and with different outlooks must learn how to cooperate.

In every attempt that has heretofore been made to explain the evolution of the elements in detail there are difficulties which must be faced. Some of these difficulties have already been considered. The integrity of the atomic weights has been called in question, and the deviation of many of them from whole numbers has not been satisfactorily explained. The theory of atomic numbers is also incomplete, for it makes no allowance for possible elements simpler than hydrogen, or between hydrogen and helium; and it reverses the observed order of three pairs of elements, namely, potassium-argon, nickel-cobalt, and iodine-tellurium. That these reversals are justifiable is by no means certain. The positive evidence should not lightly be set aside.

In the last analysis the problem of elementary evolution seems to be one of equilibria, or, which is much the same thing, of relative stabilities; and the fundamental data are those which relate to atomic structure. On this subject there is as yet no general agreement, but the scheme that has been most favorably received is that developed by Rutherford and his colleagues, to which I have already referred.

At first sight Rutherford's scheme of evolution appears to be very simple and symmetrical, but it is by no means free from difficulties, and some of these lie at its very foundations. The light electron and the massive proton are defined as "atoms of negative and positive electricity"; but what these definitions mean is not clear. As the elements above helium are developed the nuclei or groups of protons become more and more complex, and just how the protons are held together is unexplained. The uranium atom is supposed to carry 92 electrons, and this complexity of structure accounts for the recognized instability of that element, as shown by the constant emission of helium from its nucleus, the very swift alpha rays. Between hydrogen and uranium the elements are arranged in the order of their atomic numbers, which represent not only the number of electrons in each atom but also the net electric charge carried by its nucleus. But what is meant by an electric charge upon an "atom" or cluster of "atoms" of electricity? Is there not something in the proton that is not electrical, which serves as the carrier? These questions I can not attempt to answer. They involve the fundamental hypothesis that matter and electricity are identical, which is certainly not proved.

One more doubtful feature of Rutherford's system remains to be noticed. It is assumed that the progression from the simplest to the most complex element is regular and uninterrupted, step by step. But the irregularity shown by the rare-earth elements in the periodic system seems to have been ignored, and this must be taken into account in any valid scheme of elementary evolution.

In what I have said so far I have not intended to be hypercritical. It seemed necessary to point out some of the difficulties that exist in all the schemes of elementary evolution, for to ignore them is to put obstacles in the way of progress. There is really more to be said in favor of the current theories of atomic structure than can be urged against them. All of them are attempts to interpret evidence, and each one is partly successful. Their agreements are more significant than their differences.

A scientific theory has two sides, one speculative, the other utilitarian. As a mere intellectual exercise it has little importance; its real value is in its ability to classify phenomena, to express their relations, and to point the way to new discoveries. In plain language, Does it work? If the prevailing theory of atomic structure is fundamentally sound it must satisfy these conditions. Hitherto it has been developed almost entirely in its physical and mathematical aspects; its chemical aspects have received too little consideration. It is on the chemical side that the theory is likely to be most severely tested. The complete study of any chemical reaction involves problems that are difficult to solve.

A chemical reaction may be described in a general way as a readjustment of equilibria. Let us consider one of the simplest, the formation of water from its elements as represented by the equation

$$2H_2 + O_2 = 2H_2O$$

Here three stable molecules are broken up, and two new stable molecules are formed; heat is generated, and three gaseous volumes are condensed to two. A further condensation to liquid water follows.

Now, in terms of atomic structure, what does this reaction mean? How was it that three elementary molecules could be disrupted and two new ones formed? Each hydrogen atom is supposed to consist of a nucleus with one electron, and each oxygen atom of a nucleus with eight electrons. What are these electrons doing, and what is the nucleus of the new molecule of water? Why does condensation take place, and why is heat emitted? Is the loss of heat due to an arrest of motion of two or more electrons? Moreover, by electrolysis the whole reaction can be reversed and the original equilibria reestablished. These questions are as yet unanswered, and they raise the larger question as to the nature of chemical affinity. If the theory of atomic structure is sound it should ultimately shed some light upon these problems.

Let us go a step further and consider a more complicated case, one of double decomposition. When solutions of barium chloride and sodium sulphate are mixed the following reaction occurs:

$$BaCl_2 + Na_2SO_4 = BaSO_4 + 2NaCl$$

Here we have five kinds of atoms and four different molecules, but three of the molecules are partly dissociated in solution. The barium sulphate, however, is thrown down in solid form, and the reaction is not reversible. All the problems suggested by the simpler reaction appear in this new equation, with others that are equally difficult to answer. What part does water play in this double decomposition? Why is the barium sulphate condensed to a solid from diffused ions in the initial solution? What are all the electrons doing, and what are the nuclei of the four compounds? I suspect that we are a long way from any complete answer to these questions. A theory of atomic structure, to be satisfactory to chemists, must give them some clear conceptions regarding the mechanism of chemical reactions.

Examples like these might be multiplied indefinitely, but all give rise to similar problems. In every case, if we accept the electric theory of matter, we must ask the same questions: What are the electrons doing, and how are the protons held together? If for the moment we confine our attention to the evolution of the atoms, we have also to consider the conditions, external and internal, that determine their relative stability. The external conditions have already been defined; the internal conditions are those of atomic structure, its simplicity or complexity, the symmetry of the atom, and the exact electrical balance between electrons and nuclei. A simple, symmetrical atom is likely to be very stable; a complicated structure implies instability. The terms stable and unstable are of course relative; they have no absolute meaning.

In the study of elementary evolution two basic problems underlie all the others. What is the process, and what are its products? Unfortunately we are unable to reproduce the process artificially. We can not hope to build up elements as they are built up in the stars, for the conditions are too severe for us to meet. We can, however, tear down some of the more complex structures and so get some light upon their genesis. That work is now just beginning, and from it we may reasonably expect to arrive at more definite conclusions. The products of devolution we can study directly, and the two lines of evidence ought ultimately to converge.

I venture now to point out one analogy that may have some significance with regard to the character of the elements. Organic chemistry is defined as the chemistry of carbon compounds, and atoms of carbon, in chains or rings, form the skeleton, or framework, or scaffolding of the whole edifice. May not the elements be built in a similar way with atoms of helium instead of carbon? This suggestion is not altogether new: it is implied in the hydrogen-helium scheme of evolution; but here it would include nebulium as a possible part of the superstructure. It is at least worth testing, although I am not blind to possible difficulties in its detailed application.

In all discussions relative to cosmogony there is a danger of going too fast and too far. That statement holds true in the present discussion. We know that the same elements appear throughout the stellar universe, and we must assume that their evolution was governed by the same fundamental laws of chemistry and physics. But we can not assume that all solar systems are exactly like ours in chemical composition. The parent nebulae may have differed in the relative proportions of their component gases, and the rate of cooling in passing from nebula to star was not necessarily everywhere the same. It is conceivable, therefore, that different solar systems may have generated the elements in somewhat different order, and not invariably in the same relative abundance, but these dissimilarities, if they exist, are probably not very large. To assume that anything like absolute uniformity exists would, however, be quite unwarranted.

Before we pass on to the subject of the evolution of compounds, it seems well to consider briefly a question relative to what may be called scientific utility. A scientific theory, to be useful, must meet the conditions that have been stated in a former paragraph and so prove its value. Such a theory is the atomic theory of Dalton, which is the corner stone of modern chemistry. Even the modern electrical conception of matter is based upon it. Many examples of similar purport might be cited.

It has recently been asserted by high authorities that "a chemical element is defined by its atomic number." How far is this conception sustained by the test of its utility? How far can it be used in dealing with chemical problems? May it not be better to say that a chemical element is defined by the aggregate of all its properties? The theory of atomic numbers covers only part of the ground.

The atomic numbers, it should be remembered, assign to each element its place in the order of ascending atomic magnitude. That is, the atomic weights came first, and the atomic numbers followed. It is now held, however, that the atomic numbers also represent the electric charges carried by the nuclei of the atoms, and the number of electrons belonging to each one. These claims may be valid, but they have not yet been as thoroughly tested as they should be. Will they guide future research and be fruitful in discoveries? That remains to be seen.

In practical utility the atomic weights are far more important than the atomic numbers. They are the fundamental quantities of chemical arithmetic and are in constant use in chemical calculations. To the working chemist they are indispensable. In the calculation of analyses, or of the proportions in which substances shall be taken in order to perform a given quantitative reaction, atomic weights are always, directly or indirectly, employed.

They are expressed in every chemical formula and in every chemical equation, and the atomic numbers can never replace them. The laws of chemical combination are based upon the combining numbers of the elements, and these are the atomic weights. In the periodic table the atomic weights and the atomic numbers both appear; but the periodicity of physical properties is best shown in curves like that of atomic volumes. Such curves show that the physical properties of the elements are periodic functions of the atomic weights. The alleged supremacy of the atomic numbers is by no means established. The usefulness of the atomic weights is independent of the order in which they are arranged.

After all, the physical quantities that are directly related to the atomic numbers are functions of the atomic masses, and so, too, are the atomic numbers.

That the theories of atomic structure which have so far been proposed are not in close agreement has already been pointed out. One partial theory, however, deserves mention here—that of the tetrahedral carbon atom as advanced independently by Van't Hoff and by Le Bel. That theory was framed in order to account for the different optical properties of the two tartaric acids, but it did much more than that. It was the foundation of stereochemistry, a new field of research, which has been wonderfully fruitful in important discoveries. The theory was devised before electrons were known, but it is evidently adjustable to the electronic conception of matter. No such adjustment is needed, however to emphasize its proved efficiency.

NOTE.—For a critical summary of the principal theories of atomic structure see Stewart, A. W., Some physico-chemical themes, pp. 373-397, 1922. See also Webster, D. L., and Page, L., Nat. Research Council Bull. 14, 1921.

THE EVOLUTION OF COMPOUNDS.

It has already been said that the process of evolution is continuous, from the simplest forms of matter to the most complex. Between elements and compounds there is no sharp line of demarcation, and one class shades into the other. In one sense the elements are really composite, primary compounds built up from a few fundamental substances, and they are characterized by great relative stability. They have so far not been formed by any artificial synthesis, and they are not decomposable by any of the ordinary processes of the chemical laboratory. The reported decomposition by means of powerful radiations or by electrical currents of the greatest intensity will be considered in another section of this memoir. Compounds, on the other hand, are formed by the combination of elements, into which they are easily separated and from which many of them can be prepared synthetically. The terms element and compound are used here in their ordinary technical significance and are not subject to any verbal quibbling. The elements form one definite class of substances, the compounds form another, and the chief difference between them is one of stability.

Between the formation of an element and the formation of a compound there is, however, another difference. The first stage of the process was one that required a vast period of time; the second stage is marked by rapidity. The series of elements was slowly formed, and their rate of decay, as shown between uranium and lead, is also relatively slow. The formation and decomposition of compounds, on the other hand, is rapid; and for some compounds the rate is measurable. The distinction is not absolutely definite, for some of the short-lived products of radioactive decay seem to be exceptions to the rule, which in general may be stated as follows: The process of evolution is characterized by progressive acceleration, being slow at first and becoming gradually more and more rapid. Its rate of acceleration may not be uniform, but its general drift is clear. It follows the line from the simplest substances to the most complex. In all vital processes the ease and rapidity with which compounds are formed and developed is evident, and some of these substances are extremely complicated.

Just as an infinite number of words can be formed from the 26 letters of the alphabet, so myriads of compounds can be built up from comparatively few elements. At least a hundred thousand compounds are already known, but by far the greater number of them are artificial products and have no place among the relatively simple substances that are developed in a cooling globe. In that laboratory the possibilities of combination are limited. We have already seen that bands of a few compounds, such as the oxides of carbon and possibly cyanogen, have been detected in the spectra of the cooler stars and the Sun, but these compounds are all gaseous. Heavy, solid compounds would probably sink below the reversing layer and not be recognized in the spectrum. Can we decide, with any approach to probability, what solid compounds would be likely to be first formed under the conditions of a cooling globe?

The answer to this question is simple. The most stable compounds would come first, and they are such as appear among the products of the electric furnace. Carbides, silicides, phosphides, borides, and nitrides are all stable at very high temperatures, and such compounds with iron, nickel, or manganese as bases are substances of high specific gravity and would be likely to sink deeply into the cooling mass. At the surface of the Earth and probably throughout the lithosphere they would cease to exist, for water, especially in the form of superheated steam, transforms them into other compounds, such as hydrocarbons, oxides, silicates, phosphates, borates, and salts of ammonium. Water must have been a compound to appear at an early stage in the process of evolution, and it is one of the principal reagents that were and are active in determining the composition of the Earth's crust.

This speculation, which is not extravagant, receives some support from the study of volcanic emanations, of which carbon dioxide and ammonium chloride are common constituents. Hydrocarbons in small amount are also found among volcanic ejectamenta. The existence of boron nitride within the Earth is suggested by the association of boric acid and ammonium compounds in the Tuscan fumaroles and at other well-known localities. Boron nitride is a very stable compound; but when heated in a current of steam it yields boric acid and ammonia. As for silicates and oxides, they are the chief constituents of the lithosphere. The silicates would be easily formed by oxidation of the primary silicides, but only the simpler compounds, such as constitute at least nine-tenths of the present lithosphere, would appear at first. Their crystallization and segregation could take place only in the cooling of a fused magma. On this point their artificial syntheses are conclusive. From such a magma the primitive crust of the Earth was formed.

A variety of processes, some physical and some chemical, must have taken part in the solidification of the planet; but their effects could hardly have been symmetrically distributed. The temperature of the cooling mass was certainly not uniform. Whenever new compounds were formed heat was generated, the local temperature rose, and inequalities of composition were brought about by diffusion. Where the temperature at the surface of the globe was lowest there solidification began. At such points new chemical reactions became possible through contact with the gases and vapors of the primeval atmosphere. Just what the composition of that atmosphere may have been we do not know; but it must have contained oxygen, carbonic acid, and water, three powerful reagents, with possibly some of the stronger acids also.

Throughout the cooling process and indeed throughout the process of evolution from nebula to planet, gravitational energy was at work distributing the various forms of matter according to their density. In the Earth we have a heavy, probably metallic nucleus, surrounded by a zone of the denser silicates grading upward into lighter compounds, and after them a relatively thin shell of sediments and other decomposition products. Then comes the hydrosphere, and surrounding all the atmosphere. These zones are of course not sharply separated but interpenetrate one another to a greater or less extent. Volcanic effusions, for example, break through the sediments, and locally reverse the primary gravitational arrangement, which, after all, is what might be called an irregular regularity. The broad outlines of the process are clearly discernible in spite of local blurring.

This zonal structure of our planet, due to gravitational adjustment, has been of great significance in fixing the conditions upon which terrestrial compounds could be formed. It is commonly supposed that the Earth is analogous to a huge meteorite, having a nucleus consisting principally of nickel-iron with some inclusions of free carbon and a few simple compounds. This supposition will be considered in detail in the next section of this memoir; if it is correct then the nucleus of the

Earth, or centrosphere, is essentially a region of almost no chemical activity. It is protected from the outermost zones of active reagents by the intervening shells of igneous silicate rocks, which are easily modified by aqueous and atmospheric agencies and in less degree by volcanism. To cite two familiar examples of such changes magnesian rocks are converted into talc and serpentine, and feldspathic rocks are kaolinized. In short, on passing from the centrosphere to the surface of the lithosphere, the chemical changes become more and more varied and complex. Through them the sedimentary rocks were formed, and in the later stages of the Earth's history living organisms also played an important part in the production of limestone, dolomite, and marine phosphates. Leaving minor details out of account we may say that the general conditions governing the evolution of natural inorganic compounds seem to be fairly well understood, even though we know very little of the inner mechanism of the many reactions in which combinations and decompositions proceeded simultaneously. In the geologic history of the Earth's crust the more important of the chemical changes are easily traced. The artificial syntheses of many minerals also give us much information upon the problem of inorganic evolution.

At the surface of the Earth, when its crust was sufficiently cool, the evolution of compounds entered upon a new field of activity. Organic compounds were formed, and they furnished the material basis for the evolution of living beings. Organisms, each capable of reproducing its kind, became physically possible. This faculty of reproduction is something that sharply distinguishes living from nonliving matter.

The probability that carbides and nitrides were among the earliest compounds to form in a cooling globe has already been pointed out, and also that these compounds, by hydrolysis, yield hydrocarbons and ammonia. Calcium carbide yields acetylene, which easily polymerizes into benzene, from which a long list of other hydrocarbons can be derived. The carbides of aluminum, glucinum, and manganese give methane, CH_4; those of the rare-earth metals yield mixtures of acetylene, methane, and ethylene, and from some of them liquid and solid hydrocarbons are also derived. From uranium carbide Moissan[12] obtained a mixture of liquids, consisting largely of olefines with some members of the acetylene series and some saturated compounds. Hydrogen is also set free in some of these reactions.[13]

If now, by reactions such as have just been described, hydrocarbons and ammonia were formed from compounds contained in the primitive magma, a first step was probably taken toward preparing the surface of the Earth for the advent of living organisms. From metallic phosphides phosphine, the analogue of ammonia, would be generated, and it would quickly be oxidized, yielding phosphates. Among the substances that appear in volcanic emanations there are hydrogen sulphide, sulphur dioxide, carbonic acid, and hydrochloric acid, compounds which might all be formed simultaneously with the hydrocarbons. Add to these the gases of the atmosphere, and we shall have assembled much of the raw material that is essential to the later upbuilding of organic tissue. But between magma and protoplasm there is a vast gap, which science has not yet bridged. The evolution of compounds has not stopped, but our knowledge of its course is interrupted.

The moment we enter the field of biochemistry we encounter problems of great complexity. Innumerable new compounds appear, especially in the tissues of plants, and some of them are extremely complicated. Many of these compounds, however, can be isolated and analyzed. We can determine their composition and measure their physical properties, but how they were developed in the growing plant is a question that is rarely answered even in part. One group of examples will serve to show how complex the problems really are.

One of the most marvelous of chemical laboratories is contained within the seed capsule of the opium poppy, *Papaver somniferum*. In that small inclosure a juice is secreted which when dried, solidifies to that extremely complicated mixture opium. In opium about thirty different compounds have been identified, including more than twenty distinct alka-

[12] Moissan, H., Compt. Rend., vol. 122, p. 1462, 1896. See also Damiens. M. A., Annales de chimie, 9th ser., vol. 10, p. 137, 1918, on the carbides of the cerium group.

[13] For a summary of the literature relating to the inorganic syntheses of hydrocarbons, and especially from the carbides contained in cast iron, see Clarke, F. W., The data of geochemistry, 4th ed.: U. S. Geol. Survey Bull. 695, pp. 730-732, 1920.

loids, of which morphine, $C_{17}H_{19}NO_3$, is the most abundant but not the most complex, although, as we see from its formula, each molecule contains forty atoms. How many protons and how many electrons are there here, and what are they doing?

But this is not all. The capsule also contains the seeds from which other plants can be grown, and in each plant within a single season this complex of chemical syntheses is begun and completed, and so on generation after generation. The seeds are rich in oil but not in alkaloids; it is at the summit of their growth that these very complicated substances appear.

Suppose now that on this same acre of ground with the poppy are sown the seeds of a dozen or more plants. Each one will be, in a certain sense, a synthetic chemist, working out its own special set of reactions. A tobacco plant will form nicotine, mustard will generate an "oil" rich in sulphur, some species will produce hydrocarbons such as terpenes, while others will specialize in forming sugar or starch or strong acids. All are nourished by the same soil, the same water, and the same atmosphere, but each one breeds true to type and never makes a mistake in its chemistry. Does each seed contain some directive principle that guides its germination and growth? To say that the seeds differ in composition, which is quite true, may give a partial answer to this question; but it does not explain the vital factor, the capacity of each plant to reproduce its kind.

Up to a certain point the evolution of compounds within these different plants follows similar lines. All generate the vegetable fiber that is, so to speak, the fabric of their skeletons, and all produce chlorophyll, the principal coloring matter of their leaves. I use the term chlorophyll in its general sense, although this substance is usually if not always commingled with other compounds of similar character. Here a new reagent becomes of supreme influence—namely, radiant energy, the energy of the Sun's rays. It is only by means of this reagent that chlorophyll can form. Are some of the other syntheses also dependent upon it? Albuminoids and proteids are also produced, and in these colloid substances chemical complexity probably reaches its limit. They are the essential constituents of protoplasm.

In animal matter, which consists almost entirely of proteids, the complexity is even greater than in plants. Plants may contain a much larger number and variety of definite crystallizable compounds, but in animal tissues the proteids predominate, and they are of many different kinds. Into this subject I can not go at length, but I may be permitted to ask one question. Is the morphological or structural increase in complexity from the lowest to the highest forms of life accompanied by a corresponding change in the complexity of chemical constitution? This aspect of evolution has, I think, never been seriously considered, but it surely deserves attention. To show its significance I venture to offer the following illustration, which is based upon an elaborate study of the inorganic matter of marine invertebrates:[14]

In some of the lowest forms of life, as in the diatoms, radiolarians, and siliceous sponges, the skeletal matter consists chiefly of opaline silica, a very simple substance. The stony corals are built up from calcium carbonate, which is slightly more complex. The echinoderm skeletons also contain magnesium carbonate, and the shells of some brachiopods consist mainly of calcium phosphate. The shells of the higher crustaceans, such as the lobster, are still more complicated. With a large proportion of organic matter, proteid in character, they contain both carbonates and phosphates of calcium and magnesium. The progressive increase in complexity is clearly evident. It also appears in the bones of the higher mammals. In them we find organic substances, such as gelatin and fats, but also carbonates of calcium and magnesium, with a very large proportion of calcium fluophosphate. The question that was asked in the preceding paragraph is surely pertinent, and it receives the beginning of an answer here. A complete answer, however, will involve some serious discriminations, and it must also recognize the fact that we are now considering products and not processes. The two fields of investigation must, of course, be studied together, but the distinction between them is clear. A physiological process is a complex of chemical combinations and decompositions, of evolu-

[14] See Clarke, F. W., and Wheeler, W. C., U. S. Geol. Survey Prof. Paper 124, 1922.

tions and devolutions, and the two sets of phenomena are quite distinct, even though they always appear together. The one is the complement of the other. The physiological processes of the higher animals are surely more complicated than those of lower forms.

For example: In respiration we inhale oxygen and exhale carbonic acid, which is produced by the consumption of organic tissue. The formation and renewal of the tissue is a case of true evolution, to which our question properly relates; the rejected waste or excretory products can for present purposes be disregarded. We are considering the products of growth, not those of decay. The discrimination may sometimes be difficult, but it should never be ignored. The alkaloids of opium, for instance, are waste products and represent the downward path of chemical change. Their citation here, however, serves to illustrate the wonderful complexity of the processes that are involved in the growth of plants.

The formation of any new compound, whether simple or complex, natural or artificial, is an item in the scheme of chemical evolution. Under natural conditions many well-known compounds are incapable of existence; some are destroyed by even moderately high temperatures; others are decomposed by the action of water; and still others, like the fulminates, are easily exploded by percussion or friction. All these inhibitions are evaded or controlled by a skillful chemist, who can regulate temperatures and pressures and can establish for each compound the environment in which it can form. He can also work with pure materials, which are rarely found under natural conditions. The artificial compounds help us to a better understanding of those which exist in nature, and this can easily be shown.

Many of the minerals that form the solid crust of the Earth have been reproduced synthetically by methods equivalent to those followed by nature. The species that are characteristic of the igneous rocks, such as the feldspars, pyroxenes, and olivine, originate in molten magmas, and artificial magmas yield the same compounds. Quartz may be either magmatic or crystallized from aqueous solutions, and both modes of origin can be copied in the chemical laboratory. Artificial limestone is easily prepared, and so too are gypsum and a number of other minerals, all of aqueous origin, that are found in beds of salt. The researches of Van't Hoff and his colleagues upon the Stassfurt salts are especially suggestive. The compounds associated with the salt were not only prepared synthetically, but the temperature at which each one formed was also determined, giving datum points in what has been called a "geological thermometer." Similar temperature relations have been discovered for other minerals, such as the silica group and wollastonite, and they give valuable information as to the conditions under which the rocks containing them were deposited. In short, the chemical processes that took part in terrestrial evolution are being revealed experimentally. The literature of synthetic mineralogy is very voluminous, but these few examples are all that need to be cited here. They serve to illustrate the methods by which some problems of evolution are being solved.

What has been said relative to the syntheses of inorganic compounds also applies, but with serious limitations, in the organic field. Many substances that are found to exist in living organisms have been made artificially, but by methods that are surely not identical with those followed by plant or animal. In life many syntheses are effected simultaneously and rapidly; in the laboratory the conditions are quite different. The chemist starts with pure material and builds his compounds individually and slowly, but his results are nevertheless of great significance, even though they may not be directly applicable to the interpretation of vital phenomena. There is, however, a partial correlation, which is better than none at all.

This is no place for an essay on biochemistry, which may be described as the dynamic side of physiology. All living organisms, considered apart from their psychological relations, are dependent upon a complex of chemical changes, some products of which are utilized and others rejected as waste. In the digestion of food many of these changes have been traced, and a great variety of compounds take part in them. Some of the compounds, especially the proteids, are broken down into simpler forms; and their derivatives are distributed each to its proper place in the organism. The motive power that effects their distribution is thermochemical in origin and is measured in terms of calories. Finally, new proteids are formed, and wasted tissues are regenerated; and this is true chemical evolution. The evolution of the Earth's crust and the evolution of living tissue are parts of the same line of growth from the simplest to the most complicated forms of matter. The line, however, is not straight but one with many branchings.

THE RELATIVE ABUNDANCE OF THE CHEMICAL ELEMENTS.

One of the most obvious facts in chemistry is that some of the elements are very abundant and others extremely rare. It is also easy to see that this distinction is definitely related to the conditions under which the different elements were generated. The simplest and most stable ones were formed at the highest temperatures and in the greatest abundance; the most complex elements appeared last of all and in the smallest quantities. The original nebula was a finite mass of matter, and the scarcer elements represent the material left over after the more common ones had been formed. How far do these conclusions harmonize with the observed facts?

In an attempt to answer this question we must recognize certain limitations. An almost infinitesimal portion of the matter that forms the solar system is all that is available for direct quantitative investigation. Only the Ocean, the atmosphere, and a very thin outer shell of the Earth's crust are accessible to us. As for the Ocean and the atmosphere, their composition is well known; that of the rocky shell is less easily ascertained.

In order to determine the average composition of known terrestrial matter we must first fix the relative proportions of its three components. For this purpose let us assume that the crust of the Earth to a depth of 10 miles is essentially like the average rock of its surface, of the rocks which we know and can analyze. The volume of such a crust, including the mean elevation of the continents above the sea, is 1,633,000,000 cubic miles, with a probable density of about 2.7 to 2.8.

The volume of the Ocean is approximately 302,000,000 cubic miles, although some authorities give slightly higher figures, and its density is a little below 1.03. This is the maximum density found by Dittmar in the water of the great oceans, and its use here makes a liberal allowance for the saline matter, such as beds of salt, that are found in the crust of the Earth. For present purposes they are negligible quantities. If the salts of the Ocean were gathered into one solid block, they would have a volume of at least 4,800,000 cubic miles, or enough to cover the entire United States to a depth of 1.6 miles. The fresh waters of our globe are also negligible, for a quantity equivalent to 1 per cent of the Ocean would cover all the land areas to a depth of 200 feet. Even the mass of Lake Superior becomes relatively insignificant. The mass of the atmosphere, so far as it can be determined, is equivalent to that of 1,268,000 cubic miles of water, the unit of density. Combining these figures, we have for the composition of known terrestrial matter about 93 per cent of solid crust, with 7 per cent for the Ocean. The proportion assignable to the atmosphere is only 0.03 per cent, which may be regarded as a small correction to be applied when needed.[15] We are dealing with the relative abundance of the different forms of matter and not with absolute quantities. Quantitative accuracy is not attainable.

What, now, is the composition of the accessible part of the lithosphere? Neglecting the thin film of organic matter upon its surface, we need only consider two classes of rocks, the igneous and the sedimentary. Metamorphic rocks are merely the result of alterations of one or the other of these two and may be left out of account. Such inclusions as beds of coal or metallic ores are insignificant in quantity as compared with the vast mass of rocks now under consideration, which is, as nearly as can be determined, 95 per cent igneous and 5 per cent sedimentary. The method by which these figures were obtained, together with the average composition of the sediments, I have given elsewhere.[16]

As it is impossible to analyze the 10-mile crust as a whole, we must do as well as we can by the method of sampling—that is, we must take samples of igneous rocks, the parents of the others, from as many different localities as possible, and then average the

[15] For the details of this computation see Clarke, F. W., The data of geochemistry, 4th ed.: U. S. Geol. Survey Bull. 695, pp. 22–33, 1920.

[16] Idem, pp. 29–32.

analyses. Thousands of such analyses have been made for petrologic purposes and are now available for use. The material came from all quarters of the globe, and the analyses that are considered trustworthy have been assembled by H. S. Washington in a monumental volume.[17] From the data given by him 5,159 analyses rated as "superior" have been taken and averaged together, giving a fair conception of the mean composition of the igneous rocks.[18]

Now, omitting details, which can be found in the publications already cited, let us consider the significance of the following averages. The first column of figures gives the mean composition of 5,159 igneous rocks, stated in terms of elements and in percentages. The last column gives the average obtained by including accepted values for the sediments, the ocean, and the atmosphere, or in other words the mean composition of all known terrestrial matter to an assumed depth of 10 miles below sea level.

Average composition of igneous rocks and of all known terrestrial matter.

	1	2
Oxygen	46. 41	49. 19
Silicon	27. 58	25. 71
Aluminum	8. 08	7. 50
Iron	5. 08	4. 68
Calcium	3. 61	3. 37
Sodium	2. 83	2. 61
Potassium	2. 58	2. 38
Magnesium	2. 09	1. 94
Titanium	. 72	. 648
Phosphorus	. 157	. 142
Hydrogen	. 129	. 872
Manganese	. 124	. 108
Chlorine	. 096	[a] . 228
Carbon	. 051	[b] . 139
Minor constituents	. 463	. 473
	100. 00	100. 000

[a] Oceanic.
[b] In limestone.

These figures show that eight elements form 97.38 per cent of all known terrestrial matter, leaving only 2.62 per cent for all the others. The influence of the Ocean and the atmosphere is very slight, and with a thicker mass of igneous rocks it would be still smaller. In the Earth as a whole the Ocean would amount to only a small fraction of 1 per cent and therefore be negligible.

In many of the published analyses of igneous rocks figures are given showing appreciable but small percentages of some of the scarcer elements. The average amounts are as follows:

Barium	0. 081	Nickel	0. 031
Sulphur	. 080	Fluorine	. 030
Chromium	. 052	Copper	. 010
Zirconium	. 051	Lithium	. 005
Vanadium	. 041	Zinc	. 004
Strontium	. 034	Lead	. 002

Several attempts have been made to determine the composition of the Earth as a whole, all based upon its supposed similarity to a huge meteorite. The mean density of the Earth is nearly double that of its crust, and it behaves like an enormous magnet. Hence the assumption has been made, to which I have already referred, that its central portion is metallic and consists largely of iron. How far is this assumption justifiable?

To answer this question let us begin with the chemical composition of known meteorites. These extraterrestrial bodies are divided into two classes, meteoric stones and meteoric irons, which, however, are not sharply distinct. Nearly all the stony meteorites contain more or less iron, and many of the others contain stone. For instance, the pallasites are masses of iron, with something like the texture of a sponge, in which the cells are filled with nodules of olivine. Again, the meteoric shower that fell at Estherville, Iowa, in 1879, contained masses of stone and many smaller masses of iron. These were all, of course, components of the original meteor. For the average composition of 99 meteoric stones we have the following computation by Merrill.[19] The first column of figures gives the actual average; the second is recalculated to 100 per cent after rejecting the admixed nickel-iron, sulphides, and phosphides.

[17] Washington, H. S., Chemical analyses of igneous rocks, 1884 to 1913: U. S. Geol. Survey Prof. Paper 99, 1917.

[18] A detailed critical discussion of the method of averaging and the results obtained is to appear in Professional Paper 127 of the Geological Survey, by Clarke and Washington, now in press. An abstract of the averages was published in the Proceedings of the National Academy of Sciences for May, 1922.

[19] Merrill, G. P., Am. Jour. Sci., 4th ser., vol. 27, p. 469, 1909. Another average, by O. C. Farrington, appears in Field Columbian Mus. Pub. 151, 1911. It is in fair agreement with Merrill's.

Average composition of meteoric stones.

	Found.	Recalculated.
Silica	38.98	45.46
Alumina	2.75	3.21
Ferrous oxide	16.54	19.29
Lime	1.77	2.06
Magnesia	23.03	26.86
Soda	.95	1.11
Potassa	.33	.38
Manganese oxide	.56	.65
Chromite	.84	.98
Nickel, including cobalt	1.32	....
Metallic iron	11.61	....
Sulphur	1.85	....
Phosphorus	.11	....
	100.64	100.00

Some of the analyses show small amounts of copper, tin, carbon, etc., which need not be considered here. The average stone is essentially a peridotite and therefore quite different from the average terrestrial rock. A great deficiency in feldspars is evident, and they form nearly 60 per cent of the 10-mile shell of the lithosphere. There is little or no free silica indicated by the figures. That the meteorites were originally in a state of fusion is also clear, for the dominant mineral, olivine, is formed only in that way. The same is true also of the glass, which is a common constituent of meteoric stones.

It is by no means certain that the average given in the foregoing table represents with any accuracy the mean composition of all known meteoric stones, of which many were never analyzed. Even these meteorites form but a trifling fraction of the vast number that must have fallen unseen. Some doubtless fell in the ocean, and others in deserts or forests, never to be found. Nevertheless the average is not without value, when it is considered in relation to other data. As for the individual stones that are represented in the average, they show great differences in composition. A very few, of which Juvinas and Stannern are typical, consist mainly of augite and anorthite, with very little nickel-iron. The Bishopville stone is nearly pure enstatite. These stones are exceptional; in by far the greater number of known falls pyroxenes and olivine are the dominant minerals, with variable proportions of nickel-iron. The transition from stone to iron is very gradual. The very common chromite of meteoric stones is invariably associated with magnesian minerals, iron, and nickel—the same association that is found in terrestrial rocks. Oldhamite, calcium sulphide, is only known as a meteoric mineral; it dissolves in water and rapidly hydrolyzes, therefore it can not long exist except in anhydrous surroundings, and all our igneous rocks contain small amounts of water.

One very small group of meteoric stones deserves to be considered separately—the carbonaceous meteorites. The type and extreme example of these is the one that fell at Orgueil, France, in which Pisani found 13.89 per cent of water plus organic matter, which consisted essentially of hydrocarbons. Such a meteorite could reach the surface of the Earth only under very exceptional conditions. The chances are that its organic matter would be burned soon after it entered the atmosphere, and its stony portion disintegrated and scattered as dust. If so the atmosphere must receive accessions of carbon dioxide that would have a distinct influence upon plant life and would perhaps account, in part at least, for the carbon that is locked up in coal and petroleum. This, I admit, is pure speculation, but not without some plausibility. A cometary origin of these meteors is probable, for hydrocarbons are shown in the spectra of comets, and several instances are known of periodic showers of stars that have followed the paths of periodic comets which have disappeared. Biela's comet is one which after repeated returns is now represented only by a starry shower. We can not, however, assume that all meteors are the remains of comets. There is, as will be seen later, strong evidence to the contrary.

The average composition of meteoric iron is more easily determined than that of meteoric stone. The one consists mainly of an alloy of nickel and iron; the other is a mixture of different silicates. The irons contain, in minor proportions, several other substances, such as troilite, FeS; schreibersite, a phosphide of iron and nickel; daubréelite, $FeCr_2S_4$, the sulphide corresponding to the chromite of meteoric stones; lawrencite, $FeCl_2$; cohenite, $(FeNiCo)_3C$; graphitic carbon; and in the iron of Canyon Diablo, minute diamonds. Diamond is also found in the meteoric stone of Novo Urei. Carborundum, CSi, is also reported by Moissan as present in the Canyon Diablo iron. Nodules of troilite and of graphitic carbon are common, some of them as large as a hen's egg; the other inclusions are diffused in smaller amounts. Of these the lawrencite is in one way the most conspicuous, although it is rarely seen in distinct masses. On exposure to moisture it is hydrolyzed, forming basic chlorides and releasing hydrochloric acid, so that its presence is too often manifested by the tendency of an iron to rust and ultimately to fall to pieces. Everyone who has had much experience in handling collections of meteorites knows how troublesome this obnoxious compound is. It is very difficult to stop its ravages. It is not improbable that much of the chlorine in the ocean came originally from lawrencite. Was the primeval ocean strongly acid? The question is legitimate, even if it can not be definitely answered. Some of the oceanic chlorine is undoubtedly of volcanic origin, and that may have had its source in lawrencite. We do not know the facts but may be permitted to suppose. One thing is certain—namely, that the permanence of a meteoric iron depends upon the amount of ferrous chloride which it contains.

At Ovifak, in Greenland, and at several neighboring localities, native iron is found which was at first thought to be of meteoric origin. It is now known to be terrestrial iron, brought up in some manner from below, together with the basalt in which it is embedded. Some of it is in small grains and some in large masses of several tons in weight, and it resembles meteoric iron in every essential particular. It contains some lawrencite, and also carbon, which is combined with iron, probably as cohenite. The presence of a carbide was proved by George Steiger in the laboratory of the United States Geological Survey. By heating some of the Ovifak iron with ammonium chloride he obtained a mixture of hydrocarbons, both saturated and unsaturated.

For the average composition of meteoric iron and its terrestrial equivalent we now have the following data: First, the average of 318 analyses of meteoric iron, as computed by Farrington[20]; second, the average of 13 analyses of the Greenland iron, cited by Dana.[21] In the analyses of Greenland iron figures for silica and insoluble matter have been rejected as representing impurities taken up from the adjacent rocks.

Average composition of meteoric and native iron.

	Meteoric.	Terrestrial.
Iron	90.85	92.53
Nickel	8.52	2.20
Cobalt	.59	.62
Copper	.02	.23
Sulphur	.04	.28
Carbon	.03	1.78
Phosphorus	.17	.21
Chlorine	....	.06
Chromium	.01	....
	100.23	97.91

These averages, although they differ somewhat, do so no more than individual analyses of meteoric iron. No two irons are precisely alike. The absence of chlorine from the first column of figures merely means that it was not determined, and the same is true with reference to chromium in the second column. Analyses of rocks and minerals differ widely as regards completeness.

In one way the analyses of meteoric irons are likely to be slightly misleading. They represent clean, bright samples of the nickel-iron and take no account of the large inclusions of graphite, troilite, and the more generally diffused ferrous chloride. The composition of the entire mass of an iron would be unlike that of the selected metal, and the inclusions might amount to several per cent. No good estimate can be made of their average quantities. The averages given in the table, therefore, represent only approximate orders of magnitude, but the percentages of the minor constituents are certainly not large.

That the minerals of the meteoric stones were originally in a state of fusion seems to be clear. Was the meteoric iron also molten? This question can be answered in the affirmative, for the following reasons:

In the preceding section of this paper it was shown that carbides and phosphides were among the compounds that would be the earliest to form in a cooling globe. Both carbides and phosphides are found in meteoric iron, and the even more significant sulphides also. Furthermore, troilite and graphitic carbon are often found in large nodules that could

[20] Op. cit.

[21] System of mineralogy, 6th ed., pp. 28, 29, 1914.

hardly have segregated except from a fluid or semifluid mass. The diamonds of the Canyon Diablo iron tell the same story. The artificial diamonds obtained by Moissan were produced by dissolving carbon in molten iron and cooling under great pressure. Finally, the highly crystalline structure of meteoric iron points to the same conclusion. No artificial iron shows that peculiarity. All the evidence points in one direction, and the similarity of origin of stones and irons seems to be almost beyond doubt. Both stones and iron were formed in a cooling globe which in structure resembled the cooling Earth. This theory as to the origin of meteorites is the only one that is supported by positive evidence; all others are purely speculative. The theory is not original with me. It was advocated by Meunier and others and has since been fully discussed by Farrington,[22] who has made use of much the same evidence as I have cited here. He also calls attention to the fact that meteoric stones sometimes show indication of strains and of brecciated structure, similar to corresponding features that are common in the crust of the Earth. Farrington's arguments in support of his thesis seem to be incontestable.

The lines of evidence used by Farrington in his argument have recently been made much stronger by the study of a meteoric stone that fell at Cumberland Falls, Ky., on April 9, 1919. This stone, which has been thoroughly investigated by Merrill,[23] is made up of two distinct types of meteorites. The larger part is white and consists mainly of enstatite with a little diallage. It contains, however, inclusions of a black stone, made up of olivine and enstatite. There are also some scales of graphite, with a very little nickel-iron and troilite. The most noteworthy feature of the stone is that the white portion, instead of being comparatively homogeneous, is a breccia, a mass of sharply angular fragments, which could be formed only by crushing the rock under great pressure or by grinding. The only interpretation that can be given to these facts is that the meteorite is a fragment of a much larger mass, of what may be called subplanetary dimensions—one large enough for the same processes to operate that are recognized in the rocks of the Earth. How and when that planetoid was disrupted we do not know, and speculation upon that subject would be out of place in this paper.[24] Its chemical composition, however, as shown by the analyses of meteorites, must have closely resembled that of the Earth.

To complete the analogy between the Earth and the broken planetoid we should be able to calculate the percentage composition of the latter. This, however, can not be done, for much of the meteoric matter is lost. In the catastrophe that destroyed the planetoid its lighter, outer shell was probably scattered in dust, or in fragments so small that few of them, even if they reach the Earth, could ever be collected and identified. No granitic meteorite has yet been found, and the only distinctly feldspathic meteorites are those of the Juvinas and Stannern types, in which the feldspar is anorthite. Alkali feldspars occur in meteorites in very small and relatively unimportant proportions.

The suggestion that the outermost portion of the planetoid was lost is not altogether imaginative. It is supported by the well-known phenomena that attend the fall of a large meteor. These are a brilliant light and a violent explosion, with a noise which has been compared to thunder or the firing of heavy artillery. The meteor is also followed by a train of sparks as seen by night, or one of "smoke" in daytime. An explanation of these phenomena was put forth by Maskelyne[25] in 1862, about as follows: The meteor, coming from the cold of outer space, enters the atmosphere of the Earth with something like planetary velocity. By atmospheric friction its surface is almost instantly heated to incandescence; this portion of course expands and breaks away from the central mass with explosive violence. In this way the meteor is disrupted, and the fragments that are thrown off are seen in the trail of sparks or smoke which follows the falling mass. This explanation of the phenomena is very simple and seems to be satisfactory. The meteoric stone has just the composition which would result from the process described above. Its lighter surface has been blown away, and only the denser, interior portion of different composition has fallen to the ground.

So far the evidence seems to be conclusive that the meteorites are fragments of a mass of

[22] Farrington, O. C., Jour. Geology, vol. 9, p. 630, 1901.

[23] Merrill, G. P., U. S. Nat. Mus. Proc., vol. 52, p. 97, 1920.

[24] T. C. Chamberlin (Jour. Geology, vol. 9, p. 370, 1901), regards meteorites as fragments of a planetoid which was torn to pieces by near approach to a larger mass.

[25] Maskelyne, N. S., British Assoc. Adv. Sci. Ann. Rept., 1862, pt. 2, p. 188.

matter which in composition closely resembled the Earth. Of the dimensions of that mass we know nothing, except that it must have been large enough to maintain its integrity at first in a fluid state, and that after it had solidified crustal movements occurred which produced the peculiar structures of meteoric stones. Its disruption took place long ago, how long we can not say; and many, perhaps the greatest number, of its fragments reached the Earth shortly after the catastrophe. Of course we can not assume that there was only one such mass; there may have been more than one, but that question is not germane to the present discussion. The known meteorites show clear indications of a common origin; whether from one or two planetoids we need not ask.

From what has been said so far, it is clear that the Earth was once a fluid mass, in which as it cooled the iron separated from the silicates just as it does from the slag in a blast furnace. The solid Earth, then, consists of two components—a nucleus of metallic nickel-iron and an envelope of silicate rocks. This conclusion is by no means new. It has been adopted by many other writers, and especially by Wiechert,[26] whose argument is based on geodetic data. For the composition of the nucleus we have Farrington's average of 318 analyses of meteoric iron, which, however, is subject to correction for its inclusion of other substances. What, now, is the average composition of the lithosphere?

For the composition of the lithosphere we have that of the igneous rocks near its surface and that of the stony meteorites, which are supposed to represent the material closest to the central iron. Between the two, the top and bottom of the lithosphere, there is a wide gap, which can be filled only hypothetically—that is, by making probable or at least plausible assumptions. In the first place we may assume that between the lighter rocks at the surface and the heavier at the bottom there is a fairly regular gradation, from an average andesite above to a peridotite below. In this hypothesis an average basalt may be assumed to fill the gap, without much risk of serious error. For the composition of the basalt we may use the average of 161 analyses as computed by Daly,[27] but reduced here to elementary form. For the mean composition of the lithosphere there are, then, three averages to be combined, as follows: First, the average for the surface rocks; second, that of the basalt; and third, that of the meteoric stones as given by Merrill. In this combination the minor constituents are discarded, as representing small corrections that can be applied when it is desirable to do so. The incompleteness of the meteorite analyses renders the omission necessary. The three sets of figures, given equal weight, appear in the following table, together with their mean, the composition of the lithosphere.

Average composition of the lithosphere.

	Surface rocks.	Basalt.	Meteoric stone.	The lithosphere.
Oxygen	46.72	44.28	42.16	44.38
Silicon	27.76	23.27	21.21	24.08
Aluminum	8.13	8.44	1.70	6.09
Iron	5.12	8.87	15.25	9.75
Magnesium	2.10	3.76	16.12	7.33
Calcium	3.64	6.49	1.48	3.87
Sodium	2.86	2.34	.82	2.01
Potassium	2.60	1.28	.31	1.39
Titanium	.73	.83	....	.52
Manganese	.12	25	.50	.29
Phosphorus	.16	.19	....	.12
Chromium	.06	....	.45	.17
	100.00	100.00	100.00	100.00

It will be noticed that in this average the nickel-iron of the meteoric stones does not appear. It is included in the total amount of metal which is required to bring the density of the Earth up to 5.5.

Here we may venture to use a curious analogy to which Wiechert has called attention.[28] Astronomers are generally agreed that the Moon was originally thrown off from the Earth. If so, its composition should be essentially like that of the lithosphere. Its mean density, 3.34, is that of some meteoritic olivines. That density, however, is too high for the stony portion of the lithosphere and suggests that the Moon contains, like the meteoric stones, some nickel-iron. The average meteoric stone, according to Merrill's calculation, contains nearly 15 per cent of nickel-iron, sulphides, and phosphides. The average density of 78 meteoric stones, as computed by me, is 3.54, a value that fits in well with the figures given above.

[26] Wiechert, E., Gesell. Wiss. Göttingen Nachr., 1897, p. 221.
[27] Daly, R. A., Am. Acad. Proc., vol. 45, p. 211, 1910.
[28] Wiechert, E., Deutsche Rundschau, vol. 132, p. 376, 1907. English translation in Smithsonian Inst. Ann. Rept., 1908, p. 431.

To the stony matter alone of the lithosphere a probable density of 3.2 may reasonably be assigned.[29] That of the surface crust is about 2.8. For the density of the metallic nucleus the figure 7.8 is commonly assumed, but it may be a trifle too high. No allowance is made for inclusions of lighter material, but a density of 7.7 would probably be a minimum. The mean density of the Earth, as given by different authorities, lies somewhere between 5.5 and 5.6.

With the data now at hand we can compute, at least approximately, the composition of the Earth as a whole and the relative abundance of the elements in the solar system. Wiechert[30] has already shown that the iron nucleus of the Earth and its rocky envelope are roughly equal in volume. If we assign to the Earth and its two components the respective densities of 5.5, 7.8, and 3.2 this relation holds exactly, and no probable changes in these values will greatly modify Wiechert's conclusion. Whatever permissible values we assign to the densities the two volumes will approach equality. The variations will not exceed 3 per cent in either direction—that is, for a little more iron and a little less rock, or vice versa. From the volumes and the densities the relative masses of the two components of the Earth can be determined, and then Farrington's average composition of meteoric iron and that of the lithosphere can be combined together. This combination has already been attempted by Farrington,[31] but with the three densities taken as 5.57, 7.8, and 2.8. Here the figure for the density of the Earth is probably too high, and that of the lithosphere certainly too low. For the composition of the Earth by weight they give 73.6 per cent of free metals and 26.4 per cent of rock. With the densities 5.5, 7.8, and 3.2 the percentages become 70.75 and 29.25, respectively. Considered as representing orders of magnitude, and we can expect nothing more, these two estimates are not very far apart. In the following combination the two percentages are rounded off to 71 and 29. Farrington's combination, however, differs from ours not only in the assumed densities but also in assigning to the composition of the lithosphere that of its 10-mile crust. The two combinations are not comparable.

[29] Wiechert (op. cit., 1907), gives a density of 3.4. In his earlier paper he adopts the value 3.2.

[30] Wiechert, E., Gesell. Wiss. Göttingen Nachr., 1897, p. 243.

[31] Farrington, O. C., Field Columbian Mus. Pub. 151, 1911.

Average composition of the Earth.

	Nickel-iron (71 per cent.)	Lithosphere (29 per cent.)	The Earth (100 per cent).
Oxygen	....	44.38	12.77
Silicon	....	24.08	6.98
Aluminum	....	6.09	1.86
Iron	90.64	9.75	67.20
Nickel	8.51	....	6.04
Cobalt	.58	....	.41
Magnesium	....	7.33	2.13
Calcium	....	3.87	1.12
Sodium	....	2.01	.58
Potassium	....	1.39	.39
Titanium	....	.52	.15
Manganese	....	.29	.08
Phosphorus	.17	.12	.16
Chromium	.01	.17	.07
Sulphur, carbon, copper	.09	(?)	.06
	100.00	100.00	100.00

It needs no argument to show that these figures have no claim to anything like finality and that their value depends upon the assumptions that underlie the calculations. The fundamental assumption, which rests upon pretty definite evidence, is that the original mass of which the meteorites are fragments was similar in composition to the Earth and was formed in the same way.

The second assumption, that the Earth contains a nucleus composed mainly of nickel-iron, surrounded by a stony envelope, is sustained by the facts that the Earth behaves like a huge magnet and that its mean density is about double that of the surface rocks. The application of these facts to the problem in hand involves subordinate assumptions as to the relative densities of the nucleus and the lithosphere. No probable change in the figures assigned to these densities can make any great change in the orders of magnitude as given in the table. The relative order of abundance will be the same, with iron first, oxygen second, silicon third, and so on. As for the scarcer elements, those which do not appear in the table, their total amount can not much exceed 1 per cent, and their inclusion would make only insignificant changes in the percentages assigned to the really abundant substances. After making all reasonable allowances for the scarcer elements, we can say that ten of the more abundant ones, all below 60 in atomic weight, make up at least 99 per cent of all terrestrial matter. They are among the simplest and therefore the most stable elements and were formed in the largest quantities.

This rule, as has been shown already, is revealed by the evidence furnished by the stellar spectra.

Whether all the members of the Solar System are precisely alike in composition is and must remain a matter of conjecture. It is conceivable that the outer planets may be somewhat richer than the Earth in the lighter elements, such as aluminum, magnesium, calcium, and the alkali metals. On the other hand, the Sun may be richer in iron. If that supposition is correct, then the inner planets should approximate an average composition and represent the entire system. This hypothesis, of course, can neither be proved nor disproved. Definite evidence is lacking.

From the analyses of meteoric stones we can obtain some additional suggestions as to the distribution of matter within the Earth. In one of Farrington's papers,[32] which I have already cited, he has tabulated 125 analyses of meteoric stones, classified according to the quantitative system. One analysis falls in the salfemic class, 9 are dofemic, and 94 perfemic. The classes persalane and dosalane are entirely missing, for they belong to the destroyed surface of the wrecked planetoid. Now, these analyses show a distinct gradation in the amounts of nickel-iron which the stones contain. The few feldspathic meteorites, those that were nearest the surface of the parent mass, contain little or no nickel-iron, which increases with some regularity to the end of the perfemic series. The regularity is not sharp and might better be described as a tendency, for the following reasons:

In a single meteorite of large size the nickel-iron is not uniformly distributed, and the analyses were made on small fragments of not more than a few grams in weight. Adjacent fragments might have been either richer or poorer in nickel-iron than those which were analyzed. To analyze a complete stone is never practicable, nor is it feasible to sample a meteorite as one would sample an igneous rock or a carload of ore. These considerations amply account for the irregularities shown by the analyses. In spite of these difficulties the tendency toward a definite arrangement of the meteorites seems to be fairly clear. If they really represent a planetoid that originally resembled a small Earth, the distribution of matter within the Earth as set forth below is highly probable.

At the center of our planet we should have a rather ragged spheroid, with no well-defined margin, consisting mainly of nickel-iron. Near its surface the metal would assume the pallasite type and begin to show inclusions of stony matter, principally olivine. This material would gradually shade into silicate rocks containing large inclusions of free metal, and so on, step by step, until the lighter feldspathic rocks began to appear. These rocks, as the analyses show, contain little or no nickel-iron, and that present occurs in very small, sometimes almost imperceptible grains. The condition thus outlined is exactly what we should expect to result from the slow cooling of a molten globe. The heavier substances should gravitate to the center, followed in order of density by the lighter substances. The evidence at our disposal seems to warrant the conclusions drawn from it. We are dealing, however, with probabilities, not with proofs.

From the evidence presented in the preceding pages some additional conclusions may be drawn. If the Earth consists of a solid nucleus of nickel-iron, surrounded by an envelope of silicate rocks in equal proportions by volume, what is the diameter of the one and the thickness of the other? For the sake of simplicity we may assume ideal conditions, as follows: All the iron is supposed to be concentrated in the form of a perfectly smooth sphere, in uniform contact with its envelope. The volume of the Earth, as generally accepted, is 259,886,000,000 cubic miles. This corresponds to a nuclear diameter of 6,284 miles and a radius of 3,142 miles. Subtracting this figure from the mean radius of the Earth, 3,959 miles, we get 817 miles as the average thickness of the ideal lithosphere. This, however, is only a first approximation to reality, and at least one correction to it is possible.

In calculating the average composition of the lithosphere one-third of it was assumed to be equivalent to an average meteoric stone, but with one qualification. The disseminated nickel-iron, sulphides, and phosphides were withdrawn from the stone and added to the nucleus, making it too large and the true lithosphere too small. The equality of volume as given between nucleus and envelope is really that between the metallic (or rather meteoric) iron and the silicate rocks.

[32] Farrington, O. C., Field Columbian Mus. Pub. 151, 1911.

The metallic inclusions in the average meteoric stone amount to a little under 15 per cent by weight, and even less by volume. An addition of 5 per cent to the volume of the lithosphere, and a corresponding reduction to the nucleus of the Earth, only lowers the diameter of the nucleus to 6,192 miles and raises the thickness of the lithosphere to 863 miles. This is probably a maximum correction, but any attempt at a greater refinement of the figures would be useless. Absolute accuracy is unattainable, for there is no sharp dividing line between the two components of the Earth. Furthermore, all the data which have been used in the calculations, even those relative to the volume of the Earth and its density, are subject to corrections of undetermined magnitude and direction. There is, nevertheless, a strong probability that the diameter of the nucleus is of the order of 6,200 miles and that the thickness of its envelope is less than 900 miles. Similar figures have been obtained by Wiechert,[33] who assigns to the nucleus a diameter of 10,000 kilometers, or 6,214 miles, to which a thickness of its envelope of 855 miles corresponds. Wiechert's results and mine were reached by entirely different methods, and their close agreement is therefore very satisfactory. Gutenberg,[34] however, from a study of earthquake waves, gives the nucleus of the Earth a radius of only 3,500 kilometers, or 2,175 miles. The corresponding thickness of the lithosphere is 1,784 miles, or double the value found in this investigation. It is for some geodesist to explain this discrepancy.

Up to this point the vexed questions of pressures and temperatures within the Earth have not been considered. On the one hand it has been commonly assumed that because of increasing pressure the densities from the surface to the center of the Earth must have steadily increased, and a similar assumption has been made with regard to temperatures. But here we have two opposing forces, one tending to increase, the other to diminish volumes. Whether these forces balance or not is a question which needs more consideration than I can give it. In its investigation many factors, hitherto generally neglected, have to be taken into account. The Earth is not a homogeneous body. It is made up of many different substances, which are unlike in composition, in density, in fusibility, in specific heat, in conductivity, and in compressibility. Furthermore, we must determine whether compressibility is a limited property of matter or whether it can go on indefinitely. It is also necessary to consider the comparatively abrupt change from the envelope of silicate rocks to a nucleus of metallic iron, which seems to be sustained by strong evidence. The rocky shell of the Earth is more compressible than its metallic interior. Anything like a regular increase of density within the Earth because of an assumed increase of pressure is highly improbable. Unlimited compressibility would end in zero volume, which is absurd. There must be a limit somewhere, where pressure and the resistance to pressure exactly balance, and that limit may have been reached in the metallic nucleus of the Earth, an inference which is suggested by the rigidity of our planet. If it has not been reached then the volume of the Earth must be slowly shrinking, but of that there are no clear indications.

The assumption that temperatures within the Earth increase regularly with the depth is based upon a very short range of observations. In deep wells and other borings the temperature increases, but not to the same extent in all localities, the average amount being about 1° F. in 60 feet. The actual measurements are limited to depths of only a little more than a mile, and by extrapolation the conclusion has been reached that at the center of the Earth the temperature must be high enough to surpass the critical temperatures of all known substances. The temperature of the Sun, which is now well fixed as something like 6,000° C., would thus be exceeded many times over. Extrapolation sometimes leads to very surprising conclusions.

Let us now consider the heat of the Earth under two distinct headings—namely, residual or original heat and new heat such as is constantly being generated. By residual heat is meant that which was retained by the cooling Earth within its interior, mainly in its nucleus and to a less degree in the lithosphere. At and near the surface of the Earth the new heat becomes evident as the result of chemical activity, friction, and several other causes. The heat derived from radium, as shown by

[33] Gesell. Wiss. Gottingen Nachr., 1897, p. 243.

[34] Gutenberg, B., idem, 1914, p. 176.

the radioactivity of the rocks, has in recent years received much consideration, but its importance may have been exaggerated. It is, however, not negligible. That due to the impact of meteorites is relatively insignificant.

That chemical changes are constantly taking place in the crust of the Earth is a matter of common observation, and each one has definite thermal significance. Some reactions are exothermic and others are endothermic, but whether these gains or losses of heat balance or one or the other predominates is difficult and perhaps impossible to determine. Rocks are decomposed by the joint action of air and water, and heat is both gained and lost in the rather complex processes. The intensity of the reactions is greatest, of course, in humid areas and least in desert regions; it can not be the same for all localities. To discuss this question at length would hardly be justifiable in a paper of this kind: it is enough to show that the question deserves consideration. Even the heat emitted by volcanoes is in part, if only a small part, of chemical origin. The heat of some coal mines and of mines in which sulphide ores are worked is due to oxidation. Examples like these might be multiplied indefinitely. In many of the changes solar radiations also take part, and energy that may be released later is stored up within the Earth.

The crust of the Earth is constantly in motion, and every movement is accompanied by friction. The slightest tremor generates its share of heat, and its aggregate amount must be enormous. Mountains are raised to great elevations; rocky strata are folded, bent, broken, or distorted; there are landslides and all the varieties of erosion; and every one of these movements, great or small, is a source of what I have called new heat. Even volcanic heat is partly and perhaps largely due to friction. Volcanoes, as a rule, are situated along lines of weakness in the crust of the Earth, where earthquakes (and consequently friction) are most common.

All or nearly all of this new heat is generated at or near the surface of the Earth. Below the level of isostatic compensation, the depth at which surficial excesses and defects of density are balanced, there can hardly be much chemical activity and very little friction. An earthquake wave may penetrate to much greater depths, probably to the margin of the nucleus, but its thermal significance diminishes as it recedes from its focus, and below the isostatic level, which is put at about 60 miles, it can not be very great. At greater depths the temperature, whatever it may be, is due to residual heat and is not higher than the average melting point of igneous rocks.

The conditions in the nucleus of the Earth are very different from those in the lithosphere. Here we have a metallic mass more than 6,000 miles in diameter, which is a good conductor of heat. It is practically insulated by a shell of poorly conducting rock at least 800 miles thick. Under such conditions, because of its conductivity, the temperature of the nucleus should be uniform or nearly so throughout and below the melting point of iron, or 1,600° C. This conclusion implies that the nucleus has attained a state of stable equilibrium, which is also indicated by the established fact that the Earth as a whole is rigid. Only near the surface is this rigidity disturbed.

NOTE.—Some valuable determinations of the compressibility of rocks and minerals have recently been published by L. H. Adams and E. D. Williamson (Franklin Inst. Jour., April, 1923). Their data, as applied to the present discussion, show that the granitic rocks are the most compressible, and the denser rocks much less so. Granite is about three times as compressible as iron. From the surface of the earth to its nucleus, therefore, the compressibility diminishes, and the resistance to pressure must steadily increase.

THE DISINTEGRATION OF THE ELEMENTS.

Our direct, experimental knowledge of atomic disintegration began with the discovery by Ramsay and Soddy in 1903 of the emission of helium from radium. This discovery, however, was the outgrowth of two earlier discoveries—that of radioactivity by Becquerel in 1896 and of polonium and radium by the Curies two years later. From these beginnings a new field of chemical and physical research has developed, which is already rich in fundamental discoveries and is represented by a voluminous literature.

The study of radioactivity, however, covers only one phase of the main problem of elemental decay. As soon as it was clearly recognized that the most complex elements were spontaneously decomposing, investigators began to attack the problem along other lines of research, some of them experimental and others mathematical. The atoms that had been regarded as simple were seen to be complex, and it was sought to determine their structure. Attempts were and are still being made to decompose the chemical elements by artificial means, and some significant evidence of disintegration has been furnished by astronomy.

The study of radioactivity is primarily, although not entirely, a study of the radiations which the most complex elements emit. These radiations are of three kinds, known as alpha, beta, and gamma rays, which differ in velocity and in the extent to which they can penetrate an obstacle in their paths, such as a sheet of aluminum foil. The different products of radioactivity—that is, of atomic disintegration—are identified chiefly by the character of their radiations. The alpha rays are composed of helium atoms, the beta rays are "atoms" of negative electricity, and the gamma ray is regarded as possibly an electrically neutral doublet of two electrons of opposite sign. Through the study of these radiations more than thirty new substances have been discovered, which have received names and to which have been given atomic weights (except in the actinium series) and atomic numbers. In the following table, which is abridged from that recently published by the International Commission on the Chemical Elements, the present state of our knowledge of the radioactive elements is well shown. Some details, not needed in the present discussion, have been omitted from the complete table. The letter T at the head of the first column refers to the "period" of each substance—that is, the time in which the quantity of an "element" is diminished to one-half, the "half-life period," as it is commonly called. The column headed "radiation" gives the characteristic rays which the substances emit.

This table evidently has no claim to finality. It is a valuable summary and classification of experimental data, but it also contains implications which sooner or later must be revised. The basic facts are as follows: Uranium and thorium are slowly decaying, and in doing so they generate series of products which are also unstable and which seem to end in the formation of lead. A few of these products are long-lived, with periods measured by years; others change with almost incredible swiftness, and for some of them the periods consist only of minutes, or even of small fractions of a second. The disintegration of uranium and its products follows two distinct lines—one through ionium and radium, the other forming the actinium series. The thorium series, so far as we know, is single.

Each of the three series given in the table divides at about its middle into two parts, with the line of demarcation marked by the appearance of the gaseous emanations of radium, actinium, and thorium X. For these emanations the names "radon" (formerly niton), "actinon," and "thoron" are proposed. These emanations are short-lived and give rise as they decay to what are called "active deposits," which are nonvolatile and can be collected and concentrated upon negatively charged metallic points or surfaces. These deposits in turn decay, and so on to the end of the series.

Now, without doubting the accuracy of the experimental data upon which the foregoing table is based, we may examine the inferences that are drawn from them. Here we must again point out the difference between normal and abnormal or defective elements. The normal elements are those which were developed in the ordinary course of evolution; the abnormal elements are those which were produced by decay. The difference between the two classes is very definite. The normal atoms are believed to be veritable storehouses of potential energy. In the series of radioactive elements that energy is becoming partly kinetic. The distinction is perfectly clear. Some of the products of radioactivity are too ephemeral to be called elements at all. They represent matter in a state of transition from one form to another, and the atomic weights assigned to them are purely hypothetical. As for uranium and thorium, they are partly decayed and are still decaying, but they must have been originally developed as normal elements under conditions of pressure or temperature of which we know nothing. To quote an apt remark of Eddington,[35] in his lecture upon the borderland between astronomy and geology: "In radioactivity we see a mechanism running down which must at some time have been wound up." This fits the cases of uranium

[35] Eddington, A. S., Nature, Jan. 6, 1923.

The radioactive elements.

The uranium-radium series.

T.	Name.	Symbol.	Atomic weight.	Atomic number.	Isotope.	Radiation.
4.67×10^9 years	*Uranium I*	UI	238	92	U	α
24.6 days	*Uranium X_1*	UX_1	234	90	Th	β
1.15 minutes	*Uranium X_2*	UX_2	234	91	Pa	β (γ)
2×10^6 years	*Uranium II*	UII	234	92	U	α
6.9×10^4 years	*Ionium*	Io	230	90	Th	α
1690 years	*Radium*	Ra	226	88	Ra	α ($\beta+\gamma$)
3.85 days	*Radon*	Rn	222	86	Rn	α
3.0 minutes	*Radium A*	RaA	218	84	Po	α
26.8 minutes	*Radium B*	RaB	214	82	Pb	β (γ)
19.5 minutes	*Radium C*	RaC	214	83	Bi	99.97% β and γ
10^{-6} second	*Radium C′*	RaC′	214	84	Po	α
16.5 years	*Radium D*	RaD	210	82	Pb	(β and γ)
5.0 days	*Radium E*	RaE	210	83	Bi	β
136 days	*Radium F* (Polonium)	RaF (Po)	210	84	Po	α (γ)
....	*Radium Ω′* (Lead)	Ra Ω′ Pb^{206}	206	82	Pb	....
....	*Radium C*	RaC	214	83	Bi	0.03% α
1.4 minutes	*Radium C″*	RaC″	210	81	Tl	β
....	*Radium Ω″*	RaΩ″	210	82	Pb	....

The actinium series.

T.	Name.	Symbol.	Atomic weight.	Atomic number.	Isotope.	Radiation.
....	*Uranium ?*	....	?	92	U	α
1.04 days	*Uranium Y*	UY	?	90	Th	β
1.2×10^4 years	*Protoactinium*	Pa	?	91	Pa	α
20 years	*Actinium*	Ac	?	89	Ac	—
19.5 days	*Radioactinium*	RdAc	?	90	Th	α (β)
11.4 days	*Actinium X*	AcX	?	88	Ra	α
3.9 seconds	*Actinon*	An	?	86	Rn	α
2.01×10^{-3} second	*Actinium A*	AcA	?	84	Po	α
36.1 minutes	*Actinium B*	AcB	?	82	Pb	(β and γ)
2.15 minutes	*Actinium C*	AcC	?	83	Bi	α
4.71 minutes	*Actinium C″*	AcC″	?	81	Tl	β and γ
....	*Actinium Ω″* (hypothetical)	Ac Ω″	?	82	Pb	....

The thorium series.

T.	Name.	Symbol.	Atomic weight.	Atomic number.	Isotope.	Radiation.
1.31×10^{10} years	*Thorium*	Th	232	90	Th	α
6.7 years	*Mesothorium 1*	MsTh1	228	88	Ra	—
6.2 hours	*Mesothorium 2*	MsTh2	228	89	Ac	β and γ
2.02 years	*Radiothorium*	RdTh	228	90	Th	α (β)
3.64 days	*Thorium X*	ThX	224	88	Ra	α
54 seconds	*Thoron*	Tn	220	86	Rn	α
0.14 second	*Thorium A*	ThA	216	84	Po	α
10.6 hours	*Thorium B*	ThB	212	82	Pb	β and γ
60 minutes	*Thorium C*	ThC	212	83	Bi	65% β
10^{-11} second	*Thorium C′*	ThC′	212	84	Po	α
....	*Thorium Ω′* (Lead)	Th Ω′ Pb^{208}	208	82	Pb	....
....	*Thorium C*	ThC	212	83	Bi	35% α
3.1 minutes	*Thorium C″*	ThC″	208	81	Tl	β and γ
....	*Thorium Ω″* (Lead)	Th Ω″ Pb^{208}	208	82	Pb	....
....	*Potassium*	K	39.1	19	K	β
....	*Rubidium*	Rb	85.5	37	Rb	β

and thorium exactly. When the conditions that permitted the evolution of uranium ended, then disintegration began.

The atomic weights of normal uranium and thorium are unknown.

The values assigned to them really represent mixtures of the normal elements with some of their decomposition products, of which we know only those that are revealed by their radiations. That there may be residues left behind which are as yet undiscovered seems to be unquestionable. The actual determinations of atomic weight were made with masses of material containing millions of atoms, some of them intact and others represented by unexpelled products of disintegration. If all the atoms were broken down at once, there would be neither uranium nor thorium left. Furthermore, the atomic weight assigned to thorium is affected by another complication. It is doubtful whether any thorium compounds are known which are quite free from its isotope, ionium. The atomic weight of ionium has been shown by Honigschmid to be at least as low as 231.5, and probably lower. That of purified thorium must certainly be higher than the accepted 232.2, but the exact value is undetermined. The presence of ionium gives it too low a value.

The atomic weights and numbers assigned to the products of radioactive decay are, with a few exceptions, hypothetical. The atomic weight of radium as actually determined is 225.95, and it falls into place in the periodic system. For its emanation, radon, the value is near 222, but the determination is not as exact as is desirable. Radium, moreover, and also radon are still decaying, and the values given to them are therefore subject to the same uncertainties as those which affect the atomic weights assigned to uranium and thorium. If corresponding normal elements exist, their atomic weights should be somewhat higher. The so-called isotopes of lead will be considered later.

From what has been said in the preceding paragraphs it is evident that the atomic weights and numbers assigned to the radioactive "elements" are in need of careful revision. The atomic weights start from two that are certainly in error and are developed on the assumption that each step downward is due entirely due to the loss of alpha particles. But does that loss represent all the change which has taken place? And how large a proportion of the atoms in a given mass of uranium or thorium has been decomposed? Furthermore, is Moseley's law of atomic numbers applicable to products of decay—for example, to radium C'? That product of radioactivity has a period of only 10^{-6} second; it comes into existence, pays a flying call on atomic number 84, and then vanishes. To call such a substance an element verges on absurdity. Moseley's law may be valid for the normal elements, but it has not yet been tested throughout the scale of atomic weights. The evidence in its favor is incomplete. In the actinium series no atomic weights are assumed, for the reason that the exact ancestry of actinium is still uncertain. None of these doubts, however, attaches to the atomic weights of potassium and rubidium, two metals which are feebly radioactive but are independent of the uranium and thorium series.

In the table of the radioactive elements six members are reported as isotopes of lead. That is, although the atomic weights assigned to them range from 206 to 214, they are given the same atomic number with lead, No. 82, and appear in the same place in the periodic classification. These isotopes are radium B, radium D, actinium B, thorium B, uranium lead, and thorium lead. Three of them are short-lived and need not be considered further here. Radium D, however, sometimes called "radio-lead," is part of the active deposit of radon; and it has been collected in sufficient quantity for qualitative tests and gives some reactions that are like those of normal or ordinary lead. Its period is 16.5 years, and its hypothetical atomic weight is 210.

The two isotopes that end the radioactive series, uranium lead and thorium lead, are on a different footing from the others. They are obtained from minerals containing them in sufficient quantities for good determinations of atomic weight. These determinations give different values for the lead from different sources, showing that mixtures of normal lead with its isotopes are of common occurrence in radioactive minerals. In the most perfect and brilliant crystals of uraninite, which are found in granitic pegmatites, normal lead seems to be absent, and the isotopic lead has an atomic weight very close to 206, the lowest value yet found. For thorium lead, derived from ores of thorium, the lowest value is 208. Are these the real ends of the radioactive series, or does disintegration proceed still further? So far, this question is not completely answered.

The existence of these isotopes has led to a belief, or rather a suspicion, that ordinary lead is a mixture and not a single definite substance. How far is this suspicion verified? Is the atomic weight of ordinary lead constant or variable? To answer these questions Baxter and Grover made elaborate series of analyses of lead bromide and chloride from very different sources. Lead was obtained from galena, cerusite, vanadinite, and wulfenite, and the minerals came from widely separated localities—namely, Idaho, Arizona, Washington, Missouri, Germany, and Australia. Four different minerals and seven localities furnished the material for the determinations, and commercial lead nitrate was also included in the investigation. Four series of determinations were made, giving average values for the atomic weight of lead ranging from 207.18 to 207.23, an extreme difference of 1 part in 4,144, which is quite within the allowable limits of experimental uncertainty. The atomic weight of normal lead is a definite quantity and not a statistical average of the different values found for its isotopes. To maintain such a uniform average the isotopes should always be mixed in exactly the same proportions, and that is extremely improbable.

One very uncertain assumption has been made as to the nature of isotopes. Those of lead, for instance, are said to be chemically identical and not separable by chemical methods. That simply means that no such separation has yet been effected; but there is no proof that it may not be effected in the future. The prediction of impossibilities is not always verified. Many failures are on record.

That the products of radioactivity are products of decomposition is proved, but their definiteness is not so certain. All or nearly all of them are unstable and undergoing change, some rapidly and others with extreme slowness. Their isotopy, moreover, is largely hypothetical, for how can two products be called isotopic when both are undergoing alteration and at different rates? Only for uranium lead and thorium lead can isotopy be regarded as established, and even for these the claim must be held with reservations. The isotopes differ from normal lead in some physical properties, but that they are its equal as regards stability is still uncertain. The stable product of evolution and the products of decomposition are not quite the same. Their similarity may be illusive. This possibility should not be ignored.

Reference has already been made to Aston's work on "mass spectra"—work which is of great value, regardless of any interpretation that may be put upon it. Are his isotopes substances of the same order as those that appear in radioactivity?

The "mass spectra" described by Aston[36] represent an artificial disintegration of elements, and his process is roughly as follows: An element or one of its compounds is bombarded by powerful positive rays in a magnetic field. The rays, differently deflected, finally impinge upon a carefully calibrated photographic plate, upon which they give lines that are interpreted as belonging to isotopes. From the position of these lines the atomic weights of the isotopes are determined within a supposed accuracy of 1 part in 1,000, or one-tenth of 1 per cent, a rather large uncertainty.

It is not necessary for present purposes to go into the details of Aston's work. They are fully given in his book on isotopes. Suffice it to say that his apparatus, his "mass spectograph," is very complicated, and his technique is exceedingly refined. The essential fact is that the elements undergo certain changes when subjected to the action of positive rays. Other methods for attaining results similar to Aston's have been developed by Sir J. J. Thomson and by A. J. Dempster, but they also are applications of what is called positive-ray analysis. The products of these analyses, regarded as isotopic, are given in the following table, which is abridged from the table published by the International Commission on the Chemical Elements in 1923. The figure relating to glucinum is due to G. P. Thomson; those of magnesium, calcium, and zinc, to Dempster; all the others are Aston's. A number inclosed in parentheses is doubtful.

[36] Aston, F. W., Isotopes, London, 1922.

Isotopes.

Element.	Atomic number.	Atomic weight.	Minimum number of isotopes.	Masses of isotopes.
H	1	1.008	1	1.008
He	2	4.00	1	4
Li	3	6.94	2	7; 6
Gl	4	9.02	1	9
B	5	10.9	2	11; 10
C	6	12.005	1	12
N	7	14.008	1	14
O	8	16.000	1	16
F	9	19.0	1	19
Ne	10	20.2	2	20; 22
Na	11	23.00	1	23
Mg	12	24.32	3	24; 25; 26
Al	13	27.0	1	27
Si	14	28.1	2	28; 29; (30)
P	15	31.04	1	31
S	16	32.06	1	32
Cl	17	35.46	2	35; 37
A	18	39.9	2	40; 36
K	19	39.10	2	39; 41
Ca	20	40.07	(2)	40; (44)
Fe	26	55.84	(1)	56; (54) ?
Ni	28	58.68	2	58; 60
Zn	30	65.37	4	64; 66; 68; 70
As	33	74.96	1	75
Se	34	79.2	6	80; 78; 76; 82; 77; 74
Br	35	79.92	2	79; 81
Kr	36	82.92	6	84; 86; 82; 83; 80; 78
Rb	37	85.45	2	85; 87
Sn	50	118.7	7 (8)	120; 118; 116; 124 119; 117; 122; (121)
I	53	126.92	1	127
Xe	54	130.2	7 (9)	129; 132; 131; 134; 136; 128; 130; (126); (124)
Cs	55	132.81	1	133
Hg	80	200.6	(6)	(197–200); 202; 204

What do the figures in the last two columns of the foregoing table really mean? Do they represent isotopes in the accepted meaning of the term, which are merely separated by the bombardment? Or are they a record of an elemental disintegration? These alternative interpretations are both tenable, and each one can be sustained by cogent arguments. The second question is answered by Aston in the affirmative; and his views have been generally accepted or at least favored. On the other hand, the isotopes of the radioactive series are definitely products of decomposition, and those of the mass spectra may be of the same order.

The last column of the table is extremely suggestive. The simplest elements, those of low atomic weight, show little or no isotopy. Twelve of them are simple substances and may be called pure or normal elements. Nine of them, up to and including nickel, are doubled, and two are represented as triplets. With zinc a greater degree of complexity appears, which, with some exceptions, tends to increase as the atomic weights become larger. This increase, however, represents only a distinct tendency, not a definite law. How far this rule may hold remains to be determined; and it is extremely desirable that the mass spectra of the elements above mercury in the scale of atomic weights should be examined—namely, those of thallium, lead, bismuth, thorium, and uranium. Such an examination would render a direct comparison with the radioactive series possible. Would the mass spectrum of lead, for example, show the same isotopes as those which have been revealed by radioactivity? That of uranium, also, should be very instructive. The most complex elements are the most easily decomposable and should show the greatest number and variety of fractions.

So far the evidence favors the hypothesis of decomposition; but there is also evidence to support the isotopic theory. By diffusion or by distillation three elements—namely, chlorine, zinc, and mercury—have been separated into fractions that differed in density and in atomic weight. Harkins and his colleagues,[37] by fractional diffusion of gaseous hydrochloric acid, have partially separated it into two portions, one heavier and the other lighter than the ordinary compound. The heavier portion gave an atomic weight for chlorine of 35.4918, which is 0.1 per cent higher than the accepted value, 35.46. The latter value has been determined with the greatest accuracy and is probably correct within 1 part in 10,000. Results similar to those of Harkins and Hayes, but by a different method, have been obtained by Brönsted and Hevesy,[38] who separated hydrochloric acid into two fractions corresponding to a difference of 0.024 in the atomic weight of chlorine. The chlorine atom, then, seems to be a doublet; but the remarkable uniformity of its chemically determined atomic weight is difficult to explain. A mere mixture of two isotopes could hardly be so definite unless all the compounds of chlorine that were used in the determination of its atomic weight had a common origin. That possibility is still under investigation. Is the chlorine of volcanic emanations, of meteoric iron, of oceanic salts, and of igneous rocks always the same thing, and of one definite atomic weight?

By fractional distillation mercury has been separated into two portions, one heavier than

[37] See especially Harkins, W. D., and Hayes, A., Am. Chem. Soc., Jour., vol. 43, p. 1403, 1921.

[38] Brönsted, J. N., and Hevesy, G., Nature, vol. 107, p. 619, 1921.

the other, as in the case of chlorine. Harkins and Madorsky[39] evaporated mercury in a vacuum and obtained two fractions that gave differences from the accepted atomic weight of the metal of +0.052 and −0.044. Brönsted and Hevesy,[40] by a similar process, obtained results of the same order. The same chemists, however, in a later investigation,[41] determined the density of ordinary mercury from ten widely separated sources and found differences of only 2 to 6 units in 10 millions. These differences in density correspond to differences in atomic weight of 0.0004 to 0.0012.

By very thorough determinations of atomic weight Hönigschmid and Birckenbach[42] have completed the evidence as to the composite nature of mercury. Brönsted and Hevesy supplied them with samples of their heavy and light fractions, with which the determinations were made—for the heavier fraction, Hg = 200.628 to 200.638; for the lighter fraction, Hg = 200.562 to 200.568. These differences are conclusive. For ordinary mercury the same chemists, aided by M. Steinheil,[43] found Hg = 200.61, the accepted value.

Ordinary or normal mercury, if we may call it so, is therefore uniform in character far within the limits of experimental uncertainty. The same is true of lead, as we have already seen; and the work of Baxter and his colaborers have shown it to be true of iron and nickel. The atomic weights of terrestrial iron and nickel are identical with those of the two meteoritic metals. In order to account for this uniformity we must assume in each case that the component isotopes must always have been mixed in constant and definite proportions.

For the possible complexity of zinc there is only the work of Egerton,[44] who in a preliminary note reports finding small differences in the density of the metal after distillation in a high vacuum. Two fractions gave densities of 0.9971 and 1.00076, when that of the initial substance was taken as unity. These results are regarded as promising.

So far a partial separation of chlorine and mercury into distinct fractions has been accomplished, although the differences between the fractions are very small. A complete separation is yet to be effected, so that each fraction can be weighed and examined by itself. If the mass spectra really represent isotopes there should be twelve possible isotopes of mercuric chloride, ranging in molecular weight from 232 to 241, a difference of 9 units in atomic mass. The fractional crystallization of mercuric chloride, then, or else precipitation of the mercury either by electrolysis or with some suitable reagent, might yield definite results. Other lines of attack upon the problem of separation have been suggested, and they are summarized by Aston in his book. Greater detail is not needed here.

Evidence of an entirely different character as to disintegration of elements has recently been obtained by Rutherford.[45] His procedure, briefly, is as follows: A stream of powerful alpha rays, emitted from a very thin film of radium C, is passed through a current of hydrogen. A number of high-speed hydrogen atoms are liberated, which strike upon a screen of zinc sulphide and produce scintillations that can be observed through a microscope and counted. Between the zinc sulphide and the radioactive source thin screens of mica are inserted, which can be varied in thickness, so as to measure the relative penetrating power of the alpha particles and of the hydrogen atoms. The range of the hydrogen atoms is much greater than that of the alpha rays and so gives a datum for their identification. Their appearance, as found by the scintillations on the zinc sulphide, identifies them as hydrogen.

Suppose, now, that some other gas replaces hydrogen. With nitrogen the same long-range particles appear, this giving evidence that the lighter element is a constituent of the nuclei of the heavier atoms and has been separated from them. With oxygen or carbon dioxide no such change is observed, a very significant difference. The molecular weights of these gases are whole multiples of that of helium, from which carbon and oxygen are supposed to have been built up.

By this general method, with modifications in the case of solid substances, Rutherford has tested all the elements up to atomic weight 40, with the exception of helium, neon, and argon. Several other elements, higher in the

[39] Harkins, W. D., and Madorsky, S. L., Am. Chem. Soc. Jour., vol. 45, p. 591, 1922.
[40] Brönsted, J. N., and Hevesy, G., Nature, vol. 106, p. 145, 1921.
[41] Zeitschr. anorg. allgem. Chemie, vol. 124, p. 22, 1922.
[42] Hönigschmid, O., and Birckenbach, L., Deutsch. chem. Gesell. Ber., vol. 56, p. 1219, 1923.
[43] Idem, p. 1212.
[44] Egerton, A. C., Nature, vol. 110, p. 773, 1922.
[45] Rutherford, Sir Ernest, Nature, vol. 109, pp. 584–586, 614–617, 1922.

scale, were also tested, but none above phosphorus gave positive results. Boron, nitrogen, fluorine, sodium, aluminum, and phosphorus yielded long-range particles, from which it is concluded that hydrogen atoms are contained in their atomic nuclei. Elements with atomic weights that are whole multiples of 4 give no hydrogen particles when bombarded with alpha rays. The hydrogen-helium theory of the constitution of the elements thus receives some support. Will it hold good for the more complex elements? That remains to be seen. Not until an element has been completely disintegrated into identifiable hydrogen and helium can the question be definitely answered. So far only a few atoms among millions have given evidence of atomic disintegration, and we can only guess at what remains after the hydrogen particles have been expelled. However, a promising attempt has been made toward the artificial breaking down of atomic nuclei, but it is only a beginning. It would be unfair to expect much more in so young a field of research.

That the evolution of a star is accompanied by an evolution of the chemical elements seems to be established, at least to a high degree of probability. But is the process ever reversed? This question can be answered in the affirmative. Every now and then an insignificant star, visible only through a telescope, suddenly flashes into great brilliancy, sometimes even rivaling Sirius in brightness. This condition lasts for a short time, and then the "new star" gradually fades away and returns to something like its former insignificance. So much is shown by the telescope alone, but when the spectroscope is also used much more is revealed. The spectrum and therefore the composition of the star has changed, and a complex system has reverted to something simpler. When the reversal is complete its end product is a planetary nebula with a Wolf-Rayet star as a nucleus. In some cases the reversal does not go so far, and these exceptions are probably due to differences in the violence of the outburst that was revealed by the sudden appearance of the supposedly new star. The term new, however, is hardly appropriate: what has really happened was the almost instantaneous transformation of a dwarf star into a giant. In recent years the complete reversion to the nebular type has been repeatedly observed and recorded upon photographic plates.[46]

The close relation between planetary nebulae and Wolf-Rayet stars has been emphasized by Adams and Pease and also by Wright. Adams and Pease even go so far as to suggest that some of these peculiar stars were probably at some former time novae from which the nebular gases have disappeared. This is not at all improbable, for the spectra of the Wolf-Rayet stars are found to contain many lines of no known origin. Do they represent decomposition products, the end results of atomic disintegration? The novae at the summit of their careers have enormously high temperatures, at which few of our familiar elements could exist. The conclusion is almost inevitable that the process of elemental evolution has been reversed, but if that is true, what are these decomposition products, and how can they be included in the scale of atomic numbers? To this question no answer can yet be given. The evidence of disintegration, however, seems to be very strong.

To what cause, now, can we attribute the phenomena of the novae? On this subject there are two principal hypotheses. One assumes a collision between two stars, two huge masses, moving with great velocity and so generating the heat that is revealed by the brilliancy of the new star. This hypothesis, however plausible it may be, is not now generally held and needs no further consideration here. The probability of such collisions is very slight.

The other hypothesis, which seems to be more probable, assumes that a single star passes through a dark nebula, or else through a cloud of meteoric dust, with retardation of motion, attendant friction, and therefore a great development of heat. The same thing happens, but on a much smaller scale, when a meteorite enters the atmosphere of the Earth. The difference is merely one of degree. In the larger body the heat is sufficient to disintegrate the elements; in the smaller it only melts a thin film on the surface of the falling mass which is broken up into fragments.

[46] For examples see Cannon, Annie J., Harvard Coll. Observatory Annals, vol. 81, No. 3, 1920; Adams, W. S., and Pease, F. G., Nat. Acad. Proc., vol. 1, p. 391, 1915, and Astrophys. Jour., vol. 40, p. 294, 1914; Wright, W. H., idem, p. 466. Nova Geminorum No. 2 and Nova Aquilae No. 3 are two of the most typical instances of the reversal of a star to a primitive type. I am indebted to Professor Harlow Shapley for Miss Cannon's paper on Nova Aquilae.

AN EARLY EOCENE FLORULE FROM CENTRAL TEXAS.

By Edward Wilber Berry.

In 1916 I described [1] a florule collected by Alexander Deussen and L. W. Stephenson at the town of Earle, in Bexar County, Tex. This florule was tentatively considered of Midway age by these geologists, and examination of the fossil plants tended to confirm this assignment, particularly because of their lack of harmony with the extensive Wilcox flora described in the volume cited above and because of their resemblance to the described floras from the Raton and Denver formations of Colorado and New Mexico.

Subsequently, without any very definite evidence, the rocks in the area around Earle came to be regarded as of Wilcox age and were so mapped by Sellards.[2] I visited the locality in 1921 in company with A. C. Trowbridge and L. W. Stephenson but found no additional plant species.

Recently I received from O. M. Ball, of the Agricultural and Mechanical College of Texas, a small collection of fossil plants obtained near Sayersville, which is about 8 miles north of Bastrop, in Bastrop County. This collection was found to represent the same flora as that found at Earle and had been preserved in a lithologically identical sandstone. This locality is about 100 miles northeast of Earle and is in about the same relative position in the belt in Bastrop County mapped as Wilcox on Deussen's new map [3] as the locality at Earle in the Wilcox belt in Bexar County shown on the same map.

The Bastrop County locality is along the railroad about 100 yards north of the station at Sayersville. The sandstone in which the fossil leaves were found is overlain by about 10 feet of reddish clay and consists of mostly coarse, well-rounded grains in a highly calcareous cement. It is very similar in appearance to the concretionary masses often found in the Midway of Texas and is exactly like that containing the leaves at Earle, in Bexar County.

The florule from Earle contains the following species:

Pourouma texana Berry.
Ficus denveriana Cockerell.
Ficus occidentalis (Lesquereux) Lesquereux.
Ficus sp.
Platanus aceroides latifolia Knowlton.
Cinnamomum affine Lesquereux.
Laurus wardiana Knowlton.
Asimina eocenica Lesquereux.
Dolichites deusseni Berry.
Terminalia hilgardiana (Lesquereux) Berry.

Of these 10 species but 3—*Ficus denveriana*, *Ficus* sp., and *Terminalia hilgardiana*—had been recorded from the very extensive Wilcox flora, and in part because of this fact, coupled with the total absence of the genera *Pourouma*, *Platanus*, and *Dolichites* in the Wilcox, I was led to consider the Earle outcrop more probably Midway than Wilcox.

The recent collection from Bastrop County contains the following species:

Pourouma texana Berry.
Laurus wardiana Knowlton.
Asimina eocenica Lesquereux.
Terminalia hilgardiana (Lesquereux) Berry.
Asplenium primero Knowlton.
Viburnum sp.
Mespilodaphne precoushatta Berry, n. sp.
Rhamnites marginatus apiculatus?
Ficus post-trinervis Knowlton.
Rhamnus sp.
Terminalia lesleyana (Lesquereux) Berry.
Sapindus? sp.

Four of these species—*Pourouma texana*, *Laurus wardiana*, *Asimina eocenica*, and *Terminalia hilgardiana*—are common to the two localities and are the most abundant forms at both. The combined list from these two localities amounts to 18 species, of which four

[1] Berry, E. W., The lower Eocene floras of southeastern North America: U. S. Geol. Survey Prof. Paper 91, pp. 8-20, 1916.
[2] Sellards, E. H., The geology and mineral resources of Bexar County: Texas Univ. Bull. 1932, 1920.
[3] Deussen, Alexander, Geology of the Coastal Plain of Texas west of Brazos River: U. S. Geol. Survey Prof. Paper 126, pl. 8 (in press).

are doubtfully determined because of their fragmentary nature or lack of specific character due to the coarseness of the matrix.

The aspect of this assemblage as a whole is in rather marked contrast to that of the known Wilcox flora, which consists, according to the latest revision,[4] of 353 species and constitutes as complete and representative a flora as has been found at any geologic horizon. Of this large number of plants in the Wilcox only six, and one of these doubtfully, have been recognized at Earle or Sayersville, and this is exactly one-third of the forms represented at the two localities. Twelve species, or two-thirds of the whole, are different from anything known in the large Wilcox flora. Three of these are peculiar to the two localities in Bexar and Bastrop counties; nine have been found elsewhere. Of these nine species, one occurs in the Denver, Fort Union, and Hanna formations and doubtfully in the Mesaverde formation; six occur in the Raton formation; three occur in the true Laramie, and one of these is doubtfully recorded from the Dawson arkose. Of the forms common to the known Wilcox, three are certainly and one additional is doubtfully recorded from the Laramie, and one of these is found in the Lance.

The Wilcox flora falls naturally into lower, middle, and upper assemblages, and these have demonstrated that the Wilcox sedimentation was transgressive both northward up the Mississippi embayment and westward west of Mississippi River. No lower Wilcox plants have been recognized at any outcrops west of the Mississippi unless the plants from Earle and Sayersville are lower Wilcox.

Of the six Wilcox plants found at Earle and Sayersville one, *Ficus denveriana*, is known only from the upper Wilcox, but as this species is commoner in and characteristic of the Denver and Raton formations of the West, which I regard as older than the Wilcox, it can not be considered as indicative of age within the Wilcox. Another, *Ficus* sp., is found in the middle Wilcox. The other four—*Ficus occidentalis*, *Rhamnus marginatus apiculatus*, *Terminalia hilgardiana*, and *Terminalia lesleyana*—range from the bottom to the top of the Wilcox, and the occurrence of all of these, except the *Rhamnus* in the Raton formation of Colorado and New Mexico, which is probably older than the Wilcox, stamps these forms as abundant, long ranging, and without precise stratigraphic significance.

The Wilcox group in Alabama, where it contains marine faunas, is divided into four formations—from oldest to youngest the Nanafalia, Tuscahoma, Bashi, and Hatchetigbee. To the northwest, in Mississippi, where the sediments pass into those representing Eocene barrier beaches and lagoonal and estuarine clays, marine fossils are almost entirely absent, and the Wilcox group is divided, in ascending order, into the Ackerman, Holly Springs, and Grenada formations, each characterized by distinctive floral assemblages. In Tennessee the Wilcox deposits have not yet been differentiated into formations and are included in the Lagrange formation, although the floras of the Holly Springs and Grenada formations of Mississippi are represented in Tennessee.

There is some faunal as well as other evidence for correlating the Grenada formation of Mississippi with the Hachetigbee formation of Alabama. The Holly Springs sand of Mississippi is thought to represent the Bashi formation of Alabama, with its faunal and other evidence of the shoaling of the water; and the Ackerman formation of Mississippi is thought to represent the Tuscahoma formation of Alabama and also more or less of the upper part of the Nanafalia formation. The relations sketched above are shown graphically in a paper published in 1915,[5] and subsequent studies have fully confirmed the conclusions expressed in that paper.

Throughout the rest of the area occupied by the Wilcox to the west and southwest as far as the Mexican border it has not yet been found feasible to subdivide the deposits except in a small area in southwestern Texas, where Trowbridge[6] has recently proposed dividing them, in ascending order, into the Indio, Carrizo, and Bigford formations. The oldest of these, the Indio, contains oyster beds and marine Foraminifera, as well as lignite and poorly preserved plants. The plants, of which

[4] Berry, E. W., Additions to the flora of the Wilcox group: U. S. Geol. Survey Prof. Paper 131, pp. 1–21, 1922.

[5] Berry, E. W., Erosion intervals in the Eocene of the Mississippi embayment: U. S. Geol. Survey Prof. Paper 95, fig. 27, 1915.

[6] Trowbridge, A. C., A geologic reconnaissance in the Gulf Coastal Plain of Texas near the Rio Grande: U. S. Geol. Survey Prof. Paper 131, pp. 85–117, 1922.

a considerable number have been satisfactorily identified, are distinctly younger than the known lower Wilcox floras found in the eastern part of the Mississippi embayment—that is, in the Ackerman formation of the eastern Gulf area. These Indio plants could be considered as representing either the Holly Springs or the Grenada epoch of the Mississippi succession. The Indio formation is overlain in southwestern Texas by the transgressive Carrizo sandstone, which as traced toward the Rio Grande merges into the lithologically dissimilar Bigford formation. Both the Carrizo and the Bigford formations have furnished a considerable flora, which is of sufficient variety and precision to prove that they are of upper Wilcox age and is in striking contrast to the flora found near the base of the Mount Selman, the lowest formation of the overlying Claiborne group, in the same area.

As the foregoing brief sketch makes clear, nothing has thus far been discovered corresponding to the conditions found in Bexar and Bastrop counties, and there is no known paleobotanic evidence of the presence of lower Wilcox sediments in the Coastal Plain of Texas, or, in fact, anywhere west of Mississippi River.

The distribution of the plants that form the basis of the present contribution is shown in the accompanying table, from which it will be seen that several of these plants, in their distribution in other regions, are strongly suggestive of a greater age than the Wilcox. There are two alternative conclusions—either that this flora indicates a Midway age, or that it represents an early Wilcox flora that was more ancient than the flora of the Ackerman formation of the eastern Gulf area, which, as previously stated, represents the upper Nanafalia and all of the Tuscahoma of the Alabama section. Perhaps a third possibility might be added, namely, that it may represent a flora that lived in central Texas during the time which there is reason to think intervened between the deposition of the known Midway and that of the known Wilcox in the region to the east of central Texas.

I know of no method by which this question can be conclusively settled at the present time, as the Midway has never furnished satisfactorily determinable plant fossils. In 1910 I collected three species of dicotyledonous leaves from the Porters Creek Midway near Middleton, Tenn., and one of these appears to represent the Vermejo species *Ficus leei* Knowlton.[7] In 1921 Bruce Wade collected five species of plants near the base of the Porters Creek clay in Carroll County, Tenn. None of these are sufficiently well preserved to be satisfactorily determined, although one represents a fern, probably referable to the genus *Dryopteris*, and another suggests *Asimina eocenica*, which is one of the common forms at Earle and Sayersville, Tex. My own preference, which I can not say amounts to a conviction, would be to regard the flora under discussion as of Midway age. If it is really early Wilcox, as the geologists who have studied the areal relations of the Midway and Wilcox in Texas are inclined to consider it, it is of sufficient importance to merit the present discussion.

I have reproduced in Figure 8 a sketch map published originally in 1915,[8] showing the areal distribution of the lower, middle, and upper Wilcox floras. No exceptions to this interpretation have been discovered during the last 10 years unless the florules found at Earle and Sayersville form such an exception, and the abundant evidence of the transgressive character of the middle and upper Wilcox in Texas is one of the strongest reasons for considering these florules to be of Midway age.

If the Earle and Sayersville florules represent early Wilcox time, and I am frank to admit that they may, they indicate the probability that there may be other and similar areas in the western Gulf region that were not completely transgressed by the later Wilcox, which is the only part of the Wilcox that has been paleobotanically recognized in that whole region.

Such of the forms found at Sayersville as warrant the space are discussed in the following pages. The subjoined table presents the known distribution of the species found at Earle and Sayersville.

[7] Knowlton, F. H., Fossil floras of the Vermejo and Raton formations of Colorado and New Mexico: U. S. Geol. Survey Prof. Paper 101, p. 261, pl. 39, figs. 1-6; pl. 40, figs. 1, 2, 1918.

[8] U. S. Geol. Survey Prof. Paper 95, fig. 29, 1915.

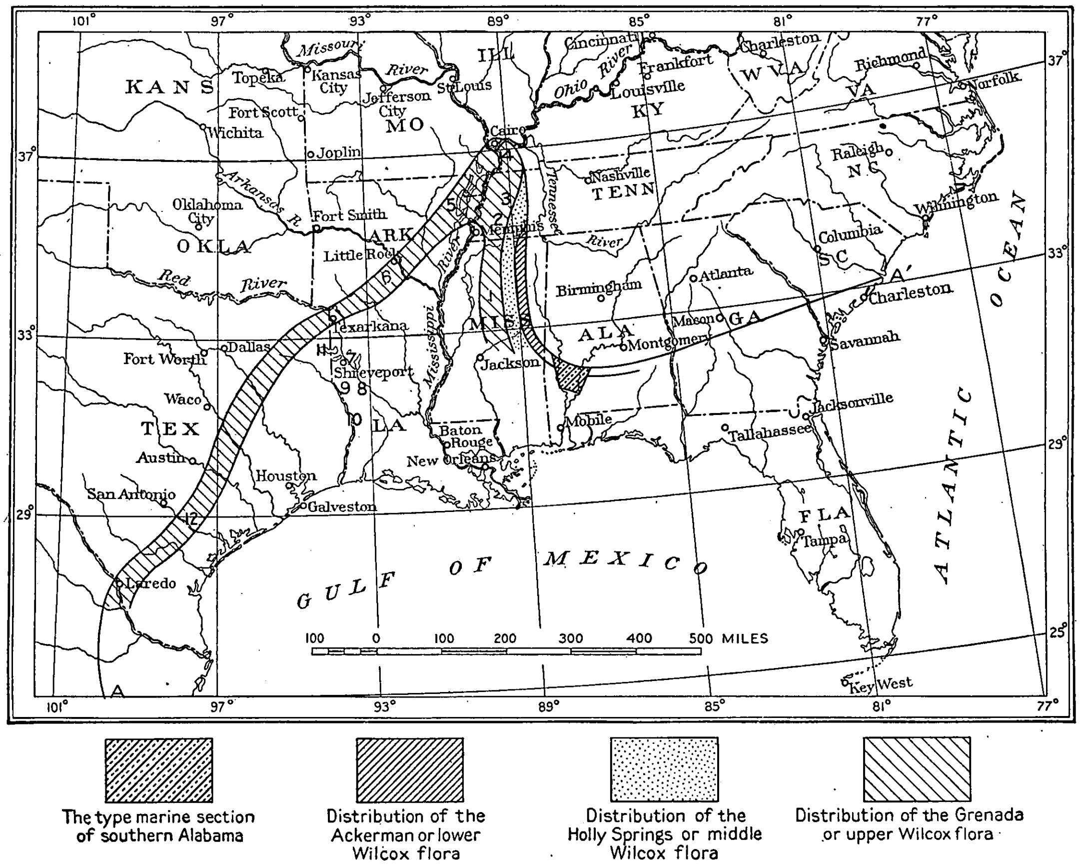


FIGURE 8.—Sketch map showing areal relations of the Wilcox floras. A–A', Maximum extent of the Wilcox transgression. Localities at which upper Wilcox species have been collected: 1, Grenada, Miss.; 2, Somerville, Tenn.; 3, near Trenton, Tenn.; 4, Wickliffe and Boaz, Ky.; 5, Bolivar Creek, Hardys Mill, and other localities on Crowleys Ridge, Ark.; 6, Benton and Malvern, Ark.; 7, several localities at or near Shreveport, La.; 8, Coushatta, La.; 9, around Mansfield and Naborton, La.; 10, Sabine River; 11, Old Port Caddo Landing, Tex.; 12, Calaveras Creek, Tex.

Distribution of florules found at Earle and Sayersville, Tex.

	Earle.	Sayersville.	Lower Wilcox.	Middle Wilcox.	Upper Wilcox.	Raton formation.	Denver formation.	Fort Union formation.	Hanna formation.	Mesaverde formation.	Laramie formation.	Lance formation.	Dawson arkose.
Asimina eocenica	×	×					×	×	×	(?)			
Asplenium primero		×				×							
Cinnamomum affine	×										×		
Dolichites deusseni	×												
Ficus post-trinervis		(?)									×		
Ficus denveriana	×				×	×	×	×			(?)	×	
Ficus occidentalis	×		×		×	×	×						
Ficus sp	×			×									
Laurus wardiana	×	×									×		(?)
Mespilodaphne precoushatta		×											
Platanus aceroides latifolia	×					×							
Pourouma texana	×	×											
Rhamnus marginatus apiculatus		(?)	×	×	×								
Rhamus sp		×											
Sapindus? sp		×											
Terminalia hilgardiana	×	×	×	×	×	×							
Terminalia lesleyana		×	×	×	×	×							
Viburnum sp		×											

Asplenium? primero Knowlton.

Plate XXIII, Figure 1.

Asplenium? primero Knowlton, U. S. Geol. Survey Prof. Paper 101, p. 285, pl. 44, fig. 4, 1917.

This species was based on the single specimen figured by Knowlton, which came from the Raton formation at Primero, Colo. It is described as follows by Knowlton:

Frond broadly lanceolate in general outline, twice pinnatifid; pinnae alternate, approximate, the lower ones lanceolate, the middle and upper ones linear, all decurrent on the rachis; lower pinnae deeply cut into numerous acute teeth, these becoming less and less marked until in the upper part they are merely slight indentations or at the extreme tip are wholly absent; nervation relatively simple, consisting of a strong midrib or secondary rachis in the pinnae, from which arise secondary branches passing to the tips of the segments or teeth, each of these again with from two to four pairs of simple branches.

A single specimen from Sayersville appears to represent a portion of the distal part of a pinna of this species. The venation is obscure, but the size and disposition of the pinnules and their characteristically toothed margins render the identification satisfactory. There are eight species of ferns recorded from the Wilcox, two of which have been referred to the genus *Asplenium*, but both of these are quite unlike *Asplenium? primero*.

Mespilodaphne precoushatta Berry, n. sp.

Plate XXIII, Figure 2.

Leaves of medium size, relatively broad, oval in general outline, widest medianly, and tapering about equally to the apex and base. Apex cuneate. Base acute. Margins entire, rather regularly and evenly rounded. Texture coriaceous. Length about 9.25 centimeters, maximum width about 4.1 centimeters. Petiole long and stout, about 2 centimeters in length. Midrib stout, prominent. Secondaries mediumly stout and prominent, eight or nine somewhat irregularly spaced pairs; closely spaced and opposite in the base, less closely spaced and subparallel to about the middle, above which they are about twice as far apart; they diverge from the midrib at angles of more than 45° and are camptodrome in the marginal region. Occasionally a subsecondary runs midway between and subparallel to the adjacent secondaries in the apical part of the leaf, where the true secondaries are more widely spaced, and one basal secondary shows abnormal branching. An apparently characteristic feature of this species is the crowding of the lower secondaries in the basal part of the leaf. The tertiaries are thin, transverse, and either percurrent or anastomosing.

This well-marked species appears to have been the immediate precursor of the rather abundant late middle and upper Wilcox species *Mespilodaphne coushatta* Berry.[9] It differs from that species in its larger size, slightly more coriaceous texture, relatively shorter petiole, more numerous secondaries, less frequently anastomosing tertiaries, and basal crowding of the secondaries. It is confined to the locality at Sayersville, in Bastrop County.

Terminalia lesleyana (Lesquereux) Berry.

Plate XXIII, Figure 3.

Magnolia lesleyana Lesquereux, Am. Philos. Soc. Trans., vol. 13, p. 421, pl. 21, figs. 1, 2, 1869; Tertiary flora, p. 248, pl. 44, figs. 1–3, 1878.
Knowlton, U. S. Geol. Survey Prof. Paper 101, p. 313, pl. 82, figs. 1–2, 1918.
Terminalia lesleyana Berry, U. S. Geol. Survey Prof. Paper 91, p. 323, pl. 89, fig. 4, 1916.

The type horizon for this species was the lower Wilcox or Ackerman formation in Mississippi, but it has since been found to range into the middle and upper Wilcox and was a fairly common coastal tree along the shores of the Wilcox Mississippi embayment. It has also been recorded from the Raton formation of Colorado and New Mexico by both Lesquereux and Knowlton. I regard the Raton formation as older than the Wilcox, and it is therefore not surprising that this species should turn up in the present association in an area nearer the western occurrences than it has been hitherto found.

As Knowlton accepts Lesquereux's reference of this species to the genus *Magnolia* a few comments may not be out of place. Hilgard submitted his early collections from Mississippi, from what has since been named the Ackerman formation, to Lesquereux, who identified the present species as a *Terminalia*, and it was so listed in Hilgard's report.[10] When the similar

[9] Berry, E. W., The lower Eocene floras of southeastern North America: U. S. Geol. Survey Prof. Paper 91, p. 307, pl. 80, fig. 6; pl. 87, fig. 3, 1916.

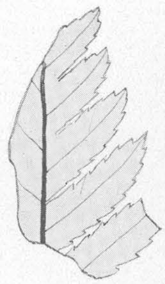
[10] Hilgard, E. W., Report on the geology and agriculture of the State of Mississippi, p. 113, 1860.

leaves that have since been considered to represent this species were collected in the Fishers Peak region of New Mexico from what has since been named the Raton formation, Lesquereux considered them identical with the European fossil species *Terminalia radobojensis* Heer. Subsequently Lesquereux transferred them to the genus *Magnolia*, comparing them with the existing species *Magnolia tripetala*. When I was preparing the report on the Wilcox flora I compared these fossil leaves with those of the existing species of both *Magnolia* and *Terminalia* and reached the conclusion that in every essential respect they differed from the former and resembled the latter. I therefore transferred them back to *Terminalia* thus confirming Lesquereux's original determination. I also reached the conclusion that a considerable number of fossil species which masquerade in the literature of paleobotany as *Magnolia* probably do not represent that genus.

Terminalia lesleyana is not, in my judgment, particularly like *Magnolia tripetala* in any features. Although smaller, it is stouter, coarser, and smoother, with a different shape and different base from any of the true Magnolias. The midrib is very stout, as are also the fewer secondaries—in fact, the venation is not that of the genus *Magnolia*. On the other hand, in all the features that are available for comparison it resembles the leaves of several recent American species of *Terminalia*, as well as certain European Tertiary species that have been referred to that genus. Moreover, American Tertiary floras of warmer climatic aspects contain several other species of *Terminalia*, in more than one locality represented by fruits that supplement and corroborate the identifications of the leaves.

Terminalia, represented by one species founded on fruits and two founded on leaves, is common in the Wilcox of the Mississippi embayment, and it is also represented in that region throughout the middle (Claiborne) and upper (Jackson) Eocene.

Terminalia lesleyana occurs at the Sayersville locality, in Bastrop County, but the associated *Terminalia hilgardiana* is present at both Sayersville and Earle, and both species are found throughout the lower, middle, and upper Wilcox of the eastern Gulf region.



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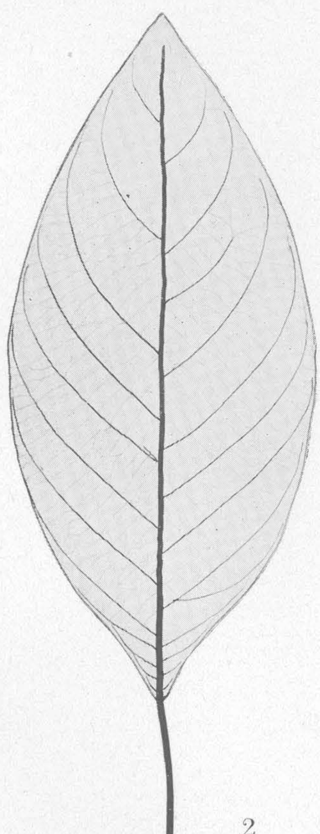

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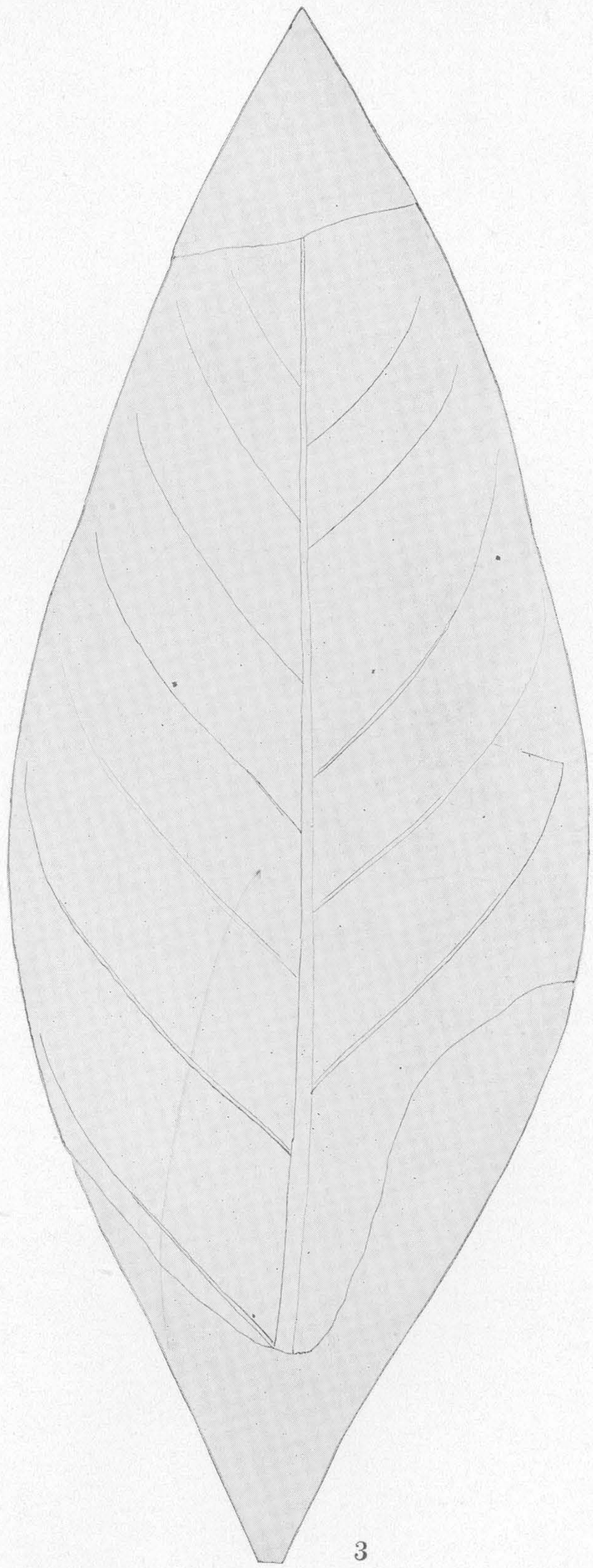


3

FOSSIL PLANTS FROM THE EARLY EOCENE AT SAYERSVILLE, TEX.

1. *Asplenium? primero* Knowlton. **2.** *Mespilodaphne precoushatta* Berry, n. sp. **3.** *Terminalia lesleyana* (Lesquereux) Berry.

RELATIONS OF THE WASATCH AND GREEN RIVER FORMATIONS IN NORTHWESTERN COLORADO AND SOUTHERN WYOMING, WITH NOTES ON OIL SHALE IN THE GREEN RIVER FORMATION.

By J. D. Sears and W. H. Bradley.

INTRODUCTION.

PURPOSE AND SCOPE OF THE REPORT.

Since the early geologic explorations of Powell, King, and Hayden the Eocene deposits of the Rocky Mountain and Plateau provinces have been the object of much attention by stratigraphers. More widespread interest in these deposits has been stimulated by the discovery of vast quantities of oil shale in the Green River formation of Wyoming, Colorado, and Utah.

The writers have had an opportunity to see the depositional edge of the Eocene formations on the northeast flank of the Uinta Mountains and to study the significance of their character along this margin as compared with their character farther out in the basin. The purpose of this report is to describe the lithology, areal distribution, and interfingering of the Wasatch and Green River formations in northwestern Colorado and southern Wyoming and to draw conclusions as to their source of material, mode of origin, time relations, and proper nomenclature. The method and place of deposition are of special importance in considering the Green River formation, as they largely determine the relative richness of the oil shale found in that formation.

EARLIER INVESTIGATIONS.

The area discussed in this paper is part of the region explored half a century ago by Hayden,[1] Powell,[2] Hague and Emmons,[3] and King.[4] Hayden named the Green River and Wasatch formations, and the latter name thus has priority over the "Vermilion Creek series" of King and the "Bitter Creek group" of Powell. In 1907 the western part of the Little Snake River coal field was examined by Ball.[5] In 1907 and 1908 Schultz [6] mapped in detail the coal-bearing formations of the Rock Springs uplift. As a result of this work and of later reconnaissance to the south and east, he prepared a map [7] covering most of the area described in this paper.

FIELD WORK.

In 1921 and 1922 a large part of Moffat County, Colo., and a few townships in southern Sweetwater County, Wyo., were examined by parties in charge of the senior writer. He was assisted in 1921 by K. K. Landes, in 1922 by James Gilluly, and in both seasons by the junior writer. Mapping was done largely by means of plane tables and telescopic alidades, on a system of triangulation extended westward and northwestward from the Craig quadrangle, Colorado. Isolated structural and areal features were mapped by means of stadia or pace traverses according to the degree of refinement desired. The mapping was tied to section corners at numerous points.

The geologic map (Pl. XXIV) accompanying this report is compiled from the work of Ball,

[1] Hayden, F. V., U. S. Geol. Survey Terr. Third Ann. Rept., 1869.

[2] Powell, J. W., Report on the geology of the eastern portion of the Uinta Mountains, U. S. Geol. and Geog. Survey Terr., 2d div., 1876.

[3] Hague, Arnold, and Emmons, S. F., U. S. Geol. Expl. 40th Par Rept., vol. 2, 1877.

[4] King, Clarence, idem, vol. 1, 1878.

[5] Ball, M. W., The western part of the Little Snake River coal field, Wyo.: U. S. Geol. Survey Bull. 341, pp. 243-255, 1909.

[6] Schultz, A. R., The northern part of the Rock Springs coal field, Sweetwater County, Wyo.: U. S. Geol. Survey Bull. 341, pp. 256-282, 1909; The southern part of the Rock Springs coal field, Sweetwater County, Wyo.: U. S. Geol. Survey Bull. 381, pp. 214-281, 1910.

[7] Schultz, A. R., Oil possibilities in and around Baxter Basin, in the Rock Springs uplift, Sweetwater County, Wyo.: U. S. Geol. Survey Bull. 702, pl. 1, 1920.

Schultz, and Sears. The location of the area is shown in Figure 9.

ACKNOWLEDGMENTS.

The writers gratefully acknowledge the cordial assistance and hospitality given by the local ranchers, especially Messrs. Sparks. Crozier, and Grounds.

TOPOGRAPHY.

In the southwestern part of the area mapped Cold Spring Mountain and other ridges on the north flank of the Uinta Mountains rise to an altitude of about 8,500 feet above sea level. To the north, northeast, and east is the Green River Basin, separated by the Rock Springs uplift into the Bridger Basin on the west and the Washakie and Sand Wash basins on the east. Although the Green River Basin is of less

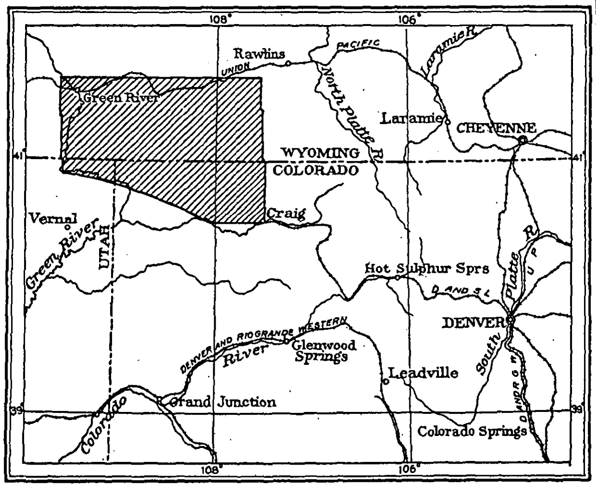


FIGURE 9.—Index map showing location of area in northwestern Colorado and southern Wyoming.

altitude than the Uinta Mountains it contains here and there high cliffs and isolated peaks; the highest point is Diamond Peak, 9,925 feet above sea level.

The major stream of the area mapped is Green River, which flows southward along its western margin. Green River, with its main tributaries, Bitter and Vermilion creeks, drains the Rock Springs uplift and a large part of the Washakie Basin. Across the southeast corner of the area runs Little Snake River, which, with its tributaries, Sand and Powder washes, drains the Sand Wash Basin and part of the Washakie Basin.

STRATIGRAPHY.

WASATCH FORMATION.

The Wasatch deposits were named by Hayden [8] because of their excellent exposures on the eastern slopes of the Wasatch Mountains. Their lithologic character in that region is illustrated by his brief description of their appearance in Echo and Weber canyons, Utah, where the formation consists of 1,500 to 2,000 feet of conglomerate. In a later report Hayden [9] described this section more fully, noting the large size and well-rounded shape of the boulders and the predominant red color of the sandstones that make up the lower 500 to 800 feet of the formation. He noted also the rapid lateral changes near the base from fine sand to coarse conglomerate.

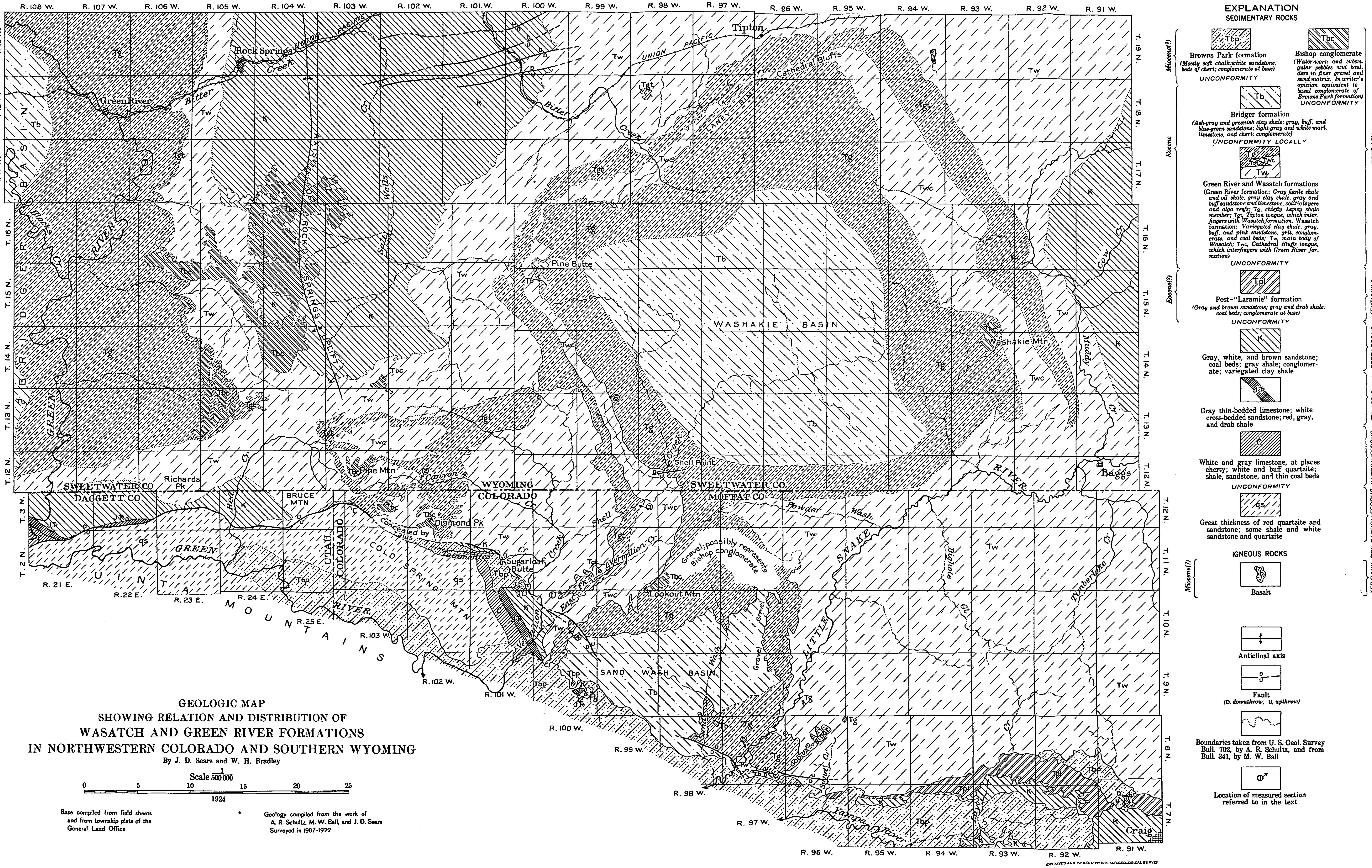
It is perhaps unfortunate that the name was taken from the Wasatch Mountains, where the formation has a lithologic character very different from that shown in most other areas. Hayden [10] described the Wasatch at Carter Station, Wyo., as consisting of pink, red, and purple indurated sandy clays, alternating with gray and reddish sandstones; this description is more applicable to the formation throughout most of its area of distribution. Hayden believed that the beds were deposited in large fresh-water lakes.

Within the area mapped by the writers in 1921–22 the Wasatch consists chiefly of variegated clay shale and irregular, crudely bedded sandstone. The predominant colors of the clay shale are red and gray, commonly banded with yellow, lavender, pink, brown, pale green, drab, and other shades. Most of the sandstone is gray, buff, or dark brown; a few beds are white, pink, or red. The materials of the sandy beds range in size from very fine grains to coarse grits, and locally the sandstone grades into conglomerate carrying boulders as much as 6 feet in diameter.

In the Vermilion Creek basin the middle part of the Wasatch contains a few beds of coal, fissile carbonaceous shale, shell marl, and many more beds of sandstone than elsewhere in the field.

In general the Wasatch formation weathers into typical badlands that support little or no vegetation. Topography of this kind is varied

[8] Hayden, F. V., U. S. Geol. and Geog. Survey Terr. Third Ann. Rept., p. 91, 1869.
[9] Idem, Fourth Ann. Rept., pp. 147, 155–156, 1871.
[10] Idem, p. 147.



GEOLOGIC MAP
SHOWING RELATION AND DISTRIBUTION OF
WASATCH AND GREEN RIVER FORMATIONS
IN NORTHWESTERN COLORADO AND SOUTHERN WYOMING

By J. D. Sears and W. H. Bradley

Base compiled from field sheets and from township plats of the General Land Office

Geology compiled from the work of A. R. Schultz, M. W. Ball, and J. D. Sears
Surveyed in 1907-1922

ENGRAVED AND PRINTED BY THE U.S.GEOLOGICAL SURVEY

by low escarpments and benches where the sandstone is comparatively resistant.

GREEN RIVER FORMATION.

Remarkable exposures along Green River led Hayden [11] to apply the name of that stream to the series of shale and sandstone overlying his Wasatch "group." The type locality of the formation is at the town of Green River, Wyo., where, according to Winchester,[12] an incomplete section has a thickness of 755 feet. Other sections near by,[13] in Tps. 17 and 19 N., R. 106 W., show a thickness of approximately 1,350 feet. In all these sections a coarse, massive brown sandstone, 125 to 245 feet thick (the "Tower sandstone" of Powell), is included in the top of the formation. The remainder of the formation at the type locality consists almost entirely of finely laminated shale, some of which is rich oil shale. A few beds of thin platy sandstone and sandy shale occur at wide intervals in these sections. A very striking feature of the Green River in this part of the field is its bluish-white color on weathered surfaces.

Farther southeast, in the outcrops surrounding the Washakie and Sand Wash basins, the formation shows a somewhat different lithology. The "Tower sandstone" of Powell was not recognized by the writers in the southern part of this area, but it may be represented by one or more of the sandstones in the upper part of their Green River. The contact between this formation and the overlying Bridger was difficult to determine; it was drawn in the field at the horizon considered to mark most plainly a change in conditions of sedimentation. This mapping includes at the top of the Green River about 135 feet of beds that resemble somewhat the overlying as well as the underlying rocks. The Green River in this part of the field is about 1,200 feet thick and consists principally of finely laminated shales, many of which are very limy, and some beds of low-grade oil shale. The formation weathers to a characteristic buff color. In the upper 500 or 600 feet there is a greater amount of clay shale and thin-bedded to massive sandstone. A few thin beds of oolitic limestone, generally silicified, and calcareous alga reefs are scattered through the section.

The Green River formation is peculiarly resistant to weathering and rises in high, steep cliffs of monotonous buff, gray, or bluish-white tints, contrasting sharply with the brightly colored badlands of the Wasatch. Almost as striking is the contrast between the Green River and the overlying Bridger, which weathers into fantastic badlands of ash or bluish gray, varied by dark-green and light-bluish sandstones and a few patches of red and orange-colored clay shale.

STRUCTURE.

The southern margin of the field is the north flank of the Uinta Mountain-Axial Basin arch. West of Little Snake River the Eocene beds, dipping away from the mountains, rest with marked angular unconformity upon the upturned edges of Mesozoic rocks, showing that uplift of the Uinta region both preceded and followed Eocene deposition. Farther southeast no angular unconformity is found below the Wasatch and Green River, a fact which indicates that movement of the Axial Basin anticline began after the end of Eocene time.

North of this great uplift is the broad Green River Basin, which in the area here mapped is divided by the north-south Rock Springs uplift into two synclinal depressions. The western depression, known as the Bridger Basin, is partly within this area. The eastern depression is separated by one or two east-west arches into the Washakie Basin on the north and the Sand Wash Basin on the south.

The present southern edge of the Eocene outcrops is determined partly by the original limits of deposition and partly by structure. At the southwest it is marked in part by the great Uinta fault, which extends for many miles westward from the northwest corner of Colorado; some if not all of the movement along this fault was post-Wasatch. It is possible that the fault between the Cretaceous and the Wasatch rocks, extending from Diamond Peak southeastward to a point beyond East Fork of Vermilion Creek, is a continuation of the Uinta fault, but their relation is concealed by recent débris.

From Vermilion Creek southeastward to Sand Creek the margin of Eocene deposits is marked by a zone of en échelon faults and sharp anticlines. These and other faults farther out in the basin have no bearing on the character and relations of the Wasatch and Green River and need not be described here.

[11] Hayden, F. V., U. S. Geol. and Geog. Survey Terr. Third Ann. Rept., p. 90, 1869.
[12] Winchester, D. E., Oil shale of the Rocky Mountain region: U. S. Geol. Survey Bull. 729, p. 125, 1923.
[13] Idem, pp. 124-126.

ORIGIN AND RELATIONS OF THE WASATCH AND GREEN RIVER FORMATIONS.

THE UINTA MOUNTAINS AS A SOURCE OF MATERIAL.

Powell[14] noted the occurrence of thick conglomerates in the basal part of his "Bitter Creek group" (Wasatch formation) on the north side of the Uinta Mountains from Richards Peak, Wyo., to a point east of Bruce Mountain, Colo. The conglomerate consists of boulders and pebbles of sandstone and limestone; in the vicinity of Richards Peak the limestone boulders contain Jurassic fossils. From these facts Powell inferred that in Wasatch time erosion of the Uinta Mountains had in places reached the Carboniferous rocks; that the conglomerate referred to was formed from sandstone and limestone of Mesozoic age, and, to a lesser extent, of Carboniferous age; and "that the badland rocks of Mesozoic age were carried from the Uinta region and redistributed as badland beds of the Bitter Creek period."[15] Powell[16] noted also that near the Uinta uplift the Green River formation "is much thickened, and the shales are replaced by sandstones and conglomerates of fine pebbles"; from this he inferred that the Green River was "derived from the Uinta region, and that the material was supplied from limestones and sandstones of Carboniferous age."

Additional evidence pointing to the Uinta Mountains as a source of material was collected by the writers in 1922. Conglomerates in both the Wasatch and the Green River are thickest and carry the largest boulders near the mountains and thin rapidly toward the basin. The most conspicuous example is at Sugarloaf Butte, in secs. 15 and 16, T. 11 N., R. 101 W., where there is in the lower part of the Wasatch an alternating series, 150 to 200 feet thick, of very coarse conglomerate, grit, and lenses of coarse cross-bedded friable buff to white sandstone. Most of the boulders are well rounded by stream action, but some are angular and subangular; the largest boulders are 6 feet in diameter. (See Pl. XXV, *A*.) This notable aggregation of coarse detritus, in which there is only the crudest kind of stratification, grades laterally within less than a mile to the north and east into carbonaceous shale, shell marl, and coarse but regularly bedded sandstone—the typical Wasatch assemblage of this vicinity. The interfingering of these several types is clearly exposed eastward in the bluffs along Talamantes Creek and to the north in deep tributary gulches. There can be no doubt that the material was derived from the Uinta uplift, as the conglomerate thins away from the mountains and consists principally of gray cherty limestone identical with the massive Carboniferous limestone now exposed high on the flank of Cold Spring Mountain, less than 2 miles to the southwest. Evidently the Carboniferous rocks of the uplift were being eroded during at least a part of Wasatch time.

Westward from Sugarloaf Butte the Wasatch contains near its base several beds of conglomeratic sandstone consisting of abundant white sugary-textured quartzite pebbles and boulders as much as 8 inches in diameter in a white or gray sandy matrix. These white quartzites are very similar to the Weber and older Pennsylvanian quartzitic sandstones exposed in the Uinta Mountains. Eastward from Sugarloaf Butte as far as East Fork of Vermilion Creek conglomerates in the lower Wasatch are characterized by pebbles of black chert; the source of the chert is unknown, but the pebbles strongly resemble those of the Dakota in color, roundness, and high polish, and they may have been reworked from that formation.

Eastward from Godiva Ridge several conglomeratic sandstones near the base of the Wasatch contain many well-rounded chert pebbles less than half an inch in diameter; these pebbles, predominantly white and to a lesser extent red and black, may have been derived either from the Uinta Mountains or from the Park Range, to the east.

The development of conglomerate close to the mountains is illustrated also in the Green River formation. Along Canyon Creek from sec. 18, T. 12 N., R. 101 W., westward to Pine Mountain the upper 300 feet of the Tipton tongue of the Green River formation is represented by massive medium to coarse grained sandstones separated by very thin partings of hard greenish shale. In these sandstones, especially in the upper ones, are zones of

[14] Powell, J. W., Report on the geology of the eastern portion of the Uinta Mountains, pp. 162–164, U. S. Geol. and Geog. Survey Terr., 2d div., 1876.
[15] Idem, p. 165.
[16] Idem, p. 166.

pebbles and boulders as large as 6 inches in diameter, of white and brown quartzite, angular red chert, hard shale, and cherty limestone; a few boulders consist of red quartzite lithologically identical with the red quartzite that forms the core of the Uinta Mountains. Schultz [17] noted these conglomeratic sandstones on Canyon Creek and says: "Upstream on Ruby Creek toward the mountains the percentage of conglomerate and the size of the pebbles rapidly increase. Within a mile boulders as large as 2 feet are encountered." Northward from the Canyon Creek coal mine, in sec. 17, T. 12 N., R. 101 W., the conglomeratic sandstone grades laterally into gray fissile shale that is characteristic of the Tipton tongue.

Another type of evidence pointing to the Uinta Mountains as a source of material may be summarized as follows. An erosional window in the Browns Park formation, in T. 9 N., R. 100 W., exposes the Bridger resting with marked angular unconformity upon Mancos and older Mesozoic rocks dipping northeastward on the flank of the Uinta Mountain arch. The Bridger is very conglomeratic, the boulders consisting largely of gray cherty limestone containing Carboniferous fossils. Inasmuch as a few miles farther north there is no angular unconformity between the Bridger and Green River, the fact that in T. 9 N., R. 100 W., the Bridger rests directly upon Mesozoic rocks seems to show that the Wasatch and Green River were not deposited this far south, and that the Bridger was laid down as an overlap beyond the margins of the older Eocene beds. This conclusion, together with the conglomeratic nature of the Bridger, indicates that the east end of the Uinta Mountains was never buried under Eocene beds but was the site of erosion that furnished the Eocene sediments. On the other hand, it seems probable that the Wasatch and Green River formations (and possibly the Bridger) of the Green River and Uinta basins were continuous around the east end of the mountains; this inference is drawn from the narrow interval (14 miles) now separating the northern and southern Wasatch and Green River outcrops east of Cross Mountain and from the lack of angular unconformity between Wasatch and Cretaceous rocks in the Axial Basin anticline, showing that that arch was not uplifted at the earliest until after Green River time.

[17] Schultz, A. R., Oil possibilities in and around Baxter Basin, in the Rock Springs uplift, Sweetwater County Wyo.: U. S. Geol. Survey Bull. 702, p. 31, 1920.

BROAD VARIATIONS AWAY FROM THE SOURCE.

In addition to the local changes within the formations near the mountains, there are large-scale lateral variations in the sediments farther out in the basin of deposition.

In the basin of Vermilion Creek the upper part of the Wasatch is principally variegated clay shale in which red is the predominant color. The lower part consists largely of gray and buff clay shale and sandstone; it includes also some brightly colored clay shale, a few beds of coal which in places are thick enough to be mined for local use, thin-bedded carbonaceous shale and interbedded shell marl (which superficially resemble the Green River formation), and at least one calcareous alga reef. In the vicinity of East Fork of Vermilion Creek, northeastward from sec. 4, T. 10 N., R. 100 W., a zone of clay shale and sandstone near the top of the lower Wasatch grades laterally into gray fissile shale of Green River appearance. Farther north this zone includes beds of low-grade oil shale; it thickens from about 200 feet in sec. 3, T. 10 N., R. 100 W., to nearly 400 feet in secs. 27 and 28, T. 12 N., R. 99 W. The method of thickening is illustrated at the base of the fissile shale in secs. 34 and 35, T. 11 N., R. 100 W., where a long wedge of papery, low-grade oil shale replaces toward the north a band of gray and buff clay shale, and the whole Green River zone thickens 100 feet in about a mile. Similar examples were noted elsewhere along the outcrop.

Thus the Wasatch is split northward into two parts by a wedge of very different material. The thickness of the lower part is unknown, as the base is not exposed. The upper part, called by Schultz [18] the Cathedral Bluffs red beds member of the Green River formation, is 1,200 feet thick at Lookout Mountain and 600 feet thick northwest of the Washakie Basin; westward and northwestward, according to Schultz, it merges laterally into typical Green River shale. The wedge of fissile shale and oil shale was named by Schultz [19] the Tipton shale member of the Green River formation.

[18] Idem, p. 28.
[19] Idem, p. 30.

On the east side of the Washakie-Sand Wash depression a similar change northward occurs in the Wasatch. Godiva Ridge is capped by the main body of the Green River formation, which in this area is the Laney shale member. Below this is exposed the entire Wasatch formation, 5,600 feet thick, consisting of brightly colored clay shale and subordinate sandstone, with no beds of Green River type. North of Baggs, Wyo., the Tipton tongue of the Green River enters in the midst of the Wasatch beds, thickens northward, and, encircling the north end of the Washakie Basin, unites with the Tipton to the west. Thus the outcrop of the Tipton tongue has the shape of the letter U with the open side toward the south. The Tipton lake may have extended southward to a line between Baggs and East Fork of Vermilion Creek; and there is a possibility that much of the Cathedral Bluffs tongue of red beds, deposited as this lake retreated, was derived from the east and southeast.

In contrast to the relations described above, Green River deposition on the east rim of the Bridger Basin was evidently not interrupted by a temporary regression of the lake, as the Wasatch and Green River show no interfingering, even close to the mountains. In this area the lake probably reached the foot of the mountains, but as the finely laminated shale and oil shale of the Green River indicate deposition in very quiet water, material must have been carried out from the mountains very slowly if at all.

On the rim of the Washakie-Sand Wash depression the main body of the Green River formation (Laney shale member) undergoes a very gradual northward change. Near the mountains it is prevailingly buff and much of its shale is limy and poor in oil-yielding organic matter. Although sandstones are numerous, only one conglomerate was observed. This conglomerate, about 5 feet thick, contains small subangular pebbles of black and green chert and of coarse-grained red quartzite, some grains of glassy quartz, and a few compact clay balls. The pebbles average a quarter of an inch in diameter; a few pebbles of black chert are an inch in diameter. This conglomeratic lens, near the top of the Laney shale member in T. 9 N., R. 100 W., passes rapidly northward into a coarse-grained sandstone with a limy cement. Just west of Little Snake River, near the center of T. 8 N., R. 97 W., two or three thin beds of coal and numerous beds of partly humified plant remains occur in the Laney shale several hundred feet above the base. The coal beds are bony and very lenticular, ranging from a few inches of carbonaceous material to beds 3 feet thick. Toward the north the Green River formation contains fewer and thinner sandstones, and its buff color changes gradually to the more characteristic bluish-white tone, probably owing to an increasing richness of the oil shale.

NOMENCLATURE.

The early explorers believed that the Green River formation is not only different from the Wasatch in lithology but is also distinctly younger throughout. Such a belief is justified in the Bridger Basin, where the Wasatch was followed by continuous Green River deposition. Farther east, however, in the Washakie-Sand Wash depression, this belief led them to draw the boundary at the base of the beds later named Laney shale member by Schultz, thus including in the Wasatch the deposits here called the Tipton tongue of the Green River formation and the Cathedral Bluffs tongue of the Wasatch formation. The boundary was drawn at the same horizon by Schultz [20] in his reports on the coal fields of the Rock Springs uplift. In a later report, however, Schultz [21] described the northwestward gradation of his Cathedral Bluffs red beds member into shale of Green River type and suggested that his Tipton shale member might die out toward the southeast, causing an interfingering of the two formations. He believed that the Green River west of the Rock Springs uplift is the time equivalent of all beds east of the uplift between the base of the Tipton tongue and the base of the Bridger, and hence he treated the Tipton tongue and the Cathedral Bluffs tongue as members of the Green River formation.

[20] Schultz, A. R., The northern part of the Rock Springs coal field, Sweetwater County, Wyo.: U. S. Geol. Survey Bull. 341, pp. 256–282, 1909; The southern part of the Rock Springs coal field, Sweetwater County, Wyo.: U. S. Geol. Survey Bull. 381, pp. 214–281, 1910.

[21] Schultz, A. R., Oil possibilities in and around Baxter Basin, in the Rock Springs uplift, Sweetwater County, Wyo.: U. S. Geol. Survey Bull. 702, pp. 25, 28–31, 1920.

Although the time equivalence suggested by Schultz is essentially correct, the writers believe that his classification does not adequately express the time and depositional relations of the Wasatch and Green River. The interfingering of these formations, now proved to exist, may be better indicated by the use of the term "tongue," introduced by Stephenson.[22] The names Cathedral Bluffs tongue of the Wasatch formation and Tipton tongue of the Green River formation are therefore here used to replace the members of Schultz. The relations of these tongues are shown diagrammatically in Figure 10.

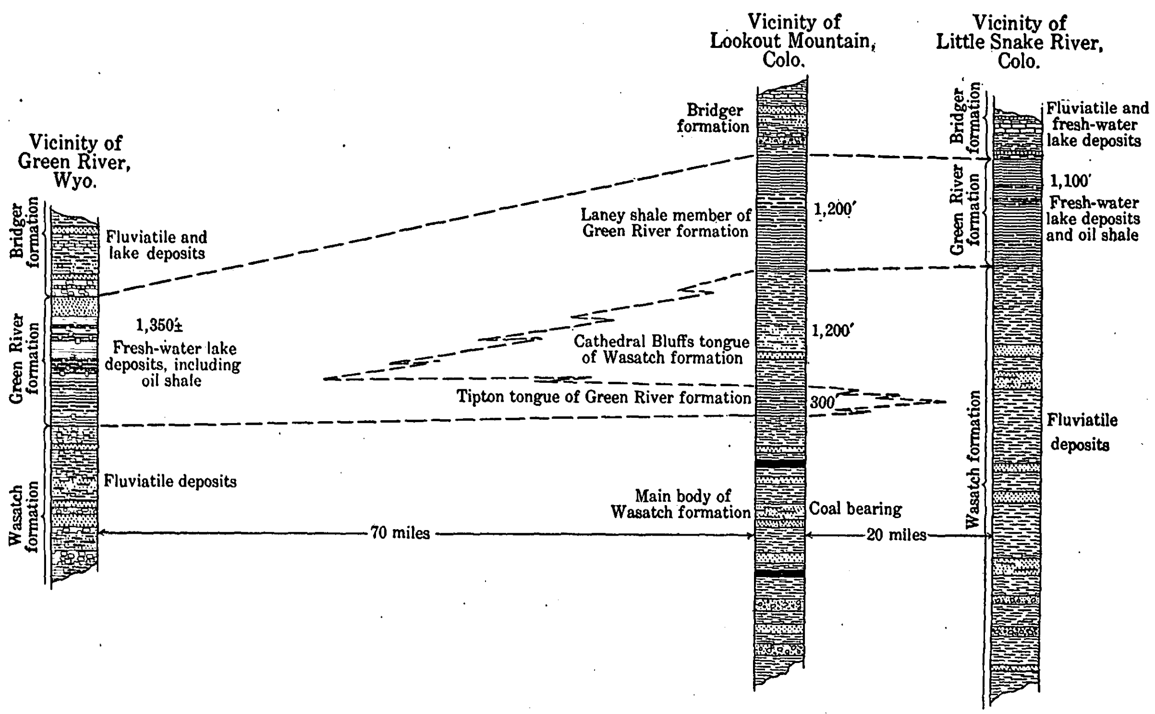


FIGURE 10.—Sections from northwest to southeast in the Green River Basin, Wyoming and Colorado, showing interfingering of the Wasatch and Green River formations.

SUMMARY OF GEOLOGIC HISTORY.

The geologic events bearing on the deposition and relations of the Wasatch and Green River in this area may be summarized as follows:

After Cretaceous time the Mesozoic and older rocks were lifted many thousands of feet in the Uinta Mountain arch, and on the north side part of this movement resulted in great faulting. Streams began a vigorous attack on the Mesozoic rocks forming the surface of the arch and carried great amounts of sediment out over the lowlands. Alluvial fans of poorly sorted boulders were built up at the foot of the mountains by torrential streams; flood-plain silts and stream-channel deposits, which later became colored clay shale and coarse, irregular sandstone, were laid down farther out in the basin. Here and there swamp conditions permitted the accumulation of plant remains, which later became carbonaceous shale and coal. To the east and west these deposits of early Wasatch time merged with material brought from the Park and Wasatch ranges. As erosion cut deeper into the mountain mass, older rocks were exposed and fragments of Carboniferous limestone were carried into the basin. Scattered shallow ponds swarmed with organisms such as *Unio* and *Goniobasis,* as is attested by the abundant shell marl interspersed in lenses of finely laminated carbonaceous shale. The increasing thickness of the Wasatch deposits caused an encroachment upon the lower flanks of the mountains, as illustrated on Vermilion Creek by the overlap of the Wasatch upon beds ranging in age from Mesaverde to Twin Creek. East of the Uinta Mountains the Wasatch was laid down upon practically horizontal Cretaceous rocks.

[22] Stephenson, L. W., Tongue, a new stratigraphic term, with illustrations from the Mississippi Cretaceous: Washington Acad. Sci. Jour., vol. 7, pp. 243-250, 1917.

Over these flood-plain deposits spread gradually a broad, shallow lake. Toward the west this lake reached the foot of the Uinta Mountains; here its transgression marked the end of Wasatch sedimentation, as the lake maintained its position until the end of Green River time. Farther east the margin of the lake was a line between East Fork of Vermilion Creek and Baggs, Wyo. Into the quiet waters of this lake was transported fine sediment, which became mixed with varying amounts of organic matter and formed the gray fissile shale and oil shale of Green River type. Some coarser débris was carried into the edges of the lake, as shown by the conglomerate in the Tipton tongue on Canyon Creek. Meanwhile sedimentation of Wasatch type was continuing over the flood plains not transgressed by the lake.

After the deposition of several hundred feet of shale, forming the Tipton tongue, the margin of the lake gradually receded to a line roughly marked to-day by the axis of the Rock Springs uplift. Within the limits of the restricted lake the formation of Green River sediments continued, while over the fine silt left exposed by its retreat was deposited the brightly colored clay shale of the Cathedral Bluffs tongue. After the formation of 600 to 1,200 feet of sediments composing the Cathedral Bluffs tongue Wasatch deposition came to an end by a new advance of the Green River lake, which this time encircled the east end of the mountains and united with the lake of the Uinta Basin. The much smaller thickness of the entire Green River formation at Green River, Wyo., compared with the thickness of its age equivalents—the Tipton and Cathedral Bluffs tongues and Laney shale member (possibly including representatives of the "Tower sandstone" and plant beds of Powell)—at Lookout Mountain, may be partly accounted for by a gradual southeastward tilting that may have been an important factor in the second transgression of the Green River lake.

Later folding and faulting have changed the attitude of the Wasatch and Green River but have not affected their relations.

Two questions may be outlined as problems for future study. What was the mode of disappearance of the Green River lake? Are the earliest Green River beds of the Uinta Basin the age equivalents of the basal Tipton tongue or the basal part of the Laney shale member?

OIL SHALE IN THE GREEN RIVER FORMATION.

PHYSICAL PROPERTIES.

The oil shale in the Green River formation may be divided into two distinct varieties, between which there are many gradations. One variety is hard and tough. On fresh surfaces it is chocolate-brown to black and generally shows no distinct lamination. When weathered it is predominantly of a bluish-white color, and its finely laminated structure is indicated by the alternation of thin dark-gray bands with bluish-white layers. (See Pl. XXV, *B*.) The fracture is commonly subconchoidal; freshly broken faces have a vitreous or pitchy luster in the richest grades and are dull in the leaner grades. The other variety has very pronounced bedding of paper thinness and is commonly called papery shale. Its laminae, which are remarkably flexible, separate very readily. (See Pl. XXV, *C*.) Fresh samples are light to dark brown or less commonly black; weathered surfaces are light bluish gray or white. In general, the tough, massive variety yields more oil than the papery shale.

CHEMICAL PROPERTIES.

Oil shale contains little or no petroleum as such, and only a small percentage of the organic matter can be extracted with common petroleum solvents such as carbon tetrachloride carbon bisulphide, and benzene. The percentage extracted varies with the character of the shale and the solvent, but according to a table prepared by Gavin [23] the average amount extracted by six solvents from three samples of Green River shales was only 1.3 per cent of the weight of the samples.

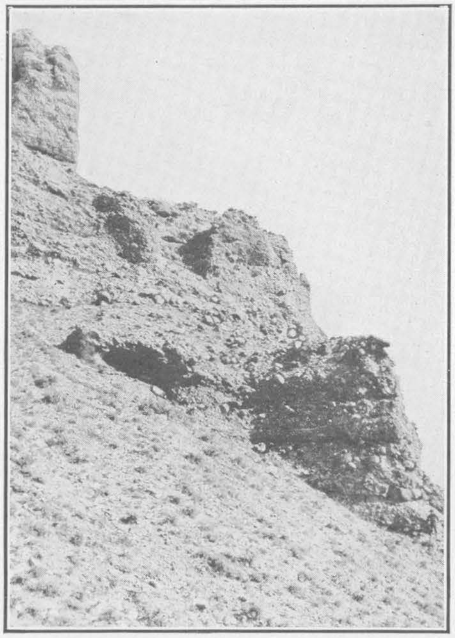
Upon destructive distillation the organic matter in the shale yields a crude oil. According to Steuart,[24] Prof. Crum Brown gave the name "kerogen" to this organic matter of indefinite and variable chemical composition.

The economic value of the shale depends upon the character of the kerogen and the proportions of kerogen and clastic mineral matter. McKee and Goodwin [25] show that

[23] Gavin, M. J., Oil shale—an historical, technical, and economic study: U. S. Bur. Mines Bull. 210, p. 28, 1922.

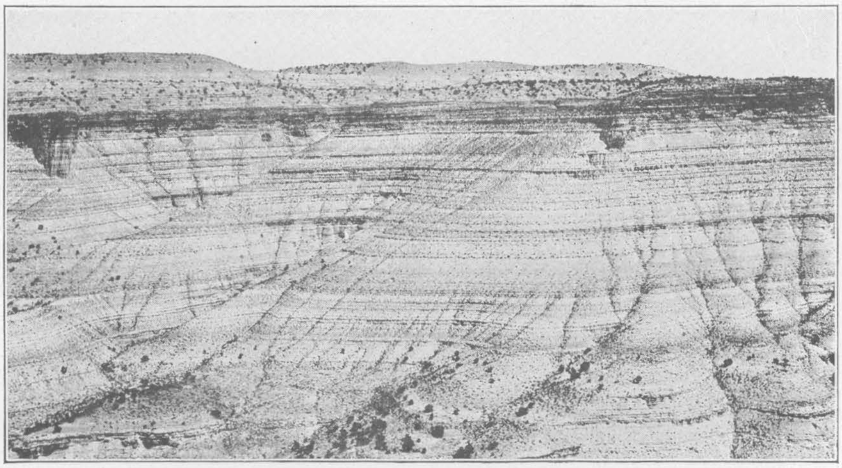
[24] Steuart, D. R., Oil shales of the Lothians, pt. 3, The chemistry of the oil shales, 2d ed., p. 159, Scotland Geol. Survey Mem., 1912.

[25] McKee, R. H., and Goodwin, R. T., A chemical examination of the organic matter in oil shales: Colorado School of Mines Quart., vol. 18, No. 1, pp. 8, 20, 1923.



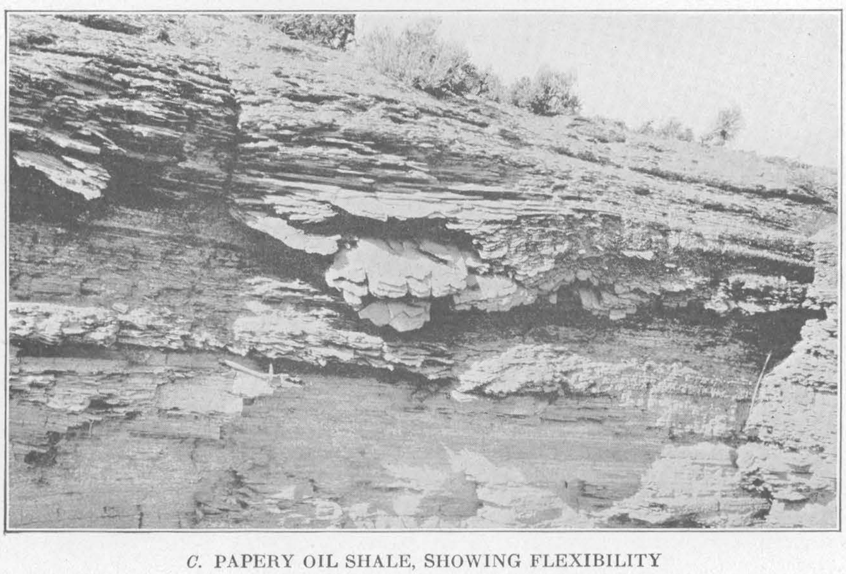
A. CONGLOMERATE IN THE LOWER PART OF THE WASATCH FORMATION AT SUGARLOAF BUTTE, SEC. 15, T. 11 N., R. 101 W., COLO.

Compare size of boulders with height of man on right side of photograph



B. OIL SHALE IN THE GREEN RIVER FORMATION, SHOWING CHARACTERISTIC THIN, REGULAR BEDDING

Photograph by D. E. Winchester



C. PAPERY OIL SHALE, SHOWING FLEXIBILITY

Photograph by D. E. Winchester

the chemical composition of the kerogen and hence of the oil distilled from it differs in different shales and even from place to place in the same formation. For example, shale oil from the Green River formation in Colorado has a mixed paraffin and asphalt base, whereas shale oil from a locality in Utah has an asphaltic base. The yield of oil is to some degree dependent upon the chemical composition of the shale, but is determined far more by the amount of kerogen present.

EFFECT OF VARYING CONDITIONS OF FORMATION

Researches of numerous careful students [26] indicate that kerogen was formed by the accumulation in fresh water of spore exines, pollen grains, the more resinous parts and somewhat macerated cuticles of larger plants, and the remains of various types of algae, particularly the more gelatinous and filmy types. The low orders of plant life, both sessile and planktonic, the drift material, and the parts of higher plants would be distributed in varying amounts through a body of fresh water according to depth, currents, wave action, source of supply of extraneous material, prevailing winds, and other factors. Where clastic material was being carried into the lake the organic content of the shale formed would be relatively smaller and the value of the shale as an oil producer would be lessened. Where the organic débris could accumulate without much influx of inorganic material the resultant shale would be very much richer in kerogen.

From this reasoning it is easily understood why the oil shale of the Green River formation near the east end of the Uinta Mountains is of very low grade. Much clastic material was carried out from the mountains and deposited in the shoreward portion of the Green River lake; the proportion of included organic material was small. Farther out in the lake, and also near shore at places where little clastic material was being supplied, the proportion of organic débris was much larger; and the shale is far richer in the oil-yielding kerogen. The variation is strikingly shown by comparison of sections of the Tipton tongue in T. 10 N., R. 100 W., Colo., and T. 12 N., R. 102 W., Wyo., with a section on Shell Creek in T. 12 N., R. 99 W., Colo.; it is indicated also by comparison of sections of the Laney shale member in T. 8 N., R. 97 W., and T. 10 N., R. 100 W., with those in T. 13 N., R. 99 W., and T. 17 N., R. 106 W. These sections, given on following pages, show a gradation northward; as the sandstones and the more limy and sandy shales disappear the percentage and richness of oil shale increase.

MEASURED SECTIONS AND TESTS.

The following sections, measured by the writers except as otherwise noted, indicate the character of the formation at different localities and present more detailed data concerning lateral changes. Results of distillation tests are given opposite the descriptions of the beds sampled. Beds described as low-grade oil shale yield less than 10 gallons to the ton.

Sections of Tipton tongue of Green River formation in Moffat County, Colo., and Sweetwater County, Wyo.

Locality 1, sec. 3, T. 10 N., R. 100 W.

	Ft.	in.
Sandstone, buff, hard, medium grained	2	6
Sandstone, brown, thin bedded, interbedded with hard gray-green shale	21	
Sandstone, gray, massive, medium grained.	2	8
Shale, gray-green, platy	2	6
Sandstone, brown, medium grained	2	
Shale, greenish brown, platy to lumpy	8	
Sandstone, brown, platy, medium grained	3	
Shale, gray-green, platy	3	
Sandstone, reddish brown, medium grained, undulating bedding planes	1	6
Shale, greenish brown, sandy, platy	8	6
Sandstone, brown, very fine grained		2
Shale, gray-green, platy	2	
Sandstone, brown, very fine grained		4
Shale, gray-green, platy	4	
Sandstone, brown, very fine grained		6
Clay shale, light gray	3	
Shale, gray-green, soft, platy	6	
Sandstone, yellow-brown, thin bedded, fine grained	8	
Shale, gray-green, platy to lumpy	5	6
Shale, brown, carbonaceous, papery; trace of oil	5	6
Shale, gray to light brown, flaky	31	
Shale, chocolate-brown, carbonaceous; trace of oil	3	6-

[26] Bertrand, C. E., Les charbons humiques et les charbons des purins: Lille Univ. Trav. et Mém., vol. 6, Mém. 21, pp. 13-178, 1898; Conférences sur les charbons de terre: Soc. belge géol. Bull., vol. 11, p. 287, 1897. Davis, C. A., On the fossil algae of the petroleum-yielding shales of the Green River formation of Colorado and Utah: Nat. Acad. Sci. Proc., vol. 2, pp. 114-119, 1916; quoted in Winchester, D. E., Oil shale in northwestern Colorado and adjacent areas: U. S. Geol. Survey Bull. 641, p. 165, 1916; Oil shale of the Uinta Basin, northeastern Utah: U. S. Geol. Survey Bull. 691, pp. 46-47, 1918. Jeffrey, E. C., The nature of some supposed algal coals: Am. Acad. Arts and Sci. Proc., vol. 46, pp. 273-290, 1910. Thiessen, Reinhardt, and White, David, The origin of coal: U. S. Bur. Mines Bull. 38, pp. 199-203, 1913; Origin of certain oil shales: Econ. Geology, vol. 16, pp. 289-300, 1921. White, David, Late theories regarding the origin of oil: Geol. Soc. America Bull., vol. 28, p. 730, 1917.

	Ft.	in.
Shale, gray, flaky	3	
Sandstone, buff, cross-bedded, medium grained		10
Shale, brownish gray, papery; contains many humified plant fragments	24	
Sandstone, buff, cross-bedded; upper 3 feet platy with shaly partings	19	
Shale, dark brown, papery, brittle, carbonaceous; contains abundant humified plant fragments	56	
Wasatch formation.		
	227	

Locality 2, sec. 15, T. 12 N., R. 102 W.

	Ft.	in.
Sandstone, brown, cross-bedded, very coarse grained, locally conglomeratic, carrying red and brown quartzite boulders as much as 5 inches in diameter	15+	
Sandstone, hard, gray; irregular thin bedding	2	6
Sandstone, light gray, cross-bedded, medium to coarse grained	2	
Sandstone, gray, very hard, thin bedded, fine grained	7	6
Interval concealed, probably fine-grained lumpy sandstone	7	
Sandstone, cross-bedded, from medium grained to conglomeratic	3	
Sandstone, hard, fine grained	4	
Sandstone, brown, massive, coarse grained	2	6
Sandstone, hard, massive, fine grained	10	
Sandstone, massive, coarse grained; carries a few pebbles	2	
Shale, hard, sandy, interbedded with thin-bedded sandstone	24	
Sandstone, platy, interbedded with thin, hard, impure limestones	6	
Sandstone, hard, platy, very fine grained	4	
Sandstone, gray, soft, thin bedded to cross-bedded, medium grained	6	
Sandstone, greenish gray, hard, irregularly bedded; contains numerous soft white specks	5	
Sandstone, buff, massive, fine grained	5	6
Sandstone, greenish gray, hard, irregularly bedded; contains numerous soft white specks	11	
Sandstone, gray, cross-bedded, in part conglomeratic	9	
Sandstone, thin bedded, fine grained, interbedded with hard brown low-grade oil shale	8	6
Sandstone, basal 3 feet conglomeratic, carrying pebbles of white quartz, hard shale, red and gray chert, and limestone; remainder fine grained and irregularly thin bedded	22	
Shale, very low-grade oil shale, interbedded with numerous fine-grained platy sandstones	6	
Sandstone, brown, slightly cross-bedded; carries subangular white and pink quartzite pebbles	12	
Sandstone, blue-gray, soft, fine grained	9	
Sandstone, light gray, very coarse grained, locally cross-bedded and conglomeratic	10	
Sandstone, massive to platy, medium to fine grained	7	
Shale, sandy, platy		6
Sandstone, greenish gray, massive, sugary textured, medium grained	3	6
Shale, sandy, interbedded with thin-bedded medium-grained sandstone	4	6
Shale, hard, brown; low-grade oil shale; contains small limy concretions	5	
Sandstone, soft, medium to coarse grained and slightly cross-bedded; several 6-inch partings of hard shale	24	
Shale, laminated to lumpy; contains sandy lenses	2	3
Sandstone, reddish brown, massive, medium grained	2	6
Shale, greenish gray, hard, lumpy	2	6
Shale, hard, brown; low-grade oil shale; weathers blue-gray	3	
Sandstone, soft, medium to coarse grained	4	
Sandstone, thin bedded; interbedded with shale	5	
Sandstone, brown, medium grained		9
Shale, dark brown, laminated; low-grade oil shale		3
Sandstone, brown, coarse grained		8
Shale, hard, brown, massive; low-grade oil shale		10
Sandstone, brown, medium grained		8
Shale, chocolate-brown, hard, massive; low-grade oil shale	15	
Sandstone, red-brown, massive to thin bedded, medium to fine grained; carries leaf impressions; numerous thin partings of sandy shale	69	
Shale, sandy, gray; few thin platy sandstones	14	
Shale, brown, papery; few thin sandstones; trace of oil	11	
Concretionary zone; probably calcareous alga reef	2	
Sandstone, soft, coarse grained, cross-bedded; lower part sandy clay shale	30	
Sandstone, brown, thin bedded, fine grained	4	
Clay shale, hard, gray	9	
Sandstone, brown, soft and friable, coarse grained	18	
Clay shale, blue-gray	15	
Shale, papery; low-grade oil shale	10	
Clay shale, sandy, hard and lumpy	18	
Shale, brown, papery; low-grade oil shale	11	
Clay shale, gray; few thin sandstones	5	
Shale, chocolate-brown, papery; low-grade oil shale	17	
Sandstone, limy; full of *Goniobasis* shells		2
Gray and maroon clay shale of Wasatch formation.		
	509+	

Locality 3, secs. 27 and 28, T. 12 N., R. 99 W.

	Ft.	in.
Red and green clay shale and sandstone of the Cathedral Bluffs tongue of Wasatch formation.		
Shale, greenish gray; upper part clayey; lower part laminated low-grade oil shale	14	
Sandstone, brown, soft, thin bedded, fine grained; ripple-marked at top	4	6
Shale, greenish gray, hard, laminated	2	
Sandstone, brown, thin bedded, fine grained, interbedded with sandy shale	6	
Shale, sandy, hard	6	7
Sandstone, light gray, soft, thin bedded, interbedded with sandy shale	3	
Shale, hard and sandy, interbedded with thin fine-grained micaceous sandstones	6	2
Sandstone, brown, hard, medium grained, in part cross-bedded; abundant mica flakes		8
Sandstone and interbedded bluish-gray shale; both micaceous	8	
Zone of hard brown sandy concretions		8
Sandstone, dark gray, much cross-bedded, fine grained; distinct parting planes of mica flakes	1	
Shale, light gray; few thin micaceous sandy lenses	10	
Alga reef, calcareous	2	
Shale, hard, dark gray, papery; low-grade oil shale		6
Sandstone, buff, medium grained; numerous partings of hard sandy shale	5	6
Sandstone, buff, very thin bedded	1	4
Shale, dark gray, papery; trace of oil		5
Shale, sandy, interbedded with irregular thin sandstones	2	3
Shale, hard, sandy, interbedded with hard light-gray shale that shows trace of oil	2	
Shale, sandy, and thin sandstone	1	6
Shale, bluish gray, hard, flaky; shows trace of oil	1	6
Shale, sandy, and thin sandstones		10
Clay shale, sandy		8
Sandstone, brown, medium grained, irregularly bedded		7
Shale, gray-green, hard; trace of oil; few thin lenses of very fine sand	6	6
Sandstone, brown, soft, fine grained, massive, micaceous	2	
Shale, bluish gray, sandy	2	6
Sandstone, buff, soft, medium to coarse grained, massive, micaceous	7	
Shale, gray, hard, sandy; few thin sandstone lenses; carries a few plant fragments	9	
Sandstone, drab, soft, medium grained, micaceous	1	6
Shale, dark gray, sandy, fissile		10
Sandstone, coarse grained, thin bedded	2	
Shale, sandy, interbedded with thin sandstones; both carry abundant mica flakes	8	
Sandstone, white, very friable, coarse grained	5	
Shale, dark gray, fissile		6
Shale, dark brown, papery, tough; low-grade oil shale	9	6
Shale, sandy, and thin sandstones	2	
Sandstone, white, friable, medium grained, micaceous	6	6
Shale, dark chocolate-brown, soft	1	4
Shale, sandy, and thin soft sandstones	6	6
Sandstone, white, very soft and sugary, medium grained, micaceous	8	
Sandstone, dark reddish brown, hard, coarse grained, cross-bedded	2	6
Sandstone, buff, massive, fine grained	6	
Sandstone, dark brown, much cross-bedded, medium grained	2	
Clay shale, light brown	3	
Sandstone, buff, soft, coarse grained		6
Shale, sandy	2	
Sandstone, brown, irregularly bedded, fine grained		6
Shale, gray, soft, flaky	10	
Shale, very dark brown, hard, tough (sample IV–53; 7.5 gallons)	5	
Shale, gray to brownish, flaky	14	
Shale, dark chocolate-brown, papery; low-grade oil shale	8	
Clay shale, greenish gray, sandy	15	
Shale, dark brown to nearly black, papery; low-grade oil shale	15	
Limestone, hard, shaly		6
Shale, dark chocolate-brown, papery, somewhat carbonaceous; low-grade oil shale	18	
Clay shale	6	
Concealed, apparently sandy shale	40	
Sandstone, fine grained, thin bedded		10
Clay shale, light gray	5	
Limestone, hard, shaly		6
Shale, chocolate-brown, papery, tough; low-grade oil shale	4	8
Shale, greenish gray, sandy, flaky	4	
Shale, dark brown, papery, flexible laminae; low-grade oil shale	6	
Shale, sandy, flaky	4	
Shale, dark brown, papery; low-grade oil shale	14	
Clay shale, sandy, and thin sandstones	4	
Shale, nearly black, papery; low-grade oil shale	32	
Silicified bed of small *Goniobasis* shells		2
Sandstone, gray, medium grained, thin bedded; carries a few larger *Goniobasis* shells	4	
Wasatch formation, main body.		
	388	4

Sections of Laney shale member of Green River formation in Moffat County, Colo., and Sweetwater County, Wyo.

Locality 4, secs. 22 and 27, T. 10 N., R. 100 W.

	Ft.	in.
Sandstone, limestone, and clay shale of Bridger formation.		
Sandstone, greenish brown, medium to coarse grained, micaceous, cross-bedded	1	6
Clay shale, sandy	7	
Sandstone, greenish brown, medium grained, cross-bedded	2	2
Sandstone, greenish brown, medium grained, platy		6
Clay shale, sandy	3	6
Shell marl, largely *Goniobasis* shells		2
Clay shale, greenish gray	7	
Sandstone, dark brown, medium grained, crudely bedded	1	8
Clay shale, gray	5	
Sandstone, brown, medium grained		6
Clay shale, greenish gray, hard	9	6
Sandstone, brown, platy		10
Clay shale, gray	11	
Sandstone, hard, limy, medium grained; carries *Goniobasis* shells		3
Clay shale, sandy	5	
Sandstone, dark brown, platy	1	8
Alga reef, calcareous; some calcareous shale	2	6
Clay shale, gray	21	
Sandstone, gray, fine grained	4	
Clay shale, greenish gray	8	6
Sandstone, brown, shaly	20	
Limestone, shaly, buff	1	
Shale, brown, flaky	2	
Shale, hard, limy		8
Shale, buff, blocky	15	
Sandstone, light gray, sugary textured, medium grained, friable, massive	22	
Clay shale, sandy, pale green	7	
Sandstone, greenish gray, fine grained	2	
Clay shale, greenish gray	8	
Sandstone, gray, medium grained	1	
Clay shale, greenish gray	6	
Shale, calcareous, platy	10	
Clay shale, gray	1	
Shale, calcareous, platy	4	
Clay shale, gray	1	
Shale, calcareous, hard, platy	4	
Clay shale, gray; contains lenses of loose fine to coarse sand	21	
Limestone, buff, shaly, hard, blocky		10
Shale, yellowish brown, lumpy	1	
Limestone, brown, hard, impure, in part crystalline		5
Shale, gray to brown, platy and flaky	12	
Sandstone, light gray, friable, medium to coarse grained		11
Clay shale, greenish gray, lumpy and flaky	7	
Limestone, shaly, buff, hard, blocky	1	4
Clay shale; contains water-rounded clay balls		10
Shale, buff, hard, platy	1	7
Clay shale, light gray; contains water-rounded clay balls	1	8
Marl, shaly; irregular bedding; carries pelecypod shells		8
Alga reef, calcareous, in part silicified; carries some oolites	1	3
Clay shale, greenish gray, lumpy	8	4
Sandstone, very friable, very fine grained	21	
Shale, carbonaceous; partly humified plant remains abundant	1	8
Shale, gray, flaky and lumpy	6	2
Shale, calcareous, hard, platy	3	
Shale, gray-green, flaky	2	6
Shale, very carbonaceous		1
Clay shale, gray		6
Sandstone, massive, medium grained	1	6
Sandstone, extremely friable, very fine grained	15	
Sandstone, medium grained		1
Sandstone, soft, very fine grained	2	6
Concealed, probably clay shale	13	
Shale, gray, flaky	7	6
Limestone, shaly, hard, buff		8
Concealed, probably soft sandstone and clay shale	52	
Shale, buff, hard, platy; trace of oil	7	
Shale, brown, hard, limy		8
Clay shale	7	
Clay shale, sandy	11	
Sandstone, brown, very friable, medium grained	1	
Clay shale, greenish gray	1	4
Sandstone, gray, fine grained, banded		2
Shale, brown, carbonaceous; thin shell marls	3	5
Clay shale, sandy; lenses of soft sandstone	28	
Clay shale, gray-green	2	6
Shale, brown to black, carbonaceous		10
Concealed, probably clay shale	17	
Shiny black, soft, earthy matter; yields some oil		4
Concealed, probably clay shale	33	
Clay shale, gray-green, sandy	2	
Clay shale, gray	4	
Shale, papery; poorly exposed	6	
Shale, dark chocolate-brown, hard, tough (sample 0114–A; 10 gallons)	2	7
Shell marl, containing flat gastropods, fish vertebrae, and bone fragments		3
Shale, limy, brown; carries plant fragments; low-grade oil shale	19	6
Shale, limy, hard	1	4
Shale, chocolate-brown, hard, tough; low-grade oil shale	11	4
Clay shale, gray	1	
Shale, reddish brown, carbonaceous, very fissile; numerous plant fragments		8
Sandstone, friable, very fine-grained carbonaceous partings	1	3
Clay shale, gray	1	
Shale, brown, platy	3	6
Shell marl; *Goniobasis* and *Unio* shells	2	1

	Ft.	in.
Shale, platy; carries ostracodes		11
Shell marl; *Goniobasis* shells		1
Shale, dark gray; some plant fragments; interbedded thin shell marls	29	
Limestone, shaly, hard		6
Shale, dark-brown, hard; carries ostracodes; low-grade oil shale	14	4
Shell marl, limy; largely ostracodes		6
Shale, dark brown, hard, platy	10	
Shell marl, sandy; mostly small pelecypods		10
Shale, gray-brown; plant fragments	5	7
Clay shale, dark greenish gray, waxy	1	10
Shale, gray-brown, soft, fissile; carries ostracodes and fragments of fish teeth	13	
Shale, dark brown, papery	3	4
Limestone, blue-gray, hard, lenticular		5
Shale, hard, pale green, blocky (sample 086–A; 4 gallons)	21	
Limestone, gray, hard		4
Shale, brown, hard, locally papery; low-grade oil shale	83	
Limestone, buff, shaly, hard		5
Shale, brown, hard, platy; some beds are low-grade oil shale	43	
Sandstone, limy; carries *Goniobasis* shells		3
Shale, brown, soft, platy	7	
Shale, dark brown, carbonaceous	10	
Sandstone, limy, hard		3
Shale, dark brown, hard, platy; low-grade oil shale	87	3
Sandstone, platy		10
Shale, greenish brown, soft	16	
Limestone, sandy; carries ostracodes		1
Shale, brown, soft	2	6
Shale, yellowish brown; abundant plant fragments	13	
Shale, limy, soft, laminated		8
Shale, light brown, laminated; low-grade oil shale	5	
Shale, gray, flaky	1	
Shale, limy, yellow-brown, papery, soft	5	
Shale, light gray, hard, platy	23	6
Limestone, sandy, crystalline	1	3
Shale, light brown, soft	5	
Shale, limy, yellowish gray, soft; traces of oil	36	
Limestone, shaly, hard		4
Shale, gray, flaky	2	1
Sandstone, yellow, coarse grained	2	
Shale, limy, yellow-brown, platy	13	8
Limestone, sandy, lenticular	3	
Clay shale, gray	5	
Shale, limy, light brown, papery, soft	9	1
Limestone, buff, shaly, hard		9
Shale, limy, light yellowish brown, papery	19	
Clay shale, reddish gray	30	
Alga reef, calcareous; abundant ostracodes	1	
Limestone, oolitic, hard		3
Shale, limy, yellow brown	1	5
Limestone, gray, hard		3
Shale, limy, gray		2
Clay shale		3
Limestone, buff, shaly, hard	1	2
Clay shale, light brown		10
Shale, limy, papery, light brown, soft	9	6
Alga reef (?)		2
Sandstone, medium grained		9
Shale, light brown, laminated; trace of oil	12	10
Sandstone, medium grained		4
Limestone, gray, hard		8
Clay shale, gray	7	
Shale, limy, papery	7	
Sandstone, buff, limy, medium to coarse grained	2	6
Clay shale, gray	3	5
Shale, limy; faint bedding	1	2
Shale, dark gray, papery; trace of oil	5	
Sandstone, buff, medium to coarse grained; carries few small pebbles; locally cross-bedded	9	8
Sandstone, shaly, blocky	5	
Sandstone, buff, soft, friable, coarse grained	3	1
Sandstone, limy, buff, fine grained	1	5
Shale, greenish, limy		3
Shale, limy, light yellow-brown, laminated	22	3
Shale, limy, hard, not laminated		1
Shale, limy, light yellow, papery		4
Limestone, shaly, lenticular		2
Shale, sandy and limy; plant fragments	4	2
Clay shale, gray	1	6
Shale, light brown, papery	18	
Clay shale, dark gray	1	6
Sandstone, buff, fine grained	1	
Clay shale, gray; grades up into gray papery shale	2	9
Clay shale of Cathedral Bluffs tongue of Wasatch formation.		
	1, 199	11

Locality 5, sec. 20, T. 8 N., R. 97 W.

Top of bluff.

Sandstone; carries *Goniobasis* and *Unio* shells.

	Ft.	in.
Shale and thin sandstones	11	10
Sandstone, coarse grained	2	
Shale and thin sandstones	28	6
Shale, limy, buff; trace of oil	5	
Shale, carbonaceous and clayey	6	
Sandstone, fine grained, thin bedded	3	
Shale, carbonaceous and clayey	21	8
Shale, limy, hard	2	3
Shale, gray, carbonaceous and clayey	41	6
Shale, greenish; plant fragments		4
Limestone, shaly, gray	1	6
Clay shale, gray	2	
Shale, limy, hard	3	
Shale, light brown, platy; low-grade oil shale	23	7
Clay shale, sandy; contains thin beds of coal	16	6
Sandstone, brown, coarse grained	5	
Shale, black, carbonaceous		3
Shale, limy, soft	1	4
Shale, brown; some plant fragments		8

	Ft.	in.
Clay shale, gray and pink	12	4
Sandstone, gray, hard, platy, thin bedded	4	7
Shale, limy, buff, platy	41	
Shale, limy, buff, hard; trace of oil	6	
Shale, gray; lower 48 feet limy; upper part low-grade oil shale	61	6
Shale, brown to black, carbonaceous		6
Shale, sandy, gray	4	5
Sandstone, fine to medium grained	9	6
Shale, sandy, hard	2	
Shale, limy, hard, buff	3	7
Sandstone, gray, fine grained	4	6
Shale, sandy, fissile	1	8
Shale, carbonaceous		1
Shale, limy	3	6
Shale, gray, hard; low-grade oil shale	20	
Shale, gray, soft; trace of oil	52	6
Shale, brown, hard; low-grade oil shale	79	10
Shale, limy, hard, barren		3
Shale, brown, laminated; low-grade oil shale	8	8
Shale, very limy, brown; low-grade oil shale	1	6
Shale, limy, hard, barren		8
Shale, brown, laminated, hard (sample II–86–88; 9.5 gallons)	3	
Shale, limy, hard (not sampled) (sample II–86–88; 9.5 gallons)		6
Shale, brown, laminated, hard (sample II–86–88; 9.5 gallons)	15	2
Shale, limy, hard, barren		10
Shale, gray to brown, hard, laminated; low-grade oil shale	2	10
Limestone, shaly, buff, hard		5
Shale, gray to brown, hard, laminated; low-grade oil shale		8
Limestone, shaly, buff, hard		3
Shale, brown; weathers papery; low-grade oil shale	9	2
Shale, black, carbonaceous		2
Shell marl, silicified	1	2
Sandstone, gray, hard, fine grained	1	2
Shale, platy, silicified		8
Shale, brown, fissile; low-grade oil shale	1	3
Shale, silicified		7
Shale, gray, fissile		2
Shale, limy, hard		6
Shale, dark brown, hard, tough; low-grade oil shale	25	4
Shale, silicified	1	2
Shale, gray to brown; low-grade oil shale		11
Shale, limy, hard		5
Shale, dark brown, hard, platy; low-grade oil shale	13	10
Limestone, silicified		5
Shale, brown to buff; trace of oil	14	
Clay shale, greenish	2	2
Shale, gray, soft	8	
Shale, dark gray, hard; low-grade oil shale	8	3
Shale, gray, hard, blocky; trace of oil; interbedded with few thin hard shaly limestones	4	4
Shale, gray, papery; limy shale interbedded	5	
Clay shale, greenish, waxy	1	2
Shale, limy, yellow, hard		9
Shale, light brown, laminated	8	
Limestone, shaly, hard, buff		4
Shale, gray to buff, hard, platy to papery; some beds of low-grade oil shale	83	6
Shale, dark gray; fragments of shells; will probably yield some oil		2
Shale, black, soft	8	1
Clay shale (?), soft, yellow, waxy		2
Shale, gray, soft	4	
Limestone, shaly, gray, hard		1
Shale, gray, sandy and limy, flaky	1	8
Sandstone and sandy shale, thin bedded	33	6
Shale, limy	27	
Sandstone, thick bedded to massive	38	4
Shale, limy, platy	14	2
Sandstone, irregularly thin bedded to massive	6	8
Shale, gray, papery	4	4
Sandstone (base of Green River)	11	
	814	3

Locality 6, sec. 3, T. 13 N., R. 99 W.

[According to Schultz.[27]]

	Ft.	in.
Top of bluff.		
Sandstone, coarse grained, not massive	50	
Sandstone, containing fossil shells		4
Sandstone, coarse grained, thin bedded	10	
Covered, probably sandy shale	35	
Sandstone, coarse	8	
Covered, mostly shale	30	
Shale, papery, drab, lean	5	
Shale, thin, barren, and sandstone	72	
Shale, drab, thin, lean	3	
Shale, thin, drab, barren	20	
Shale, thin, lean	30	
Sandstone, concretionary	1	
Shale, thin, lean	14	
Oolite and chert.		
Shale, thin bedded, lean	14	6
Shale, thin bedded; weathers blue; rich (sample 1; 30 gallons.)	2	
Shale, gray, sandy (not included in sample) (sample 1; 30 gallons.)	1	7
Sandstone, yellow (not included in sample) (sample 1; 30 gallons.)	1	
Shale, thin bedded; weathers blue; rich (sample 1; 30 gallons.)	3	
Shale, yellow, sandy	28	
Shale, papery, lean	40	
Shale, drab, fissile	10	
Sandstone, concretionary	1	
Shale, drab, papery (over 15 gallons)	13	
Oolite		6
Shale, drab, papery (over 15 gallons)	10	
Sandstone, oolitic		4
Shale, drab, fissile	12	6
Sandstone, micaceous	1	
Sandstone, yellowish	3	
Shale, drab; thin sandstone lenses	26	
Sandstone, shaly, yellowish	1	

[27] Schultz, A. R., Oil possibilities in and around Baxter Basin, in the Rock Springs uplift, Sweetwater County, Wyo.: U. S. Geol. Survey Bull. 702, p. 54, 1920.

	Ft.	in.
Shale, drab, papery, barren	5	
Sandstone, shaly, yellowish	1	6
Shale, greenish drab	37	
Cathedral Bluffs tongue of Wasatch formation.		
	489	4

Locality 7, secs. 17 and 19, T. 17 N., R. 106 W.

[According to Winchester.[28]]

		Ft.	in.
Sandstone, massive, brown, coarse ("Tower sandstone" of Powell)		125	
Sandstone, thin bedded		35	
Shale, papery, gray		25	
Sandstone, shaly, gray		32	
Shale, sandy, lean		65	
Shale, hard; contains fish remains (sample 120; 14 gallons)		5	
Shale, lean		20	
Shale, thin, with lenses of very rich waxy shale		55	
Shale, hard		15	
Shale, hard (sample 119; 12 gallons)		5	
Shale, hard, lean		12	
Shale, gray, sandy		20	
Shale, hard, rich (more than 15 gallons)		1	4
Shale, gray, sandy, thin sandstones, and a few 1 to 3 inch beds of rich shale		90	
Shale, hard, thin, medium rich		1	6
Shale, barren		15	
Shale, medium, with large gypsum crystals		1	6
Shale, thin, barren		80	
Shale, medium, with gypsum crystals			8
Shale, gray, sandy		26	
Shale, medium, with gypsum crystals		1	6
Shale, hard, rich (over 15 gallons)			10
Sandstone, thin, gray		8	
Shale, hard, rich (over 15 gallons)			10
Shale, gray, sandy		17	
Shale, hard, rich (over 15 gallons)			2
Shale, thin, gray, sandy		9	2
Shale, hard, rich (over 15 gallons)			10
Shale, sandy		118	
Sandstone, gray		4	
Shale, sandy, greenish		6	
Sandstone, gray, thin bedded		1	
Shale, sandy, green		27	
Shale, sandy, thin bedded, gray		21	
Sandstone and shale, green, in beds 2 feet thick; sandstone concretionary		58	
Shale, sandy, gray, slope		97	
Sandstone, massive, cross-bedded, forming ledge and capping hill		5	
Shale, forming slope		43	
Sandstone, rather massive, forming ledge		10	
Shale, soft, thin, platy, barren		30	
Shale, medium hard, rather thin, very lean		4	11
Shale, medium hard (sample 116; 4 gallons)		4	10
Shale, sandy, lean to barren		70	
Shale, medium hard, very lean		10	
Shale, lean		4	6
Sandstone, brown, persistent			8
Shale, lean		3	6
Shale, hard to medium hard (sample 115; 9 gallons)		4	6
Shale, lean to barren		75±	
Shaly sandstone, barren		15	
Shale, sandy, forming slope, lean		47	
Shale, hard (sample 114, lower 4½ feet; 11 gallons)		5	6
Shale, hard (sample 113; 10 gallons)		5	3
Shale, hard	(sample 112; 9 gallons)	1	4
Sandstone			3
Shale, fairly soft, thin bedded		2	9
Shale, hard		1	
Shale, hard, rich (sample 111; 19 gallons)		5	4
Shale, hard, rich (sample 110; 19 gallons)		6	3
Shale, soft	(sample 109; 11 gallons)		7
Shale, hard, rich		2	5
Shale, soft			6
Shale, hard, rich		2	3
		1, 360 ±	

[28] Winchester, D. E., Oil shale of the Rocky Mountain region: U. S. Geol. Survey Bull. 729, pp. 124, 125, 1923.

DISCOVERY OF A BALKAN FRESH-WATER FAUNA IN THE IDAHO FORMATION OF SNAKE RIVER VALLEY, IDAHO.

By W. H. Dall.

In 1866 Gabb [1] described *Melania taylori* and *Lithasia antiqua* "from a fresh-water deposit on Snake River, Idaho Territory, on the road from Fort Boise to the Owyhee mining country. Collected by Mr. A. Taylor." He states that a small bivalve, perhaps a *Sphaerium*, was associated with them.

In 1870 Meek [2] described two species of *Sphaerium*, one from Fossil Hill, Nev. (included by King in his Truckee group), and one from Castle Creek, Idaho. Both these species occur in the Idaho material, and the presumption is strong that the two deposits are of the same age. In 1877 Meek [3] redescribed and figured them, considering their age as probably Miocene.

In 1882 C. A. White [4] added another species, *Latia dalli*, from the Idaho deposits and referred the formation on King's authority to the Miocene. King [5] does refer his Truckee group to the Miocene, but on another page [6] he specifically refers the Idaho lake beds to the Pliocene. In this he is followed by Cope,[7] who proposes for these beds an "Idaho group," which he regards as of middle or lower Pliocene age. As the molluscan fauna of the Truckee formation is practically the same as that of the Idaho formation, this conclusion would carry at least part of the Truckee into the Pliocene column.

In 1898 Lindgren [8] gave the name Payette formation to plant-bearing lake deposits in the lower part of the Snake River valley, which he referred to the Miocene on the evidence of the flora as determined by Knowlton, and stated that "this formation is probably not the same as Cope's Idaho formation, to which a Pliocene age was assigned." A footnote on the same page records the later conclusion that the Payette and Idaho formations represent two successive stages of the same lake and that it is not always easy to separate the two formations.

In the latest publication on the Payette formation R. W. Chaney,[9] who has revised and added to the flora, concludes that the formation is Miocene, and states that this determination from the flora is also supported by the evidence of vertebrate fossils obtained by Buwalda.

In a discussion of Pliocene mammalian faunas from the Pacific coast and Great Basin provinces John C. Merriam [10] says:

> The Idaho formation is not as yet satisfactorily separated from the Payette Eocene or Miocene and from a Miocene or Pliocene stage which may intervene between the Payette and the Idaho. It is, however, quite certain that there exists over a large area of southwestern Idaho a formation several hundred feet thick which may show evidence of deformation and which contains a fauna of a stage representing either the latest Pliocene or the earliest Pleistocene.

The fresh-water molluscan fauna which is the subject of this paper apparently comes from the same beds that yielded the Pliocene or Pleistocene vertebrate fauna referred to by Merriam. The fresh-water deposits in Serbia, Hungary, and other parts of southeastern Europe are sometimes referred to in the literature as Miocene but are generally called Neogene without attempting to discriminate between Miocene and Pliocene ages. They are characterized by very numerous species of the genera *Limnocardium*, *Congeria*, *Melanopsis*, *Neritina*, and operculate forms related to *Bythinia*, none of which occur in North American lake beds so far as now known. In addition they contain a

[1] Gabb, W. M., Paleontology of California, vol. 2, p. 13, pl. 2, figs. 21–22, 1866.
[2] Meek, F. B., Acad. Nat. Sci. Philadelphia Proc. for 1870, pp. 56–57, 1870.
[3] Meek, F. B., U. S. Expl. 40th Par. Rept., vol. 4, pt. 1, p. 183, pl. 16, figs. 17–20, 1877.
[4] White, C. A., U. S. Nat. Mus. Proc., vol. 5, p. 100, pl. 5, figs. 17–20, 1882.
[5] King, Clarence, U. S. Geol. Expl. 40th Par. Rept., vol. 1, p. 412, 1878.
[6] Idem, p. 440.
[7] Acad. Nat. Sci. Philadelphia Proc. for 1883, pp. 153–166, 1883.
[8] U. S. Geol. Survey Eighteenth Ann. Rept., pt. 3, p. 632, 1898
[9] Notes on the flora of the Payette formation: Am. Jour. Sci., 5th ser., vol. 4, pp. 214–222, 1922.
[10] California Univ. Dept. Geology Bull., vol. 10, p. 432, 1917

number of genera strikingly different from any now living in the fresh waters of the globe, such as *Valenciennesia*, *Velutinopsis*, *Papyrotheca*, *Orygoceras*, and *Baglivia*. There are also a few of the smaller forms like *Caspia* which are found living or represented by close analogues in the Caspian Sea and Lake Baikal, both of which, it may be noted, are "relicten Seen."

The chief interest of the present paper lies in the discovery of some of these anomalous fresh-water genera in American lake beds of the Idaho formation, together with one or two curious forms not represented in Europe.

In 1909 A. A. Hinkley obtained from the wash of the Panuco River system, in the Mexican State of San Luis Potosi, some amnicoline shells which were recognized by H. A. Pilsbry as closely related to some of the forms from the Serbian lake beds, described by Brusina, and which were described by Pilsbry[11] under the names *Emmericiella* and *Pterides*. It is not certain that these bleached specimens represent living species, as they might have been washed out of unconsolidated marl.

The genus *Tryonia* Stimpson, 1865, from the Colorado Desert fossil fauna, is undoubtedly an American type, but conchologically many of the shells named *Prososthenia* by Neumayr in 1869, from the Balkan lake beds, are almost identical with our *Tryonia*, which ranges from supposed Miocene deposits in Guatemala to the recent fauna of certain springs in California, to which it has retreated from the growing salinity of the former Lake Bonneville, now desert.

The United States Geological Survey recently received from Prof. F. A. Thomson, of the Idaho School of Mines, a piece of rock collected by W. H. Campbell from Castle Creek, Owyhee County, Idaho, and containing numerous fresh-water shells.

A fine iconography of the Mollusca of the Balkan lake beds was published by the late Spiridion Brusina[12] in 1902, and an examination of the Idaho material showed at once the presence of some of the remarkable European forms hitherto unknown in the Western Hemisphere.

The matrix consists of rather large rounded sand grains firmly cemented together and containing numerous fresh-water shells. The matrix is so flinty and the minute shells so extremely fragile that several specimens crumbled during the attempt to extricate them, and subsequent work was confined to the recording of such descriptive data as could be derived from an inspection of the more or less embedded individuals on the surface of the rock specimen.

The interest excited by this discovery led to an examination of all the material in the collection which had been obtained from this district, some of which had been tentatively reported on many years ago. Specimens were found which had been collected during the Fortieth Parallel Survey, by I. C. Russell, G. R. Mansfield, G. H. Eldridge and others, most of which had a matrix of fine-grained sandstone or shale. Curiously enough, none of them showed any trace of the Balkan species, except one found near Glenn's Ferry, in the Snake River canyon, which contained a fragment now recognizable as part of a species of *Orygoceras*. Though fossils were abundant, they represented only a few species which had been described by Gabb, Meek, and White in the publications above referred to. Taken altogether the number of lots is small, and their fossil content meager.

The condition of the matrix in the Thomson specimen is such that, while the generic relations of most of the fossils are determinable, for many of them it is not practicable to obtain sufficient data for specific determination, and some of the shells show evidence of having been worn or eroded before fossilization.

In enumerating the fossils of the Balkan type I have retained the nomenclature of Brusina, leaving questions of synonymy, if any, to be determined later.

PELECYPODA.

Genus SPHAERIUM Scopoli.

Sphaerium rugosum Meek.

Sphaerium rugosum Meek, Acad. Nat. Sci. Philadelphia Proc. for 1870, p. 56, 1870; U. S. Geol. Expl. 40th Par. Rept., vol. 4, pt. 1, p. 182, pl. 16, figs. 1, 1a, 1877.

White, C. A., U. S. Nat. Mus. Proc., vol. 5, p. 100, pl. 5, figs. 14–15, 1882; U. S. Geol. Survey Third Ann. Rept., p. 234, pl. 32, figs. 12–13, 1883.

Fossil Hill, Kawsoh Mountains, Nev.; Meek. Castle Creek, Owyhee County, Idaho; W. H. Campbell.

These specimens are identical with Meek's type. His locality was later included in the State of Idaho.

[11] The Nautilus, vol. 23, pp. 45–49, 1909.

[12] Iconographia molluscorum fossilium in Tellure tertiaria Hungariae, Croatiae, Slavoniae, Dalmatiae, Bosniae, Hertzegovinae, Serbiae, et Bulgariae inventorum, pp. x, 30, pl. 30, Agram, 1902.

Sphaerium meeki Dall, n. sp.

Plate XXVI, Figure 8.

Castle Creek, Idaho; Campbell.

A single valve of a small *Sphaerium* was obtained which is distinctly different from the preceding species. It is roundly rectangular in outline, the beak nearer the anterior end, low and smooth; sculpture of about ten cordlike concentric ridges with subequal interspaces, more crowded and less elevated toward the base; the valve thin, compressed, the anterior end somewhat more bluntly rounded than the other; the hinge and interior obscured by matrix. Longitude 5 millimeters; altitude 3 millimeters. U. S. Nat. Mus. catalog No. 333521.

Sphaerium idahoense Meek.

Sphaerium idahoense Meek, Acad. Nat. Sci. Philadelphia Proc. for 1870, p. 57, 1870; U. S. Geol. Expl. 40th Par. Rept., vol. 4, pt. 1, p. 183, pl. 16, figs. 1, 1a, 1877.

White, C. A., U. S. Nat. Mus. Proc., vol. 5, p. 100, pl. 5, figs. 12–13, 1882; U. S. Geol. Survey Third Ann. Rept., p. 34, pl. 32, figs. 14–15, 1883.

Castle Creek, Idaho, Meek; also Campbell.

This species is a much heavier shell than any of the recent Sphaeria and according to Meek has a sinuation of the palleal line like the old world Cyrenas, while the recent American species have a simple entire palleal line. I have not been able to detect any sinuation in the specimens I have examined. Meek was uncertain to which genus to refer it but tentatively placed it in *Sphaerium*. The shape is more like *Cyrena*.

GASTROPODA.

Family LYMNAEIDAE.

Genus LYMNAEA Lamarck.

Lymnaea? sp.

A shell having much the outline of *Lymnaea vetusta* Meek, with a distinctly truncate pillar and a gyrate internal axis, was obtained by G. R. Mansfield from the Salt Lake formation in the N. ½ sec. 24, T. 10 S., R. 43 E., in Idaho. It is perhaps not a *Lymnaea*, but the form is so obscured by a hard shaly matrix that a definite determination of the genus is not practicable.

Family PLANORBIDAE.

Genus PLANORBIS Müller.

Planorbis? sp.

Fragments and partial impressions of shells which may be planorboid are not rare in the material at hand, but they are not sufficiently well preserved to distinguish them from small or young specimens of *Vorticifex*.

Subfamily POMPHOLIGINAE.

Genus VORTICIFEX Meek.

Vortifex Meek, Acad. Nat. Sci. Philadelphia Proc. for 1870, p. 59; type *Carinifex* (*Vortifex*) *tryoni* Meek, loc. cit., sole example.

Vorticifex tryoni Meek.

Carinifex (*Vortifex*) *tryoni* Meek, Acad. Nat. Sci. Philadelphia Proc. for 1870, p. 59, 1870.

Carinifex (*Vorticifex*) *tryoni* Meek, U. S. Geol. Expl. 40th Par. Rept., vol. 4, pt. 1, p. 188, pl. 17, figs. 10, 10a–10c, 1877.

White, C. A., U. S. Nat. Mus. Proc., vol. 5, p. 100, pl. 5, figs. 8–9, 1882.

Fossil Hill.

Vortifex, according to Meek, 1877, was a typographic error. It is extremely doubtful whether this form and its Pleistocene relatives have any distinctive characters separating them from *Pompholyx* Lea (not Gosse), *Pompholopsis* Call, and *Parapholyx* Hanna.

Generally the large *Carinifex binneyi* has been figured as typical of *Vorticifex*, but Meek did not originally place it in this group, which consisted only of the present species and its varieties.

An examination of the large series of recent *Pompholyx* in the National Museum reveals a great amount of variation. Nearly every lot of the recent shells contains a few more or less distinctly umbilicate specimens, though the typical form is imperforate. The Pleistocene specimens are smaller, more solid, and generally umbilicate; the Pliocene ones more distinctly so. One must recognize in this material, as with many other fresh-water gastropods, either one form with a multiplicity of varieties merging into one another, or a lot of species that can not be diagnostically separated.

Genus MEGASYSTROPHA Lea.

Megasystropha Lea, Acad. Nat. Sci. Philadelphia Proc., 2d ser., vol. 8, p. 5, January, 1864. Type, *Planorbis newberryi* Lea, 1858.

Carinifex Binney, W. G., Smithsonian Misc. Coll. No. 143, pt. 2, p. 74, September, 1865. Type, *Planorbis newberryi* Lea, Acad. Nat. Sci. Philadelphia Proc. for 1858, p. 41, 1858.

December 9, 1863, while Mr. W. G. Binney was engaged in preparing an account of the land and fresh-water shells of the United States for the Smithsonian Institution, desiring the opinion and criticism of his colleagues, he induced Professor Henry to send out a set of proof sheets (not for sale) to a few persons who were interested in the study of mollusks. In the preface to these sheets Professor Henry, while explaining their purpose, remarks: "As a mere proof which will undoubtedly receive many corrections, these pages should not be quoted as authority or referred to as a published work."

These proofs were in page form printed on one side of the paper, and on the eleventh sheet occurs the absolutely nude name "*Carinifex newberryi* Lea." There was, prior to the issue of this proof, an *Ancylus newberryi* Lea, 1858, a *Planorbis newberryi* Lea, 1858, a *Melania newberryi* Lea, 1860, and a *Goniobasis newberryi* Lea, 1863, but no *Carinifex newberryi*, nor was there in the proof sheets referred to any indication which of the above-named species might be intended by Binney's *Carinifex newberryi*.

The first publication of the genus *Carinifex* occurred, as indicated in the preceding synonymy, in September, 1865. But Lea's name had been fully diagnosed and published in January or February, 1864. It would seem that, under the circumstances and according to the rules, *Megasystropha* should be accepted.

Megasystropha binneyi Meek.

Carinifex binneyi Meek, Acad. Nat. Sci. Philadelphia Proc. for 1870, p. 59, 1870.

Carinifex (*Vorticifex*) *binneyi* Meek, U. S. Geol. Expl. 40th Par. Rept., vol. 4, p. 187, pl. 17, figs. 11, 11a, 1877.

Fossil Hill.

Meek, in 1877, attempted to make this species the type of *Vorticifex*, but as it was not included in the subgenus as originally proposed, this, under the rules, can not be accepted.

This species differs from the typical *Megasystropha* in having the spire deeply sunken instead of elevated, and the peripheral edges rounded instead of carinate. This gives it a much more planorboid aspect. It may typify a section *Paradines*. *Pompholopsis* Call, 1888, typified by *P. whitei* Call, may form another section for fossil forms more turbinate, solid, and umbilicate than the recent type. The relations of *Choanomphalus* Gerstfeldt, a recent form of Lake Baikal, to the present group are in need of elucidation.

Subfamily PAYETTINAE.

Genus PAYETTIA Dall, n. gen.

Payettia dalli (White).

Latia dalli White, U. S. Nat. Mus. Proc., vol. 5, p. 100, pl. 5, figs. 17–20, 1882; U. S. Geol. Survey Third Ann. Rept., p. 45, pl. 32, figs. 37–40, 1883.

Fifty miles below Salmon Falls, Snake River; White. Castle Creek, Owyhee County, Idaho; Campbell. Also various other localities in the Idaho formation.

This is one of the relatively few species which appear to be widely distributed in the lake-bed deposits.

Though White recognized the differences between the Australasian and Japanese genus *Latia* and the present fossil, he nevertheless tentatively referred the fossil to the same genus.

Latia is a small fresh-water shell, with a short deck from which a prominent spurlike process projects. *Payettia*, on the other hand, has a simple deck like a *Crepidula*, but relatively smaller, and the shell grows to many times the size of *Latia* and is thin and undulated. The geographic distance between the two faunas alone would suggest the probable generic distinctness of the two forms, which is definitely confirmed by the shell characters. *Payettia*, however, is not represented in the Balkan fossil fauna.

Family ANCYLIDAE.

Genus ANCYLUS O. F. Müller.

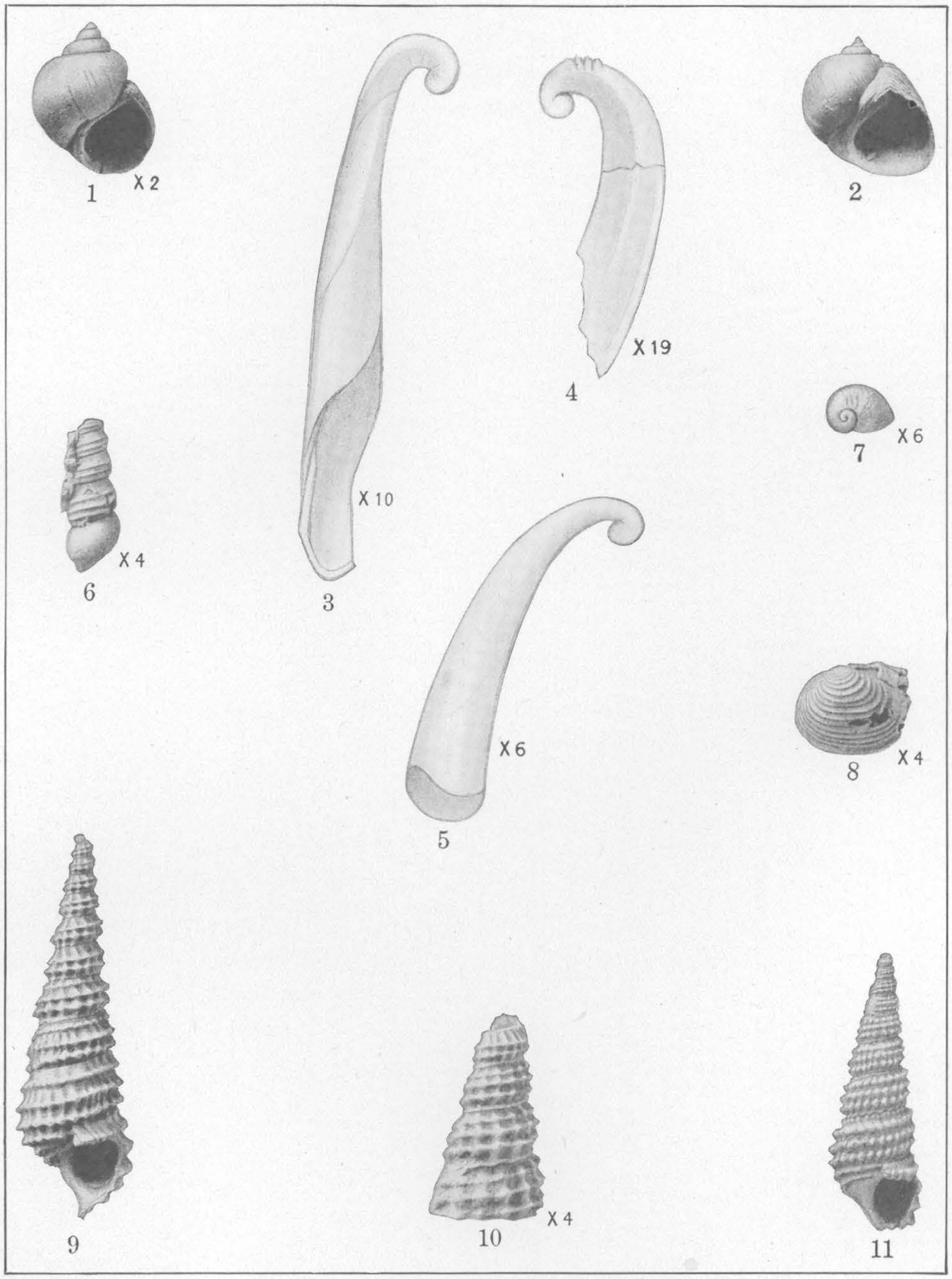
Ancylus undulatus Meek.

Ancylus undulatus Meek, Acad. Nat. Sci. Philadelphia Proc. for 1870, p. 57, 1870: U. S. Geol. Expl. 40th Par. Rept., vol. 4, p. 186, pl. 17, figs. 12 a–b, 1882.

White, U. S. Geol. Survey Third Ann. Rept., p. 45, pl. 32, figs. 10, 10a, 1883.

Fossil Hill.

I have not seen this species.



FOSSILS OF THE IDAHO FORMATION.

1. *Lithoglyphus campbelli* Dall.
2. *Lithoglyphus antiquus* (Gabb).
3. *Orygoceras* (*Ibicicornu*) *idahoense* Dall.
4. *Orygoceras* (*Ibicicornu*) *crenulatum* Dall.
5. *Orygoceras* (*Ibicicornu*) *arcuatum* Dall.
6. Apical whorls of *Goniobasis taylori* (Gabb).
7. *Aphanotylus whitei* Dall.
8. *Sphaerium meeki* Dall.
9. *Goniobasis taylori* (Gabb).
10. *Goniobasis taylori* (Gabb), upper part of spire.
11. *Goniobasis* (*taylori* var.?) *calkinsi* Dall.

Family ORYGOCERATIDAE.

Genus ORYGOCERAS Brusina.

Orygoceras Brusina, Beitr. Paläontologie Oesterr.-Ungarns u. des Orients, vol. 2, p. 33, Wien, 1882; Iconographia molluscorum fossilium, p. viii, pl. 2, 1882.
Fischer, Manuel de conchyliologie, p. 735, fig. 504, 1885.

This extraordinary genus, resembling *Parastrophia* of the Caecidae among marine mollusks, but probably not operculate, is divisible into several quite distinct sections. No type was selected by the author, and therefore I select the example figured by Fischer, *O. cornucopiae* Brusina, as representing the typical section.

I. Section *Orygoceras* (strict sense). Shell tubular, with a small spiral apex, straight or slightly arcuate, cylindrical, gradually expanding, sculptured with regularly spaced transverse lamellae. Type *O. cornucopiae* Brusina.

II. Section *Ibicicornu*. Shell longitudinally subcarinate, with a dextral twist. Type *O. fistula* Brusina.

III. Section *Bovillina*. Shell smooth, with circular section, more or less arcuate. Type *O. corniculum* Brusina.

IV. Section *Incilicornu*. Shell nearly straight, longitudinally finely striate, slightly twisted near the apex. Type *O. leptonema* Brusina.

Members of sections I and IV have not yet been detected in America.

Orygoceras (Ibicicornu) idahoense Dall, n. sp.

Plate XXVI, Figure 3.

Castle Creek, Owyhee County, Idaho; Campbell.

Shell minute, nearly straight, except the spiral nucleus of about one whorl, beyond which the whorl describes a semicircular arc equal to about half a revolution, beyond which the slowly enlarging tube becomes nearly straight; on the basal side of the spire a low rounded carina is initiated, which continues as far as the anterior end of the tube, making about half a revolution around it, the surface behind it appearing slightly flattened, the total aspect indicating a twist of the tube; the transverse section of the otherwise smooth tube, except for the slight indentation at the end of the carina, being circular. Longitude about 7 millimeters; diameter 1.5 millimeters. U. S. Nat. Mus. catalog No. 333522.

This resembles *O. fistula* Brusina but is longer and has the apex arched loosely, whereas in the Balkan species the apical part joins the nearly straight tube without an open arch.

Orygoceras (Ibicicornu) crenulatum Dall, n. sp.

Plate XXVI, Figure 4.

The apical portion and part of the succeeding tubular part of another species was found with the shell described above. The spiral apex is somewhat less involved, and the arch narrower; above the arch the periphery of the tube has four or five prominent transverse crenulations; the succeeding portion of the tube, in addition to the chief carina, has the beginning of a feebler second carina above it and near the periphery of the tube. The remainder of the shell was buried in the matrix and inaccessible. The length of the visible portion is about 3 millimeters. U. S. Nat. Mus. catalog No. 333523.

Orygoceras (Ibicicornu) arcuatum Dall, n. sp.

Plate XXVI, Figure 5.

Castle Creek, with the preceding species.

Shell minute, smooth, arcuate, rather rapidly enlarging, the spiral part reduced to a minute bulb at the apex of the tube, the carina feeble but evident and becoming obsolete anteriorly; the twist in the tube well marked. Longitude 7.5 millimeters; diameter 1.7 millimeters. U. S. Nat. Mus. catalog No. 333524.

This is nearest to *O. cnemopsis* Brusina but is at least one-third longer, is less angular, and increases more rapidly in diameter.

Orygoceras (Bovillina) tuba Dall, n. sp.

Castle Creek, with the preceding species.

Shell small, smooth, ecarinate, the apex loosely coiled, forming hardly more than one-half of a revolution; the cross section of the earlier part of the tube is slightly compressed laterally but later becomes circular; the aperture has its sides slightly arcuately produced, the edges receding between them; there is no trace of a carina, but a slight twist is perceptible. Longitude 8 millimeters; diameter of aperture 2 millimeters. U. S. Nat. Mus. catalog No. 333525.

This is nearest to *O. corniculum* Brusina, which is only 3 millimeters long and has a less even arcuation and a closely coiled nucleus, with no arch to speak of. A fragment of *O. tuba* on another piece of rock, without apex or aperture, is 7 millimeters long and indicates that a perfectly adult specimen might reach a length of over 10 millimeters.

Family MELANIIDAE.

Genus GONIOBASIS Lea.

The forms described below are devoid of the anterior angularity of the margin of the aperture which suggested the generic name, but in a large number of the recent species now referred to the genus this feature is also absent, so it seems more probable that the fossil forms are related to the American genus than to the exotic typical *Melania*, which is not represented in the recent American fauna.

Goniobasis taylori (Gabb).

Plate XXVI, Figures 6, 9, 10.

Melania taylori Gabb, Paleontology of California, vol. 2, p. 13, pl. 2, fig. 21, 1865.
White, U. S. Nat. Mus. Proc., vol. 5, p. 100, pl. 5, fig. 3, 1882; U. S. Geol. Survey Third Ann. Rept., pt. 3, p. 55, fig. 3, 1883.
Goniobasis tayloriana Pilsbry, Nautilus, vol. 13, p. 66, 1899.

Castle Creek, Owyhee County, Idaho; A. Taylor, W. H. Campbell. Near Glenn's Ferry; I. C. Russell.

The typical *G. taylori* has sharp sculpture with the arcuate axial ridges sharp and prominent, usually with wider interspaces; on the last whorl there are six, on the preceding two whorls three, and on the earlier whorls two sharp spirals. The spire is elongate, tapering to an acute apex, and comprises ten or twelve whorls. The earlier ones are often eroded and appear nearly or quite smooth.

A variety of this species, more abundant at Castle Creek than the typical form, has the axial sculpture inconspicuous, the nodulation at the intersections rounded, and behind the last whorl all the whorls of the spire have three similar spirals. This may take the name *G. taylori* var. *calkinsi* (Pl. XXVI, fig. 11). This was also collected in the Snake River canyon 1 mile east of Slick Bridge, on the south side of the river, by F. C. Calkins. U. S. Nat. Mus. catalog No. 333526.

Genus MICROMELANIA Brusina.

Micromelania Brusina, Fossile Binnen-Mollusken aus Dalmatien, Kroatien und Slavonien, p. 133, Agram, 1874. Type, *M. cerithiopsis* Brusina.

These are small subcylindric shells with numerous whorls and well-impressed suture. The aperture is simple. The original type is a sculptured shell, but of ten species figured in his Atlas, Brusina shows only one with pronounced sculpture. In the matrix of the material from Castle Creek there are a number of internal casts and fragments which might be referred almost indifferently to this genus or to *Pterides*, but in no specimen is the aperture preserved.

Family HYDROBIIDAE.

Genus CASPIA Dybowski.

Caspia Dybowski, Mal. Blätter, neue Folge, Band 10, p. 34, 1887. First species *C. baeri* Dybowski, p. 36, pl. 3, figs. 4 a–b, which may be taken as the type.

This small operculate is found living in the Caspian Sea, and numerous species occur in the Balkan fresh-water deposits. Internal casts which might belong to a species like that (unnamed) which is figured in Brusina's Atlas, Plate XI, Figures 14–15, occur in the Castle Creek material but can not be positively identified.

Genus NEMATURELLA Sandberger.

Nematurella Sandberger, Conchylien der Vorwelt, p. 575, 1874. Sole example, *N. flexilabris* Sandberger, p. 575, pl. 20, figs. 24, 24*c*.
Brusina, Atlas, p. viii, pls. 9, 11, 29, 1902.

Two worn specimens from the Castle Creek material are very close to the unnamed species figured in Brusina's Atlas, Plate XI, Figure 26, but are hardly well enough preserved for description.

Genus SANDRIA Brusina.

Sandria Brusina, Atlas, p. ix, pl. 9, figs. 22–27, 1902. Type, *S. kochi* Brusina, pl. 9, figs. 22–24.

These are small shells, much resembling minute *Bythinella*. I have not been able to find a reference to the earlier description of *S. kochi* or the genus *Sandria*. Three species in a more or less imperfect state of preservation are represented in the Castle Creek material if their resemblance to Brusina's figures may be trusted.

Subfamily LITHOGLYPHINAE.

Genus LITHOGLYPHUS Mühlfeldt.

Lithoglyphus (Mühlfeldt MS.) Hartmann, in Sturm's Fauna Deutschl., vol. 6, Heft 5, p. 57, 1821.
Ziegler, in Menke, Synops., p. 42, 1830. Type, *Paludina naticoides* Ferussac.

Lithoglyphus antiquus (Gabb).

Plate XXVI, Figure 2.

Lithasia antiqua Gabb, Paleontology of California, vol. 2, p. 13, pl. 2, fig. 23, 1865.
White, U. S. Nat. Mus. Proc., vol. 5, p. 100, pl. 5, fig. 4, 1882; U. S. Geol. Survey Third Ann. Rept., pt. 3, p. 59, pl. 32, fig. 4, 1883.

This is one of the most widely distributed and conspicuous members of the fresh-water fauna of the Idaho formation. It is a typical *Lithoglyphus* and the first genuine member of that genus to be reported from the Western Hemisphere. The species reported by authors from South America in the Recent fauna belong to quite different genera.

Lithoglyphus campbelli, Dall, n. sp.

Plate XXVI, Figure 1.

Mouth of King Hill Creek near Glenn's Ferry, Snake River canyon, Idaho, U. S. Geol. Survey station 3486: I. C. Russell; very abundant.

Shell small, solid, with a rather acute apex, a pustular nucleus, and about five well-rounded whorls; suture distinct, the whorl in front of it flattened a little, giving a slightly turrited aspect to the spire; last whorl much the largest, naticoid; surface smooth except for incremental lines; base rounded, imperforate; aperture subovate, simple, the margins sharp, the inner and outer lips connected over the body by a thick layer of callus. Altitude, 11 millimeters; maximum diameter, 8 millimeters; aperture, 6.5 millimeters. U. S. Nat. Mus. catalog No. 333527.

Named in honor of W. H. Campbell, collector of the Castle Creek material.

Family VALVATIDAE.

Genus VALVATA O. F. Müller?

Brusina refers to *Valvata* a considerable number of turbinate shells from the Balkan deposits, figuring them on his Plates XIII and XIV. In general, they appear heavier and thicker than the recent shells familiar to us, and some of them with a different type of sculpture remind one of the marine trochoid *Machaeroplax* Friele. One such specimen occurs partly embedded in the Castle Creek material, the aperture and base inaccessible, the upper surface showing about three whorls encircled by two inconspicuous carinae. It is probable that with a better knowledge of these animals a portion at least of the species will prove to be separable from typical *Valvata*.

Genus APHANOTYLUS Brusina.

Aphanotylus Brusina, Jour. de Conchyliologie, vol. 41, pp. 179, 182, 1893. Type, *A. cossmanni* Brusina, op. cit., p. 185; Atlas, p. v, pl. 14, figs. 22–27, 1902.

These are minute planorboid shells with a closed or nearly closed umbilicus, having a remarkable resemblance to the marine genus *Pseudorotella* Fischer.

Aphanotylus whitei Dall, n. sp.

Plate XXVI, Figure 7.

Castle Creek, Owyhee County, Idaho; W. H. Campbell.

Shell minute, of about two whorls, the nucleus hardly raised above the flattened spire, the surface smooth, the suture inconspicuous, the last whorl rather rapidly enlarging; the aperture subcircular with sharp-edged margin and no lirae internally; base well rounded, imperforate. Diameter, 1.6 millimeters; height, 1.2 millimeters. U. S. Nat. Mus. catalog No. 333528.

Another species, represented by broken specimens in the matrix, has a raised cord running spirally in front of the suture and somewhat separated from it. It is a larger shell than *A. whitei*.

THE RESUSCITATION OF THE TERM BRYN MAWR GRAVEL.

By F. Bascom.

In the course of geologic and physiographic work in eastern Pennsylvania, it has seemed to the writer that the time was ripe for the restriction of the term Brandywine formation, now including presumably both Pliocene and Pleistocene gravels, and the reinstatement of the old term Bryn Mawr gravel for a portion of the divided Brandywine. A brief history of the nomenclature and usage involved will show the grounds for the choice of terms.

In 1888 the term "Appomattox" was used by McGee [1] for the "older terrace sediments," and in 1891, in conference with Hilgard [2] and others, McGee correlated these sediments with the deposits of Lafayette County, Miss., which had been assigned to the early Quaternary and which were then called the "Lafayette formation." Since that date the term "Lafayette" has been very generally used. Recent work, however, has shown that the "Lafayette formation" of the type locality in the Gulf region is not Quaternary but of Wilcox Eocene age. A new name was therefore proposed in 1915 for the Atlantic coast deposits by Clark,[3] who called them the Brandywine formation, from a type locality in the vicinity of Brandywine village, Prince Georges County, Md. The name was defined to cover all the gravels that lie above the Sunderland formation at 200 feet, in Maryland reaching an altitude of 480 feet and having a width from northwest to southeast of 40 miles. At that time the Brandywine formation was questionably referred to the Pliocene on the ground that it had suffered extensive erosion and that its constituent minerals showed great decay. Clark was himself inclined to think that the deposits were earlier Pleistocene rather than Tertiary. In thus naming these deposits it was the intention to replace by a term signifying a specific age and stratigraphy older terms which included deposits at that time recognized to be of different ages. The term Brandywine itself, however, has in turn been found to cover deposits of more than one level and age.

In 1920, in the Elkton-Wilmington geologic folio,[4] the Brandywine formation was for the first time separated into early (high-level) and late (low-level) Brandywine. The early Brandywine gravels are found in the Elkton-Wilmington district at an altitude of 380 feet, capping Egg Hill and other outstanding hills on the western border of the Elkton quadrangle. The late Brandywine gravels lie at altitudes of 220 feet or more. As the firm hard layers and decomposed pebbles of the early Brandywine gravels indicate a greater age than the Pleistocene, they were referred to the Pliocene (?), and it was stated that the later gravel, though provisionally included with the Brandywine formation, might be of early Pleistocene age. The deposit at the type locality in Maryland is the low-level (200–300 feet) or late Brandywine, presumably of Pleistocene age, as Clark was led to believe; the high-level gravels (390–480 feet) are presumably of Pliocene age. Such a time interval between the early and late gravels as is now recognized has made it infeasible to treat the deposits as a unit. It is therefore proposed to restrict the term Brandywine formation to the late or lower-level deposits of the type locality, and to reinstate the old term Bryn Mawr gravel for the early or high-level deposits of Pennsylvania, Delaware, and Maryland (Cecil County).

[1] McGee, W J, Three formations of the middle Atlantic slope: Am. Jour. Sci., 3d ser., vol. 35, p. 328, 1888.

[2] Hilgard, E. W., Orange sand, Lagrange, and Appomattox: Am. Geologist, vol. 8, pp. 128–131, 1891.

[3] Clark, W. B., The Brandywine formation of the middle Atlantic Coastal Plain: Am. Jour. Sci., 4th ser., vol. 40, p. 499, 1915.

[4] U. S. Geol. Survey Geol. Atlas, Elkton-Wilmington folio (No. 211) p. 12, 1920.

The history of the term Bryn Mawr is as follows: Carvill Lewis first proposed the term for the deposits of gravel and ironstone conglomerate on the "Upland Terrace" of eastern Pennsylvania. The report upon these gravels, which was made to the Academy of Natural Sciences of Philadelphia in November, 1878, and published in 1880,[5] contains the following descriptions:

This hill is easily recognized where uncrossed by creeks, being remarkably straight and of uniform height. Being the first hill of importance west of the Delaware, it often commands a fine view and is a favorite site for residences.

The geographical position of this ancient terrace may be more exactly defined in the vicinity of Philadelphia as the hill which crosses Second Street Pike near Foxchase * * * and runs north of Kellyville, Clifton, and Morton, to Swarthmore College and thence past Village Green into Delaware.

This hill, which is approximately parallel not only to the river [Delaware] but also to the shore of the Atlantic Ocean and the line of strike of the Cretaceous formations of New Jersey, forms, as we have seen, the main dividing line between the ancient and the modern formations.

We shall call it for convenience "the Upland Terrace."

A description of the Pleistocene clays and gravels deposited between the "Upland Terrace" and Delaware River follows, and then the report continues:

Upon the summits of some of the highest hills in the gneissic region back of Philadelphia, at a mean distance of about 9 miles from the river and at elevations of from 325 to 450 feet above it, there are isolated patches of an ancient gravel, different from any yet described, to which we have given the provisional name of "the Bryn Mawr gravel." It can always be recognized by the presence of sharp or partially rounded fragments of a hard, heavy iron sandstone or conglomerate. Such fragments are often covered by a brownish-black iron glaze. More than ten years ago the writer noticed in the soil of the upper part of Germantown pieces of this conglomerate, unlike any known rock, and it is only of late that its origin has been suspected. It consists of well-rounded pebbles of quartzite or siliceous sandstone cemented by iron into a stone which is often very hard. This conglomerate is found in occasional fragments upon ground over 300 feet high but is not found in abundance until an elevation of over 400 feet is reached. At these highest points it occurs in a red gravel whose pebbles are identical with those of the conglomerate. * * * A similar tract of this gravel occurs at Bryn Mawr, extending from that place to near Cooperstown. A good section is exposed in the railroad cut below the station. From this locality, so easy of access from the city, we have named the formation. It is here about 450 feet high and 9 miles from the river. The gravel is 10 feet deep and lies upon a steeply dipping gneiss so completely decomposed that it is as soft as clay.

At a later meeting (March, 1879) Lewis reported that "the Upland Terrace has now been traced continuously from near Trenton, through Bucks, Philadelphia, and Delaware counties to beyond Wilmington in Delaware." He calls attention to

the great development of the Bryn Mawr gravel in Delaware, and to the indications of its assuming an important position in the geology of the Southern States. * * * Numerous hills in Delaware County have been found to be capped by this formation, and in northern Delaware it covers the gneissic hills in patches several miles long and comes close to the river. * * * This formation so abundant in Delaware is thus proved to be by no means a local one, and it is probable that it will be identified with some of the formations grouped together under the name of "Southern drift."[6]

It is plain from this account that by the "Upland Terrace" was meant the upland the lowest slopes of which are at the 300-foot level, separated by an escarpment from the lower terrace upon which lie the low-level Brandywine deposits and rising to the northwest to the 480-foot level, with a dominating level of 400 feet; and that by the term Bryn Mawr gravel was meant the gravel and ironstone conglomerate capping the interstream areas of this terrace. The gravels of the type localities described by Lewis are plainly the high-level or early Brandywine gravels, and the term Bryn Mawr as used by Lewis covered only the high-level Brandywine deposits as they occur in Pennsylvania and Delaware. The term received considerable usage prior to the introduction of the designation "Lafayette." The Second Pennsylvania Geological Survey referred to the Bryn Mawr gravel as Tertiary or Upper Cretaceous. McGee at first regarded it as of Columbia age and later classified it as lower Potomac.

The term Bryn Mawr gravel is here proposed for the high-level Brandywine because it has the claim of priority, preceding in usage all other designations for the Tertiary deposits of the Atlantic slope, because the gravels of the type locality are the older gravels, and because

[5] Lewis, H. C., The surface geology of Philadelphia and vicinity: Acad. Nat. Sci. Philadelphia Proc., vol. 32, pp. 258–272, 1880; see also pp. 277–278, 288, 296–309.

[6] Op. cit., pp. 277–278.

the 400-foot terrace, upon which the early Brandywine deposits lie, is so prominent a physiographic feature in eastern Pennyslvania, where these gravels and terraces were so early described and given a local name.

The correlation of the Bryn Mawr formation with other Tertiary gravels near the fall line depends upon the origin of the gravels and upon their topography. Whatever origin is eventually ascribed to the high-level Brandywine by those at work on the Tertiary and Pleistocene deposits of the Atlantic coast, it will doubtless be required to explain acceptably all the high-level gravels, so similar are these deposits and so uniform are the levels upon which they are found.

That these high-level gravels were originally deposited in detached areas is quite possible, but their approximate equivalence is so little to be doubted that until it is disproved the less misleading and less cumbersome method would seem to consist in the use of a single term. The logical alternative is to give a separate name to every patch of gravel above the low-level or typical Brandywine—that is, above the 300-foot level—an alternative which would lead to confusion and which would not reflect the present state of our knowledge.

ORIGIN OF THE BOGHEAD COALS.

By Reinhardt Thiessen.

The bituminous rocks of sedimentary origin may be classified roughly under two main heads—coals and bituminous shales. In a strict sense no definite line can be drawn between these two groups, because coals may insensibly grade into bituminous shales. Chemically the boghead coals are preeminently bituminous.

COAL.

Coal is composed in the main of the residues of the components of plants. The residues of the ligno-cellulosic components—that is, the woody portions—form the larger part. With these are always associated in varying amounts the residues of the more resistant components and products of plants, of which the resins, resin waxes, fats, and oils or their derivatives are the most abundant. Besides these, many other resistant plant products, too many to enumerate, enter into the formation of coal. The mineral content of coal is relatively low.

BITUMINOUS SHALE.

A shale is generally defined as a rock formed by the consolidation of clay mud or silt, having a finely stratified, laminated, or fissile structure. Some sand is usually mingled with the silt. If such a rock contains organic matter and is dark colored it is termed carbonaceous shale; if the organic matter is of a bituminous nature (highly hydrogenous) the rock is called bituminous shale; and if the rock is rich enough in bituminous substances to yield oil and gas in relatively large amounts on distillation it is called oil shale. The mineral matter in bituminous shales may vary greatly; in oil shales the organic matter is generally less than the mineral matter. Rock in which the mineral and organic matter are approximately in equal proportions may be called cannel slate or cannel shale; and rock in which the organic matter is considerably more abundant than the mineral matter is generally called cannel coal.

Under bituminous shales, therefore, are here considered all bituminous rocks usually designated cannel coals, boghead coals, oil shales, torbanite, tasmanite, and cannel "slates." These rocks have never been classified satisfactorily in accordance with their genetic characters; it is impossible to classify them definitely according to their general appearance and physical properties. However, they may be classified definitely and specifically into several well-defined groups, according to their origin or the origin of their predominant constituent or constituents.

The chief components of organic shale are humic matter—that is, ligno-cellulosic and other matter formed by the degradation of carbohydrates—resinous matter, spore matter, cuticular and other ceric matter, and oil-algal matter. It contains also small amounts of certain other components of unknown origin.

According to their origin, therefore, the bituminous sedimentary deposits may be classed as (1) humic, if the predominant organic constituent is matter derived from the degradation of carbohydrates—that is, such substances as wood, cellulose, lignin, bark, or suberin, gums, mucilage, and starch; (2) spore, if the predominant organic matter is derived from spores; (3) ceric or waxy, if the predominant organic matter is derived from the waxy substances of plants, including oil or fat; (4) resinous, if the predominant organic matter is derived from the natural resins of plants; (5) algal, if the predominant organic matter is derived from oleaceous algae, as in the boghead coals.

Each of these substances is invariably admixed with one or more of the others in different proportions. Usually one predominates, but two or even three components may be present in equal or about equal proportions, with others in less amounts.

THE BOGHEAD COALS.

Boghead coals differ little from any other bituminous shales in outward appearance, and it is often difficult if not impossible to distinguish them. They are close grained, brownish black to black, very tough, elastic, and difficult to break; usually they break with a conchoidal or subconchoidal fracture. In mass they show definite layering, but they will rarely split along definite horizontal planes.

When examined under the microscope in thin sections boghead coals are at once found to differ from all other bituminous shales in that they contain or are composed largely of peculiar irregular oval yellow bodies, through the structure and composition of which they are easily distinguishable from all other bituminous rocks.

Other names have been applied to these deposits, such as kerosene shales, torbanite, torbanehill mineral, brown cannel coal, bathvillite, algal coal, albertite, bituminite, parrot coal, and cannel coal. But as the term "boghead coal" has been most often used, has in general been so consistently applied to deposits of this type and is so thoroughly incorporated into the literature, it can not well be discontinued, although it is not satisfactory. It is used in this paper for want of a better name.

NOMENCLATURE.

The term "boghead" was first applied to coal of this variety found on the Boghead estate, near Bathgate, Linlithgow, Scotland. At Torbane Hill, also near Bathgate, it was called "torbanehill mineral" and "torbanite."

"Kerosene shale"[1] was first applied to boghead coals by the oil-shale industries of Mount Kembla, near Wollongong, New South Wales, Australia, and became identified with the industries at other localities and in other countries. The term is still used in Australia. "Kerosene coal" is a term used by J. R. M. Robertson,[2] of Scotland.

"Wollongite" was proposed by B. Silliman[3] for the substance found at Hartley, New South Wales.

"Petroleum-oil cannel coal" is a term applied by John Mackenzie[4] to the Australian deposits.

"Bituminite" is a name proposed for torbanite by T. S. Traill.[5]

"Parrot coal" is a Scotch term arising from the crackling noise produced when torbanite is placed in the fire.

"Cannel coal," a corruption of "candle coal," was first applied to torbanite because of its property of burning with a clear flame, like a candle, and later became a synonym of torbanite and boghead. The term was soon applied to all coals of similar texture and appearance and so became a generic instead of specific term.

"Brown cannel" was later used by W. B. Clarke[6] to distinguish a boghead from ordinary cannel coal.

"Algal coal" was applied to the boghead coals by Bertrand and Renault.[7]

DISCOVERY AND EARLY HISTORY.

Torbanite was discovered at Torbane Hill, Linlithgowshire, Scotland, in 1850, and later was found at Boghead, Bathville, Inchroos, and Cappers, all near Bathgate, in Linlithgowshire. It was soon found to be a substance exceedingly rich in oily constituents and on this account was brought into special industrial prominence both in Europe and in America. It was about this time that, the patents of Dr. Albert Gesner[8] having been sold to the North American Kerosene Gas Light Co., kerosene was manufactured from coal and introduced generally to the American public. This kerosene or "coal oil" was objectionable on account of its unpleasant odor, and therefore large quantities of torbanite were shipped to America for the manufacture of kerosene that would not have the odor. This led to litigation over patent rights both in America and in England. In England the oil made from tor-

[1] Carne, J. E., The kerosene-shale deposits of New South Wales: New South Wales Geol. Survey Mem., Geol. No. 3, Dept. Mines and Agr., 1903.

[2] Robertson, J. R. M., Min. Inst. Scotland Trans., vol. 14, pt. 6, pp. 88–112, 1892.

[3] Silliman, B., Am. Jour. Sci., 2d ser., vol. 48, p. 85, 1869.

[4] Mackenzie, John, Mineral production of New South Wales, 1887; New South Wales Dept. Mines and Agr., Annual report for 1887.

[5] Traill, T. S., Roy. Soc. Edinburgh Trans., vol. 21, pp. 7–13, 1857.

[6] Clarke, W. B., Geol. Soc. London Quart. Jour., vol. 22, p. 446, 1866, and elsewhere.

[7] See footnote 18, p. 124.

[8] Gesner, G. W. (son of Albert Gesner), A practical treatise on coal, petroleum, and other distilled oils, 1865.

banite was called "paraffin oil" and was used in "mineral-oil lamps." The litigation over the patent rights led to the institution of a lawsuit that became famous—that of Gillespie *v.* Russel. The dispute concerned the question whether torbanite was coal or not coal and affected the ownership of the deposits. A large number of scientific men in Europe were brought before the court to decide whether the so-called boghead coal is coal or bituminous clay, and the suit incidentally led to the study of the origin of this substance.

Quecket [9] maintained that torbanehill mineral is not a coal; that it is not like any of the combustible substances used in Great Britain as coal; that, although possessing some of the properties of coal, it is nevertheless a mineral having a basis of clay which is strongly impregnated with a peculiar combustible substance; and that any plants found in it are accidental and have no more been concerned in the formation of the mineral than a fossil bone in that of the rocks in which it may be embedded.

Bennett's opinion [10] was that the torbanehill mineral, although it presents essentially no trace of vegetable structure, is rich in bituminoid substances—a circumstance explained by the fact that it is found in the neighborhood of coal, so that the bituminoid or resinoid matter formed in the partly woody structure of the coal has flowed out, mixed itself with, and solidified in the essentially earthy substance of the torbanehill mineral.

Balfour [11] maintained that torbanite was of the same class as black cannel coal.

OTHER EARLY WORK ON BOGHEAD COALS.

Redfern,[12] lecturer in anatomy, physiology, and histology in the University of Aberdeen, supported the plant origin of the torbanehill mineral and argued that it is like all other cannel coals. Speaking of the yellow bodies of which the mineral is largely composed, he said that he knew of no other interpretation except that they are produced by free vegetable cells, such as spores or pollen grains, yet he could not confidently affirm that they are such; but whatever they may be, they are always to be found in other cannel coals.

The kerosene shale in Australia was discovered long before that in Scotland. Probably the earliest reference to it was published in Paris in 1807, after the return of a French scientific expedition that visited Australia in 1802. It was not utilized, however, until 1865. David,[13] a professor in the University of Sydney, New South Wales, was the first to investigate the kerosene shale of Australia by the most advanced methods of research and the first to propound the hypothesis that this shale is of fresh-water algal origin. The first scientist, however, to suggest the algal origin of the very richly bituminous shales was T. S. Ralph,[14] who claimed that the organic matters forming tasmanite were algae; but in this he was incorrect, as tasmanite is described as a spore cannel coal.[15]

Clarke [16] thought that kerosene shale unquestionably resulted from local deposits of resinous wood and passed gradually into ordinary coal. Dixon [17] argued that the idea of resinous origin must be abandoned, as the resins yield aromatic products and not paraffins. He also thought it more probable that the shales came from oil-producing or wax-producing plants, most likely the latter, in view of the considerable yield of solid paraffins from the shales.

The algal theory of the origin of the boghead coals was most prominently developed by Renault and Bertrand, and the result of their investigations ranging over 25 years was

[9] Quecket, John, On the minute structure of a peculiar combustible mineral from the coal measures of Torbane Hill, near Bathgate, Linlithgowshire, Scotland, known in commerce as Boghead cannel coal: Micr. Soc. London Trans., vol. 2, pp. 34-36, 1853.

[10] Bennett, J. H., An investigation into the structure of torbanehill mineral and of various kinds of coal: Roy. Soc. Edinburgh Trans., vol. 21, pp. 173-185, pls. 1-2, 1857.

[11] Balfour, J. H., On certain vegetable organisms found in and from Fordel: Roy. Soc. Edinburgh Trans., vol. 21, pp. 187-193, 1854.

[12] Redfern, P., On the nature of torbanehill and other varieties of coal: Micr. Soc. Quart. Jour., 1855, pp. 106-127.

[13] David, T. W. E., Note on the origin of kerosene shale: Linnean Soc. New South Wales Proc., 2d ser., vol. 4, pp. 483-500, 1889.

[14] Ralph, T. S., Royal Soc. Victoria Trans., 1865, p. 4; cited by Carne, J. E., The kerosene-shale deposits of New South Wales; New South Wales Geol. Survey Mem., Geol. No. 3, p. 61, 1903.

[15] Newton, E. T., On tasmanite and Australian white coal: Geol. Mag., vol. 2, pp. 337-342, 1875; New South Wales Dept. Mines Ann. Rept. 1879, p. 33.

[16] Clarke, W. B., Industrial progress of New South Wales, 1871, p. 449; cited by Carne, J. E., op. cit., pp. 59-61.

[17] Dixon, W. A., Australasian Assoc. Adv. Sci. Proc., vo. 1, p. 134, 1887; cited by Carne, J. E., op. cit., p. 61.

summed up by Renault.[18] A fundamental jelly, a sort of gelatinous precipitate, supposed to have existed in the ancient lakes, pools, and swamps, is one of the chief assumptions in their theory. In this jelly were suspended spores, pollen grains, plant cells, cuticles, and minute vegetable débris, but paramount were certain gelosic algae surrounded by a gelatinous sheath or matrix, something like the *Nostoc* of to-day. Besides these, certain secretive cells are supposed to have been held in suspension, still presenting in detail their protoplasmic and nuclear contents. The fundamental jelly is supposed to have been produced by the action of microorganisms upon the organic matter, possibly upon the algae themselves. It is the essential part of all coals, and the algae, spores, pollen grains, and other minute bodies are merely accidental; one or another of these nonessential constituents may predominate, thus determining the particular character of the coal.

A careful distinction is therefore drawn by these two investigators between boghead and cannel coals. In the boghead coals the suspended matter consists chiefly of gelosic algae; in the cannel coals it consists of spores. Between the two are found all grades of mixtures, and there may be boghead cannel coals where the algae are more abundant than the spores and cannel bogheads where the spores are more abundant than the algae.

The size of the yellow bodies composing the boghead coals is only a little smaller than it must have been when living. As the mass in the known living gelosic algae contains only a small percentage of solid matter, the remainder being water, it seems clear that such algae could not form the mass of the yellow bodies as found in the bogheads. In order to account for this discrepancy, the algae are supposed to have had a great affinity for bituminous substances and to have been impregnated with and enriched by them to the extent of the present volume. No satisfactory explanation is offered for the origin of the bituminous matter, but probably it was produced by the decomposition of the algae themselves through bacterial activities.

This theory was widely accepted at one time, although some refuted it, foremost among whom was Jeffrey,[19] who concluded from the study of numerous thin sections made from an abundance of material that the bodies interpreted as algae by Bertrand and Renault are not algae but the highly sculptured walls of the spores of cryptogams. When sufficiently thin sections of the bodies in question are cut tangentially through the sculptured spore coats the resemblance to certain algal structures is made very plain. Reconstructions made from serial sections were thought to afford additional evidence of the true spore nature of these bodies by their alveolar structure and triradiate markings and their occurrence in tetrads. With reference to the larger "supposed algae" Jeffrey does not make his case so satisfactory, presumably owing to the distorted condition in which they exist and the difficulty of interpreting thin sections of a larger size. But he presents the apparently reasonable argument that if those which are best preserved and by reason of their size are most easily studied in thin sections of coal prove not to be of algal affinities, a similar conclusion must be applied to the remaining organisms, which either by their large size or their imperfect condition of preservation can not be satisfactorily subjected to microscopic investigation.

At first Zalessky[20] supported Jeffrey's opinion, which he thought was confirmed by examination of a preparation of a siliceous nodule found in the boghead of Autun. The alga, *Pila bibractensis,* seemed to him to be a spore with a reticular sculptured surface, and the walls of the supposed cells seemed to have the form of ribs jutting out on the surface of the

[18] Renault, B., Sur quelques microorganismes des combustibles fossiles. Soc. ind. min. St.-Étienne Bull., 3d ser., vol. 13, pp. 895–1191, 1899; vol. 14, 456 p., 66 figs., 30 pls., 1900.

See also Bertrand, C. E., Le boghead d'Autun: Soc. ind. min. Bull., vol. 6, pp. 453–506, 1892; Bertrand, C. E., and Renault, B., *Pila bibractensis* et le boghead d'Autun: Soc. hist. nat. Autun Bull., vol. 5, pp. 159–253, 1892; Bertrand, C. E., and Renault, B., *Reinschia australis* et premières remarques sur la kerosene shale de la Nouvelle-Galles du Sud: Soc. hist. nat. Autun Bull., vol. 6, pp. 321–425, 1893; Bertrand, C. E., Nouvelles remarques sur le kerosene shale de la Nouvelle-Galles du Sud: Soc. hist. nat. Autun Bull., vol. 9, pp. 193–292, 1896; Bertrand, C. E., Conclusions générales sur les charbons humiques et les charbons de purins: Compt. Rend., vol. 127, pp. 822–825, 1898; Bertrand, C. E., Description d'un échantillon de kerosene shale de Megalong Valley, N. S. W.: Linnean Soc. New South Wales Proc., vol. 25, pp. 617–649, 1901.

[19] Jeffrey, E. C., The nature of some supposed algal coals: Am. Acad. Arts and Sci. Proc., vol. 46, pp. 273–290, pl. 1–5, 1910.

[20] Zalessky, M. D., On the nature of the yellow bodies of boghead, and on sapropel of the Ala-Kool Gulf of the Lake Balkash: Com. géol. Bull., vol. 33, pp. 495–507, Petrograd, 1914; Flore gondvanienne du bassin, de la Petchora, I, Rivière Adzva: Soc. ouralienne amis sci. nat. Bull, vol. 33, 1913.

spores. Studies of material sent to him later by Bertrand and Combray changed his opinion to one in support of Renault and Bertrand's algal theory. In preparations of these siliceous boghead samples he clearly observed the cellular *Pila* structure, as if occurring in a more or less natural state in the bog, giving good evidence to accept that these cellular bodies are algae.

As illustrating the nature and origin of boghead coal Zalessky offers an example from the plant world of to-day in an alga, which he calls *Botryococcus braunii*,[21] growing in the brackish, shallow Ala-Kool Gulf, overgrown with marsh and aquatic plants, at the southern extremity of Lake Balkash, in Turkestan. This alga, bearing a considerable amount of oil, comes to the surface of the water. Zalessky states that when these algae accumulate on the shore, a hydrogen sulphide fermentation takes place; and finally, when in contact with the air, they dry and change from a dark-green into a yellow-brown elastic, rubber-like mass, which can be easily cut with a knife. Thin sections of this mass sometimes clearly show the structure of the algae, which much resemble the bodies in the siliceous boghead sample examined. From this observation deductions are made as to the origin of the bogheads. A further study of the habits of the algae and their transformation into the elastic mass had not been made.

Similar conclusions[22] are drawn from a study of sapropelic substances found at the bottom of Lake Bioloe at Tver, Russia, in a deposit 9 meters thick, said to be composed of blue-green algae, principally of the genera *Microcystis*, *Aplanocapsa*, *Alphanatheca*, *Chroococcus*, *Gleotheca*, *Synechococcus;* and of the green algae *Scenedismus obliquus*, *Scenedismus bijugatus*, and *Pleurococcus vulgaris*.

Later Zalessky[23] found that the bituminous rock of the "Lower Silurian" in Petrograd and Esthonia along the Baltic coast, called kukersite, were similar in nature to the boghead shales of Autun. The fossil organisms in these rocks have a structure very similar to that of the blue-green algae of the genus *Gloeocapsa*, and Zalessky therefore proposed the name *Gloeocapsamorpha prisca* for them.

Conacher[24] examined the oil shale and torbanite of England and Scotland and concluded that they are derived from the same substances as coal but that in the shale there has been a much larger elimination of the woody matter, leaving a large proportion of resinous matter mixed with sand.

In 1914 the present writer[25] maintained that no algae were found in any of the boghead coals he investigated, although many of the bodies called algae by various investigators were found. Many of these, however, were shown to be spores; others were of unknown origin. Some of Renault's illustrations of *Reinschia*, showing both cross and horizontal sections, were certainly those of spore exines. The weakest points in Renault and Bertrand's algal theory, however, were those clauses relating to the "fundamental jelly" and the "bituminous affinity" of the algae. No algae having the structure revealed by the yellow bodies in the boghead coals were known to the writer, nor any that had as massive a cell wall as those in the bogheads indicated. Ordinary living algae, as well as those in the ancient swamps referred to as being analogous, contain at the most only a small quantity of solid matter, by far the largest part of their mass being composed of water. Also, the cell walls of ordinary algae are of pectic-cellulosic nature—that is, they are carbohydrates, which are readily attacked by putrefying organisms and are quickly decomposed under ordinary conditions. Any algal bodies that might have been preserved in the coals would be represented by only an exceedingly thin residue. Renault and Bertrand probably also realized this difficulty, and to overcome it they propounded the hypothesis of bituminous affinity, through which the gelatinous cell walls of the algae were supposed to have absorbed a certain amount of bituminous substances, to account for their solidity and relative massiveness as represented by the yellow bodies in the coals. The fundamental jelly in which these bodies were supposed to have been suspended has never been observed

[21] Zalessky, M. D., On the nature of *Pila* of the yellow bodies of boghead and on sapropel of the Ala-Kool Gulf of the Lake Balkash: Com. géol. Bull., vol. 33, pp. 495-507, Petrograd, 1914. Litinsky, L. L., Balchash-Sapropelite: Petroleum, vol. 17, pp. 437-440, 1921.

[22] Zalessky, M. D., Soc. paléont. Russie Annuaire, vol. 1, pp. 25-42, 1916.

[23] Zalessky, M. D., Sur le sapropélite de l'âge silurien formé par une algue cyanophycée: Soc. paléont. Russie Annuaire, vol. 1, pp. 25-42, 1916.

[24] Conacher, H. R., A study of oil shales and torbanites: Geol. Soc. Glasgow Trans., vol. 16, pt. 2, pp. 164-192, 1917.

[25] White, David, and Thiessen, Reinhardt, The origin of coal: U. S. Bur. Mines Bull. 38, p. 277, 1914.

by the writer. These points—namely, the structure and chemical nature of algae as then known and the unacceptability of the hypotheses of bituminous affinity and the fundamental jelly as proposed by Renault and Bertrand—were sufficient in the writer's mind to overthrow the algal theory.

On the other hand, the writer could not agree that the yellow bodies in the bogheads were invariably spores. The kerosene shales of New South Wales, the typical *Reinschia* coals, stood out most clearly as contravening the theory of spore origin, and the bodies of unknown origin in the cannel coal from the Pottsville of Kentucky could not be classed as spores. For this reason the boghead and cannel coals have been objects of thought and investigation from time to time. Their nature and structure have now been fairly well worked out.

The boghead coals that have been studied were the kerosene shales from Newnes, New South Wales; bogheads from Torbane Hill and from Bathgate, both in Scotland; and American bogheads from Alaska and from Kiskiminetas Junction, Pa.

STRUCTURE OF THE YELLOW BODIES COMPOSING CERTAIN BOGHEAD COALS.

The organism that gave rise to these boghead coals was colonial—that is, a number of individuals were united into a larger body. (See Pls. XXXII–XXXVII.) In many places a number of such colonies were united into a larger mass. Some of the colonies were apparently in the form of a hollow sphere.

The protoplasmic or living part of the organism was of an oval form, as shown in thin sections and illustrated in Plates XXXIII, *B;* XXXIV, *A;* XXXV, *B;* XXXVI–XXXVIII, *A*, and was surrounded by a relatively thick cell wall. This constituted a unit cell or organism. A considerable number of these were joined together into spherical bodies or colonies by a matrix of slightly different character. Whatever the nature of the cell wall and its cementing matrix, they were resistant enough to withstand weathering, putrefying, and oxidizing agencies and the coal-forming processes so well as to retain more than half of their original volume. Their structure points clearly to an organism other than spore matter of any plant.

THE BOGHEAD-FORMING ORGANISM.

The kind of organisms that gave rise to the bogheads is clearly represented by an oil-bearing organism now living in salt lakes and salt lagoons of South Australia and surrounding islands. A recent study of this organism has shed much light on the nature of the yellow bodies composing the boghead coals and on the formation of the bogheads themselves.

The exact position of the organism in the plant kingdom, together with its life history and habits, are yet unknown and are still under investigation. It resembles in some respects certain of the blue-green algae, but in the nature and chemistry of the cell wall it differs greatly from the ordinary blue-green algae.

As no family or genus group to which this organism could be assigned is described in monographs such as Engler and Prantl's "Die natürlichen Pflanzenfamilien" or Toni's "Sylloge algorium," a new name had to be found for the organism. The name *Elaeophyton*,[26] meaning oil plant, is therefore suggested. As the plant examined was found near The Coorong, the specific name *coorongiana* is also proposed.

At the end of each winter a green scum called "seepage material" is formed on the lakes and lagoons and is blown by the prevailing winds to the southeastern shores. As the hot weather progresses and the lakes dry up this material is deposited on the sand of the bank and quickly dries and solidifies into large sheets of a rubber-like dark-brown material, called coorongite. This material has been the object of much discussion, and all endeavor to discover its origin has heretofore been unsatisfactory.[27]

Samples of both the green seepage material and the coorongite were obtained through the courtesy of Mr. John Claffey, of Adelaide. The organisms are colonial: a considerable number of unit individuals or cells are associated into colonies and form globules just visible to the naked eye. (See Pl. XXVII, *A*.)

[26] On account of the resemblance of this organism to forms that are often termed cocci and the large amount of oil it yields, the name *Elaeococcus* was first proposed for it by the writer and has appeared in print. But it was found that the term *Elaeococca* had been applied by Moritz Hill to one of the Euphorbiaceae found in Japan and China, *Elaeococca vernicia*. The name *Elaeococca* therefore has priority over *Elaeococcus*, which had to be abandoned.

[27] Data from personal communication from John Claffey, of Adelaide, South Australia.

These colonies may be either single or compound; in the latter type a number of single or primary colonies are united. A number of colonies may be coalesced into larger globules (Pl. XXVII, *A*), or a larger number of colonies may in turn be united into a large mass (Pl. XXVII, *B*). Plate XXVIII, *A*, represents a stained colony at a high magnification, somewhat flattened under the cover glass.

The structure may be best seen through stained thin sections. The section of a single colony, as on Plate XXVIII, *B*, shows it to be composed of an outer zone of living cells, usually several cells deep, irregularly forming a thick spherical shell. This shell incloses a number of irregular cells of variable size and without protoplasmic contents, thus forming a central blank core. Plate XXVIII, *B*, shows several colonies. Usually several primary colonies are coalesced into secondary or compound colonies, in which the central blank cores of the primary colonies are in communication with one another. (See Pl. XXIX.)

The protoplasmic or living part of the cells is of an oval shape and relatively small, not over 5 microns (0.0002 inch) in length and 3 microns in diameter. No definite nucleus is distinguishable, but the whole cell content takes up a nuclear stain and is shown as a granular mass. In the living condition it contains chloroplasts of a blue-green color (Pls. XXX, XXXI). The protoplasmic part is surrounded by a relatively thick colorless cell wall of a clear and not particularly firm consistency, which stains with difficulty. The cell walls of the several individuals are cemented together by slightly denser matter of similar appearance, which, however, stains more readily (Pl. XXXI). As shown in Plates XXVIII, *B*, and XXIX, the active living cells are formed irregularly into a thick zone, several to many cells deep, inclosing a group of blank cells in the center. These central blank cells are on the whole larger but are more variable in size, are irregular in shape, and together form a looser structure than the outer living cells (Pls. XXIX, *B;* XXX; and XXXI, *B*).

Where several colonies are united into larger secondary colonies, the cells at the junction have either lost their protoplasmic contents or have been squeezed out and replaced by the central blank cells. (See Pl. XXIX, *A*.) A colony or a larger number of colonies form a soft, flexible, but not mobile nor waxy mass. When they are placed under a cover glass considerable pressure is required to flatten or spread them out.

The cell walls lend the organisms their peculiar properties. They do not decay or putrefy when exposed to the air in mass but congeal into a rubbery, elastic mass, which does not undergo further marked changes and, as already noted, forms the substance called coorongite. They are not composed of pectin, mucin, pectocellulose, or mucocellulose, as in ordinary algae, but consist largely of oils or oily substances, the nature of which is under investigation.

COORONGITE.

ORIGIN.

There can be no doubt that coorongite is formed from the green seepage material or mass of living *Elaeophyton*. When a mass of the green living organisms is exposed to the air it quickly changes its color to a dark brown or grayish black and congeals to an elastic, rubber-like mass, exactly like the coorongite, in which the colonies and individual organisms and their structure are more or less clearly discernible, together with a small amount of extraneous matter, like sand grains, bits of plant tissues, cuticles, diatoms, and other algae.

Coorongite as received from the field is plainly seen to be composed of the same organisms and contains the same kind of extraneous matter. Some of the colonies and individual cells of the organism are very well preserved, others not so well; but even in the most poorly preserved material the characteristic structure is still recognizable.

HISTORY.

Coorongite was discovered in 1865 on the shores of The Coorong, in South Australia. It has been variously known and described as Australian caoutchouc, mineral gumboge, elaterite, elastic bitumen, and coorongite, and it has been the object of curiosity and discussion ever since its discovery. The discussions have mostly concerned its origin, whether mineral or organic, and they are so numerous and generally so unauthoritative that it is impossible to give even a summary of the ideas presented. A number of eminent scientists, however, have investigated coorongite and have made reports on it. Among these are Thiselton-Dyer,[28] Boodle,[29] Cumming,[30] Höfer,[31] and Wiesner.[32] An accurate description of coorongite in the field is given by De Hautpick,[33] who says:

Coorongite is found in the depressed portions of occasionally submerged sandy plains of considerable extent and is spread upon the ground chiefly near the edges of the depressions at the high-tide mark. Coorongite occurs in this district spread over a great area in the form of cake lying on the sand without any connection with the ground on which it is deposited. It represents undoubtedly the solidification of some substance which previously floated on the surface of the water and then was deposited on the sand and gradually dried up, absorbing and uniting with, during the drying process, all matter that happened to come in contact with it. Coorongite is of various thickness from an inch to 1 foot, and in color and appearance it is closely akin to the so-called "paraffin dirt" of the Gulf coast oil fields of Texas and Louisiana.

Coorongite shows a peculiar rubber-like texture. When moist the material breaks much after the fashion of "green cheese." Although rubbery under compression, it does not resemble rubber in tenacity or cohesion, and in this respect it is identical with its twin, the "paraffin dirt" of America. It is clear, then, that coorongite is not a caoutchouc, although in appearance and color it resembles caoutchouc. It is soft, flexible, and easily cut, clammy to the touch, yet does not soil the skin. It has a characteristic "swampy" or "mucky" odor when wet and a characteristic odor of humic soils when moist. If the material is brought into suspension in water, very fine sand settles out and may be recovered by successive washing and decantation. When moist, it is gelatinous but neither markedly adhesive nor plastic. It is easily affected by water but is insoluble therein. In thin slips it burns like a taper, melting before the flame, which is smoky.

A substance very similar to coorongite, called n'hangellite, is found in Portuguese East Africa. Boodle[34] quotes a report made by J. Gething Hancock as follows:

N'hangellite is an elastic description of bitumen and may be termed a mineral india rubber. It is dark green in color and is lighter than water and has probably been formed in the oxidation of petroleum. It is most prevalent in the plain to the north and northwest of Lake N'hangella and to a large extent may be described, as far as this neighborhood is concerned, as peculiar to that locality.

The n'hangellite in occurrence is generally about half an inch in thickness and lies in patches varying from a few square yards to probably half an acre in extent. It is chiefly found in long, narrow strips on the surface anticlines of slightly undulating ground and gives the impression that it has been washed there by water, having largely the appearance of a high-tide mark. On the other hand, it is occasionally found in small pans, again indicating that it has been taken there by water and remained after the water had subsided. * * * I made the most searching inquiries * * * and was informed by many that after the rains it is possible to see this deposit gradually collecting and that it is then of a light-brown color and gelatinous in appearance.

Boodle's description of n'hangellite is as follows:

Specimens of this substance, when examined microscopically, prove to consist of a yellowish matrix, in which are embedded diatoms, sand grains, and sometimes sponge spicules, pollen grains, spores, etc.; but these inclusions are unimportant, forming only a small proportion of the mass. Fungal hyphae are also present and are often crowded and very distinct near the surface of the specimens, more sparse and forming an irregular reticulum in the interior.

The yellowish matrix, when examined in thin sections under a high power, is usually seen to contain numerous very small cells, which are more refractive and for the most part more colored than the substance in which they are embedded. The latter may appear colorless in very thin sections, while the cells in question are yellow or brownish or pale green. They are usually elongated, and their sectional shape is elliptical or pyriform, or circular when seen in end view. In length they vary from 2 to 6 microns, or occasionally 8 microns, and their breadth may be about half as great or more. Frequently no definite arrangement can be distinguished, but occasionally in favorable places one can demonstrate that the cells are grouped in colonies, which appear to be roughly spherical when small, elliptical or botryoidal when large. The cells are arranged so that their length is radial with regard to the colony, in which they form a peripheral layer, one or sometimes two or more cells thick. Their lateral distance from one another is variable but generally greater than their own diameter. When rather crowded, they are sometimes clearly arranged in pairs or groups of four. The substance in which the cells are embedded shows no structure and might well be the product of mucilage only. It is only here and there that colonies of definite shape can be distinguished; the scattered arrangement of the cells in other parts of the matrix may be explained as either due to flattening or distortion of colonies of similar form and size, or to the colonies having had indefinite growth, so that only young stages would show a regular form.

From such details as can be determined there seems to be no doubt that the matrix has been derived from

[28] Thiselton-Dyer, W. T., On a substance known as Australian caoutchouc: Jour. Bot., 1872, pp. 103–106.

[29] Boodle, L. A., N'hangellite and coorongite: Roy. Bot. Gardens, Kew, Bull. 5, pp. 146–151, 1907.

[30] Cumming, A. C., Coorongite, a South Australian elaterite: Chem. News, vol. 87, pp. 306–308, 1903.

[31] Höfer, Hans, Das Erdöl und seine Verwandten, pp. 262–264, 1922.

[32] Wiesner, Julius, reviewed by Höfer, op. cit.

[33] Hautpick, E. de, Coorongite, a petroleum product: Australian Min. Standard, 1923, pp. 1000–1001.

[34] Boodle, L. A., N'hangellite and coorongite: Roy. Bot. Gardens, Kew, Bull. 5, pp. 145–151, 1907.

a gelatinous organism belonging almost certainly to the blue-green algae, among which it would be classed under the Chroococcaceae. Prof. G. S. West, F. L. S., who kindly examined the organism for me, agrees that it certainly appears to be a blue-green alga and compares it with *Coelosphaerium* Naeg. but adds that it is not exactly like anything with which he is acquainted. Its precise determination must be reserved until living material, or such as represents early stages in the formation of n'hangellite, can be obtained. Conversion into bituminous substance must imply extensive chemical changes in the mucilage, whereby the original characters of the alga may have been altered to some extent as regards the spacing and form of the cells. Changes have no doubt also taken place in the cell contents; hence the occasional greenish color of the cells may be secondary and not a remnant of their original pigment. On soaking or boiling a section in water the cells undergo a curious change; their cavities become enlarged and often appear as though empty, but when transferred to strong glycerine they gradually regain their original appearance.

In some parts of the specimens the matrix shows no structure, but as the loss of structure is often not abrupt but preceded by a transitional boundary where the algal cells are collapsed or indistinct, it is probable that the structureless condition is secondary and due to more destructive changes than those which took place elsewhere. One may therefore assume that the whole of the matrix represents a gelatinous alga.

This description tallies very closely with that of coorongite.

CHEMICAL PROPERTIES.

When heated in a tube coorongite will all melt, forming a sirupy liquid, which remains viscous after cooling. On distillation it yields large quantities of oil.

An analysis made in a laboratory of the South Australian Government gave the following results:

Analysis of coorongite.

Moisture and volatile substances at 120° C	0. 8
Gaseous distillates with acid reaction	14. 0
Oily distillate	69. 2
Tarry matter and coke	10. 1
Mineral matter	5. 9
	100. 0

The oily distillate was redistilled and gave a series of oils of varying densities in the following fractions:

Results of redistillation of oily distillate from coorongite.

Fraction at 110° to 170° C	6. 7
170° to 240° C	27. 7
240° to 295° C	25. 3
295° to 300° C	27. 3
Residue	14. 0
	100. 0

An ultimate analysis gave the following results:

Ultimate analysis of coorongite.

Moisture	0. 46
Carbon	64. 73
Hydrogen	11. 63
Ash	1. 79
Fixed carbon	1. 005
Oxygen, etc	20. 375
	100. 00

Analyses made in the Bureau of Mines laboratory at Pittsburgh gave the following results:

Analyses of coorongite.

	As received.	Moisture free.	Moisture and ash free.
Proximate analysis:			
Moisture	1. 6		
Volatile matter	90. 1	91. 5	97. 2
Fixed carbon	2. 6	2. 7	2. 8
Ash	5. 7	5. 8	
	100. 0	100. 0	100. 0
Ultimate analysis:			
Hydrogen	11. 3	11. 3	12. 0
Carbon	73. 8	75. 1	79. 7
Nitrogen	. 7	. 7	. 7
Oxygen	8. 4	7. 0	7. 5
Sulphur	. 1	. 1	. 1
Ash	5. 7	5. 8	
	100. 0	100. 0	100. 0

These figures agree fairly well with a number of determinations made by other analysts.

Coorongite is partly soluble in carbon bisulphide, chloroform, ether, and benzol. A preliminary extraction with carbon bisulphide yielded about 70 per cent of soluble matter. The residue is of a tough, leathery consistency and has lost much of its elasticity. Besides the residue of the oil algae, it contains a few fragments of tissues and cuticles of higher plants, also mineral matter consisting of some diatoms and largely of sand. The ash amounts to 5.8 per cent in the untreated coorongite. All the insoluble extraneous substances have naturally been concentrated in the residue. The soluble matter is in the form of thick, viscous oil of a yellow color, which gradually turns darker on exposure to the air.

Cumming [35] carried the investigations on the extraction with carbon bisulphide further. He obtained 24 per cent extract, leaving a resi-

[35] Cumming, A. C., Coorongite, a South Australian elaterite: Chem. News, vol. 87, pp. 306-308, 1903.

due containing 30 to 40 per cent of ash. The soluble matter therefore amounted to about 33 per cent of the original coorongite. This consisted of a clear yellow, translucent, waxlike substance, which softened at 35° C. and was quite fluid at 42°. It was readily soluble in all proportions in benzene, ether, toluene, chloroform, and carbon bisulphide. Cumming was not able to saponify it and therefore concluded that it was of the nature of a mineral oil. Its composition (C, 77.92; H, 11.69; O, 10.39) and its molecular weight correspond to the formula $(C_{10}H_{18}O)_8$.

The insoluble constituent was an unelastic, tough substance, which burned with a luminous flame, melted before the flame, and had an odor like burning fat. It was saponifiable with alcoholic potash. Its composition (C, 64; H, 10.52; O, 25.26) and molecular weight conform to the formula $C_{10}H_{18}O_3$. The chemical examination of coorongite and the oil derived from it has not been completed.

CONCLUSIONS.

The study of *Elaeophyton* therefore furnishes proof of the theory of the algal orgin of the boghead coals. The plan of organization, the structure, and even the form and size of the organism agree so closely with the corresponding character of the yellow bodies that constitute the boghead coals as to leave no room for doubt of their close biologic relation and their similarity in composition. The chemical nature of these organisms is so resistant to the agencies of putrefaction as to enable them, in a favorable environment, to survive the coal-forming processes with more or less complete preservation in the forms found in the boghead coals.

The most important fact concerning *Elaeophyton* with reference to the formation of coorongite, in consideration of the theory that boghead coals owe their origin to similar organisms, is the chemical composition of its cell wall. The cell walls in the living organism are composed largely of oil or oily substances. No theory of chemical changes from cellulosic or mucous substances into an oil or fat is necessary. The oil is such in the living plant. There is probably a slight oxidation of some constituents but no radical change. The fact that the cell walls do not appear to putrefy nor undergo any further oxidation after the first change of color seems to account for the more or less complete preservation of the organisms in coorongite.

YELLOW BODIES OF BOGHEAD COALS COMPARED WITH ELAEOPHYTON.

In the light of the structure and other features of *Elaeophyton* as above set forth, we can now return to the boghead coals and by comparison and analogy get a more complete idea of the nature and the structure of the organisms that formed them, and so of the nature, structure, and origin of the fossil bogheads themselves. By comparison of horizontal sections at a lower magnification the similarity is evident. Plate XXXII, *B*, represents a horizontal section of the Australian kerosene shale containing *Reinschia australis*, and in comparing this with Plate XXVII, *B*, showing the living *Elaeophyton*, all magnified at 200 diameters, the resemblance is clearly shown. At a higher magnification, at which the cellular structure is more definitely brought out, the similarity is definitely shown and is seen to correspond to a striking degree. Although almost any of the illustrations will serve, the most surprising similarity is shown in Plate XXXI, *A*, representing the living organism, and Plate XXXIV, *A*, representing a section of the Australian kerosene shale. Plate XXXIII, *B*, illustrating *Reinschia*, also shows a striking resemblance.

It should be remembered that a photograph will not represent all the structural features as clearly as they can be seen directly under the microscope, where, by focusing up and down, the structure may be followed throughout. When the two forms are thus studied, and allowances are made for the changes resulting from coalification processes, no doubt is left as to their common origin.

The yellow bodies in the boghead coals can now be interpreted as colonies and compounds of colonies, exactly as in the living material. The smaller yellow bodies represent primary colonies in the central part of which the blank cells may often be discerned (see Pls. XXXIV, *A;* XXXV, *B;* and XXXVI, *A*); others are fusions of two, three, or four primary colonies, in which also the blank cells may be recognized (Pl. XXXVII, *A*). Probably most of the yellow bodies are of this kind; in others, the large yellow bodies, a large number of colonies are united. The outlines of the primary colonies can usually be distinguished in the compound colonies, as in the living material. (See Pls. XXXIII, *B;* XXXIV, *A;* XXXVI, *A;* XXXVII, *B;* XXXVIII, *A.*)

The protoplasmic or once living parts of the organisms are represented by the darker areas shown in the illustrations, most of them clearly of an oval outline, though some are contorted and disarranged. In thin sections of the boghead coals these portions are shown to be oval or ovoid sacks, or contorted or shriveled-up sacks that once were ovoid. Usually the contents are brown to dark brown. However, in the bogheads from different localities they may vary considerably in state of preservation, color, size, form, and definiteness of outline. In the Scotch torbanite examined, for example, the cell contents of *Pila*, the yellow body, are much lighter in color and may even be of the same color as the cell-wall matter, the coloring matter being absent, so that the cell wall is indicated merely by a line of different refraction. In the Australian kerosene shale the colonies of *Reinschia* are in many specimens particularly well preserved, and the sacks contain much brown coloring matter; for this reason these shales furnish most favorable material for study. Each of the brown sacks is surrounded by a light-colored, usually relatively thick wall, which in turn is embodied in a slightly darker material, the medium cementing the cells into colonies. The oval sacks with their surrounding cell walls are grouped in a zone toward the outside. This zone may be two or more cells deep. Their arrangement commonly is irregular—that is, there is generally no definite orderly arrangement. In this respect they are similar to the living form. At the central part of each of the multiple colonies is found a blank structure—that is, cells without the brown sacks. These undoubtedly are analogous to the blank cells of the living colonies of *Elaeophyton.*

COMPARISON OF THE BOGHEAD COALS EXAMINED.

In comparing with one another the boghead coals studied considerable differences in structure and the degree of preservation may be observed. Many of these differences are, however, possibly due to extrinsic causes and are not differences that existed in the organisms themselves when living.

AUSTRALIAN BOGHEAD, OR "KEROSENE SHALE."

The boghead coal from the Wolgan Valley, New South Wales, in a formation of Permian age, is compact and homogeneous in its outer appearance and shows but little stratification. It is of a dark or dull-brown color, breaks with a typical conchoidal fracture, and can not be made to split along any particular cleavage plane.

As seen in thin sections, the yellow bodies, the colonies of *Reinschia australis*, are somewhat loosely packed. This is shown in Plate XXXII, *A*, in which the bodies are represented by irregular, elongated patches and the groundmass by the black areas. There is, however, a considerable difference in this respect in different parts of the same sample or even in the same thin section. The colonies or yellow bodies have been flattened considerably, the larger ones more than the smaller ones. The ratio of the larger diameter to the shorter averages about 2:1; in the smaller bodies it is 3:1. Most of the smaller bodies represent single colonies; the larger ones represent compound colonies.

The colonies are embedded in an opaque, dirty-looking groundmass, which, in general, is composed of matter produced by organic degradation and a small amount of mineral matter. A large part of this organic matter is the result of degradation of the yellow bodies themselves; besides this, bits of plant tissues and plant fibers and remnants of cuticles form a very small part of it. Spores are not numerous in this boghead but are invariably present, as is to be expected.

The yellow bodies or colonies of *Reinschia* in this sample are the best preserved of all the algae in the boghead coals examined. There is, however, a considerable variation in their state of preservation. In some the structure is remarkably well preserved, every detail of the structure of the organism being intact; in others it is very obscure. Between these two extremes all shades of preservation may be observed. The sacks—that is, the once living protoplasmic contents—contain much brown coloring matter, which differentiates them clearly from the remainder of the cell and also lends the section as a whole a brown color under the microscope.

BOGHEAD COAL (TORBANITE) FROM TORBANE HILL, SCOTLAND.

In its outward appearance the sample of boghead coal from Torbane Hill, Scotland, resembles an ordinary spore cannel coal. It is slightly laminated, and although the cross and oblique fracture is conchoidal in general, it will split along certain horizontal bedding planes. It represents the celebrated deposit of torbanite found in the Calciferous sandstone series, of Mississippian age.

As seen in thin sections, the yellow bodies, the colonies described as *Pila scotica,* are a little more closely packed than the colonies in the Australian shales and are not nearly so much compressed. This is clearly shown in an examination of the photographs of the cross section reproduced in Plate XXXIV, *B*, and in a comparison with the horizontal section in Plate XXXV, *A*. The groundmass is of the same appearance and probably of the same composition as that in the Australian shales, though it is somewhat more opaque. The sacks, or once living protoplasmic parts of the cells, contain little or no brown coloring matter and hence are not well differentiated from the remainder of the cell. That they are present is clearly revealed through a difference in refraction of the cells along the borders of the sacks, although this may not be reproduced distinctly in the photographs; yet every photograph taken shows clear evidence of the structure. The lack of the brown coloring matter makes the sections of a much lighter color than those of the Australian boghead. The algal colonies appear to have suffered considerable changes during the peat stage and look as if they were waterworn. A careful comparison shows that their general structure was very similar to that of the Australian deposit.

Spores are invariably present in this coal, though in relatively small numbers.

BOGHEAD COAL FROM BATHGATE, SCOTLAND.

Only one small sample from the deposit at Bathgate, Scotland, has been examined. Experience shows, however, that one section is indicative of the characteristics of a deposit for a considerable space around the sample. The material is from the Calciferous sandstone series, of Mississippian age.

The yellow bodies (colonies referred to *Pila scotica*) in the Bathgate boghead coal are considerably more flattened than those in the Torbane Hill deposit and have a more pronounced brownish color. (See Pls. XXXVI, *B*, and XXXVII, *A*.) The embedding medium is of the same appearance as that in the Torbane Hill boghead. The structure is much better preserved than that in the Torbane Hill coal but not quite as well as that in the Australian shale. The sacks are well preserved and well differentiated from the cell walls, owing to their dark-brown contents. The structure is very similar to that in the Australian boghead. The differences in preservation are due to outside influences; evidently the organisms that gave rise to the deposit at Bathgate and Torbane Hill were very similar to those in the Australian deposits, to which they are most clearly related.

BOGHEAD COAL FROM ALASKA.

In outward appearance the Alaskan boghead, according to the one sample on hand, is very similar to an ordinary cannel coal. This sample came from a district drained by Colville River; the exact locality and the geologic age of the beds are not known. It is compact and dark grayish black. When examined at a low magnification (200 diameters), it presents the same general appearance as the boghead coals from Scotland and Australia and at once gives the impression that it is of the same kind. (See Pls. XXXVIII, *B*, and XXXIX, *A*.) But under a higher magnification it presents a marked difference, and offhand it gives the appearance of not belonging to the same kind at all. The yellow bodies on the whole are somewhat smaller than in the samples previously described, the large majority have no brown coloring matter in the sacks, and they reveal no definite structure or only a faint structure. But a careful survey of the sections, both horizontal and cross, discloses here and there yellow bodies whose structure has been well preserved and whose entire organization may be reconstructed. These show that the general structure is similar to that in the Australian boghead coal, if not the same, and that they must have been derived from an organism of the same nature as that which gave rise to that coal. Between those that are well preserved and those in which little or no structure has been retained all grades of transition are found; and as the general appearance, nature, and form of all the yellow bodies are the same, it must be concluded that all were derived from the same source.

The alga characterizing the Alaska boghead is almost certainly of the same nature and is probably closely related to those forming the yellow bodies in the other boghead coals here described, as well as the living *Elaeophyton.*

BOGHEAD COALS OF THE KISKIMINETAS REGION, PENNSYLVANIA.

The boghead coal at Kiskiminetas Junction, Pa., in the region where Kiskiminetas River joins Allegheny River, is found in a thin bed, not more than 2 feet in thickness, in the limestone between the Upper and Lower Freeport coals, in the Allegheny formation, of Pennsylvanian age. It begins with an ordinary shale at the bottom, which quickly changes into a bituminous "slate" and then within a few inches into a rich boghead coal. It much resembles a bituminous shale throughout its thickness. (See Pl. XXXIX, *B.*) It is laminated and will split horizontally along certain bedding planes.

In thin sections its resemblance to the other boghead coals is at once apparent. The yellow bodies are, on the whole, of the same size as those in the Alaskan boghead but smaller than those in the Scotch and Australian samples. In general form and appearance the yellow bodies (Pl. XL, *A*) are the same as those in the other bogheads, but on comparison of the minute structure they are found to differ markedly, showing very little organized structure or none at all. Here and there the microscopist may imagine that he recognizes the brown sacks, but in the last analysis there is no positive proof of them. If conclusions were to be based upon the structure of the bodies in this coal alone, they would be relegated at once to the category of the unknown; but in looking over the bogheads from different places and considering the varying state of preservation of the structure, a continuous series can be constructed—at one end those in which the structure is perfectly preserved, gradually and imperceptibly grading into those at the other end, in which no structure is observable, the same or very similar general form, color, and nature being maintained throughout the series. Such a result gives strong support to the reasoning that the whole series is of the same origin. Such a series comprises the Australian bogheads, with the structure in a perfect state of preservation, at one end, and the Pennsylvanian bogheads, with no structure preserved, at the other. In this light, until further evidence is found to the contrary, it may be assumed that the deposit at Kiskiminetas Junction is of the oil-algal origin and a true boghead coal.

CANNEL COAL FROM UPPER POTTSVILLE FORMATIONS IN WESTERN PENNSYLVANIA AND EASTERN KENTUCKY.

Samples of cannel coal from the upper Pottsville at Lesley, near Paintsville, Ky., were also examined. The bed at Lesley is approximately 5 feet 9 inches thick. At the bottom is a layer of ordinary bituminous coal about 2½ inches thick, changing soon into cannel coal, which continues to the top, with the exception of a 4-inch layer of stratified bituminous coal in the middle of the bed. The bed has a roof of rather gritty gray shale containing carbonized plant remnants and residues.

The cannel is black and tough and cleaves in slabs of varying thickness; but the cross and oblique fractures are distinctly conchoidal. The cannel is really a spore cannel coal, because by far the larger part of the organic matter consists of spore matter. Spore exines of a number of different kinds, both microspores and megaspores, enter into its composition. Much macerated spore matter and some cuticular matter are observed in the ground mass.[36]

Among the spore exines are peculiar yellow bodies in varying amounts, resembling those of the boghead coals in certain respects. No definite organized structure, however, can be discerned in them. These bodies have been described by the writer[36] as follows:

> The coal contains interesting objects that are very abundant in certain strata, where they constitute more

[36] White, David, and Thiessen, Reinhardt, The origin of coal: Bur. Mines Bull. 38, p. 253, 1914.

than half of the bulk. In other strata they are comparatively rare. On the whole, they constitute only a small proportion of the total mass. They are in general appearance distinctly similar to Renault's genus *Pila* of his supposed algae.

These bodies vary greatly in size, ranging roughly from 30 to 175 microns in diameter. In color they are almost of a paraffin-white, which in thicker sections becomes a light brass-yellow. Their form is roughly oval, with an irregular outline. This irregularity consists of processes, often pseudapoda-like, and irregular cavities or depressions, reaching often to the center or even through the body.

The structure of these bodies is, in fact, so irregular that an adequate description of it is difficult. It is probable that these yellow bodies had their origin in an organism similar to that which gave rise to the Australian and European boghead coals.

Numerous yellow bodies, apparently comparable to those described in the foregoing pages, are found in a cannel coal occurring in the Mercer shale on Neshannock Creek near Leesburg, in Springfield Township, Mercer County, Pa. As shown in Plate XL, *B*, this coal contains much material of humic origin. Besides the spore exines and the yellow bodies, of which the latter are plainly recognizable in the photograph, the section discloses large numbers of cuticular fragments and numerous lumps of resin, two kinds of which, one dark and the other lighter, are seen on the left.

It is likely that a close examination of cannel coals will reveal algal colonies in many of them, as is to be expected on account of the open-water environment in which they were laid down. In view of the interesting results of the present study of bogheads and cannel coals, a more systematic examination of the cannel series, of which abundant material is already in hand, is contemplated.

SUMMARY.

According to origin, bituminous shales and cannel coals may be classified into humic, spore, ceric, resinous, and algal deposits.

This paper endeavors to show that the yellow bodies of the boghead coals are not derived from spores but represent colonies of alga-like organisms heretofore not well known. In all the bogheads investigated these colonies, described as *Reinschia* and *Pila*, are similar to an organism now living in the salt lakes and salt lagoons of South Australia and neighboring islands. The living organism has been termed *Elaeophyton* because of the large amount of oil it contains.

Elaeophyton is a colonial organism in some respects resembling some of the blue-green algae, but its cell wall differs from that of the algae ordinarily described. The colonies, which are just visible to the naked eye, may be single or compound; they are solid and of globular form. Each colony is composed of an irregular outer zone of living cells, several cells deep, inclosing a core of irregular inner cells that lack protoplasmic contents. The living cell contents are of oval or ovoid form, are relatively small (about 3 microns in diameter and 5 microns long), and contain no definite nuclei. They are surrounded by a relatively thick cell wall of irregular thickness. The different cells are cemented together by a medium apparently similar to the cell walls. These colonies appear on the lakes and lagoons toward the end of winter, are blown to the shore, and there form a rubber-like mass called coorongite. Coorongite does not appear to decompose or oxidize further; it is rich in oil and volatile matter, burns with a bright, hot flame, and melts before burning. When heated in a closed test tube it melts into a sirupy liquid, becoming viscous on cooling. When distilled, it yields about 70 per cent of oils, some tarry matter, some gas, and very little solid residue. Coorongite is the peat stage of boghead coal.

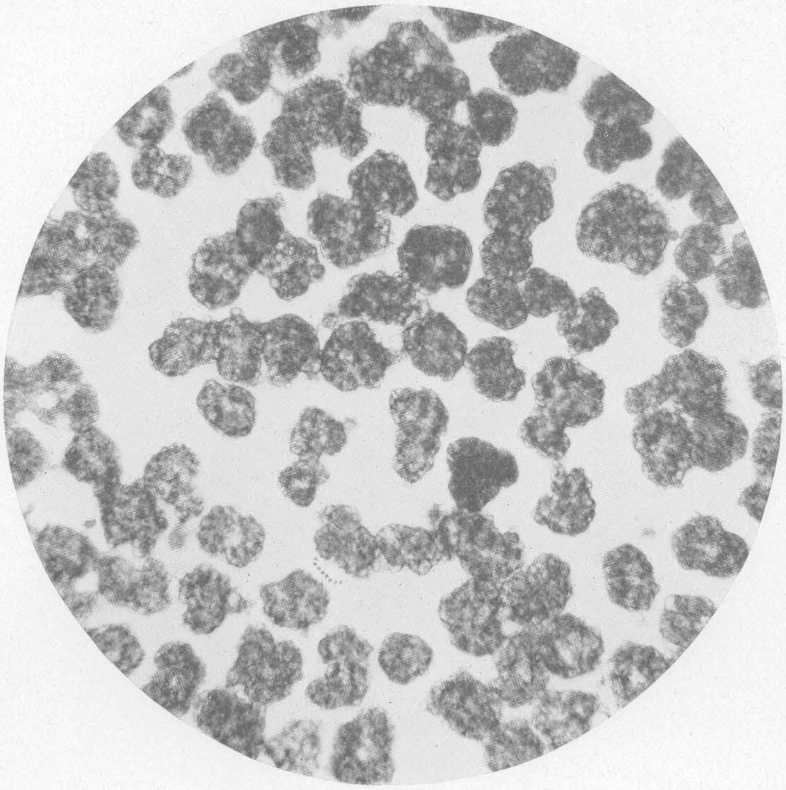
The structure and size of the yellow bodies in the boghead coals examined correspond closely to those of the colonies of *Elaeophyton.* The yellow bodies contain an outer zone of thick-walled cells inclosing oval sacks, most of which have brown contents. These sacks represent the once living protoplasmic contents of the cell. The preservation of the structure as a whole differs in deposits at different localities, the coals examined showing a range from a very well preserved structure to a condition in which the structure has been completely effaced. A similar range occurs to some extent

in the deposits of well-preserved material. By analogy and through the similarity in structure, appearance, and qualities of the yellow bodies in the boghead series, it is concluded that all had a similar source—that is, colonial algae of the same general nature and of a composition similar to that of the colonies of the living *Elaeophyton*.

ACKNOWLEDGMENTS.

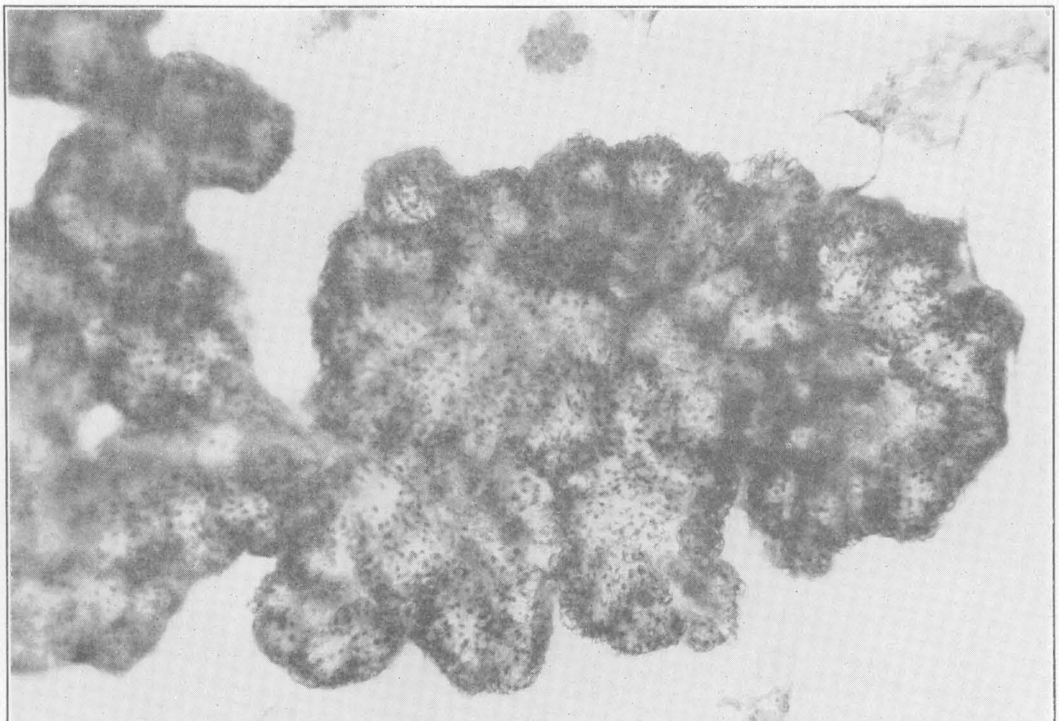
In addition to numerous suggestions made by members of the Bureau of Mines staff, whose names need not be mentioned, the writer is indebted for extensive and constructive criticism to David White, most of whose suggestions have been incorporated in these notes.

PLATES XXVII—XL



A. COLONIES OF THE LIVING ONE-CELLED ALGA, ELAEOPHYTON N. GEN., FROM THE COORONG DISTRICT, SOUTH AUSTRALIA

Single as well as compound colonies are shown. The size of the compound colonies depends on the number of primary colonies in them. The small bodies are apt to be single colonies, the larger ones compound colonies. × 200

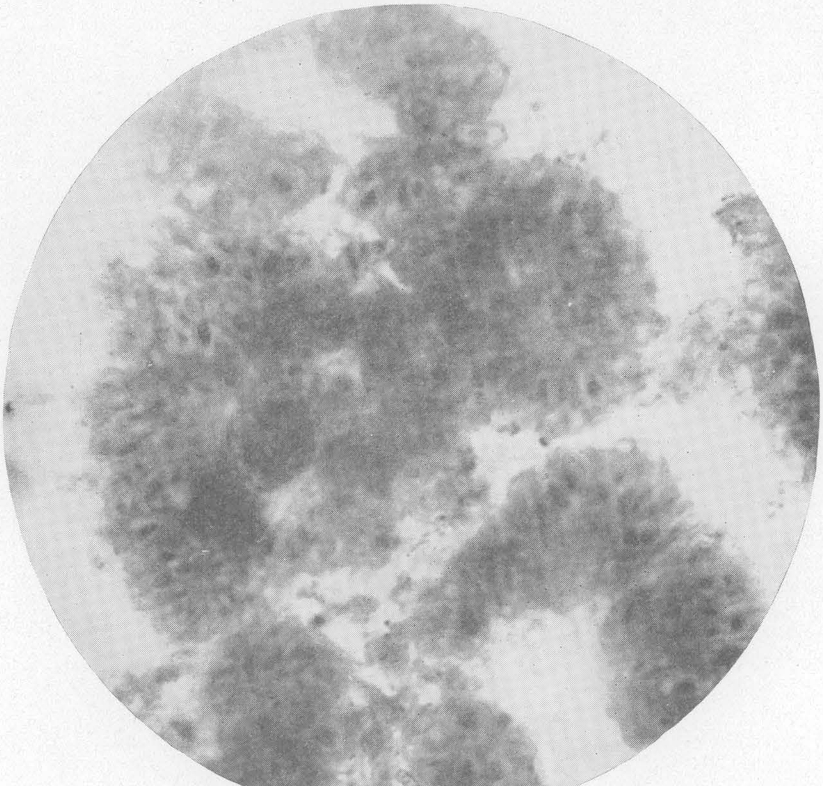


B. A NUMBER OF COLONIES OF ELAEOPHYTON MERGING INTO A LARGER MASS

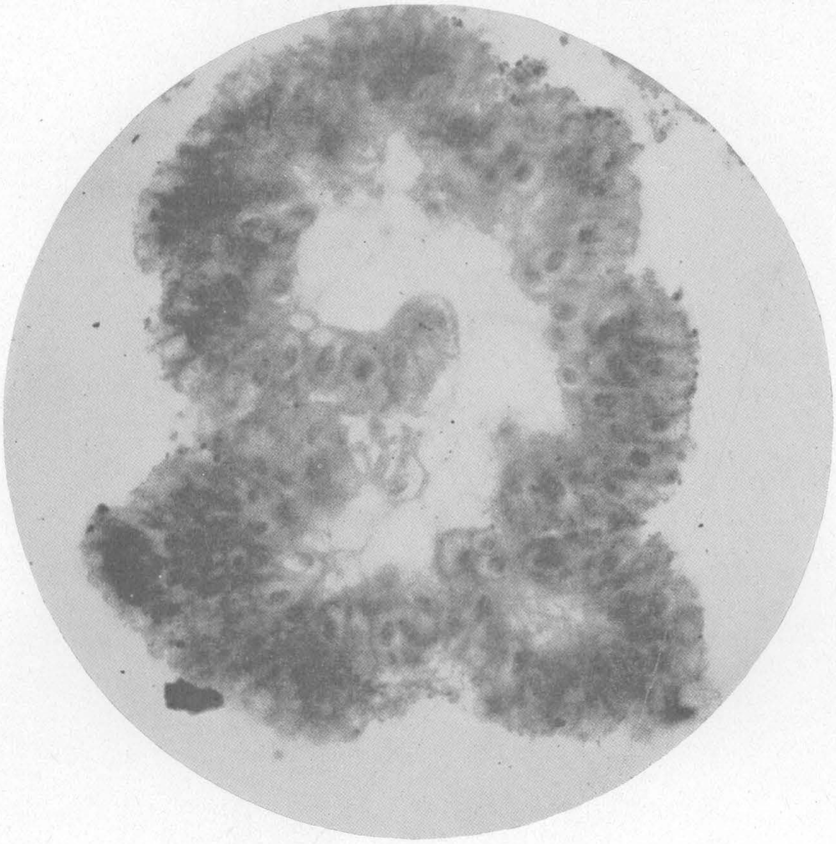
The black specks represent the living cell contents. × 200

A. A COLONY OF THE LIVING ELAEOPHYTON, COMPRESSED UNDER THE COVER GLASS AFTER STAINING WITH SAFRANIN

The dark oval or ovoid spots represent the living cell contents. At many points the outlines of the cell walls are shown. × 1,000

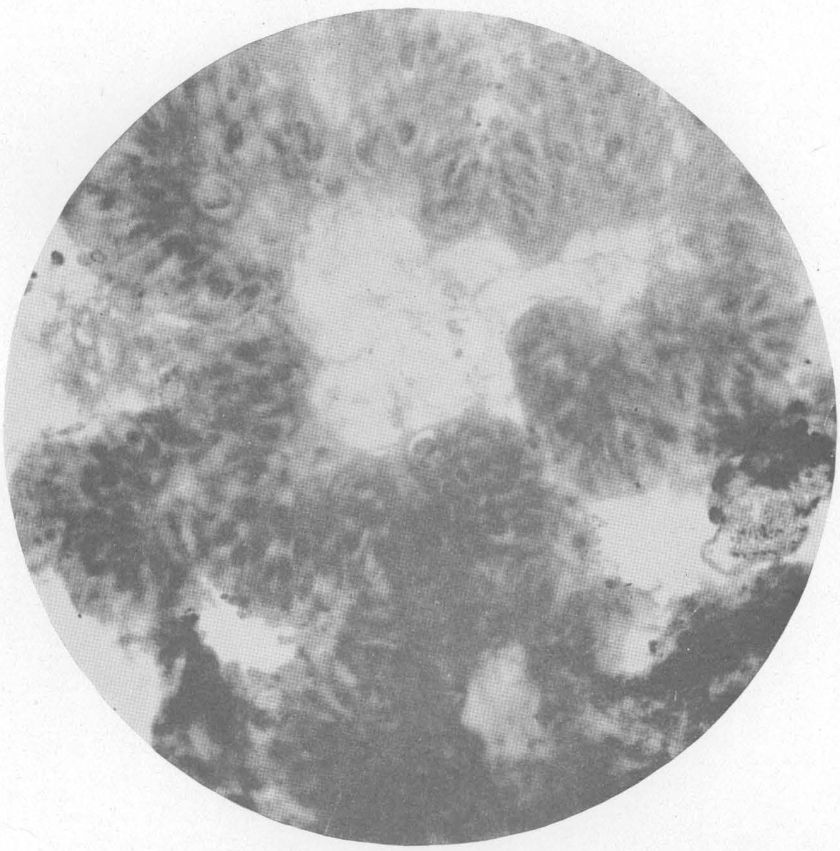


B. SECTIONS OF SEVERAL COLONIES OF ELAEOPHYTON, TWO OF WHICH SHOW THE CORE OF INNER BLANK CELLS. × 600



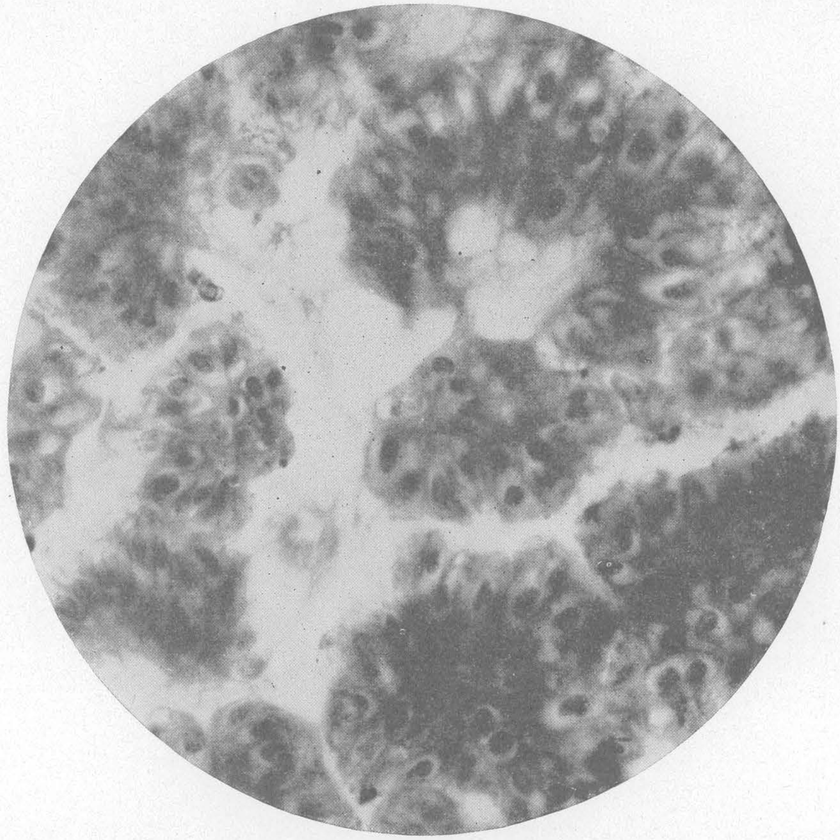
A. SECTION OF A SMALL COMPOUND COLONY OF ELAEOPHYTON

Showing the thick zone or shell of living cells, and the structure of the inner core of blank cells. × 600



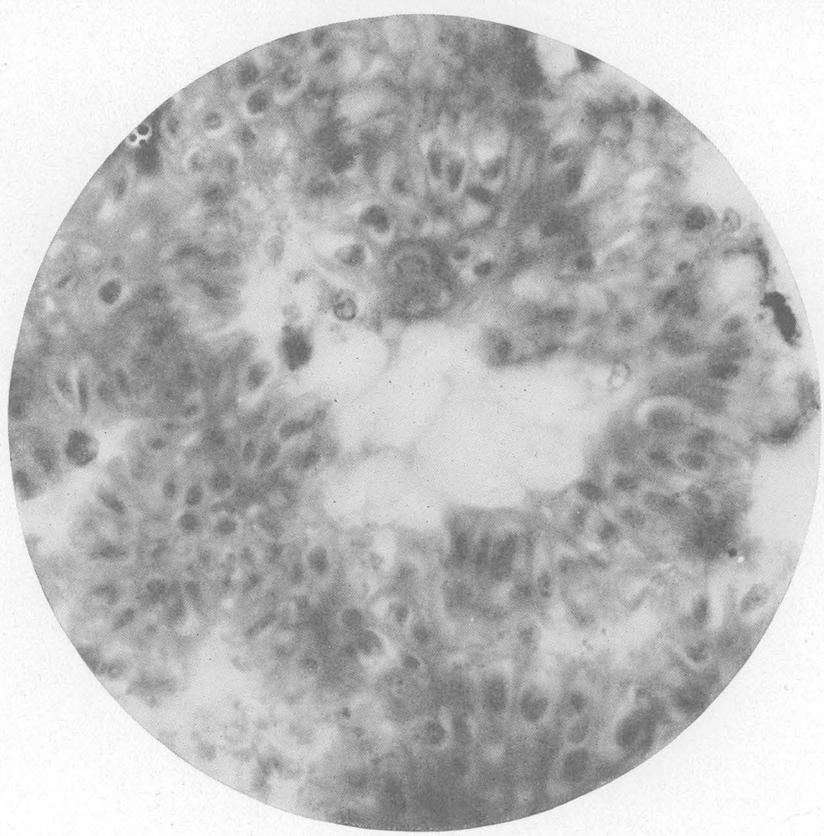
B. SECTION OF COMPOUND COLONY OF ELAEOPHYTON AND OF AN ADJOINING SINGLE COLONY

Showing the blank inner tissue surrounded by an outer zone of living cells. × 600



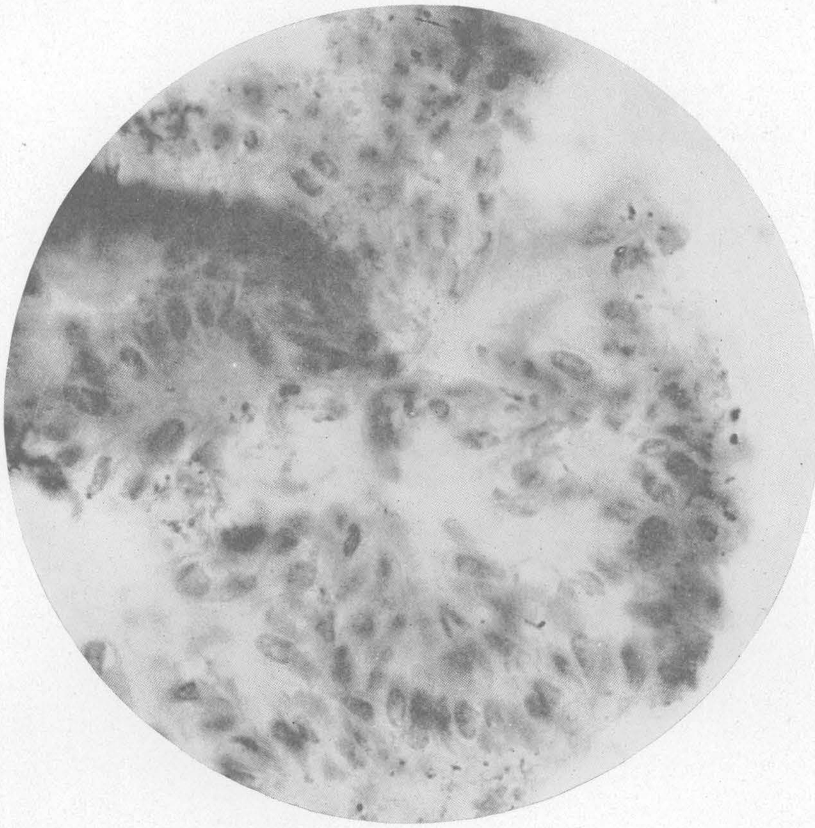
A. SECTION OF COMPOUND COLONY OF ELAEOPHYTON AND PARTS OF NEAR-BY COLONIES AT A HIGHER MAGNIFICATION

Plates XXX and XXXI show more definitely the organization of the individual cells. The oval dark spots represent the contents of the living cell, the lighter area bordering each of these spots represents the reinforcement of fatty or oily matter deposited inward on the primary cell wall, and the darker heavy lines surrounding the cells and uniting them represent the cementing matter. The lighter areas of irregular structural pattern represent the blank cells. The irregular light strips represent open spaces between the colonies. × 1,000



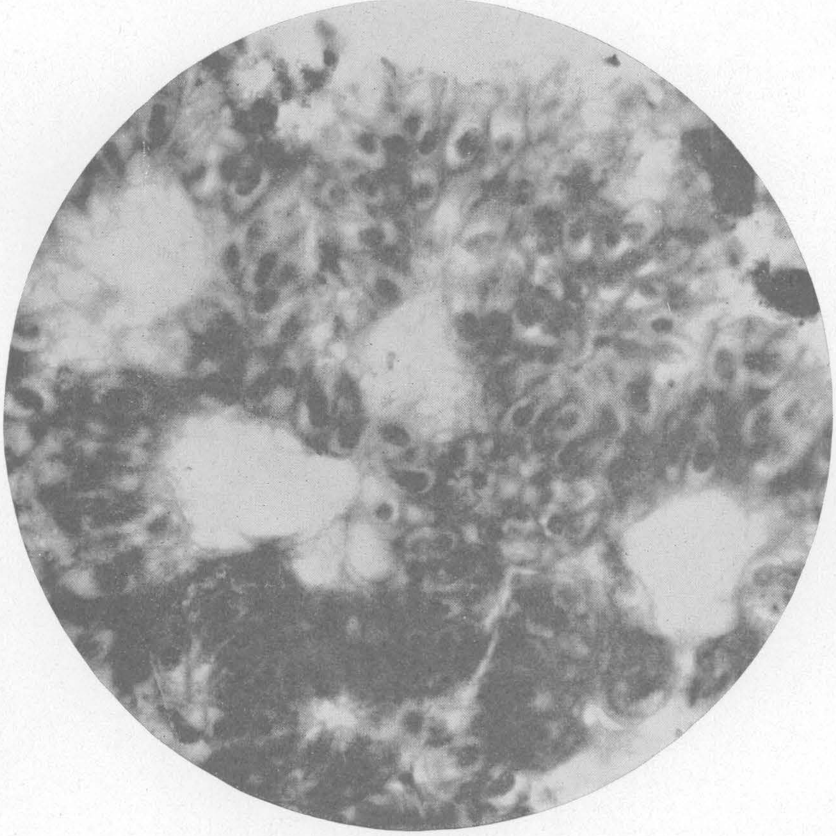
B. SECTION OF COMPOUND COLONY OF ELAEOPHYTON

Showing in particular the aspect and variation of the blank cells in the center of the colony. × 1,000



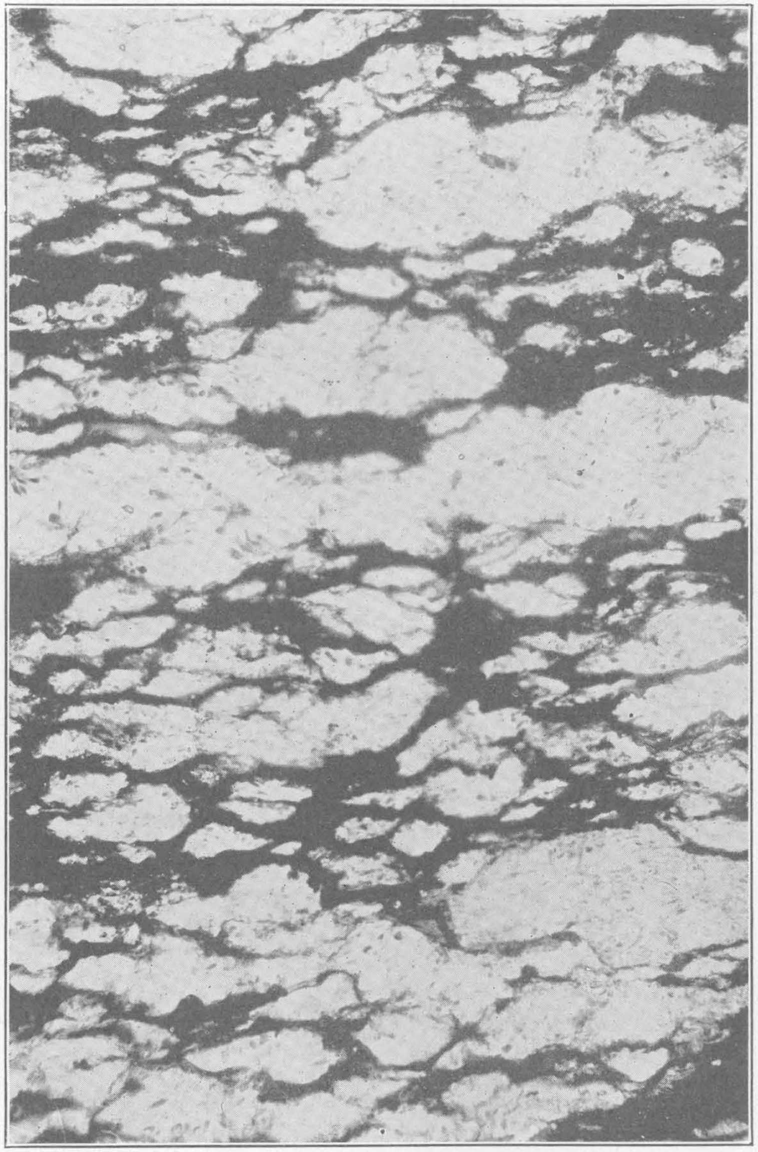
A. SECTION OF COMPOUND COLONY OF ELAEOPHYTON

Showing the thick fatty matter deposited about the cavity of the cell and forming its thick wall. Compare this figure with Plate XXXIV, *A*. × 1,000



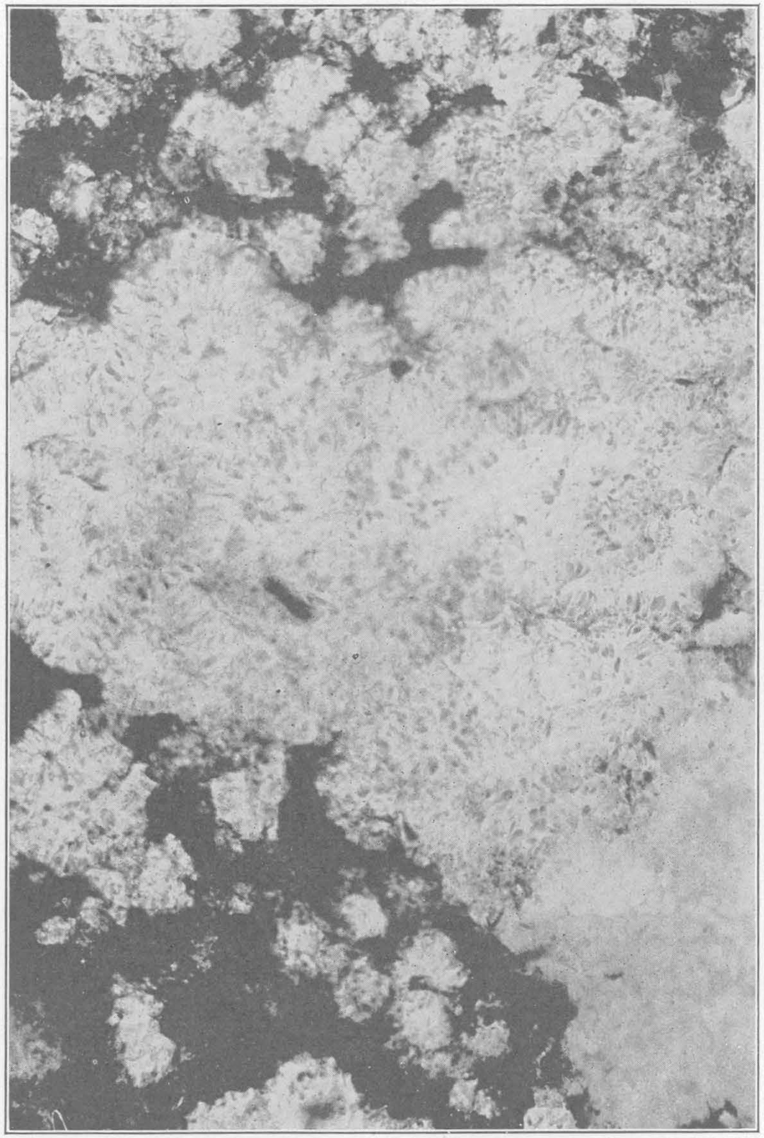
B. SECTION OF COMPOUND COLONY OF ELAEOPHYTON

Showing variability in size, form, and aspect of blank cells; also relations of fatty inner cell thickening about the central cavity to the cementing matter and the blank cells. × 1,000



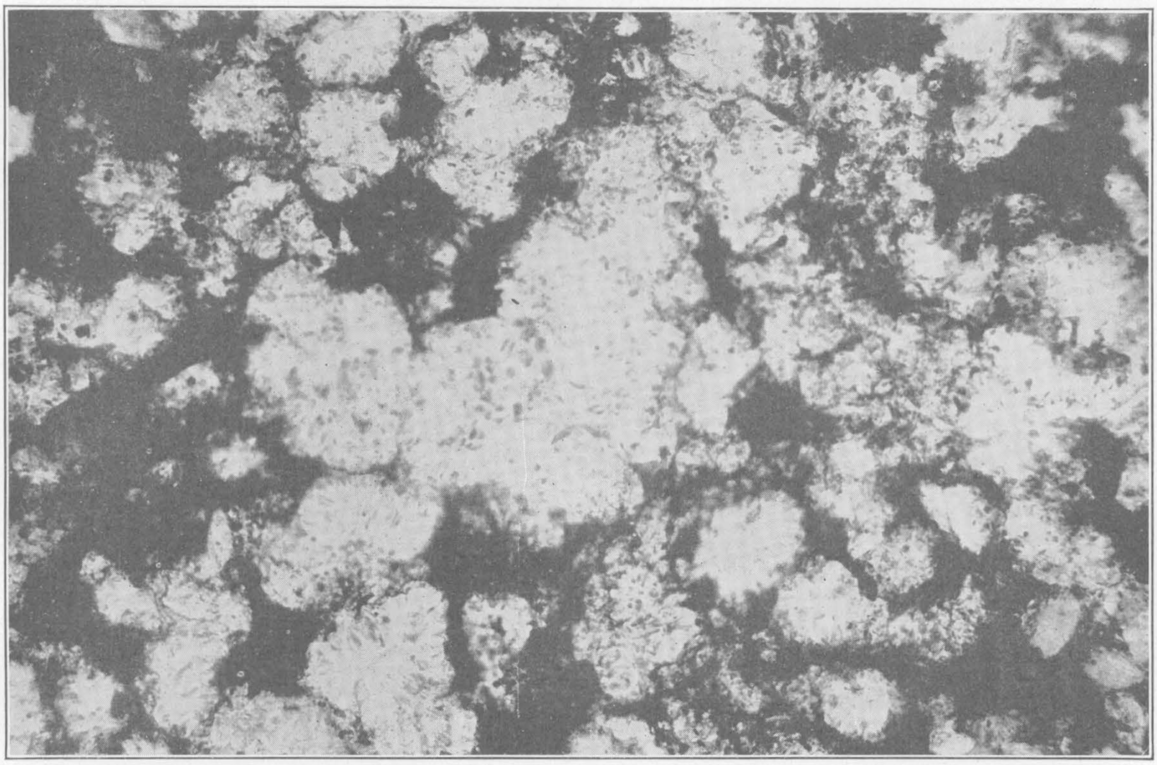
A. CROSS SECTION OF BOGHEAD COAL (THE SO-CALLED KEROSENE SHALE) OF PERMIAN AGE FROM THE WOLGAN VALLEY, NEWNES, NEW SOUTH WALES, AUSTRALIA

The irregular, light, somewhat spongy masses that form "yellow bodies" in this fossil deposit are the compound colonies of the one-celled alga Reinschia australis B. Renault. × 200



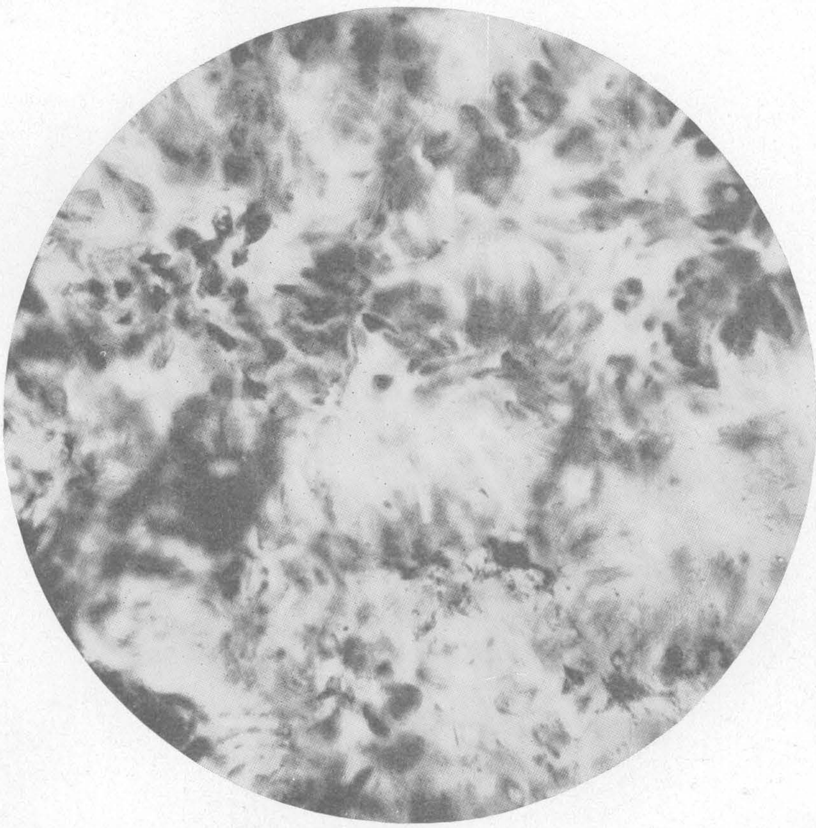
B. HORIZONTAL SECTION OF BOGHEAD COAL OF PERMIAN AGE FROM THE WOLGAN VALLEY, NEWNES, NEW SOUTH WALES

The section shows large and small colonies of Reinschia australis B. Renault. × 200



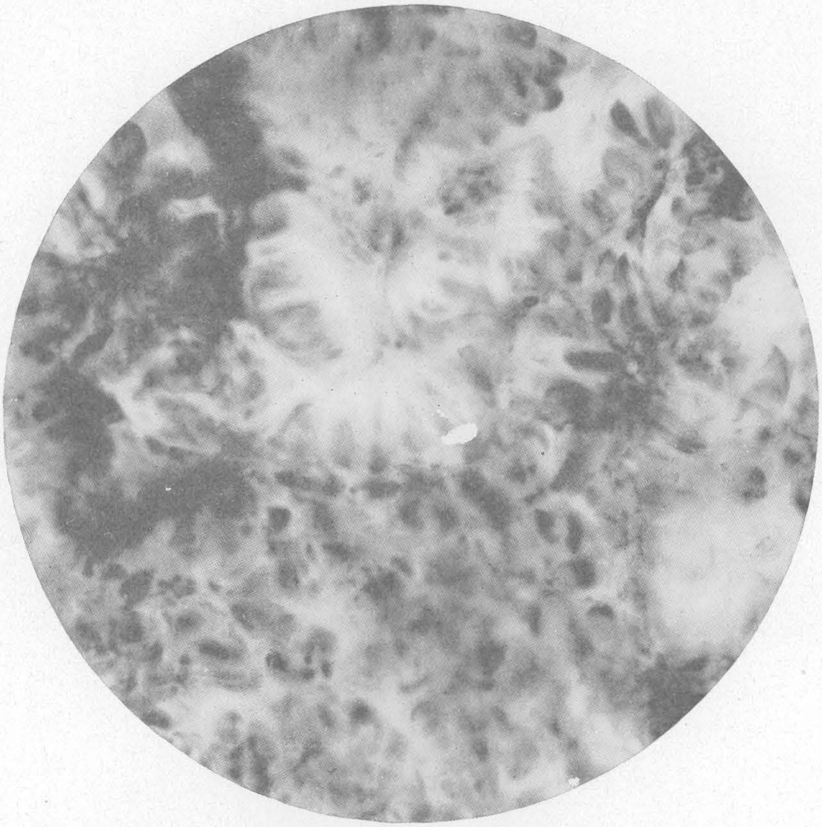
A. HORIZONTAL SECTION OF BOGHEAD COAL OF PERMIAN AGE FROM THE WOLGAN VALLEY, NEWNES, NEW SOUTH WALES, AUSTRALIA

This section shows compound colonies, mostly of rather small size, of the fossil alga Reinschia australis B. Renault. × 200



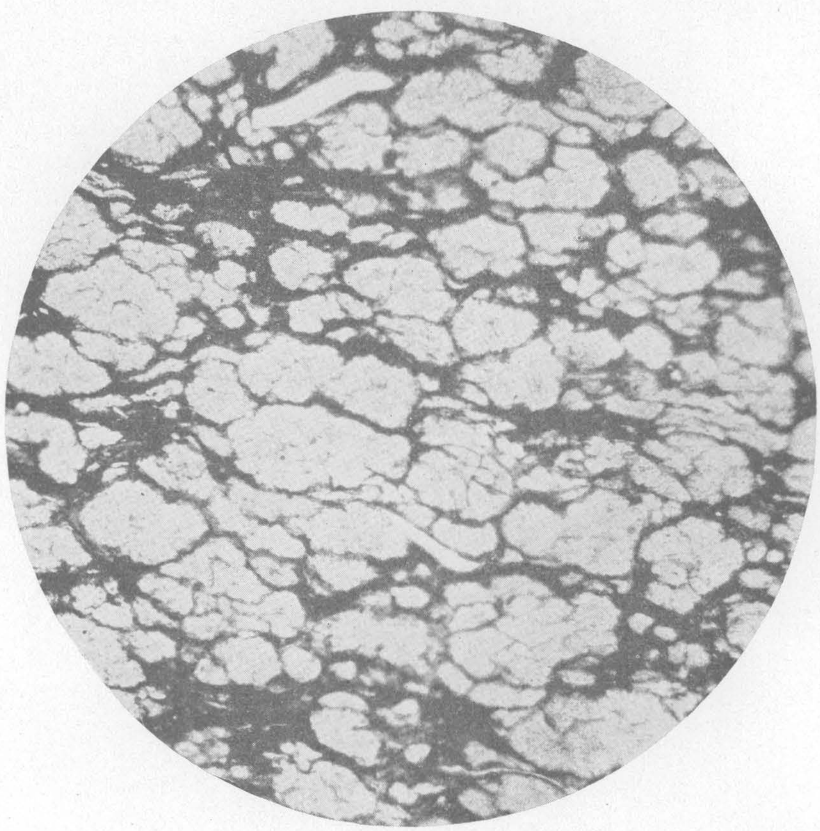
B. HORIZONTAL SECTION OF BOGHEAD COAL OF PERMIAN AGE FROM THE WOLGAN VALLEY, NEWNES, NEW SOUTH WALES, AUSTRALIA

More highly magnified to show a number of primary colonies of the fossil alga Reinschia australis B. Renault. The dark oblong spots represent the remains of the contents of the living cells, now stained dark by biochemical decomposition products more or less distinctly humic. × 1,000



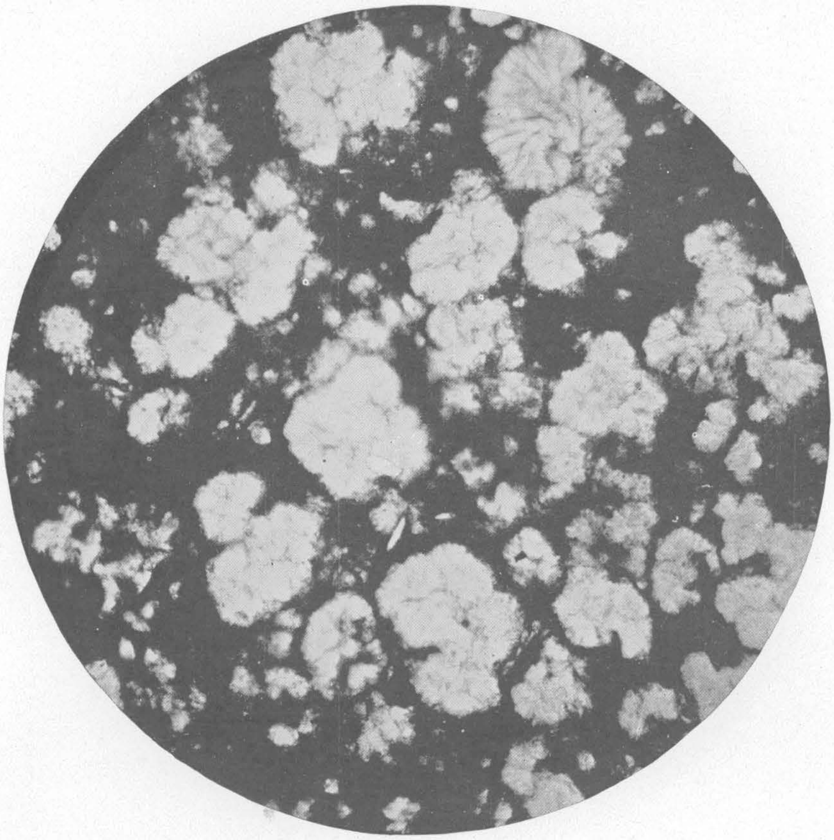
A. HORIZONTAL SECTION OF BOGHEAD COAL OF PERMIAN AGE FROM THE WOLGAN VALLEY, NEWNES, NEW SOUTH WALES, AUSTRALIA

Showing colonies varying in size of the fossil alga Reinschia australis B. Renault, characteristic of the kerosene shale. The more completely the rock is made up of these colonies of fatty algæ the more voluminous the distillate and the better its quality. × 1,000



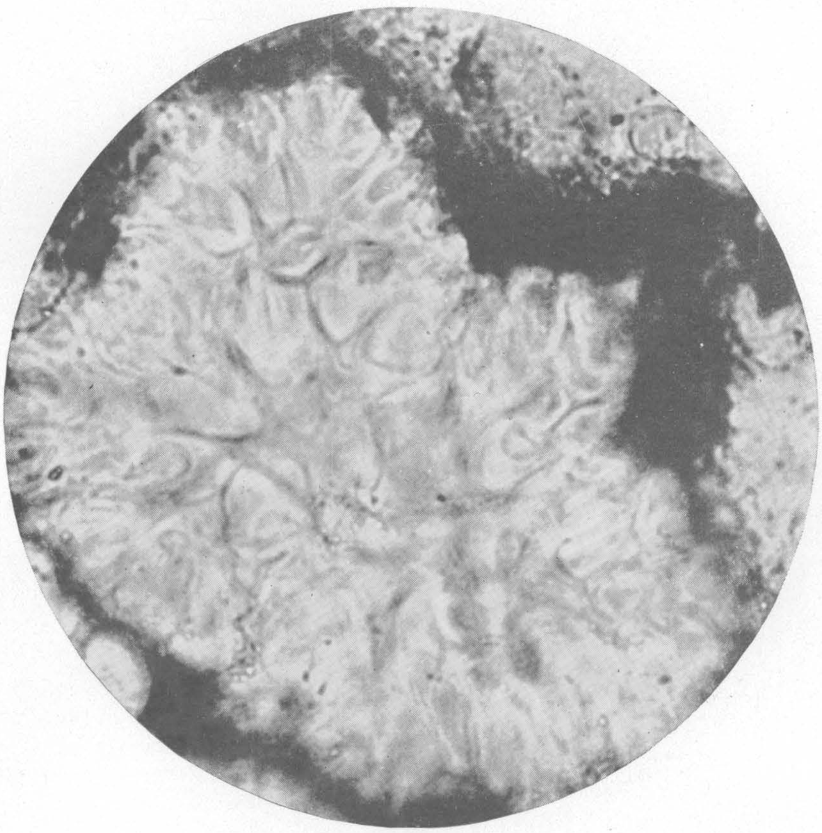
B. CROSS SECTION OF BOGHEAD COAL (TORBANITE) OF MISSISSIPPIAN AGE FROM TORBANE HILL, SCOTLAND

The section shows the colonies of the one-celled alga Pila scotica B. Renault, now fossil and embedded in a general attritus of dark-brown color. But little flattening has taken place. × 200



A. HORIZONTAL SECTION OF BOGHEAD COAL (TORBANITE) OF MISSISSIPPIAN AGE FROM TORBANE HILL, SCOTLAND

The colonies of the fossil one-celled alga Pila scotica B. Renault, which form the "yellow bodies," are embedded in an attrital matrix of dark-brown color, "the groundmass," in which is mingled a considerable amount of dirt. The large macerated body at the top appears to represent the fossil organism described by B. Renault as Cladiscothallus, a fungus. × 200



B. HORIZONTAL SECTION OF A COLONY OF PILA SCOTICA B. RENAULT FROM THE SAME LOCALITY AND DEPOSIT AS THE SPECIMEN ILLUSTRATED IN *A*

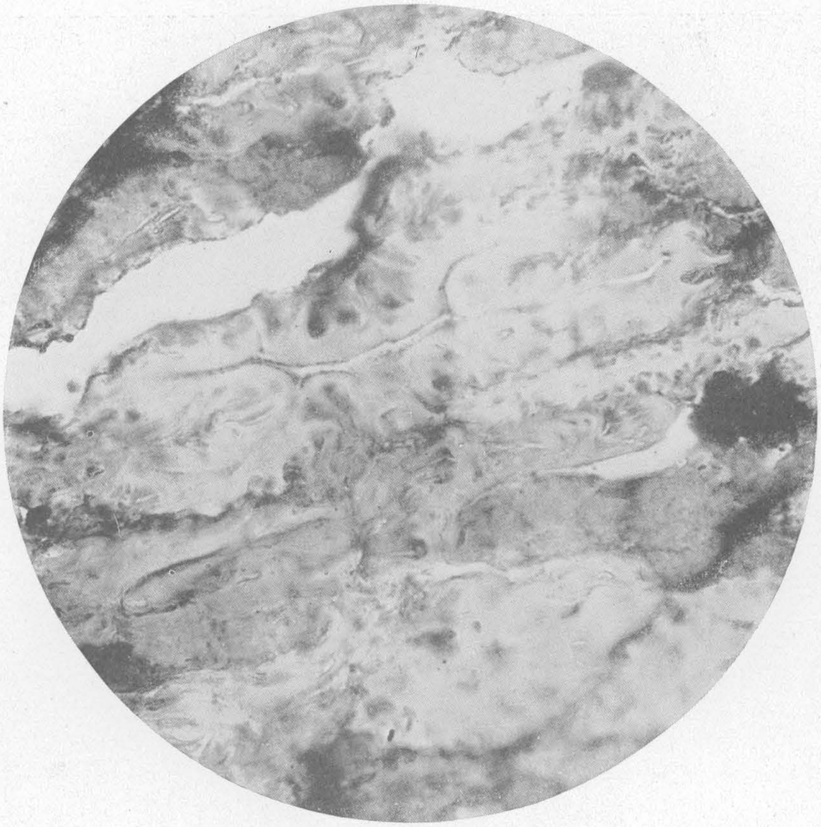
Shows an outer zone of cells surrounding the inner core of blank cells in the fossil species just as in the living Elaeophyton. The brown cell contents of some of the cells are distinguishable. The algae of the colonies are slightly decomposed around the edges of the colonies. × 1,000

A. HORIZONTAL SECTION OF AN ALGA COLONY, PILA SCOTICA B. RENAULT, IN THE BOGHEAD COAL (TORBANITE) OF MISSISSIPPIAN AGE FROM TORBANE HILL, SCOTLAND

The primary colonies are easily distinguishable; also the inner core of blank cells. The brown oval contents of the cells have largely disappeared, as is common in this boghead coal, but the outlines of the cells are still visible through a difference in refraction. × 1,000

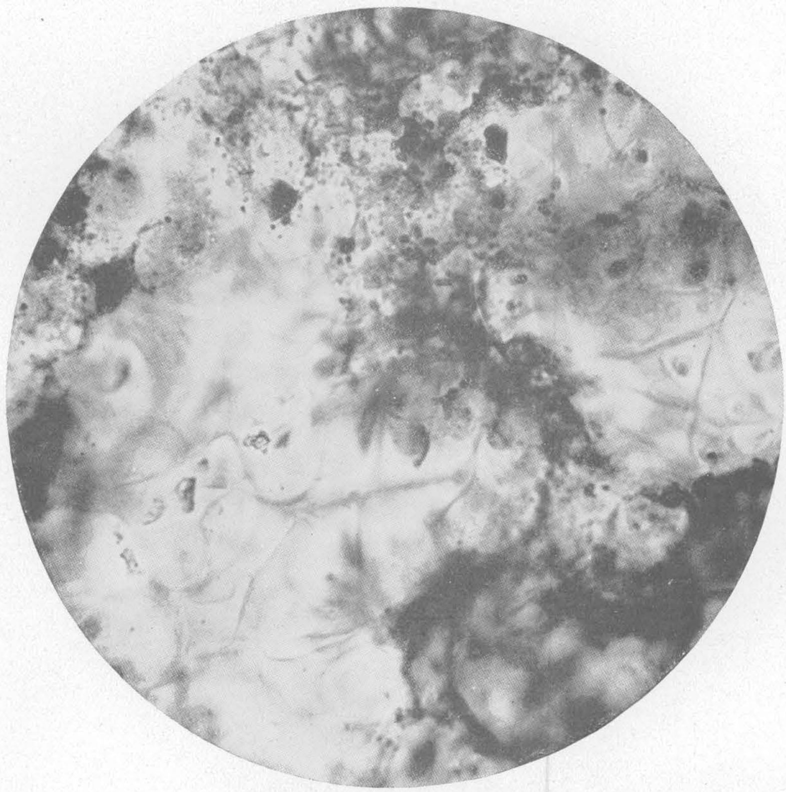
B. CROSS SECTION OF BOGHEAD COAL OF MISSISSIPPIAN AGE FROM BATHGATE, SCOTLAND

The "yellow bodies," compound colonies of the one-celled alga Pila scotica B. Renault, have been much more flattened than are those in the deposit at Torbane Hill. (See Pl. XXXV.) The blank cells of the core of the colony have been more flattened than the individual algae, thus giving the colony the appearance of a highly sculptured spore exine. × 1,000



A. CROSS SECTION OF BOGHEAD COAL OF MISSISSIPPIAN AGE FROM BATHGATE, SCOTLAND

The "yellow body" in the central part of the photograph is clearly shown to be a compound colony of the one-celled fossil alga Pila scotica B. Renault. The primary colonies are well marked off. × 1,000

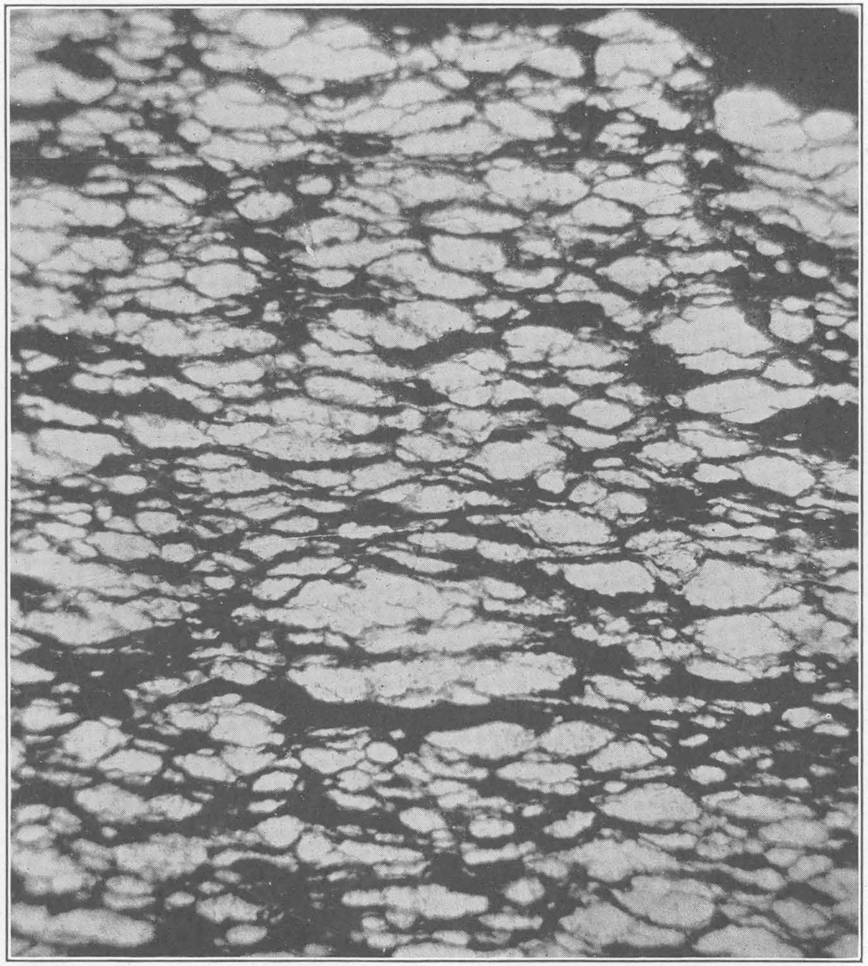


B. HORIZONTAL SECTION OF BOGHEAD COAL OF MISSISSIPPIAN AGE FROM BATHGATE, SCOTLAND

The outlines of the cells of the individual algae (Pila scotica B. Renault) in this highly magnified thin section are rather clearly shown, and the brown oval cavity which once contained the protoplasm of the alga is shown distinctly. × 1,000

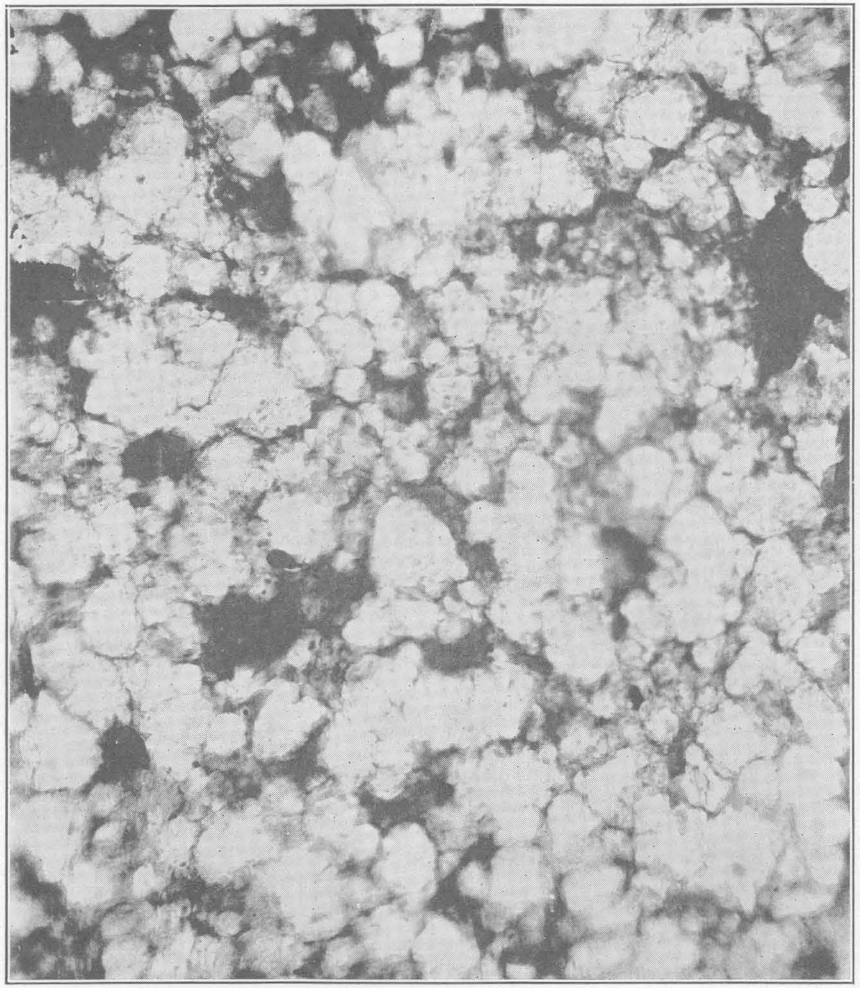
A. HORIZONTAL SECTION OF BOGHEAD COAL OF MISSISSIPPIAN AGE FROM BATHGATE, SCOTLAND

This section outlines the primary colonies of the oil-forming fossil alga Pila scotica B. Renault, and the brown cell contents are clearly distinguishable. This and the four preceding illustrations should be compared with the photographs of the living Elaeophyton shown in Plates XXIX, XXX, and XXXI. × 1,000



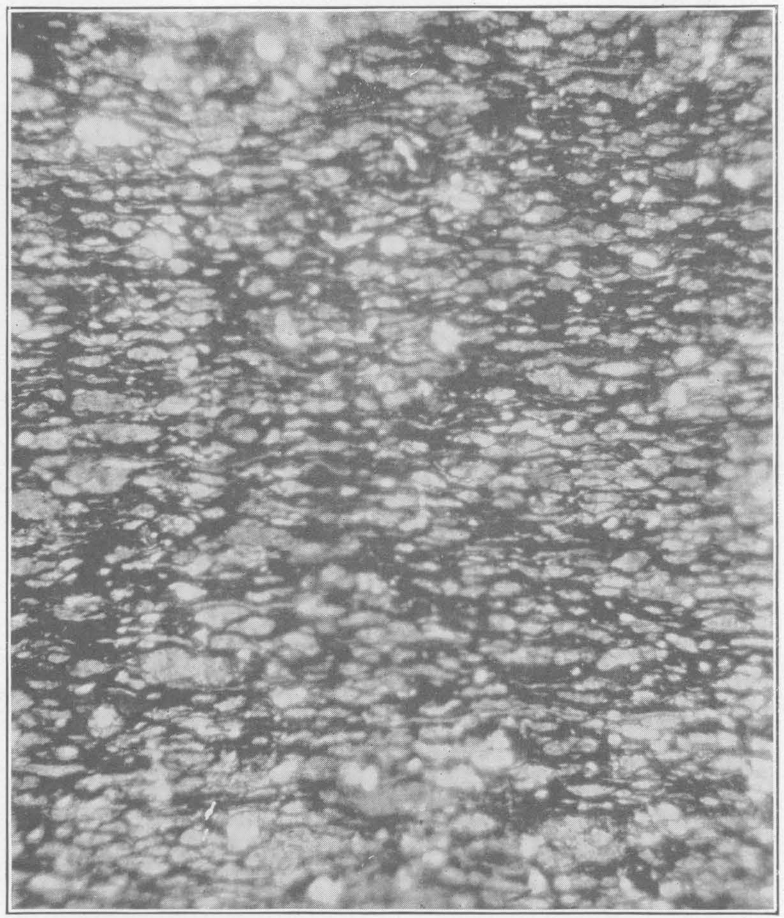
B. CROSS SECTION OF A BOGHEAD COAL FROM COLVILLE RIVER, ALASKA, SHOWING YELLOW BODIES

The obscurely indicated structure is comparable to that of the living Elaeophyton and to the fossil alga colonies characteristic of the kerosene shale (torbinate) and other bogheads. The Alaska yellow bodies also are probably compound colonies of a related alga. × 209



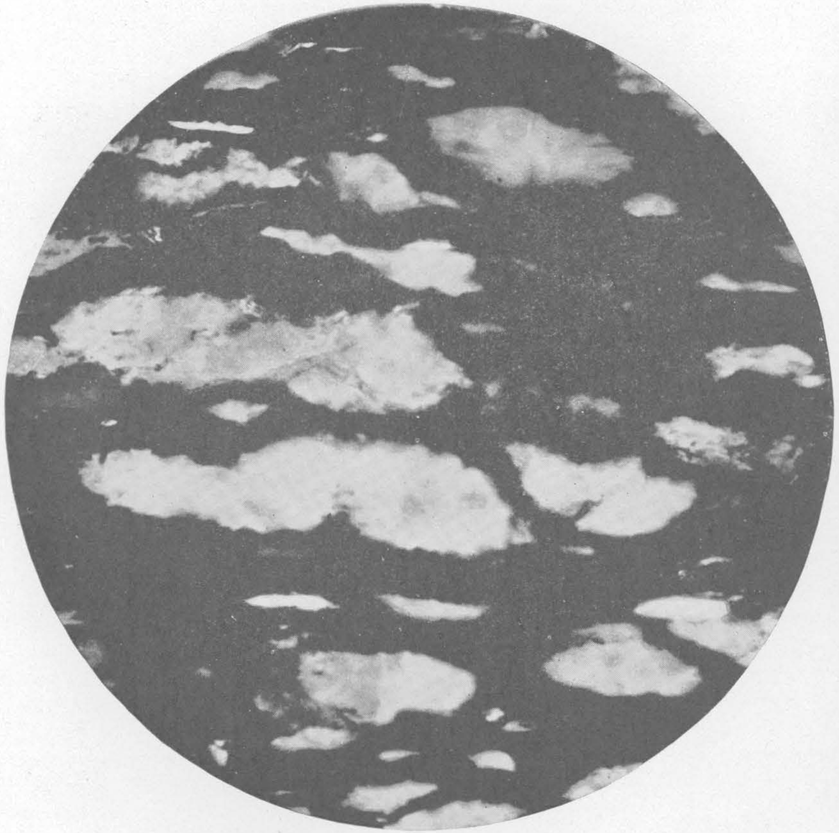
A. HORIZONTAL SECTION OF BOGHEAD COAL FROM COLVILLE RIVER, ALASKA

The similarity between the yellow bodies in this fossil deposit of unknown age in Alaska to the compound colonies of Elaeophyton (see Pl. XXVII) and to the fossil boghead algae of different ages is at once apparent. × 200



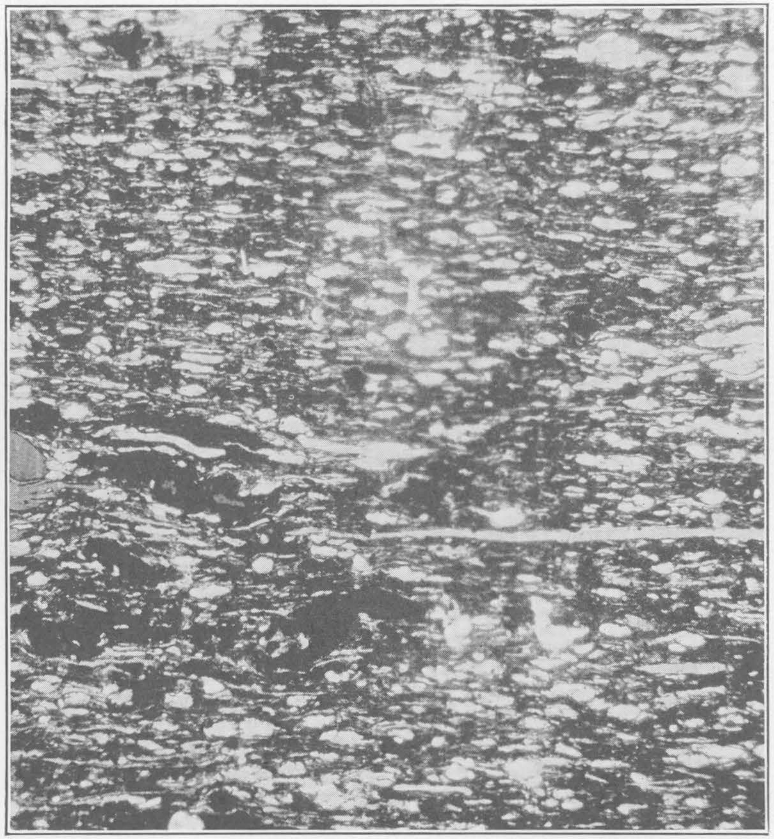
B. VERTICAL SECTION OF BOGHEAD COAL, LYING MIDWAY BETWEEN THE UPPER AND LOWER FREEPORT COALS, IN THE ALLEGHENY FORMATION AT KISKIMINETAS JUNCTION, WESTMORELAND COUNTY, PA.

The organic matter in this deposit is composed very largely of yellow bodies, apparently comprising algal colonies closely comparable in general aspect and to a degree at least in structure with Elaeophyton and the fossil types of boghead colonial algae. Relatively very few spores are present. The deposit begins with an ordinary shale at the bottom, which first gradually and then quickly changes into a rich boghead coal. × 200



A. CROSS (VERTICAL) SECTION OF CANNEL COAL FROM A FREEPORT BED OF THE ALLEGHENY FORMATION AT KISKIMINETAS JUNCTION, WESTMORELAND COUNTY, PA.

The yellow bodies in this section, here seen in greater enlargement, are strongly suggestive of Elaeophyton and are probably alga colonies similar in general composition to the living and the fossil forms shown in the preceding illustrations. × 1,000



B. CROSS (VERTICAL) SECTION OF CANNEL COAL FROM THE MERCER SHALE (UPPER POTTSVILLE) ON NESHANNOCK CREEK NEAR LEESBURG STATION, PA.

This section shows spore exines, lumps of resin (at left), and a number of yellow bodies, probably colonial algae related by nature and composition to Elaeophyton. The section exhibits the characteristic aspect and constitution of a cannel coal in which spore exines predominate and in which occur also minor amounts of resin lumps, alga colonies, fragments of cuticle, etc. × 200

ANIAKCHAK CRATER, ALASKA PENINSULA.

By Walter R. Smith.

The discovery of a gigantic crater northwest of Aniakchak Bay (see fig. 11) closes what had been thought to be a wide gap in the extensive series of volcanoes occurring at irregular intervals for nearly 600 miles along the axial line of the Alaska Peninsula and the Aleutian Islands. In this belt there are more active and recently active volcanoes than in all the rest of North America. Exclusive of those on the west side of Cook Inlet, which, however, belong to the same group, this belt contains at least 42 active or well-preserved volcanoes and about half as many mountains suspected or reported to be volcanoes. The locations of some of these mountains and the hot springs on the Alaska Peninsula and the Aleutian Islands are shown on a map prepared by G. A. Waring.[1] Attention has been called to these volcanoes for nearly two centuries, but a record of their activity since the discovery of Alaska is far from being complete, and an adequate description of them as a group has never been written. Owing to their recent activity or unusual scenic beauty, some of the best known of the group are Mounts Katmai, Bogoslof, and Shishaldin, but there are many other beautiful and interesting cones and craters.

Aniakchak Crater (Pls. XLI, XLII) was discovered in August, 1922,[2] by a United States Geological Survey party, in charge of R. H. Sargent, topographic engineer, in the course of a reconnaissance topographic and geologic survey of the country west of the Aleutian Mountains between Wide and Aniakchak bays. The first evidence of an ancient volcanic eruption in the district was observed 30 miles northeast of the crater, in the form of thin deposits of fine ash concentrated in small depressions on the hillsides. As the work progressed southwestward the deposits of volcanic ash became more numerous and the material coarser. Along Ray Creek, 18½ miles from the crater, pieces of scoria and fine ash had consolidated and subsequently been cut by the stream until vertical walls stand 6 to 12 feet high on both banks. (See Pl. XLIII, *A*, *B*.) The floor of the broad valley of Cinder River was found to be entirely covered by volcanic ejecta, but the source of the material was not discovered until the summit of Elephant Mountain was occupied by Mr. Sargent and the writer. Prior to the view of the crater, however, locations on the topographic map of a group of peaks in the distance had assumed the form of a circle, but the reason of the arrangement was not suspected.

Aniakchak Crater is 24 miles northwest of Aniakchak Bay, approximately in the central part of the Alaska Peninsula, on the divide between the Pacific Ocean and Bering Sea. Although there are no trails, the district is easily accessible from either side of the peninsula. Aniakchak River, the largest stream on the peninsula flowing into the Pacific Ocean, rises within the crater and breaks through the east side of the rim in a narrow and picturesquely castled canyon which has been named "The Gates" (Pl. XLIII, *C*), from two long, nearly symmetrical mountain spurs that diverge from the canyon, one on each side of the river, and inclose the upper valley. The crater is nearly circular in outline and has a maximum diameter of 6¾ miles and a minimum diameter of a little over 5¾ miles. The lowest part of the crater floor is 1,100 feet above sea level and contains Surprise Lake, a body of water with an area of 2 square miles. The walls are well preserved and rise almost vertically in places to altitudes of 1,200 to 3,000 feet above the bottom of the crater. A large truncated cinder cone, the summit of which is 2,200 feet above Surprise Lake, occupies the south-central part of the area inclosed within the crater rim.

[1] Waring, G. A., Mineral springs of Alaska: U. S. Geol. Survey Water-Supply Paper 418, pl. 1, 1917.

[2] It has recently been reported that W. W. French, an engineer, and party visited the crater in July, 1921, but no report of the discovery was made at that time.

The crater was first mentioned without a name by R. F. Griggs [3] in a book that was printed shortly after the return of Mr. Sargent's party. Under the name "Old Crater" report [4] on the geology of the district. In a chronologic account of observed volcanic activity in Alaska, Grewingk [5] gives the geographic position of Veniaminof volcano as

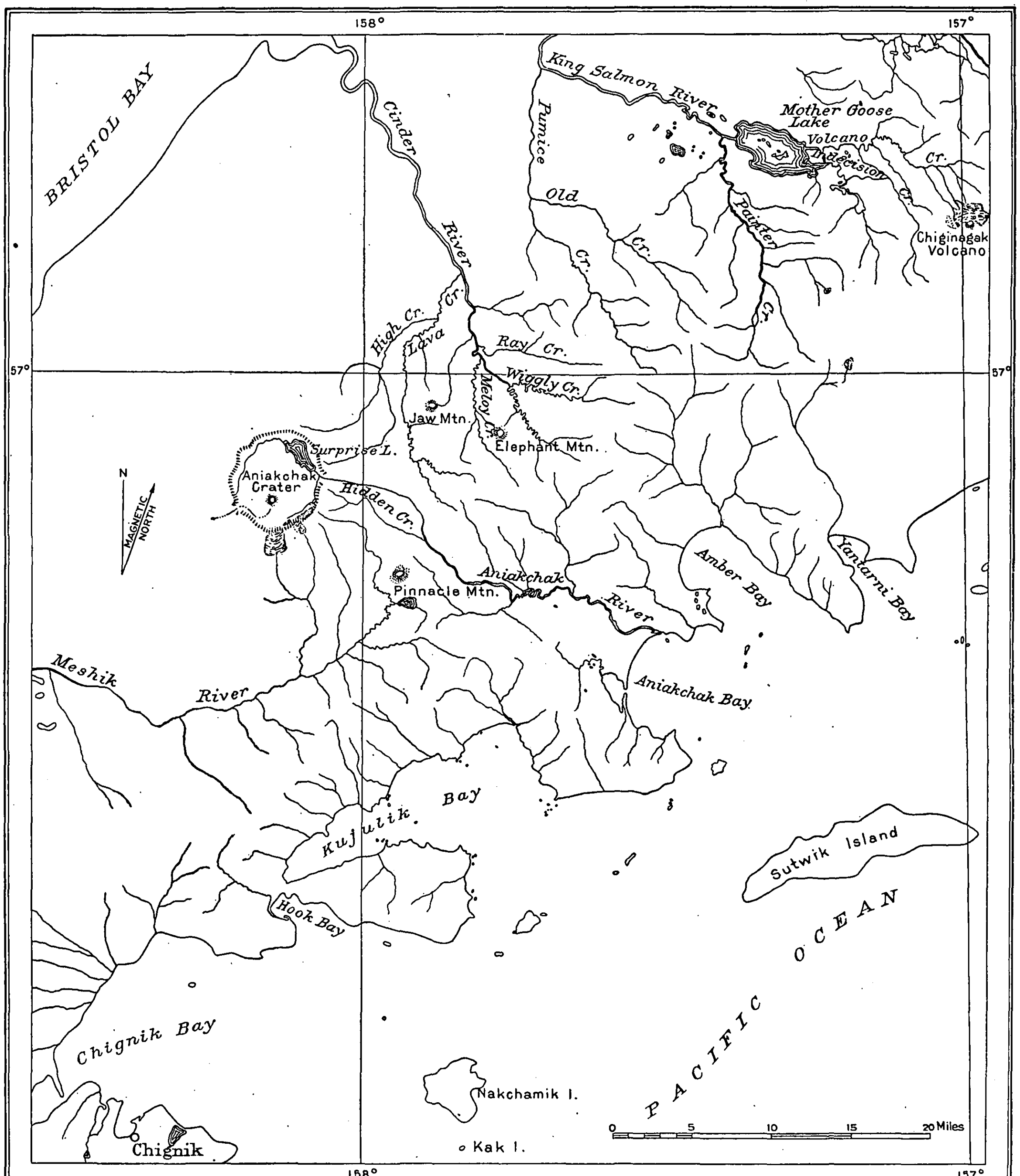


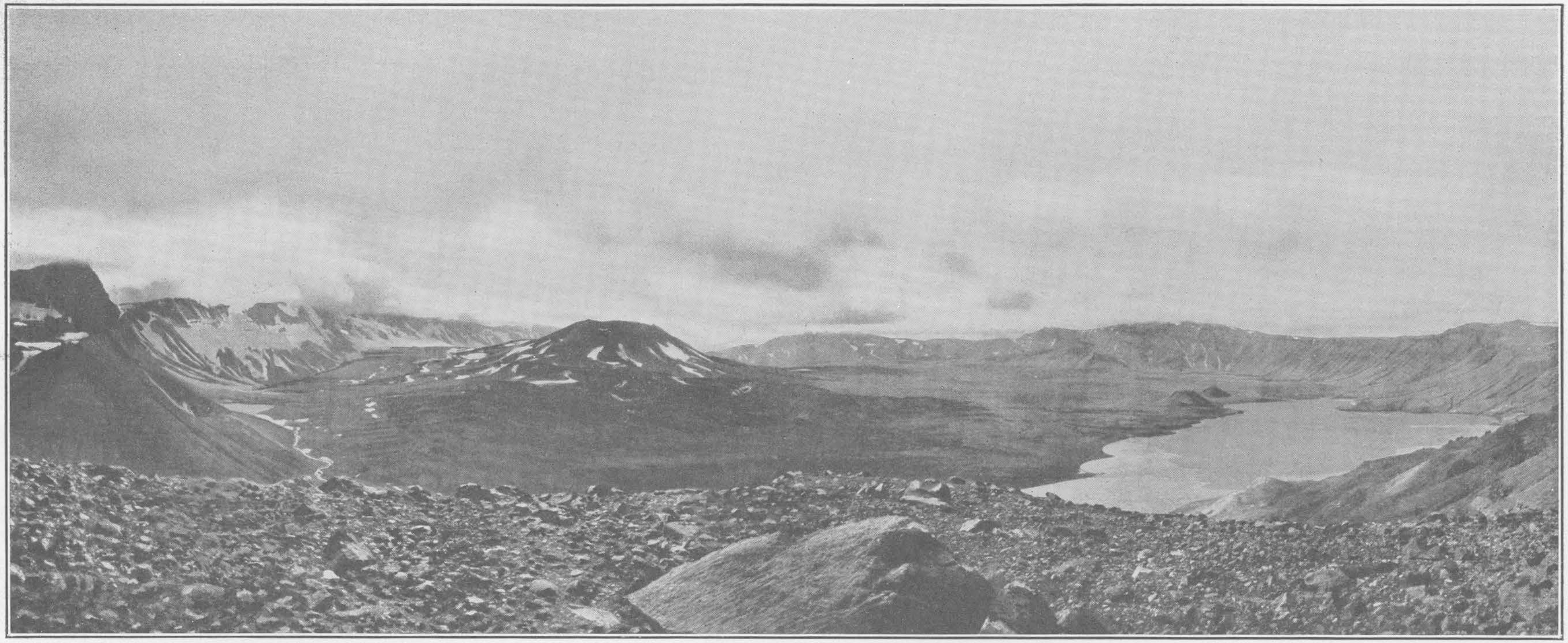
FIGURE 11.—Sketch map showing location of Aniakchak Crater, Alaska Peninsula.

its position is indicated on the map of Alaska published by the Survey in 1923. A very brief description of the crater was included in a

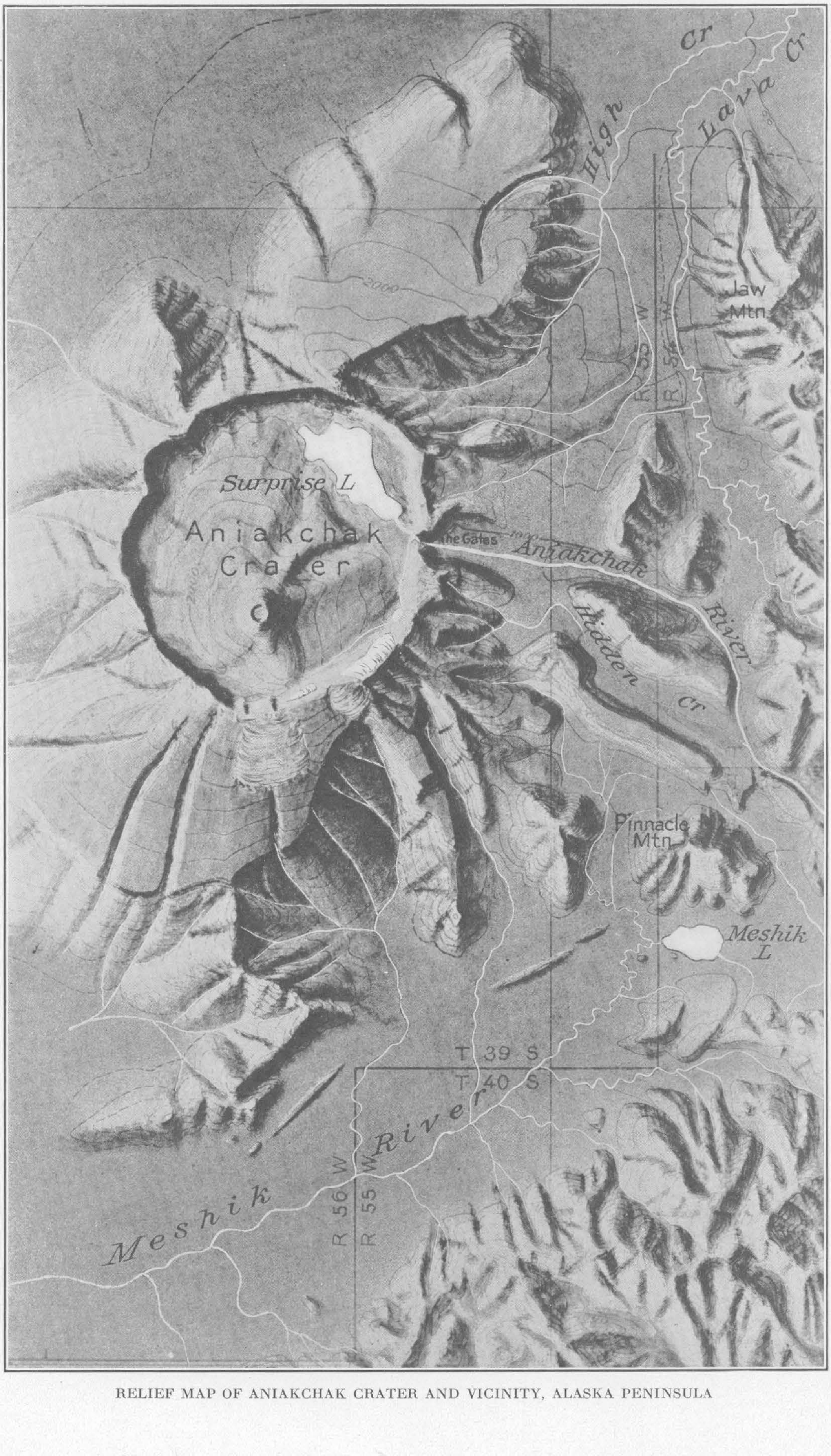
[3] The Valley of Ten Thousand Smokes, p. 65, footnote, 1922.

[4] Smith, W. R., and Baker, A. A., The Cold Bay-Chignik district: U. S. Geol. Survey Bull. 755, p. 157, 1924.

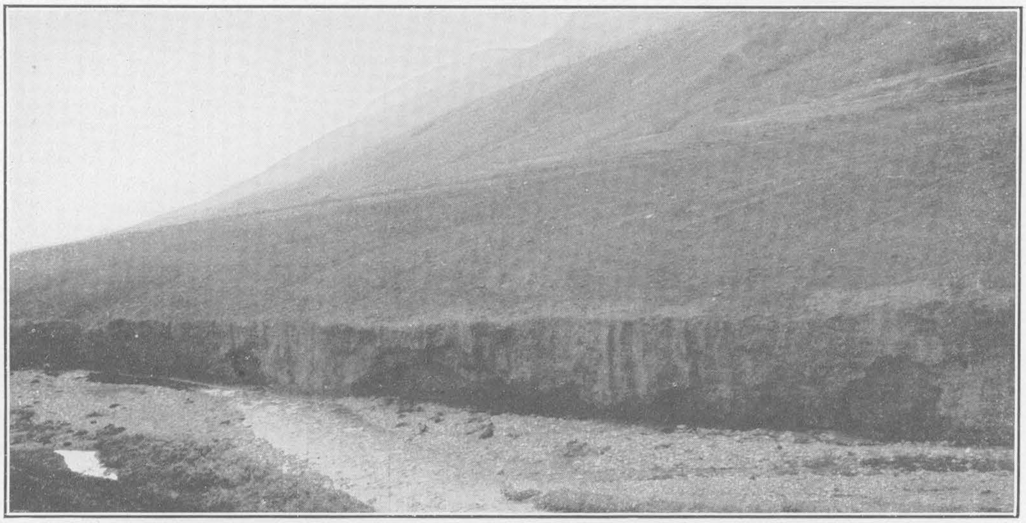
[5] Grewingk, Constantin, Beiträge zur Kentniss der orographischen und geognostischen Beschaffenheit der Nord-west Kuste Amerikas, mit den anliegenden Inseln (with geologic and other maps), St. Petersburg, 1850.



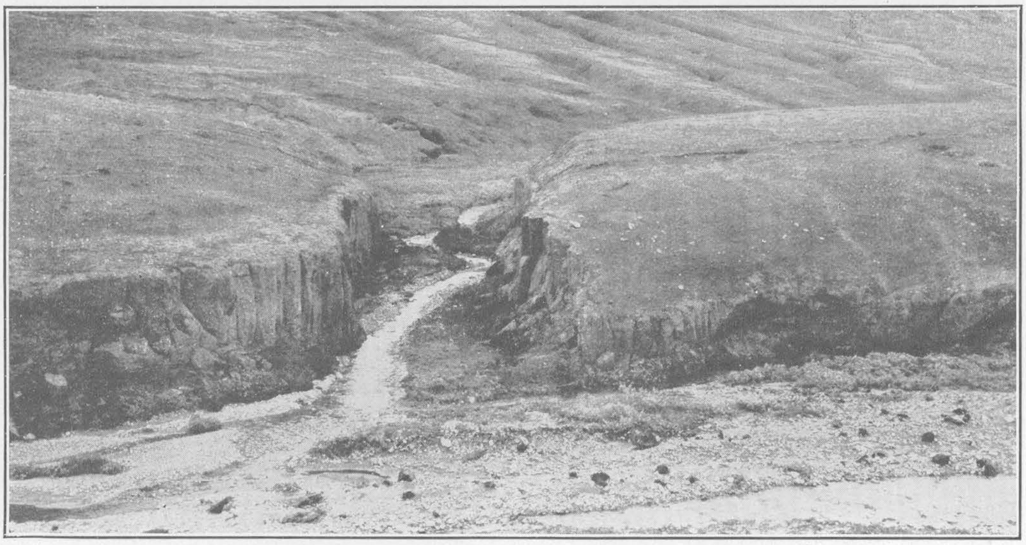
ANIAKCHAK CRATER, ALASKA PENINSULA



RELIEF MAP OF ANIAKCHAK CRATER AND VICINITY, ALASKA PENINSULA

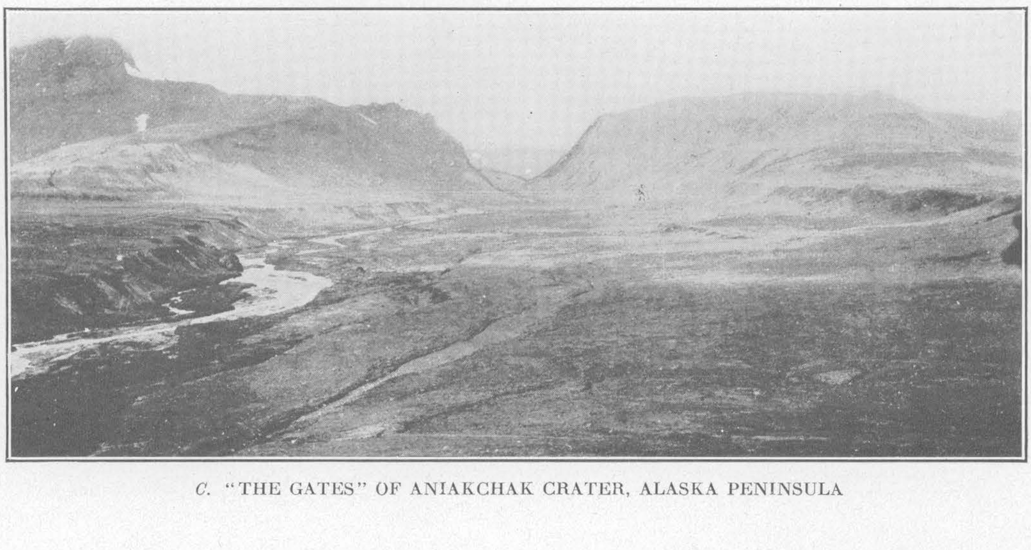


A

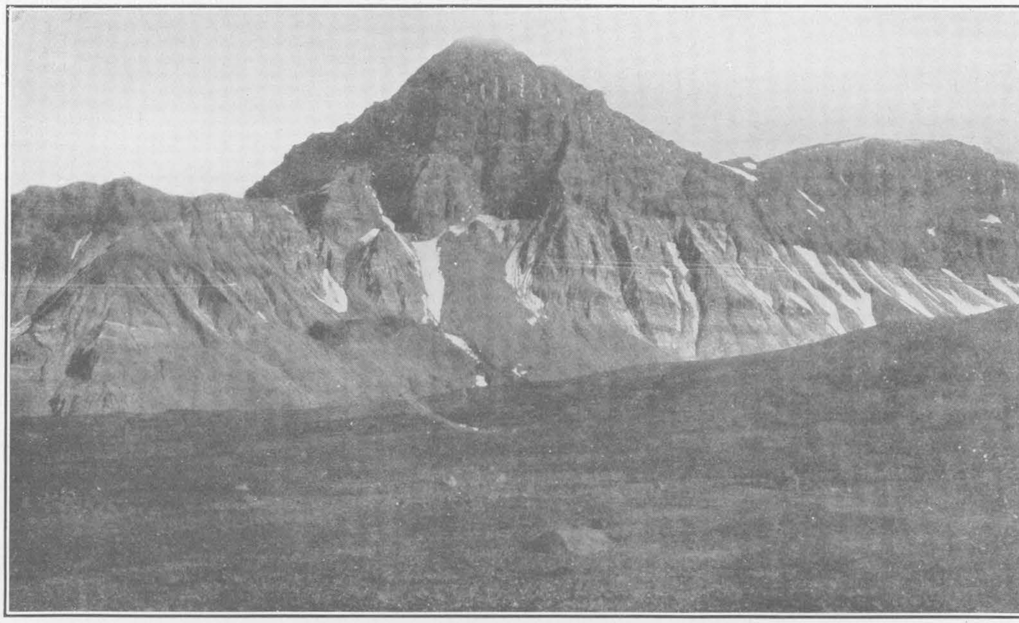


B

A, B. EXPOSURES OF VOLCANIC ASH ON RAY CREEK, ALASKA PENINSULA



C. "THE GATES" OF ANIAKCHAK CRATER, ALASKA PENINSULA



A. BLACK NOSE, ALASKA PENINSULA

B. MOUNT CHIGINAGAK, ALASKA PENINSULA

latitude 56° and longitude 158° to 159°. This position is rather close to that of Aniakchak Crater, which is latitude 56° 45′ and longitude 158° 9′, but from the short account given it is quite evident that Grewingk meant the volcano known at present as Veniaminof, latitude 56° 17′ and longitude 159° 15′, and not Aniakchak Crater. Although the Russian scientists and travelers recorded many interesting and valuable observations regarding the volcanoes of Alaska Peninsula, they made no mention, so far as known to the writer, of the immense crater discovered in 1922. It is quite probable that some of the Russian fur hunters, or perhaps a prospector or trapper of more recent days, came across the crater but either failed to recognize it as such or failed to report it. Inquiries were made of the inhabitants of Chignik, the nearest settlement, and of local trappers, all of whom knew nothing about the crater. The present paper is based on observations made by the writer during a few hours. Time was not available to determine the age of the crater or the exact manner in which it was formed.

The observer at a distance would not suspect the existence of a huge crater within the cluster of rather gentle peaks which are separated from the other mountains of the district by broad level areas. The valleys of Meshik and Aniakchak rivers west of the crater are in general less than 200 feet above sea level. The boldest portion of the outer rim of the crater is along the east side of the mountains, where cliffs rise abruptly from the tributary valleys of Aniakchak and Meshik rivers. Over these precipitous cliffs many streams cascade from the glaciers near the summit of the rim. One of these streams has a vertical fall of at least 1,000 feet. The west and north sides of the rim slope more gently away from the crater and are covered to a great depth by ash and cinders. Gullies 30 feet deep on these slopes do not expose the solid rock beneath but show rudely stratified layers of ash and large lava and scoria boulders 4 feet and less in diameter.

The panorama of the crater (Pl. XLI) conveys a rather poor conception of its magnitude, owing to the large size of the area inclosed within the proportionally low rim and to the absence of an object of known dimensions. However, the greatest length of Surprise Lake visible in the photograph is 2½ miles, and the small cones near the upper end of the lake rise about 200 feet above the floor of the crater. The summit of the large cinder cone is 4½ miles from the point at which the picture was taken; the mountains beyond the cone are 6 miles from the observer. The inner wall is abrupt—at places nearly vertical—and so far as known it can not be easily descended except just north of The Gates. A view of Black Nose (Pl. XLIV, *A*), the peak immediately south of The Gates, taken from a cinder ridge within the crater, gives an idea of the steepness of parts of the inner wall. The south side of the crater rim affords a gathering ground for the snow, and here vigorous alpine glaciers have been formed on the steep slopes. Evidence of slumping along the inner wall was not noted except for several talus slopes in the canyon of Aniakchak River and near the base of Black Nose. The circumference of the crater is nearly 19 miles. The rim is broken in two places—the sharp notch through which Aniakchak River flows and a depression on the west side which was not seen in 1922 but has been reported by M. W. Taylor, of Seattle, who visited the crater in 1923. On the south side the highest point on the rim is 4,200 feet above sea level and 3,000 feet above Surprise Lake. This peak and several others close by were obscured by clouds at the time the photograph reproduced in Plate XLIV was taken. The greater part of the crest of the rim is not jagged, although Black Nose and several other sharp peaks rise above the average altitude, which is approximately 3,000 feet.

Along the north and northeast sides the inner wall is partly covered by detritus, but in the few exposures seen the rocks appeared to be layers of pink and black lava, probably obsidian, several hundred feet thick, overlying a light-colored quartz diorite. Most of these exposures are inaccessible and were not closely examined, but a specimen of the quartz diorite was taken on the outer wall northeast of the crater. Exposures in the cliffs along the canyon and near the bottom of Black Nose consist of nearly horizontal sedimentary rocks, chiefly very massive gray sandstone. In the lower 500 feet the rocks exposed in the canyon are abundantly fossiliferous; the greater part of the fossils belong to several species of *Aucella* that are characteristic of the Naknek formation, of Upper Jurassic age. From a distance the summit of Black Nose apparently consists of lava, but the upper portion may be in part sedimentary rock, presumably of Tertiary age. The unconformity and the contrast in lithology between the rocks of the two kinds can be seen in Plate XLIV, *A*. Although the high mountains forming the south side of the rim were not closely examined, they probably consist entirely of sedimentary rocks, the greater part of which are Upper Jurassic. A rugged spur north of the north wing of The Gates is composed of very coarse agglomerate or tuff similar to that overlying large areas in the vicinity of Aniakchak and Kejulik bays. Most of the large and small boulders that make up the agglomerate are angular, but some are rounded. Individual blocks attain 16 feet in diameter and display the darker shades of red, green, and gray. Many of the boulders are black, and all of them show a scoriaceous texture.

The area of the bottom of the crater is approximately 30 square miles. The entire floor is covered to an unknown depth by black and gray scoria ranging in coarseness from very fine material to pieces several feet in diameter. About one-third of the floor is level; around the base of the large cone ridges of cinders, 200 to 800 feet high, radiate toward the crater wall. The formation of the cones and the position of the material within the rim are undoubtedly the results of activity subsequent to the major eruptions that produced the great crater. The later activity probably decreased the original depth of the crater by partly filling it with cinders, The upper 800 feet of the large cone is remarkably circular and well preserved. It is thought to be formed entirely of cinders, as no lava was observed on the ridges around the base. The summit is truncated and may be slightly depressed. An attempt was made to reach the top, but traveling over the loose material is wearisome, and the attempt was given up late in the evening with the realization that a trip of 10 miles to camp was yet to be made. The small cones near the head of the lake were not examined. Toward the west side of the crater, 5 miles from the writer's nearest point of observation, another small cone, which was not caught by the camera, could be seen by aid of a field glass. Near this cone a curious bowl-shaped deposit of white material, probably formed by hot mineral waters, stands out in contrast to the surrounding black scoria, which appeared to be very coarse at that locality. Only a rough estimate of the dimensions of the bowl can be given, but it is at least 200 feet in diameter.

Surprise Lake, in the northeastern part of the crater, is irregular in outline and has a maximum length of 2½ miles and average width of three-fourths of a mile. It covers an area of nearly 2 square miles, but the bluish-green color of the water indicates that the depth is not great. The lake may have formerly covered a much larger area, before the river had deepened its channel through the canyon, but terraces or high-water marks could not be detected on the wall at the few places examined. An ill-defined bench occurs well up on the sides of the cinder cone, however, but the bench is not continuous nor sufficiently well preserved to consider it an ancient lake shore. A small circular lake or pool several hundred feet higher than Surprise Lake is situated at the base of Black Nose. Although a stream of considerable size flows from the lake and unites with Aniakchak River just inside The Gates, the lake has no affluents and must derive its supply of water from the snow fields and glaciers by seepage through the cinders.

The narrow notch in the crater's rim through which Aniakchak River flows has undoubtedly been deepened by the erosive power of the stream, which is very turbulent as it emerges through The Gates. The break in the wall, however, is thought to be caused by a rift, which may extend across the crater and account for the depression on the west side. No evidence of relative vertical displacement of the opposite sides of the canyon was noted. The photograph of The Gates (Pl. XLIII, *C*), taken through the haze from a point 5½ miles down the valley, does not do justice to their profoundly impressive beauty. Several terraces formed by the river in the ash and pumice can be seen in the foreground. The crater can be entered through The Gates without difficulty on the south side of the river. The stream was too swift to be waded within the canyon when it was visited in August, and an attempt to pass through on the north side of the river terminated by climbing a precipitous cliff 1,600 feet high.

Only the east side of the crater was visited, but the country to the north could be seen from Jaw Mountain and the southeast outer wall from Pinnacle Mountain. All the valleys of the surrounding country for many miles are covered by thick deposits of ejecta from the crater. The material consists of fine ash, fragments of black and pink lava, and gray, black, and red pumice. The greatest observed thickness is exposed in the steep banks of Lava Creek. The stream has developed many beautiful terraces and its present bed, west of Jaw Mountain, is cut, perhaps 50 feet, into a deposit of black volcanic glass, as reported by Mr. Sargent. The glass or obsidian is 10 miles from the nearest point on the crater's rim, and whatever its source it was extruded before the great eruptions of the volcano, as it is overlain by at least 150 feet of loose material, the greater part of which is black pumice. This is the only lava seen in place except on the inner wall of the crater, but many fragments of black obsidian, containing a few glassy lath-shaped crystals of feldspar, were found on the mountains many miles from the crater. Indications of extinct fumaroles were sought in the ash-covered area east of the crater, but much of the volcanic material has been worked over by streams, and no evidence of fumarolic activity was found. The upper valley of Meshik River and also the valley of Aniakchak River in the vicinity of Albert Johnson Creek have been filled with volcanic débris to such an extent that the present valley floors are very broad and nearly level. A few low isolated hills near the margins of the level area appear to have been partly buried, with only their summits left exposed, but this is probably an illusion. Several high mountains southeast of the crater are sharp-peaked, especially Pinnacle Mountain, and are composed of hornblende andesite. A stream of considerable size, Hidden Creek, a tributary of Aniakchak River, flows through a subterranean channel beneath the ash and cinders for a distance of 5 or 6 miles and emerges on the west bank of the river. The Aniakchak is about 100 feet wide and 4 feet deep below the North Fork. The current is swift enough to transport small pieces of pumice along the bottom. At 4 miles from its mouth the river has eroded a picturesque gorge through a thick deposit of volcanic agglomerate. The southwest side of the gorge is formed by a rugged spur that projects across the valley from the hills to the southwest and is locally known as Cape Horn. (See fig. 11.) The river is navigable by small boats as far as the meanders below the mouth of Mystery Creek.

A broad marshy lowland lies between the shore line of Aniakchak Bay and the hills toward the northwest. In this area a remarkable series of nine crescent-shaped ancient beaches can be seen from the mountains north of the river in the form of low ridges conforming in direction to the present shore line. A large part of the material in these ridges consists of volcanic ash and pumice washed ashore by the waves after having been trsnsported into the bay by the river. The bay is uncharted and is not a protected harbor, although deep water is reported by masters of fishing schooners who have entered the bay. Hook Bay, 25 miles directly south of the crater, affords an excellent harbor for boats of moderate size. An old trail leads from this bay over the mountains toward Meshik River valley and is probably the best route from the Pacific coast to the crater, although in fair weather a landing can be made at the mouth of the river at Aniachak Bay. From this point the distance to the crater is not so great as from Hook Bay, and the route is over level country. Chignik is the nearest settlement and is 40 miles southwest in a direct line from the crater but at least 60 miles by trail. A trapper's cabin has been built near the lagoon at Aniakchak Bay and one on the south side of the valley below Albert Johnson Creek. The trappers occupying the cabins during the winter had traveled over the cinders as far west as Meshik Lake for many years, but they did not know of the existence of Aniakchak Crater.

Vegetation has gained a footing in places throughout the area covered by ash, and even within the crater several tufts of grass and low flowering plants were seen. Large areas, however, within a radius of 20 miles of the crater, are entirely barren of plant life and have the appearance of arid plains. Alder bushes have grown to a height of 6 feet in the valleys of High and Lava creeks and furnish sufficient fuel for camp purposes, but they are not straight enough to be used for tent poles. Foxes and Kodiak bears inhabit the region, Small herds of caribou were seen near the valley of Pumice Creek.

The wide general use of the term "crater" includes several varieties or types, which have been differentiated as impact craters, subsidence craters, upbuilt craters, and explosion craters. An impact crater may be formed by the fall of a body, such as a large meteorite or a projectile from a cannon. Such a bowl-shaped hollow or pit may have nothing in common with volcanic activity. A subsidence crater is a depression below the general level of the country or a concave area on a mountain, made by the collapse of the roof of a cavity. In limestone countries such depressions are common, but the use of the term is restricted by many geographers to pits occurring in volcanic regions. These pits are usually caused by the collapse of cavities formed in volcanoes by the eruption of lava and other material. Craters formed in this manner are also known as caldrons. The largest and some of the best-known craters on the earth are of this variety, to which belong Kilauea, in the Hawaiian Islands (2.93 miles in diameter); the pit of Crater Lake, Oregon (5½ miles in diameter); Ngorongoro, East Africa (12 miles in diameter); and Aso-san, in Japan (dimensions, 9 by 14 miles). An upbuilt crater has the form of a more or less circular mound surrounding an aperture, relatively small in diameter but usually deep, which serves as a vent for the lava, ash, and fumes thrown out by a volcano. This is the normal and most common type of craters and occurs on the summits of Lassen, Etna, Cotopaxi, Fuji, and scores of other volcanoes. Stromboli, in the Mediterranean Sea, is taken as the type of the explosion craters. Better examples, however, are known, such as the crater formed by the ancient explosion of Vesuvius, A. D. 79, of which Mount Somma is a remnant, and the ruins of Krakatoa in 1883 and of Katmai in 1912. Excavations made by erosive agents have been referred to and classified as craters, but they have nothing to do with volcanic action.

All the evidence now available points to the origin of Aniakchak Crater by explosive activity and not by subsidence. Besides the vast quantities of rather fine material thrown from the crater and concentrated in the valleys of the surrounding country, huge projectiles were hurled many miles. On the north slope of Elephant Mountain, 1,000 feet above the valley of Meloy Creek and 23½ miles from the center of the crater, a block of black obsidian was found which measured at least 2 cubic feet in volume. About 14 miles southeast of the crater an angular mass of sandstone, 5 feet in diameter and containing fossils similar to those found near Black Nose, occurs near the summit of a small hill composed of agglomerate. The large boulder is not waterworn, and there is slight probability that it was carried to its present position by a glacier. The ash contains smaller fragments of sandstone that have the same lithologic character as that exposed in the southeast wall of the crater and were not derived from rock in the immediate vicinity in which they were found. That tremendous explosive forces were active at the time the present crater was formed is quite evident. All the known craters of the world as large as Aniakchak Crater or larger are thought to have been formed by subsidence. Katmai Crater, 3 miles in diameter, 151 miles to the northeast, was formerly considered the largest crater of the explosive type known, but it is greatly surpassed by Aniakchak Crater, 6¾ miles in diameter. In diameter and general outline the caldron of Crater Lake, Oreg., and Aniakchak Crater are remarkably similar, although the two are of entirely different types.

The form of the mountain mass that occupied the present site of the crater prior to the eruptions that resulted in the formation of the depression can of course only be conjectured. Before the existence of the volcano the area now within the crater was probably occupied by one or more mountains of moderate altitude—that is, by analogy with other mountains in the district, between 3,000 and 4,000 feet—which were composed of very slightly folded sedimentary rocks, intruded on the north by a large mass of quartz diorite. Why volcanic vents should be formed near the summits of high mountains composed of nearly horizontal strata is difficult to explain, but on the Alaska Peninsula many of the active and extinct volcanoes originated in mountains of this type. This is especially true of the volcanoes toward the northwest, of which Mounts Katmai, Magiek, Peulik, and Chiginagak are examples. These volcanoes and many others on the Alaska Peninsula have formed cones and increased their altitudes to heights ranging from 5,000 to nearly 10,000 feet by successive lava flows over the sedimentary rocks. Mount Chiginagak (Pl. XLIV, *B*), an active volcano 43 miles northwest of Aniakchak Crater, is an impressive and typical example of an upbuilt cone. That a similar cone once towered above the site of Aniakchak Crater is suggested by beheaded lava flows, remnants of which are exposed on the east wall of the crater, on the summit of Black Nose, and possibly in the bed of Lava Creek. An imaginary cone reconstructed a mile in height above the present floor of the crater would be slightly over 6,000 feet above sea level, an altitude which is very low in proportion to the diameter of the base and also relatively low if compared with the altitude of other volcanic cones. But even if a low cone is postulated the amount of material to be accounted for is enormous and the force necessary to remove it in one or several explosions is beyond imagination. The capacity of the crater alone, if 1,600 feet is taken as the average height of the rim, is about 9 cubic miles. Subtracting 1 cubic mile for the large cinder cone still leaves space for 8 cubic miles within the crater. To this must be added at least 7 cubic miles if the low cone, suggested above, ever existed. Between 300 and 400 square miles of adjacent country on the east and south is known to be covered to various depths by volcanic ash and cinders, and if an equally large area north and west of the crater is also overlain by ejecta, certainly an appreciable part of the supposed total of 15 cubic miles is still to be seen.

Ordinarily the Bering Sea coastal plain on the northwest side of the peninsula is dotted with thousands of small lakes, but in the area north of the crater no lakes could be seen from Jaw Mountain. That all depressions in this part of the plain were filled by material from the crater is a fair deduction. The volume of material ejected from Katmai is estimated at 4.75 cubic miles, but Katmai Crater has a capacity of only 2 cubic miles. The ejection of vast quantities of material from a single source and perhaps during a single period of eruption is not unheard of in volcanism. Capps [6] has estimated a volume of 10 cubic miles of volcanic ash thrown from a vent in the upper White River basin, and other large estimates have been made. Most of these computations, however, were made from measurements of the material ejected and not from the capacity of the crater.

Few data are now available for estimating the age of Aniakchak Crater. However, it is believed to be one of the oldest of the series of volcanoes along the Aleutian Range. That the eruption antedates historic record is suggested by the amount of stream erosion, especially in Lava Creek, and the vegetation of the area, including alders. If the absence of evidence of glaciation since the eruption is taken as a criterion it would appear that the eruption is of post-Pleistocene age. Although the ash is more or less concentrated in the valleys it is not in the form of glacial moraines, and unless an ice sheet in which there was little or no movement covered the entire area, moraines of the loose pyroclastic material would be expected had this material been deposited before glaciation. A few of the valleys, such as that of Ray Creek, in which thick deposits of ash occur, are rather narrow and probably have been formed almost entirely by stream erosion. Most of the valleys are broad and suggest extensive glaciation before they were partly filled by ash. A detailed study is necessary for a more definite age determination.

An examination of the relief map (Pl. XLII) will perhaps convey a better idea of the giant crater than a description. Nearly all distances were scaled from Mr. Sargent's skillfully drawn topographic map, on which the relief map by Mr. Renshawe is based. The topographic map is published separately as the Cold Bay-Chignik map.

The writer wishes to acknowledge his indebtedness to Mr. Sargent for cooperation during the field work and for valuable assistance and criticism in the preparation of this paper. Thanks are also expressed to Mr. Sidney Old, who accompanied the writer into the crater and led the way across Aniakchak River.

The scenery of the Aniakchak district, with its broad prairie-like valleys, margined by majestic, sharp-peaked mountains, is impressive and in many respects unique. The once active scene of terrific earth convulsions is now almost oppressively silent. The coloration of the country is somber and together with the fretfully driven clouds tends to create a rather pleasing weirdness. Aniakchak Crater is one of the great natural curiosities of North America and is certainly worthy of further investigation. Although small in comparison, it is probably the nearest counterpart on earth to the craters of the moon in regard to the manner of its formation. Were it not so remote from the usual paths of travel the setting apart of this crater as a national monument would be justified.

[6] Capps, S. R., An ancient volcanic eruption in the upper Yukon basin: U. S. Geol. Survey Prof. Paper 95, p. 62, 1915.

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