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GEOLOGY OF THE NAVAJO COUNTRY

A RECONNAISSANCE OF PARTS OF ARIZONA, NEW MEXICO, AND UTAH

BY

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GEOLOGY OF THE NAVAJO COUNTRY.

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Chapter I.—INTRODUCTION.

NATURE AND SCOPE OF THE WORK.

The region bordering the Colorado canyons between Little Colorado and San Juan rivers and extending southward to the line of the Atchison, Topeka & Santa Fe Railway is difficult of access. Satisfactory maps are lacking, roads are few, and trails are poorly marked, water is scanty and generally poor, and food for animals is scarce. The white population, outside of villages along the railway and the San Juan Valley, according to official estimates for 1912, numbers 521 and includes Government officials, traders, and missionaries, living at widely separated places. The Indians, who number 32,488, are assigned to six vaguely defined reservations and are none too friendly. Geologic field work in such a country is necessarily reconnaissance; some of it, in fact, is exploratory.

The primary object of my investigations, begun in 1909 and continued during 1910, 1911, and 1913, was to "spy out the land," with a view to suggesting ways in which the country could be more fully utilized. The region is arid, and the geologic field work was therefore designed chiefly to obtain information concerning the water supply. Streams and springs as well as canyons and washes were examined, and the sedimentary formations were studied somewhat in detail. Where the demands of the particular problem in hand permitted, geologic mapping was carried on and the most significant geologic features were noted. Stratigraphy naturally received the most attention, and the chapter on that subject—Chapter III—contains the most detailed descriptions. Igneous geology, structure, economic geology, and physiography are treated somewhat less fully. It is believed that, in view of the limits imposed by the nature of the work, the geologic map represents fairly well the areal geology and that the text presents the essential facts in the geologic history of the Navajo country.

PREVIOUS WORK.

Prior to the beginning of my investigations in 1909 geologic work in northeastern Arizona and southeastern Utah had been restricted to the borders of the area here discussed. About 60 per cent of the Navajo country has not heretofore been described in geologic literature. The results of the reconnaissance studies of earlier workers are discussed at several places throughout this paper, but for convenience of reference the published material bearing on the geology of this area is summarized below.

In 1853 Whipple's expedition passed along the present line of the Santa Fe Railway from Campbell Pass to Sunset Crossing (near Winslow) and thence westward to San Francisco Mountain. A description of this region by Marcou[1] constitutes the first geologic report on any part of the Navajo country.

[1] Marcou, Jules, Résumé of a geological reconnaissance extending from Napoleon, at the junction of the Arkansas with the Mississippi, to the Pueblo de Los Angeles in California: U. S. Pacific R. R. Expl., vol. 3, pt. 4, pp. 165-171, 1856.

J. S. Newberry, geologist of the Ives expedition, describes a belt of country along the route from the Little Colorado to Oraibi and thence eastward to Fort Defiance.[1] Newberry served also as geologist of the Macomb expedition of 1859. Among the results of his work is a description of the Mesozoic formations along the San Juan from Bluff to Canyon Largo.[2]

Marvine and Howell, of the Wheeler Survey, contributed a brief report on the geologic features of the Little Colorado Valley, and in a traverse from the Little Colorado to Fort Defiance, Howell[3] made observations on stratigraphy and structure that supplement the observations of Newberry, who had followed essentially the same route.

Holmes,[4] of the Hayden Survey, crossed the San Juan and studied the Carrizo Mountains.

Dutton's monograph on the Grand Canyon includes a description of the Echo monocline,[5] and in his report on the Zuni Mountains he discusses the Mesozoic strata of Dutton Plateau.[6]

The studies of Ward in the Little Colorado Valley in 1899 and 1901 constitute the first detailed stratigraphic work undertaken on the Navajo Reservation.[7]

The reconnaissance surveys of Schrader[8] and Shaler[9] along the eastern border of the Navajo Reservation resulted in outlining an extensive coal field, which has been examined more fully by Gardner.[10]

Sterrett[11] visited the Navajo garnet and peridot fields in 1908 and discussed the economic value of these gem stones.

[1] Newberry, J. S., Geological report, in Ives, J. C., Report upon the Colorado River of the West, explored in 1857 and 1858, pt. 3, 1861.

[2] 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.

[3] Howell, E. E., U. S. Geog. and Geol. Surveys, W. 100th Mer., vol. 3, pp. 227-301, 1875.

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

[5] Dutton, C. E., Tertiary history of the Grand Canyon district: U. S. Geol. Survey Mon. 2, p. 205, 1882.

[6] Dutton, C. E., Mount Taylor and the Zuñi Plateau: U. S. Geol. Survey Sixth Ann. Rept., pp. 105-198, 1885.

[7] Ward, L. F., Status of the Mesozoic floras of the United States: U. S. Geol. Survey Mon. 48, pp. 37-40, 1905.

[8] Schrader, F. C., The Durango-Gallup coal field of Colorado and New Mexico: U. S. Geol. Survey Bull. 285, pp. 241-258, 1906.

[9] Shaler, M. K., A reconnaissance survey of the western part of the Durango-Gullup coal field of Colorado and New Mexico: U. S. Geol. Survey Bull. 316, pp. 375-426, 1907.

[10] Gardner, J. H., The coal field between Gallup and San Mateo, N. Mex.: U. S. Geol. Survey Bull. 431, pp. 364-378, 1909.

[11] Sterrett, D. B., U. S. Geol. Survey Mineral Resources, 1908, pt. 2, pp 823-827, 832-835, 1909.

Since the beginning of my surveys in 1909 several papers dealing with certain phases of the geology of the region have been published.[12]

ACKNOWLEDGMENTS.

The helpful cooperation of W. C. Mendenhall and M. R. Campbell, who spent 10 days with me in a traverse of the southern part of the reservation in May, 1909, is gratefully acknowledged. As the work progressed assistance has been freely given by T. W. Stanton, F. H. Knowlton, G. H. Girty, E. C. Case, S. W. Williston, R. S. Lull, and Charles Schuchert. To L. V. Pirsson I am indebted for contributions to the chapter on igneous rocks.

Members of the Indian Office, both in Washington and in the field, have cheerfully responded to all requests. Without the kindly assistance of Peter Paquette, superintendent at Fort Defiance, and of the Franciscan Fathers at St. Michaels, who explained my work to the Navajos, the establishment of friendly relations with the Indians might have been difficult. The knowledge of the Indians and of the country possessed by Indian traders was freely given. In particular Mr. Lorenzo Hubbell, Mr. S. S. Preston, and Messrs. Wetherill & Colville rendered valuable assistance, frequently at financial loss to themselves. Under the efficient guidance of Mr. John Wetherill the difficulties of finding a way through rough and untraveled country were reduced to a minimum. K. C. Heald, W. B. Emery, and J. E. Pogue, scientific aids and former students, cheerfully endured the hardships of pioneer work and contributed valuable scientific data.

I have given elsewhere[13] an account of the history and exploration of the Navajo country and a description of its geographic features.

[12] Darton, N. H., A reconnaissance of northwestern New Mexico and northern Arizona: U. S. Geol. Survey Bull. 435, 1910.

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

Campbell, M. R., and Gregory, H. E., The Black Mesa coal field, Ariz.; U. S. Geol. Survey Bull. 431, pp. 229-238, 1911.

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

Robinson, H. H., The San Franciscan volcanic field, Ariz.: U. S. Geol. Survey Prof. Paper 76, 1913.

Gregory, H. E., The Shinarump conglomerate: Am. Jour. Sci., 4th ser., vol. 35, pp. 424-438, 1913.

Gregory, H. E., A reconnaissance of a portion of the Little Colorado Valley, Ariz.: Am. Jour. Sci., 4th ser., vol. 37, pp. 491-501, 1914.

Gregory, H. E., The igneous origin of the "glacial deposits" on the Navajo Reservation: Am. Jour. Sci., 4th ser., vol. 40, pp. 97-115, 1915.

[13] Gregory, H. E., The Navajo country; a geographic and hydrographic reconnaissance of parts of Arizona, New Mexico, and Utah: U. S. Geol. Survey Water-Supply Paper 380, 1916; The Navajo country: Am. Geog. Soc. Bull., vol. 47, pp. 561-577, 652-672, 1915.

CHAPTER II.—GEOGRAPHY.

LOCATION.

The Navajo country occupies northeastern Arizona and parts of New Mexico and Utah. It lies approximately between parallels 34° 55′ and 37° 17′ and meridians 108° and 111° 45′. The valleys of large rivers—the Puerco, the Little Colorado, the Colorado, and the San Juan—outline the country on three sides and form natural boundaries that have long been recognized by the native tribes. The eastern boundary is arbitrarily drawn at the 108th meridian. The region thus outlined contains about 25,725 square miles.

This region is occupied almost exclusively by Indians, whose lands, for administrative purposes, are divided into several reservations —the Pueblo Bonito, San Juan, Navajo, Navajo Extension, Western Navajo, and Hopi, each in charge of a superintendent. These six reservations comprise 14,333,351 acres, or about 22,400 square miles, and form the largest area of undeveloped Indian land in the United States. Though these reservations are officially regarded as distinct, their boundaries have no geographic significance; in fact, their precise limits are unknown to Indians and whites alike. In this report all the lands set aside for the Indians are treated as a unit, to which is applied the general term Navajo country.

The area is shown on the accompanying map (Pl. I, in pocket). This map has been compiled from reconnaissance topographic maps of the United States Geological Survey and other published maps, as well as from manuscript maps of the War Department, the Office of Indian Affairs, the General Land Office, and the Bureau of American Ethnology, supplemented by personal observations. Many new names have been added, and the spelling of Navajo and Hopi terms has been revised and has received the official sanction of the United States Geographic Board, and it is believed that the map represents fairly well the present state of knowledge regarding the salient geographic features of the Navajo country.

FORM OF THE LAND.

The Navajo country is part of the Colorado Plateau province, a region of folded and faulted sedimentary rocks traversed by innumerable canyons. Parts of the area are so intricately dissected by interlaced gorges that the original surface of the plateau appears to have been destroyed and is now represented by a bewildering array of scattered mesas, buttes, isolated ridges, and towering spires, among which dwindling streams follow their tortuous paths. When the region is viewed as a whole, however, it can be recognized as a plateau whose general surface stands at an altitude of about 5,500 feet, above which the mountains rise and below which the canyons are sunk. About 32 per cent of the Navajo country is between 6,000 and 7,000 feet above sea level, and 10 per cent between 7,000 and 9,000 feet; 156 square miles is below 4,000 feet, and only 42 out of 25,725 square miles is above 9,000 feet. The highest and lowest altitudes are found near the mouth of San Juan River, where the crest of Navajo Mountain (10,416 feet) rises above the bed of the Colorado (3,400 feet), showing a difference of over 7,000 feet in a horizontal distance of 8 miles.

Two of the mountain masses, Carrizo and Navajo, are laccolithic in origin and rise like domes above the surrounding country. The other mountains, Chuska, Black Mesa, and Segi Mesas, are essentially mesas slightly modified by folding of the strata and bordered by sheer cliffs of commanding proportions. Mesas of the second and third order and innumerable buttes of both igneous and sedimentary origin are characteristic features. Mesa, butte, volcanic neck, canyon, wash, repeated indefinitely, are the elements of the Navajo landscape. Alcoves, recesses, and miniature erosion forms of great variety and rare beauty stand as ornamental carvings on the larger architectural features.

The topographic features of all grades show the influence of aridity. Most of the stream channels carry no perennial water, yet enormous accumulations of coarse alluvium, the product of floods, are everywhere to be seen. Bedrock is in many places swept clean by winds but is elsewhere covered with dunes; instead of talus slopes there are walls of bare rock. The desert, however, is a "painted desert," showing not the gray tones of many other regions but vivid reds and browns, blues and greens, in masses extending for miles or mingled to form the "variegated shales" of the earlier explorers.

DRAINAGE.

Except for an insignificant quantity carried by San Jose River to the Rio Grande, the surface water of the Navajo country eventually finds its way to the Colorado, the master stream of the Plateau province. The drainage from 14,000 square miles is contributed to the Colorado by the San Juan; that from 9,900 square miles reaches the Colorado through the Little Colorado, and that from 1,880 square miles reaches it through minor tributaries. A few of these drainage channels are broad washes interrupted by stretches of canyon, but most of them are sharply cut canyons in which the water is accessible only at certain places. All the streams fluctuate widely in response to climatic changes; most of them alternate between stages of flood and of dryness. The Colorado is the only stream in the region that maintains a strong perennial flow, and even in this river the difference between high and low water at Lees Ferry is said to exceed 30 feet.

A study of 52 streams of the Navajo country[1] shows that they fall into two classes, perennial and intermittent. The intermittent streams are perennial through parts of their courses or flow only in response to showers or seasons of rain. These distinctions, which are of the utmost importance to the inhabitants and to travelers, are shown on the map (Pl. I, in pocket). The San Juan is perennial, but the Little Colorado is intermittent through a large part of its course and receives no perennial through-flowing stream from a drainage basin on the north and east covering 9,900 square miles. The Colorado receives also the water of Navajo Creek, which is perennial throughout 54 miles of its course, and of Oak, Nasja, Bridge, and other short, canyoned creeks that drain Rainbow Plateau. Of streams tributary to the San Juan, Junction, Cha, Desha, Nokai, Copper, Moonlight, and Gypsum creeks carry a little water throughout the year; Piute Creek is perennial, and the lower Chinle and the Tyende are rarely if ever entirely dry.

Many of the tributaries to the intermittent streams are perennial; most of them are but a few miles long and are themselves intermittent. Spruce Brook and the stream occupying Canyon de Chelly flow for distances of 18 and 15 miles, respectively, as permanent streams. Walker Creek, rising in Carrizo Mountain, flows for 38 miles before joining the intermittent stretch of the Chinle. In general, streams rising on mountains and plateaus above an altitude of 8,000 feet may be relied upon to furnish water in their upper courses.

Three large valleys in the Navajo country are occupied by intermittent streams—Chinle Creek, Black Creek, and Moenkopi Wash—draining areas of 4,790, 969, and 272 square miles, respectively.

Throughout the Navajo country streams that flow only in response to showers form the prevailing type. Through-flowing and intermittent streams traverse probably less than 1 per cent of the linear extent of the drainage channels. During the dry season the ratio of valleys occupied by streams to valleys without water is, for channels exceeding 25 miles in length, about 1 to 100 and for channels between 5 and 10 miles in length about 1 to 340. No permanent stream except a part of the Moenkopi was found west of the Chinle Valley and south of latitude 36° 14′—a district constituting about one-third the area mapped. The Kaibito Plateau and the larger part of the Gothic Mesas province are also without perennial streams.

The summer rains radically change the aspect of the country. The dry valley floors are covered with rivers and tributary brooks. A single shower may convert any one of a score of intermittent rills into a through-flowing stream and raise a group of dry washes to the dignity of rivers. The Chinle system becomes united, and tributaries of the third and fourth degree

[1] Gregory, H. E., The Navajo country: U. S. Geol. Survey Water-Supply Paper 380, pp. 85–102, 1916.

furnish their daily supply. During this period the forbidding dry, hot valleys leading to the Little Colorado are transformed into a series of silt-laden rivers, some of them exceeding 100 miles in length, and the Little Colorado itself becomes a river of commanding proportions, ranking with the Gila and the San Juan in the volume of water carried to the Colorado.

CLIMATE.

The Navajo country is on the northern edge of the world zone characterized by high pressure and consequent aridity and outside of the usual path of cyclonic storms. In several respects its climate resembles the modified monsoon climate of Spain. Within the reservations topography is of primary importance in determining climate. At stations in the Little Colorado and San Juan valleys the weather is warmer and drier than at higher altitudes near the center of the area. In this region, where the effect of exposure to the sun's rays assumes high values, even secondary topographic features exercise a significant control on the climate. The floor of a canyon may have a climate quite unlike that of the canyon rim, and the cliff dwellers long ago learned that one canyon wall may afford favorable sites for settlement that are not to be found on the opposite wall.

The mean annual rainfall at eight stations in or near the Navajo country is as follows: Hite, Utah (altitude 3,500 feet), 6.92 inches; Aneth, Utah (altitude 4,700 feet), 4.96 inches; Fruitland, N. Mex. (altitude 5,200 feet), 6.89 inches; Keams Canyon (altitude 6,600 feet), 10.94 inches; Winslow, Ariz. (altitude 4,853 feet), 7.07 inches; Tuba, Ariz. (altitude 4,700 feet), 5.30 inches; Holbrook, Ariz. (altitude 5,069 feet), 9.15 inches; Fort Defiance, St. Michaels (altitude 6,900 feet), 12.80 inches. The amount of rainfall received from year to year varies from half the normal to twice the normal. At Fort Defiance an annual rainfall of 19.37 inches in 1911 was followed in 1912 by 7.90 inches. At Holbrook 5.20 inches of rain fell in 1904 and 17.63 inches in 1905. The records at other stations are similar. The variation for corresponding months in different years is also great. Rainfall of 4 inches and more has been recorded for months usually dry; and only a fraction of an inch may fall in July and August, the normal wet months.

About 37 per cent of the annual mean precipitation occurs in July, August, and September, and 12 per cent in April, May, and June. The groups comprising January to March and October to December occupy intermediate positions, the precipitation in these months being respectively 26 per cent and 25 per cent of the total for the year.

The characteristic storm of the Navajo country is the short and extremely violent thunder shower. Lightning is an almost universal feature of the summer storms and ranks first as a cause of forest fires. Some of the winter storms are accompanied by snow, which falls even in the Painted Desert. Many of the showers are local and cover only a few hundred acres; others evaporate before they reach the ground. On the other hand, the total precipitation in a rainy month may consist in a single shower.

The mean annual temperature at meteorologic stations in the Navajo country ranges from 47.6° at Fort Defiance (altitude 6,900 feet) to 60.6° at Hite. The lowest monthly means are 51.9° at Holbrook, 50.8° at Aneth, and 44.1° at Fort Defiance. The highest monthly means range from 52.6° at Fruitland to 63.6° at Fort Defiance. At all stations in this area temperatures below zero are recorded, the maxima ranging from −8° (Keams Canyon) to −24° (Fort Defiance); and temperatures exceeding 100° for several days in each year are normal to all stations except Fort Defiance. The maximum annual range averages 118° for seven stations and is greatest—127°—at Holbrook. The average daily range of temperature throughout this region probably exceeds 40° and in the most arid parts ranges of 50° or more are not uncommon.

At Holbrook and St. Michaels, where the direction of wind is recorded, the wind blows from the southwest every month of the year, and the work of the wind, which is widely displayed in dunes and eroded surfaces, indicates that this is the prevailing direction throughout the region.

The keynote of the climate of the Navajo country is variability, marked by sudden changes in temperature and wide fluctuation in rainfall. An intensely hot summer day may be followed by a chilly night; sunlight is synonymous with heat, shade with cold. The high temperature of the forenoon may be lowered by a cold rain or by a hailstorm, only to become reestablished within an hour. When storms come the country is flooded; at other times the task of finding water for man and beast taxes the skill of the most experienced explorer.

VEGETATION.

The difference of 7,000 feet in elevation between the lowest and highest lands in the Navajo country is vividly expressed in the zonal arrangement of trees and brush. At altitudes below 5,000 feet vegetation of all kinds is sparse and over large areas nearly lacking. Between 5,000 and 6,000 feet sagebrush (*Artemisia*) and greasewood (*Sarcobatus*), with scattered groves of juniper (*Juniperus monosperma*) and piñon (*Pinus edulis*) are conspicuous. At elevations between 6,000 and 7,000 feet juniper and piñon inclosing parks of sagebrush and of grass make up the larger part of the flora. Within the zone of yellow pine, between altitudes of 7,000 and 8,500 feet, forests of merchantable timber are found on Defiance Plateau and on Chuska, Carrizo, and Navajo mountains. The pine trees are widely spaced and inclose groves of oak and grass-floored parks of singular beauty. Above 8,500 feet the flora resembles that of humid regions. Engelmann spruce is the chief timber tree, but groves of aspen, willow, and oak are found. Berry bushes attain vigorous growth, and flowers in large variety are dotted over the luxuriant grass. F. A. Gutches, forester of the Indian Office, estimates the spruce of Navajo Mountain at 12,000,000 feet and the merchantable yellow pine of the reservations, averaging 80 feet in height, at 1,550,000,000 board feet.[1]

POPULATION AND INDUSTRIES.

The population of the Navajo country for 1912 was estimated at 33,009, or about 1.3 per square mile. Of this number 30,016 were Navajos, 2,272 Hopis, and 200 Piutes. In the midst of these 32,488 Indians 521 white persons carried on their work as Government officials, traders, and missionaries. The Hopis, the direct descendants of the cliff dwellers, are agriculturists. By the practice of dry farming and irrigation they have attained remarkable skill in the cultivation of corn, melons, and peaches. The Navajo is a stockman, a nomad who follows his flocks in search of forage and water. Raising sheep and weaving blankets form his daily occupation. The Indians own 330,000 horses, 33,000 cattle, and more than a million and a half sheep. The value of the crops raised on 20,400 acres of land in 1912 exceeded $200,000, and the sale of blankets that year brought $437,000.

[1] Unpublished report. A map showing the distribution of forests in the Navajo country is published as Plate XIX of U. S. Geol. Survey Water-Supply Paper 380, 1916.

CHAPTER III.—SEDIMENTARY ROCKS.

GENERAL STRATIGRAPHIC RELATIONS.

The consolidated sedimentary rocks exposed in the Navajo country are chiefly of Mesozoic age—Triassic, Jurassic, and Cretaceous. Beds of probable Permian age are revealed by erosion in three widely separated localities, and Pennsylvanian strata are exposed in the canyon walls of the Colorado, the Little Colorado, and the San Juan. Paleozoic sediments older than the Carboniferous are lacking, and one small outcrop of pre-Cambrian quartzite is the only representative, either sedimentary or igneous, of the Proterozoic era. The youngest rocks in the region have been assigned to the Eocene (?) series.

With the possible exception of the Tertiary deposits, the strata now distributed in detached masses were formerly spread over the entire region. Where structure permits, formations in regular succession are revealed by erosion; none are lost from the series, and most of them show little change at widely separated points. For example, the Chinle strata dip westward beneath Black Mesa and emerge at Echo Cliffs without significant change. With short breaks at Comb Ridge and along Glen Canyon, this formation encircles the Arizona and Utah portions of the region, and throughout this course of over 400 miles its characteristic features—petrified forests, limestone conglomerates, and variegated marls—are found at appropriate horizons. The sandstones of the La Plata group on Lukachukai Mountain are almost identical in character with those which form the cliffs along the Moenkopi and in Glen Canyon of the Colorado. The other formations exhibit similar relations.

The predominant rock of the whole Navajo country is sandstone of medium grain; limestone and conglomerate are much less common, and typical clay shale is rare. These general stratigraphic features are summarized in the sections and tables. (See Pl. III.)

Generalized section of rocks of the Navajo country.

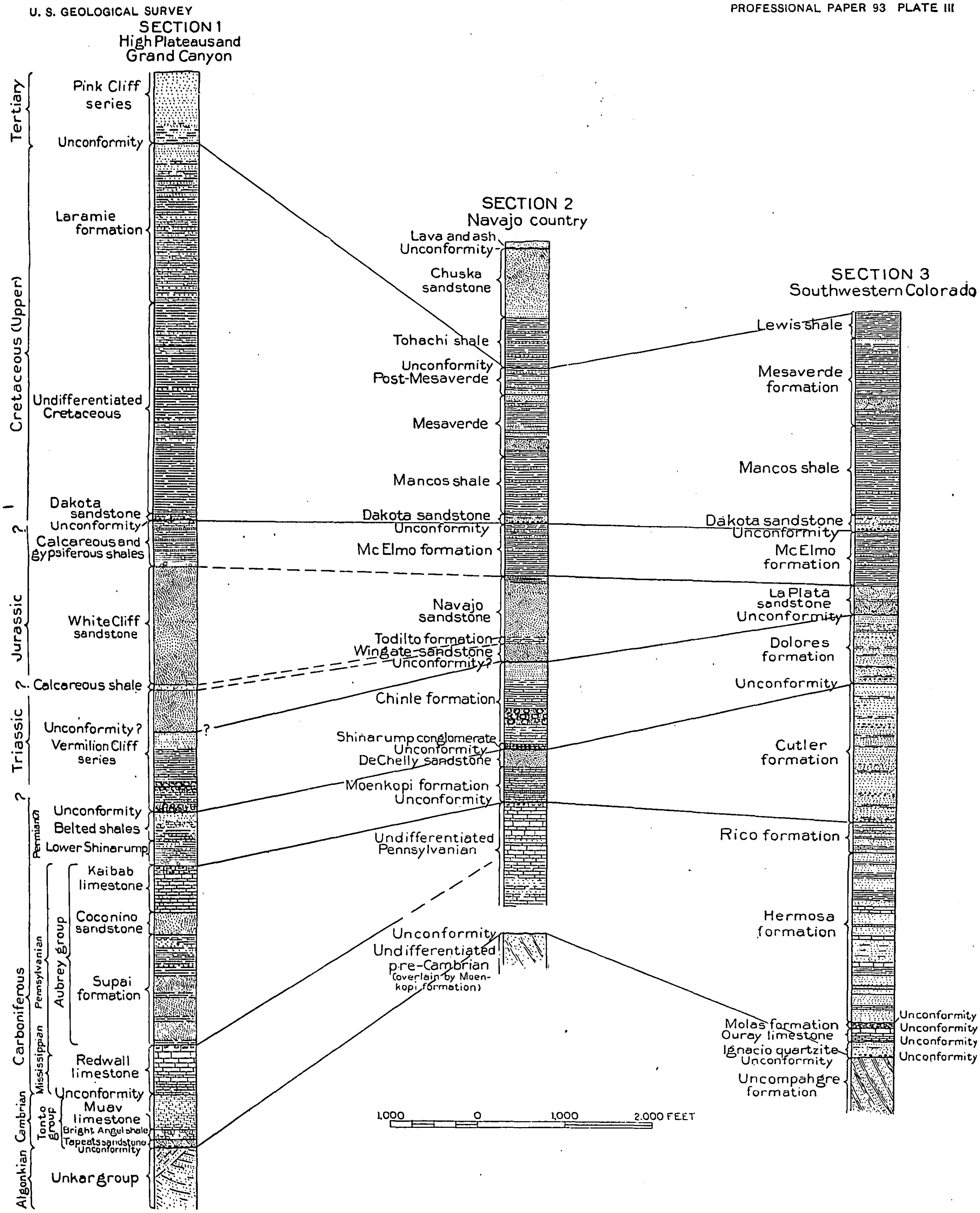
[See Pl. II, in pocket.]

System.	Series.	Group and formation.	Thickness, in feet.	Lithologic character.
Quaternary.				Alluvium, recemented gravels, eolian deposits, volcanic ash, and lavas.
Tertiary.	Eocene (?).	Chuska sandstone.	700-900	Gray and white fine to medium grained sandstone, with lenses of conglomerate; beds at some places thin, at others 40 to 50 feet thick; cross-bedded; forms cliffs.
		Unconformity——		
		Tohachi shale.	200-1,100	Shales and thin sandstone with few lenses of lignite, poorly consolidated; banded drab, red, blue, yellow, brown, and white; stratification extremely irregular; plant and animal fossils.
		Unconformity——		
Cretaceous.	Upper Cretaceous.	Post-Mesaverde rocks.[a]	300+	Unevenly deposited beds of gray and drab shales and sandstones, with coal.
		Mesaverde formation.	275-800	Massive sandstones at base and top; sandstones with arenaceous and argillaceous shales and workable coal beds in central portion; forms cliffs; fossils of Montana and Colorado (?) age.

[a] Includes areas which have previously been mapped as Lewis shale and "Laramie" formation.

Generalized section of rocks of the Navajo country—Continued.

System.	Series.	Group and formation.	Thickness, in feet.	Lithologic character.
Cretaceous.	Upper Cretaceous.	Mancos shale.	500–800+	Drab argillaceous and arenaceous shales, with lenses of impure limestone and coal; fossils of Colorado age.
		Dakota sandstone.	0–295	Gray and brown coarse sandstones, with lenses of arenaceous and argillaceous shale and coal; stratification very irregular; conglomerate in places; plant fossils.
		Unconformity—		
Jurassic ?.		McElmo formation.	400–700	Green-white, gray, and brightly banded sandstones and shale with beds of gypsum; fossils of Morrison age.
		Unconformity?—		
Jurassic.		La Plata group. Navajo sandstone.	400–1,000	Light-red massive cross-bedded, uniformly fine-grained sandstone, with variable amounts of lenticular limestone near top; prominent cliff maker.
		La Plata group. Todilto formation.	3–200	Limestone and calcareous and arenaceous shales; dinosaur footprints.
		La Plata group. Wingate sandstone.	30–450	Massive cross-bedded, uniformly fine-grained, bright-red sandstone; cliff maker.
		Unconformity?—		
Triassic.		Chinle formation.	1,182	Shales with thin sandstone and limeston econglomerate; gypsiferous and calcareous. Division *A* (top), banded red shales and shaly sandstones; *B*, alternating bands of red shale and gray-purple limestone conglomerate; *C*, shales and "marls," lenses of limestone conglomerate, variegated and banded pink, red, purple, ash, etc.; *D*, red and chocolate-colored shales and shaly sandstones. Fossil wood abundant; vertebrate and invertebrate remains. Forms badland topography.
		Unconformity?—		
		Shinarump conglomerate.	20–100	Cross-bedded lenticular conglomerate and sandstone; pebbles chiefly quartz, quartzite, and petrified wood.
		Unconformity—		
Carboniferous.	Permian (?)	De Chelly sandstone.	0–585	Light-red uniform-grained cross-bedded sandstone; cliff maker.
		Moenkopi formation.	300–500	Chocolate-red and banded arenaceous shales and thin sandstones, and rare limestone; extremely variable in stratification; gypsiferous; fossil plants.
		Unconformity—		
	Pennsylvanian.	Aubrey group in Little Colorado River region; Goodridge formation in San Juan River region (relations unknown).	0–1,500+	Kaibab limestone of Aubrey group exposed; buff arenaceous thin-bedded limestones. Goodridge formation: Buff and red limestones and sandstones. Fossils of Pennsylvanian age.
		Unconformity—		
Pre-Cambrian (?).			100+	Massive and bedded gray quartzite at one locality, overlain unconformably by Moenkopi formation.



COLUMNAR SECTIONS OF SEDIMENTARY STRATA IN ARIZONA, COLORADO, NEW MEXICO, AND UTAH.

1, Permian (?) and above compiled from Dutton (High Plateaus of Utah); Pennsylvanian and below from Noble (Shinumo quadrangle). 2, Average of measured sections described in this paper. 3, Compiled from Cross; Dolores and above from La Plata folio, Cutler and below from Rico folio.

PRE-CAMBRIAN (?) QUARTZITE.

FIELD RELATIONS.

The oldest strata in the Navajo country are quartzites, probably of pre-Cambrian age. They occur at only one locality, an area about half a square mile in extent, traversed by the meandering canyon of Quartzite Creek. The canyon walls of dark-gray quartzite are 50 to 100 feet high and are set several hundred feet apart, except at the canyon mouth, where the creek enters Bonito Valley through a gateway 50 feet wide. Four sets of joints, trending N. 15° W., N. 55° W., N. 15° E., and N. 70° E., divide the rock into cubes, diamonds, and prisms, and joint planes with glistening surfaces outline the sheer walls and the even-treaded steps, 20 to 100 feet high. (See Pl. IV, *C*, p. 20.)

The beds below the quartzite are not exposed, but above it are the chocolate-colored and red arenaceous shales of the Moenkopi formation, fitting nicely into the depressions on the quartzite surface, which is made up of a series of flattened domes and rounded or rarely angular knobs exhibiting a maximum relief of 50 to 100 feet. The unconformity between quartzite and shale is readily traced. In a few places unweathered quartzite and unweathered shale are in direct contact; elsewhere the underlying rock is coated with a film of soil and is discolored, especially along joints, for several feet below the contact. The overlying shales are much wrinkled, minutely cross-bedded, and crowded into irregular bunches of disks that are concave upward—features suggestive of the shrinking of unconsolidated mud-cracked sediments. At the extreme northwest end of the area the upper surface of the mass is weathered to a depth of 4 feet, and pebbles of quartzite are embedded in overlying lumpy, imbricated mud shales. At the northeast edge of the area, 20 feet above the contact, is a 6-foot lens of conglomerate which probably represents talus from an ancient ridge. It consists of angular pebbles of quartzite (90 per cent), sandstone (5 per cent), and gray concretionary limestone (5 per cent), 1 to 4 inches in diameter. The quartzite mass in general appears to have been swept clean of débris before the shales were deposited, and it is probable that the muds and sands of the Moenkopi formation derived little or no material from the knob itself during the process of covering its summit.

STRUCTURE, TEXTURE, AND COMPOSITION.

For the most part the pre-Cambrian quartzite is massive, but stratification in beds 1 to 8 inches thick is not uncommon. The bedding planes are coated with the finest sand, including muscovite fragments, or with a layer of flattened pebbles of slate. Conglomerate lenses, usually an inch or less but rarely 1 to 2 feet thick, containing crushed pebbles of slate, phyllite, and weathered quartzite one-fourth inch to 2 inches long, are irregularly distributed. Angular cross-bedding is common, ripple marks are abundant, and a few mud cracks were seen. Hematite is disseminated through the mass, and ribbons of black, massive hematite one-sixteenth of an inch or less in thickness occur among the cross-bedding laminae and give to parts of the rock a banded appearance. Under the microscope the quartzite is found to consist of extremely irregular angular quartz grains bound together by a primary siliceous cement. A few well-rounded grains of zircon are also included. The hematite, which probably represents original magnetite, evidently accumulated during the time of deposition.

AGE AND CORRELATION.

So far as evidence from the immediate field is concerned the age of the rock in Quartzite Canyon may be determined only as pre-Moenkopi (Permian ?). The absence of features characteristic of the Carboniferous, Devonian, and Silurian sediments described as occurring elsewhere in the southwestern part of the United States suggests an age not later than the Cambrian. The descriptions of Cambrian (Tonto group ?) sediments on the borders of the Colorado Plateau province by Newberry,[1] Gilbert,[2] Marvine,[3] and Lee [4] are too meager in lithologic detail to permit comparison, and Walcott's description of the 550 feet of thin-bedded mottled limestones and green arenaceous, micaceous shales which constitute the Tonto of the Grand Canyon [5] can not be applied to the outcrops in Quartzite Canyon. It is

[1] Newberry, J. S., Geological report, in Ives, J. C., Report upon the Colorado River of the West, explored in 1857-58, pt. 3, pp. 42, 55, 1861.

[2] Gilbert, G. K., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, pp. 163, 164, 184-186, 521, 522, 1875.

[3] Marvine, A. R., idem, pp. 198-201.

[4] Lee, W. T., Geologic reconnaissance of a part of western Arizona: U. S. Geol. Survey Bull. 352, pp. 15, 19, 1908.

[5] Walcott, C. D., The Permian and other Paleozoic groups of the Kanab Valley, Ariz.: Am. Jour. Sci., 3d ser., vol. 20, pp. 221-225, 1880; Pre-Carboniferous strata in the Grand Canyon of the Colorado, Ariz.: Idem, vol. 26, pp. 437-442, 1883.

possible, however, that the quartzite preserves a record of Lower Cambrian time not elsewhere found in the Plateau province.

Of the two terranes of Algonkian age in Arizona, the younger (Chuar) is predominately shale and the older (Unkar) consists of a series of shales and of shaly and massive sandstone resting on a thin basal conglomerate and including over 1,500 feet of sandstone and quartzite. The strata described by Noble[1] as divisions *a* and *b* of the fourth member of the Unkar resemble the quartzite of the Navajo country in composition and texture, and the ripple marks and mud cracks noted by Walcott[2] are additional elements of similarity. The Vishnu schist (Archean) of the Shinumo area, as described by Noble, has nothing in common with the rocks at Quartzite Canyon.

In the absence of more distinctive criteria and of strata successively above and below, correlation with sediments of distant regions has little value, but I am inclined to believe that the pre-Cambrian quartzite dates from lower Algonkian time. If this conclusion is verified the absence from the Navajo country of the mile of Paleozoic sediments displayed in the walls of the Grand Canyon may mean that the entire Paleozoic record has been erased during one or more periods of pre-Permian erosion. That the knob of quartzite was buried by strata of considerable thickness is indicated by the regional metamorphism which the rock has undergone, but whether this cover was formed of strata removed during a pre-Cambrian epoch of erosion or included Tonto (Cambrian) or eo-Paleozoic sediments is indeterminable. If deposition was active in Silurian and Devonian time it has left no record in this area; and if strata of Pennsylvanian age once covered the quartzite the pre-Moenkopi erosion interval, elsewhere poorly marked, becomes here a stratigraphic feature of great significance. In my opinion the quartzite is a monadnock of a pre-Cambrian erosion surface—an elevated mass which outlived its contemporaries through Cambrian, Silurian, Devonian, and early Carboniferous time, only to be itself buried by the streams of Permian time. Because of its relatively shallow burial this knob was the first to reappear at the surface as a result of the widespread denudation that prevailed during the Tertiary and Quaternary periods.

[1] Noble, L. F., Contributions to the geology of the Grand Canyon, Ariz. The geology of the Shinumo area: Am. Jour. Sci., 4th ser., vol. 29, pp. 497-528, 1910.

[2] Walcott, C. D., Pre-Cambrian igneous rocks of the Unkar terrane, Grand Canyon of the Colorado, Ariz.: U. S. Geol. Survey Fourteenth Ann. Rept., pt. 2, pp. 511-512, 1894.

CARBONIFEROUS FORMATIONS.

PENNSYLVANIAN FORMATIONS.

LOCATION AND EXTENT.

Though strata of Pennsylvanian age floor the central part of the Colorado Plateau and attain magnificent proportions in the Grand Canyon of the Colorado, they are found at only two localities in the Navajo country—in the Little Colorado Valley and northward to Lees Ferry and in the San Juan Valley.

On Little Colorado River Pennsylvanian sediments were observed 1½ miles above Tolchico, where 20 feet of buff limestone forms a canyon wall about half a mile long. At Wolf Crossing a canyon 20 to 50 feet deep, trenching a low anticline, brings Pennsylvanian strata again to view, and except for slight interruptions they may be traced continuously from this point nearly to Black Falls. From the mouth of the Moenkopi to Colorado River Carboniferous beds form an increasing proportion of the wall of the Little Colorado Canyon, until 2,000 feet of strata are exposed. Marble Canyon of the Colorado and the trenchlike channels of Roundy Creek and other streams from the Echo Cliffs are likewise cut in Pennsylvanian formations.

In the San Juan Valley Pennsylvanian strata form the surface of two uplifts separated by 1½ miles of Permian (?) beds. In the Raplee anticline more than 1,000 feet of strata are exposed. Mitten Butte anticline, a flat dome of limestone, is bisected by the San Juan Canyon, whose walls are formed of Pennsylvanian strata. The area over which limestone is exposed at the surface in San Juan Valley has a width of 5 to 10 miles and a length measured along the river of about 35 miles. It is noteworthy that the uppermost bed of the Pennsylvanian in this locality is a layer of remarkably hard cherty limestone, which, though only 2 to 4 feet thick, forms a continuous cap for the hills and valleys. Only the master stream has been able to dissect it.

West and south of the Little Colorado Pennsylvanian limestone is exposed on the San

Francisco Plateau and on Mogollon Mesas, and near Fort Wingate it again appears on the flanks of Zuni Mountain. East of the reservation line rocks of Pennsylvanian age are exposed in the Rio Grande valley. North of the San Juan Pennsylvanian strata crop out in the Rico district of Colorado and in the canyon of the Colorado north of Hite, Utah. It thus seems probable that strata of Pennsylvanian age underlie the entire Navajo country, and that deep burial by Mesozoic sediments permits their exposure only at the summits of eroded domes and in the bottoms of profound canyons.

HISTORICAL SKETCH.

LITTLE COLORADO VALLEY.

Fossiliferous limestones from the vicinity of Tolchico were described by Marcou as Permian—the equivalent of the Magnesian limestone of England.[1] Newberry's studies of the limestone floor of San Francisco Plateau, including the localities visited by Marcou on Little Colorado River, lead to the conclusion that "we want the first shadow of proof of the Permian age of the rock, and it is plainly required of us to regard it as an integral portion of the Carboniferous series." [2] The collections made by Newberry include: *Productus occidentalis, P. costatoides, P. semireticulatus, Streptorhyncus umbraculum, S. pyramidalis, S. occidentalis, Athyris subtilita, Spirifer lineatus, Chonetes verneuiliana,* and *Rhynchonella uta.*

Studies of the Carboniferous by the geologists of the Wheeler Survey resulted in the well-known threefold division—Aubrey limestone, Aubrey sandstone, and Redwall limestone.[3] The Redwall limestone was doubtfully referred to the Lower Carboniferous, the Aubrey group to the Upper Carboniferous, and a few feet at the top to the Permo-Carboniferous.

Darton [4] has simplified the nomenclature of the Carboniferous by the introduction of the terms Kaibab limestone (formerly "Upper Aubrey" limestone), Coconino sandstone (formerly "Upper Aubrey" sandstone), and Supai formation (formerly "Lower Aubrey sandstone and shale").

[1] Marcou, Jules, U. S. Pacific R. R. Expl., vol. 3, pt. 4, p. 153, 1856.
[2] Newberry, J. S., Geological report, in Ives, J. C., Report upon the Colorado River of the West explored in 1857–58, pt. 3, p. 73, 1861.
[3] U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, pp. 176–180, 213, 1875.
[4] Darton, N. H., A reconnaissance of parts of northwestern New Mexico and northern Arizona: U. S. Geol. Survey Bull. 435, 1910.

The limestone outcrops bordering Little Colorado River on the west were assigned by Robinson [5] to the Kaibab formation of the Pennsylvanian epoch, from fossil evidence supplied by Meek and Frech.

During the course of my field work (1909–1913) the Pennsylvanian of the Little Colorado Valley between Tolchico and Marble Canyon was studied with the assistance of Messrs. Heald and Pogue. I have followed a conservative course in assigning the Kaibab formation to the Pennsylvanian. The evidence, however, is unsatisfactory, and fuller investigation may result in placing all or part of the Kaibab among Permian formations.

SAN JUAN VALLEY.

In 1909 attention was called to the existence of Pennsylvanian strata in the canyon of San Juan River near Goodridge, Utah.[6] This field was again visited in 1910, and an area including a large part of the Carboniferous was studied in detail by Woodruff.[7] In the absence of satisfactory data for correlation with the Hermosa formation of Colorado or with the Aubrey group of Arizona, the term Goodridge formation was introduced to designate the strata measured at Honaker trail.

PHYSICAL FEATURES OF THE KAIBAB LIMESTONE OF THE AUBREY GROUP.

Five miles above the mouth of the Little Colorado Mr. Pogue found exposed 2,100 feet of Carboniferous strata, including the Redwall limestone and the Supai formation; 965 feet of combined Coconino sandstone and Kaibab limestone were measured. Of these formations only the Kaibab limestone was mapped. At other localities studied along the Little Colorado only the Kaibab limestone is present. The Kaibab strata rarely exceed 5 feet and in places are less than 6 inches in thickness. (See Pl. IV, *B*.) Beds 5 to 10 feet thick were measured at Wolf Crossing, at Coconino Point, and near Colorado River, and a massive stratum 30 feet thick was noted below Box Spring. On the other hand, strata 3 to 5 inches thick are not uncommon.

[5] H. H. Robinson, The San Franciscan volcanic field, Ariz.: U. S. Geol. Survey Prof. Paper 76, pp. 24-25, 1913.
[6] Gregory, H. E., The San Juan oil field, San Juan County, Utah: U. S. Geol. Survey Bull. 431, pp. 11-15, 1911.
[7] Woodruff, E. G., Geology of the San Juan oil field, Utah: U. S. Geol. Survey Bull. 471, pp. 76-104, 1912.

In composition the rock ranges between an arenaceous limestone and a calcareous sandstone. A variable amount of dolomite is present, but in none of the specimens examined is the proportion of this mineral sufficient to justify the term magnesium.[1] In addition to the disseminated grains of quartz sand, silica occurs as nodules 1 to 2 inches in diameter, as small, flat lenses, some of which are reddish, and as quartz geodes. Calcite in irregular pockets and tiny geodes decomposes in such a manner as to give the limestone a pitted surface. Fragmentary fossils of sponges in the chert and of brachiopods and other invertebrates in the more calcareous portions are characteristic features. On weathered surfaces the rock is prevailingly buff, though fresher material is characteristically gray or even white. The marine origin of the Kaibab is evident, but its wide diversity in composition suggests that conditions of deposition were not uniform and that the calcareous muds were laid down on the outer margin of the littoral zone rather than in seas of great depth.

PHYSICAL FEATURES OF THE GOODRIDGE FORMATION.

The Carboniferous beds exposed in the San Juan oil field are lithologically unlike those in the Little Colorado Valley. In the 1,541 feet of strata studied by Woodruff [2] there are 639 feet of sandstone and sandy shale, including three beds more than 50 feet thick. (See Pl. IV, *A*.) The upper half (816 feet) of the section at Honaker trail contains 585 feet of arenaceous sediments; the lower half (725 feet) contains 652 feet of limestone, 493 feet of which is represented by six beds. This predominance of limestone in the lower beds and of sandstone in the upper beds is characteristic of all localities visited in the San Juan Valley.

The limestones of the Honaker trail section are prevailingly drab, with shades of blue, blue-gray, gray, purple-gray, and pink, but the buffs of the Kaibab are absent. Most of the beds are massive and consist of hard crystalline rock in which nodules of jasper and gray and jet-black chert are common. Between Goodridge and the Honaker trail a 2-inch bed of black chert was traced for 300 feet, and a bed at a lower horizon was found to contain masses of jasper ranging in diameter from 3 inches to 3 feet. In several beds the limestone is nodular near its upper and lower surfaces, and at one point a 10-foot bed of conglomerate composed of limestone pebbles one-eighth inch to 1 inch in diameter was noted. Thin limestone lenses in the shales and shale lenses in limestone were observed at several localities. The density and continuity of some of the beds may be judged by the fact that a 2-foot stratum of limestone forms an impervious cap for the "Goodridge oil sand" throughout the San Juan oil field. Fossils are widely distributed within the beds and in places constitute veritable shell heaps.

About 50 per cent of the shales of the San Juan sections are red, brown, and pink; four thin beds are black; one is green; the remainder are gray or drab. The red shales are arenaceous, are cemented by lime, and differ little from the thin-bedded red sandstones. The black shales are argillaceous and arenaceous and thinly foliated. Two layers contain carbonaceous material, and two may properly be termed bituminous shales.

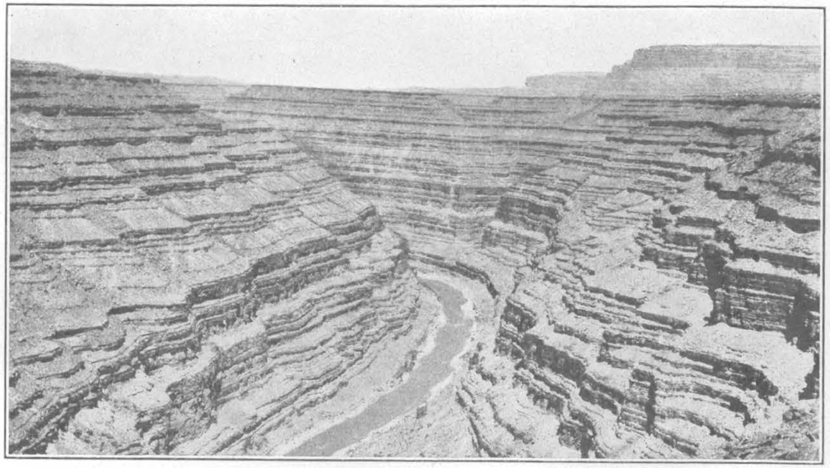
The sandstones are both massive and thin-bedded. All are fine grained, so far as observed, and the rounded quartz fragments are cemented by lime. The predominating color is gray, but some beds in the upper third of the canyon wall are pink, and some near the bottom are greenish gray. The sandstones containing oil consist of clear quartz grains cemented by lime, the removal of which has produced a porosity favorable for the accumulation of the widely disseminated petroleum. (See p. 145.) Portions of several strata are inconspicuously cross-bedded, and one 8-foot bed of yellow-white shaly sandstone, 170 feet above the river bed, is strongly cross-bedded throughout.

Marine invertebrates were obtained from limestone, sandstone, and shale beds from top to bottom of the canyon wall. None of the species obtained demand a deep-water habitat, and the presence of limestone conglomerate, cross-bedded sandstone, and carbonaceous shale, the thinning of the sandstone along the strike, and the bunching of fossils into shell heaps point to deposition within the littoral zone. Moreover, that certain strata may have been exposed to the air is suggested by planes of local unconformity at two horizons.[3]

[1] For an analysis of this rock by F. N. Guild, see Robinson, H. H., op. cit., p. 24.

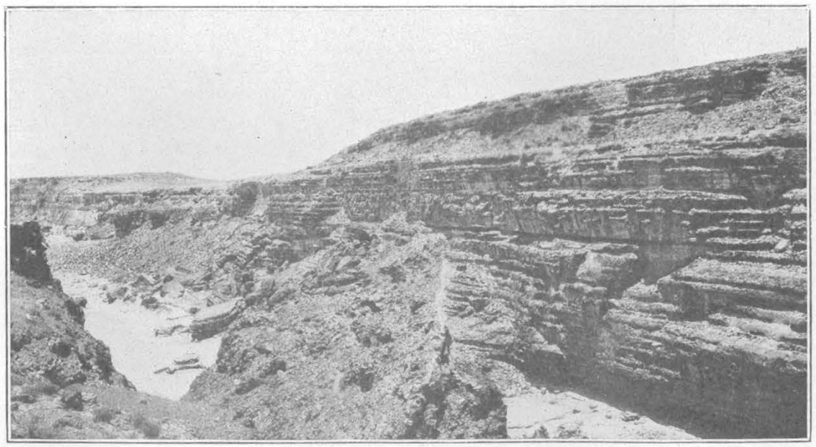
[2] Woodruff, E. G., Geology of the San Juan oil field, Utah: U. S. Geol. Survey Bull. 471, pp. 76-81, 1912.

[3] Gregory, H. E., op. cit., p. 15. Woodruff, E. G., op. cit., p. 78.



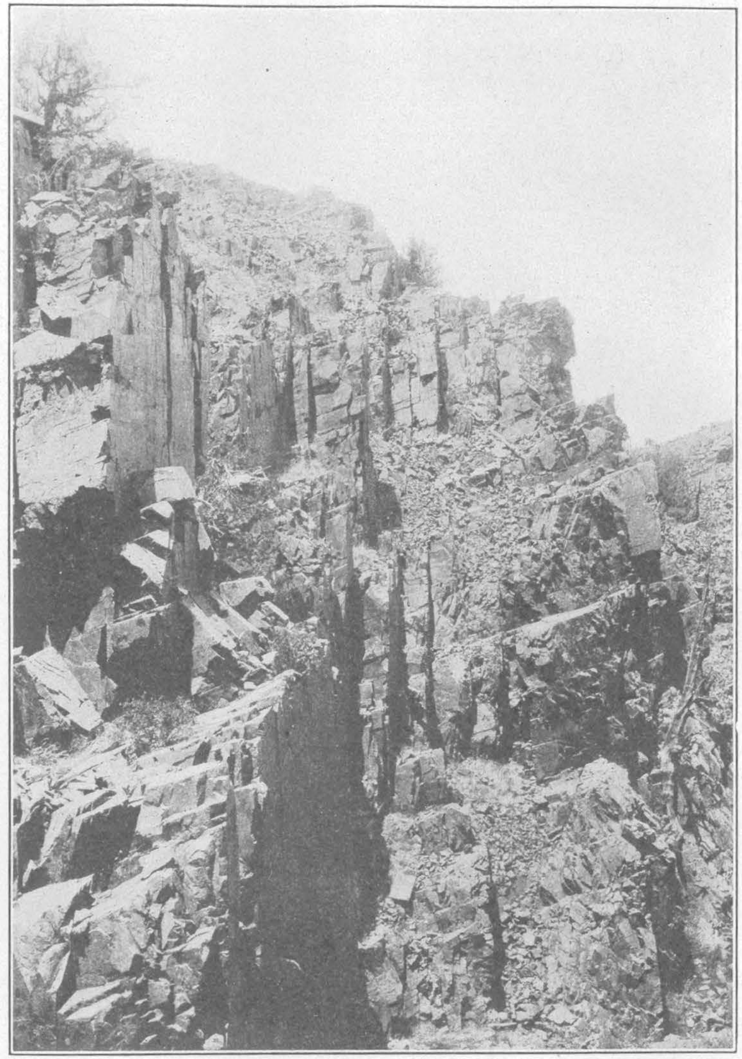
A. WALL OF CANYON OF SAN JUAN RIVER NEAR HONAKER TRAIL, UTAH.

Strata of Goodridge (Pennsylvanian) formation. Photograph by E. G. Woodruff.



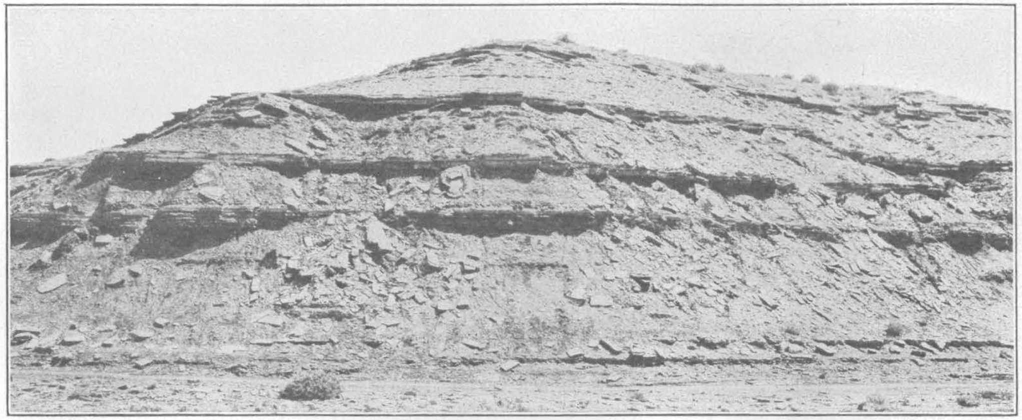
B. WALL OF LITTLE COLORADO CANYON BELOW GRAND FALLS, ARIZ.

Composed of Kaibab limestone.



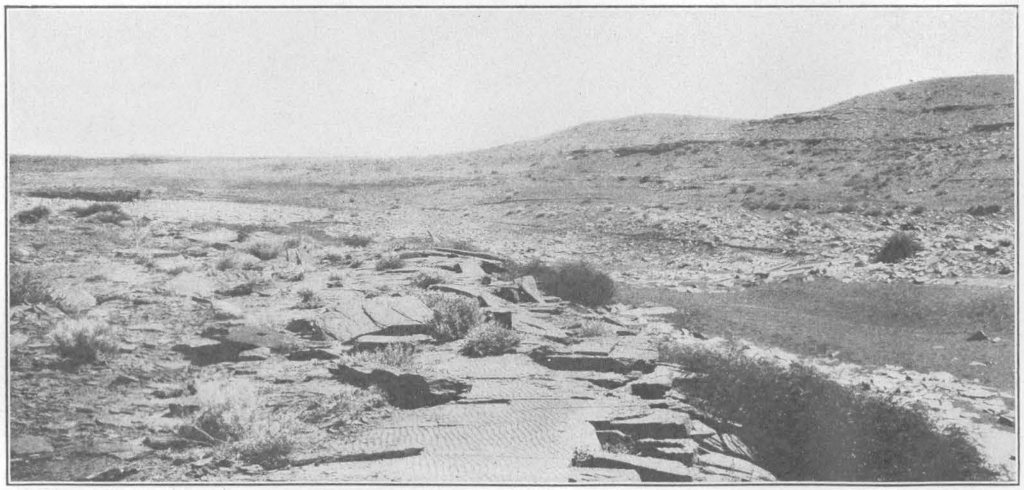
C. WALL OF QUARTZITE CANYON, ARIZ.

Showing structure of pre-Cambrian quartzite. Photograph by K. C. Heald.



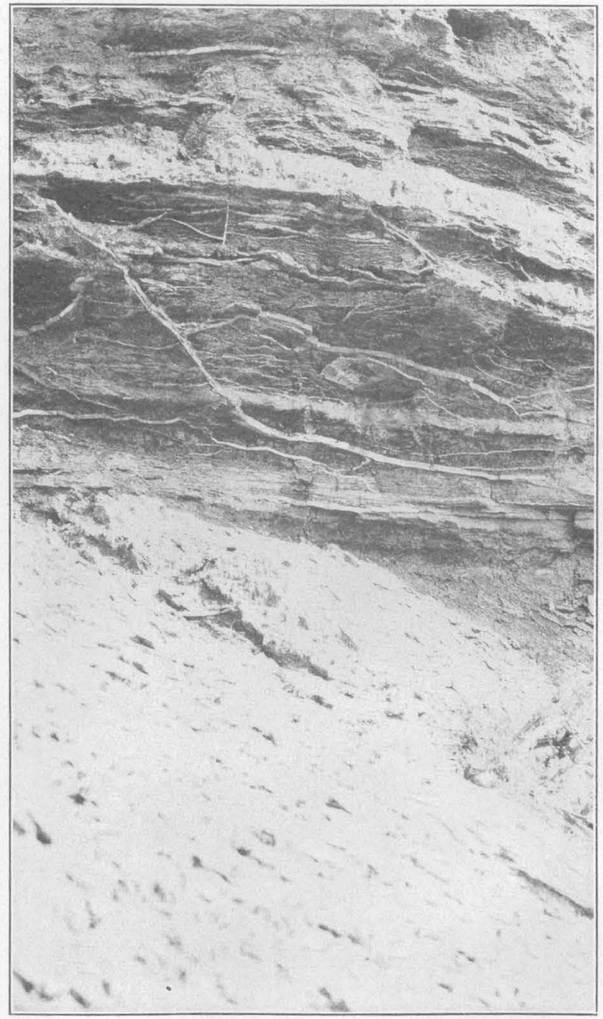
A. BUTTE NEAR LEUPP, ARIZ.

Composed of strata in middle part of Moenkopi formation.



B. VIEW NEAR MOUTH OF CANYON DIABLO, ARIZ.

Moenkopi strata on both sides of the stream. Ripple marks in foreground are developed on many surfaces.



C. DETAIL OF CLIFF NEAR HOLBROOK, ARIZ.

Showing seams of gypsum.

PENNSYLVANIAN-PERMIAN (?) CONTACT.

Marcou[1] found the "Magnesian limestone [Kaibab ?] in concordant stratification with the new Red" [Moenkopi ?]. Newberry[2] observed that the limestone passed under beds of red shale and sandstone which are conformable with it. Gilbert[3] noted that at the mouth of the Paria the "cherty limestone (Upper Aubrey) [Kaibab] is unevenly worn, and in its depressions are beds of conglomerate, the pebbles of which are derived from the chert of the limestone itself." Walcott[4] found similar relations in Kanab Valley. In the Zuni Mountains Dutton[5] found the Permian well separated lithologically from the Pennsylvanian below. Ward[6] states that the Moenkopi rests in marked unconformity upon the underlying Paleozoic rocks ("Upper Aubrey"); and Robinson[7] speaks of an erosional unconformity at the base of the Moenkopi. Occasion was taken to study the contact of Pennsylvanian and Permian (?) strata in the Little Colorado and San Juan valleys. At all places examined in the Little Colorado Valley it was found to be marked by a thin bed of conglomerate. About 1½ miles south of Tolchico the upper surface of cherty Kaibab limestone exhibits a relief of 1 to 3 feet in an area of half an acre, and into the irregularities of the firm buff limestone are fitted the lower parts of a conglomerate consisting of angular pebbles of massive limestone, calcareous concretions, and angular and subangular pebbles of red, black, and gray quartz set in a matrix of lime and quartz sand. The pebbles are one sixty-fourth to one-fourth inch in diameter, and among them are lozenges of buff and red calcareous clay one-half inch to 1 inch long. The conglomerate is arranged in overlapping lenses, all of which exhibit cross-bedding. At Wolf Crossing this conglomerate bed, which rests in shallow pockets in the Kaibab but is conformable with shale above, is 3 feet thick and contains concretionary limestone pebbles an inch or more in diameter. At Grand Falls the slightly wavy surface of the Kaibab is overlain by 4 feet of hard, thin-bedded buff-colored concrete composed of limestone pebbles, the largest 2 inches in diameter (70 per cent), and quartz the size of millet seed (30 per cent). Below the mouth of the Moenkopi Mr. Pogue found 10 feet of this conglomerate "including small subangular quartzes and shale pellets with a calcareous cement." The beds at this locality are 1 foot thick near the bottom and become thinner toward the top until they pass by unappreciable gradations first into gray and then into red shales. At all places where the contact was studied the overlying arenaceous and calcareous shale and shaly sandstone exhibit irregular, imbricated partings marked by ripples, mud cracks, and sun-dried surfaces. Much of the rock is flaky mud silt speckled with minute fragments of muscovite. The coarser material exhibits cross-bedding, and worm casts (?) and plant impressions (?) were observed at Grand Falls. The change in color from buff limestone to red, brown, or chocolate-colored shales takes place both at the top of the conglomerate and within that stratum.

On the San Juan the transition from the fossiliferous limestone to the overlying red-brown calcareous shales and sandstones is not so abrupt as in the Little Colorado Valley, and red beds occur below as well as above the top stratum of the Goodridge formation. No undisputed evidence of unconformable relations between the Pennsylvanian and Permian (?) was obtained at this locality. The top of the Goodridge formation is, however, in places marked by limestone conglomerate, and the lowest Moenkopi beds are nodular and flaky and contain 4 to 10 feet of limestone conglomerate consisting of rounded and angular, flattened fragments of gray, blue, and black limestone and rare quartz. The pebbles range in diameter from one sixty-fourth inch to 3 inches, but those larger than 2 inches are uncommon.

The evidence suggests that sediments of nearly pure limsetone forming the middle Kaibab and the lower part of the Goodridge formation became increasingly more arenaceous as the water became shoaler, until the sediments were exposed at the surface. The conglomerate probably represents erosion conditioned by an arid climate, the evidence of which in the lowest Moenkopi beds appears to be fairly satisfactory

[1] Marcou, Jules, op. cit., p. 153.
[2] Newberry, J. S., op. cit. (Ives expedition), p. 75.
[3] Gilbert, G. K., Geology of the Henry Mountains, p. 8, 1880.
[4] Walcott, C. D., The Permian and other Paleozoic groups of the Kanab Valley, Ariz.: Am. Jour. Sci., 3d ser., vol. 20, pp. 221-225, 1880.
[5] Dutton, C. E., Mount Taylor and the Zuñi Plateau: U. S. Geol. Survey Sixth Ann. Rept., p. 135, 1885.
[6] Ward, L. F., Status of the Mesozoic floras of the United States: U. S. Geol. Survey Mon. 48, p. 19, 1905.
[7] Robinson, H. H., The San Franciscan volcanic field, Ariz.: U. S. Geol. Survey Prof. Paper 76, p. 24, 1913.

AGE AND CORRELATION.

Sections of Pennsylvanian strata measured with sufficient detail to permit comparison have been published for the Grand Canyon area,[1] the Mogollon Mesa,[2] the San Juan Mountains,[3] and the San Juan oil field.[4] These sections show unexplained but significant differences in sequence and lithologic character, and the study of the fossils collected has so far resulted in showing only a broad equivalence of the upper Carboniferous faunas from various localities in the Plateau province.

In two small collections from the wall of the Little Colorado 5 miles above its mouth G. H. Girty [5] found "nothing determinable save a species of *Bakewellia* or *Pteria* resembling *Bakewellia parva* and one, possibly two species of *Schizodus?*, an *Allerisma?*, *Pleurophorus?*, and *Euphemus*." He says: "I have little doubt that these collections come from what used to be called the Aubrey group, and their fauna and lithology are those of the calcareous sandstone which I have supposed to belong to the Kaibab limestone." The rock from which these fossils were collected is described by Mr. Pogue in the following terms: "Light-gray, very fine grained dense, firm, hard calcareous sandstone, weathering to a buff or dull gray. Is abundantly filled with siliceous geodic concretions, the largest 1 inch in diameter, and many containing minute quartz crystals. Mostly in beds 5 to 10 feet thick, the lower portion prominently cross-bedded. Thickness 965 feet."

Fossils collected in 1909 from the San Juan River canyon below Goodridge were assigned by Schuchert to the Pennsylvanian, "not so low as the Pottsville nor to the horizon near the top of the series." [6] A much more complete assemblage of faunas from this locality is discussed by Girty,[7] who concludes that "these collections are to be compared rather with those of the San Juan region of Colorado (Rico, Hermosa) than with those of the Grand Canyon section (Kaibab limestone)." The strata "represent the upper part of the typical Redwall limestone," the lower part of which is Mississippian.

So far as lithologic features are concerned the Carboniferous strata of the Grand Canyon section are not duplicated farther east. The massive Redwall limestone loses its identity, being replaced in southeastern Utah and southwestern Colorado by beds that indicate shallow water if not occasional exposure to the air, and Dutton's studies [8] indicate that land occupied northwestern New Mexico at this time. The Mississippian sea apparently extended south and west of the valley occupied by the Puerco and Little Colorado in Arizona. The Supai formation may be represented by beds in the Goodridge formation, but typical sediments of Coconino time are lacking northeast of the Little Colorado, and the lithologic features of the Kaibab limestone are not duplicated by strata of the Goodridge, Rico, or Hermosa formations along the San Juan and its tributaries. The Kaibab limestone is probably also absent from the Zuni Mountains, where the highest Carboniferous beds consist of 300 to 350 feet of sandstone overlying 100 to 150 feet of blue-gray, limestone.[9] Dutton's descriptions,[10] however appear to indicate that strata equivalent in age to both Kaibab and Coconino are included in 400 feet of undifferentiated "Upper Aubrey." It seems reasonable to suppose that land existed in the Navajo country near the close of Pennsylvanian time.

PERMIAN (?) FORMATIONS.

HISTORICAL SKETCH.

The limestone beds in the Little Colorado Valley, ascribed by Marcou [11] to the Permian, are, as shown by Newberry,[12] in part, at least, Pennsylvanian (Kaibab ?). Newberry distinguished a series of "deep blood-red soft sandstones," overlain by "heavier beds of soft red argillaceous shales with layers of red and green foliated ripple-marked fine-grained micaceous

[1] Newberry, J. S. (section in canyon of Cascade Creek [probably Cataract Creek]), op. cit., p. 62. Gilbert, G. K. (Kanab Creek section), U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, pp. 161-162, 1875. Noble, L. F. (section near Fossil Mountain, Coconino Plateau), U. S. Geol. Survey Bull. 549, pp. 70-71, 1914.

[2] Gilbert, G. K. (sections on Carrizo Creek and Camp Apache), op. cit., p. 164.

[3] Cross, Whitman, U. S. Geol. Survey Geol. Atlas, Engineer Mountain (No. 171), Needle Mountains (No. 131), Ouray (No. 153), and Rico (No. 130) folios.

[4] Gregory, H. E., The San Juan oil field, San Juan County, Utah: U. S. Geol. Survey Bull. 431, pp. 13-15, 1911. Woodruff, E. G., Geology of the San Juan oil field, Utah: U. S. Geol. Survey Bull. 471, pp. 77-78, 1912.

[5] Letter to T. W. Stanton, June 11, 1914.

[6] U. S. Geol. Survey Bull. 431, p. 15, 1910.

[7] Woodruff, E. G., U. S. Geol. Survey Bull. 471, p. 83, 1912.

[8] Dutton, C. E., Mount Taylor and the Zuñi Plateau: U. S. Geol. Survey Sixth Ann. Rept., p. 132, 1885.

[9] Howell, E. E., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 287, 1875.

[10] Dutton, C. E., op. cit., p. 133.

[11] Marcou, Jules, op. cit., p. 170.

[12] Newberry, J. S., op. cit., p. 73.

sandstones" and including near Sunset Crossing (Winslow) 20 feet of conglomerate.[1] These beds Newberry called "Red sandstone formation" or "Saliferous series" and compared with the Triassic of Connecticut and New Jersey. Marcou considered them the equivalent of the Bunter Sandstein. According to my interpretation, the group discussed by these explorers includes the Moenkopi formation (Permian ?), the Shinarump conglomerate (Triassic), and part of the Chinle formation (Triassic). That the Permian (?) is represented in the series was shown by fossils collected by Marvine[2] south of Sunset Tanks and by Gilbert[3] on Kanab Creek. Walcott[4] called attention to the existence of 855 feet of Permian in Kanab Valley and furnished the basis for dividing the strata assigned to this series into an upper (710 feet) and a lower group (145 feet).

In mapping the geology of the Navajo country it was found that strata of Permian (?) age are more widely extended than had previously been supposed. They occur not only in the Little Colorado Valley but along the San Juan and at a number of localities on Defiance Plateau. In the western part of the reservation they mark the beginning of the red beds and are easily distinguished as a whole from the underlying Kaibab by abrupt changes in color and in composition.

Two Permian (?) formations are recognized—the Moenkopi, which presents many features common to the Permian of the Southwestern States previously described, and the De Chelly sandstone, which, so far as known, is not represented in other areas.

MOENKOPI FORMATION.

TYPE LOCALITY.

The term Moenkopi formation was applied by Ward to that portion of the Mesozoic beds of the Colorado Plateau lying below the Shinarump group of Powell.[5] The name is taken from Moenkopi[6] Wash (Hopi=running water), at the mouth of which these beds were first found "in their full development." The original description of the Moenkopi,[7] apparently generalized for the entire Little Colorado Valley, is as follows:

> These [beds] occupy the lowest portion of the group [Mesozoic strata], having a maximum observed thickness of between 600 and 700 feet. They present several distinct phases, but the greatest part of them consists of dark-reddish brown, soft, laminated, argillaceous shales, nearly destitute of silica, highly charged with salt and gypsum, tending on exposure to assume the character of nearly homogeneous marls. * * * The gypsum often forms thin sheets which appear as fine white lines and which do not follow the planes of stratification but cross the beds irregularly and also cross one another, giving the exposures a peculiar striped appearance.
>
> Between these beds of shale there occurs, usually at more than one horizon, brown sandstones. These are more or less argillaceous * * * These sandstone ledges, which are very uniform in composition, sometimes have a thickness of 100 feet or more, though such heavy beds are usually interrupted by several layers of the shale.
>
> Toward the lower part of the Moenkopi beds the shales gradually become calcareous, and there is in nearly all good exposures a horizon of white, impure limestone, well laminated in its central portion but becoming very thin and hard below and finally passing either into the typical shale or into homogeneous marls. The extreme upper and also the extreme lower portions of the Moenkopi beds always consist, so far as observed, of the typical dark-brown argillaceous shale. * * * It is very probable that the lower portion of the Moenkopi beds belongs to the Permian.

Placed in tabular form the sequence of the strata described by Ward is shown in the following section:

Section of Moenkopi formation in the Little Colorado Valley.

[Compiled from descriptions by Ward.[8]]

	Feet.
"Lithodendron member of the Shinarump formation."	
1. Shale, dark chocolate-brown, argillaceous, devoid of grit and highly charged with salt and gypsum	200
2. Sandstone, dark brown, argillaceous, soft	100
3. Shale, dark brown, argillaceous, highly saliferous; includes gypsum layers; becomes calcareous below	200
4. Shale, mostly white, calcareous	100
5. Shale, brown, argillaceous, soft; contains salt and gypsum	100
Carboniferous limestone.	
	700

[1] Newberry, J. S., op. cit.

[2] Marvine, A. R., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 213, 1875.

[3] Gilbert, G .K., idem, p. 177.

[4] Walcott, C. D., The Permian and other Paleozoic groups of the Kanab Valley, Ariz.: Am. Jour. Sci., 3d ser., vol. 20, pp. 221-225, 1880.

[5] Powell, J. W., Report on the geology of the eastern portion of the Uinta Mountains, pp. 68-69, U. S. Geol. and Geog. Survey Terr., 2d div., 1876.

[6] The spelling Moenkopi has been adopted by the United States Geographic Board in place of the older form Moencopie.

[7] Ward, L. F., Status of the Mesozoic floras of the United States: U. S. Geol. Survey Mon. 48, pt. 1, pp. 18-19, 1905.

[8] Ward, L. F., Geology of the Little Colorado Valley: Am. Jour. Sci., 4th ser., vol. 12, pp. 401-413, 1901; Status of the Mesozoic floras of the United States: U. S. Geol. Survey Mon. 48, pt. 1, pp. 18-19, 37-46, 1905.

A careful study of Ward's papers and of his field notebooks disclosed no measured sections, but the localities indicated are so faithfully described that no difficulty was experienced in finding the "type locality." In the absence of detailed sections of the Moenkopi it seemed highly desirable to find a place where the entire Permian (?) portion of the red beds was displayed. A search was accordingly made for this coveted section, and after wearily tramping along the dry hot floor of the Little Colorado and later wading its muddy flood waters, Mr. Heald and I discovered a spot where the canyon wall included the entire Permian (?) series, with the Kaibab limestone below and the Shinarump conglomerate above. It is proposed to substitute this section for the more generalized descriptions of Ward and to supplement the record by descriptions from other localities.

Section of Moenkopi formation in wall of Little Colorado Canyon, about 5 miles below Tanner Crossing, Ariz.[1]

[Strike N. 15° W.; dip 2° NE.]

	Feet.
Shinarump conglomerate; gray and mottled, cross-bedded; pebbles of quartz, quartzite, calcareous shale, and petrified wood.	
Unconformity; marked by sudden transition of shale to conglomerate and by wavy, irregular contact, including pockets in shale filled by sandstone and conglomerate.	
1. Shale, red; bleached white at top, arenaceous and argillaceous, compact, hard, of microscopic fineness; weathers into rounded disks.	3
2. Shale, red-brown and gray banded, argillaceous, lenticular, with lenses of sandstone at bottom.	25
3. Shale, red-brown, argillaceous, and thin cross-bedded sandstones; abundant plant impressions, like grass or stems of reeds arranged in masses; contacts not exposed	16
4. Sandstone, chocolate-colored to red, calcareous, extremely fine	3
5. Shale, brown and maroon, arenaceous and calcareous, ripple marked and mud cracked	2
6. Sandstone, red-brown, massive, extremely fine grained, micaceous	2
7. Shale, banded chocolate-colored and red-gray, arenaceous, becoming argillaceous at the top; tiny veins of gypsum	11
8. Sandstone, red-brown, with white band at top, composed of extremely fine quartz grains with flakes of muscovite; plant impressions	3
9. Shale like No. 27	8
10. Sandstone, chocolate-colored, fine grained, micaceous, thin bedded at top; forms bench.	6
11. Shales, banded red of various shades and gray-green, arenaceous, argillaceous, calcareous	26
12. Sandstone, thin bedded, ripple marked	1
13. Shale, red-brown, with streaks of purple and green-gray and blotches of white; includes lenses of sandstone; bedding planes sun-baked	20
14. Sandstone, red brown, thin bedded, cross-bedded, marked by ripples, mud cracks, and worm casts; muscovite on bedding planes; plant impressions on lumpy uneven surfaces include striated stems and radiating groups	2
15. Shale, banded chocolate-color, red, gray, and green, arenaceous and calcareous at bottom, argillaceous at top, ripple marked, mud cracked, lenticular	10
16. Sandstone like No. 14	2
17. Shale like No. 15	12
18. Sandstone in 3-inch beds, wavy, irregular, lenticular, cross-bedded, ripple marked	4
19. Shale, red-brown, arenaceous, calcareous, banded and lenticular; shows worm casts, sun-baked surfaces, and impressions of plants	7
20. Sandstone, red-brown, thin bedded lenticular, with bands of argillaceous and calcareous shale; mud cracked, and ripple marked; plant impressions	2
21. Shale, banded dark red, light red, and purple, with elliptical blotches of green-white, yellow-green, and ash-gray, calcareous, argillaceous, and arenaceous	18
22. Sandstone like No. 20	2
23. Shale like No. 21; bands of color one-half inch to 3 inches thick	5
24. Sandstone like No. 20	2
25. Shale like No. 21	2
26. Sandstone, chocolate-colored, highly calcareous, with scattered limestone pebbles	3
27. Shales, chocolate-colored to red, with gray and lavender lenses; arenaceous, imbricated, ripple marked; 15 feet from the bottom is a 6-inch bed of sandstone, and thin sandstone lenses occur throughout; the top 10 feet is dark-red argillaceous shale in regular beds traversed by veins of gypsum, probably of secondary origin	40
28. Sandstone, chocolate-red, with streaks of maroon and purple; fine-grained quartz with calcareous cement; cross-bedding both angular and tangential; fine to medium grained; size of grain varies with each lamina. Near middle of bed are lenses of conglomerate, 2 inches to 12 feet wide, 6 inches to 100 feet long, highly irregular in shape, and composed of chunks and slabs of argillaceous shale, sandy shale, and sandstone; muscovite abundant on bedding plane; forms vertical cliff	52
29. Shales, chocolate-colored with white bands; arenaceous and micaceous strata, thin as cardboard or 2 to 3 inches thick; show ripple-marked, mud-cracked, sun-baked surfaces, curled disks, tiny folds, and faults	100
Unconformity.	
Kaibab limestone; beds 2 to 6 feet thick; buff; fossiliferous; cavities filled with calcite.	
	389

[1] This section in modified form has appeared in Am. Jour. Sci., 4th ser., vol. 38, pp. 497-498, 1914.

The foregoing analysis of the Moenkopi beds is based on two sections about 300 feet apart, measured with the assistance of K. C. Heald The bedding is very irregular throughout Strata of shale and sandstone appear and disappear along the strike, and individual laminae within the beds are markedly discontinuous. Arenaceous beds prevail, typical clay shales are very rare, and pure limestone is absent. Mr. Heald noted that the strata became increasingly calcareous upward until bed No. 3 is reached. Gypsum in tiny horizontal and vertical seams is common. A large part of it, perhaps all, is secondary. Several small unconformities were noted but no hiatus that necessarily involved a long period of corrasion or of weathering. Part of the color banding appears to be genetically related to conditions of deposition; much of it is better explained as due to leaching by ground water. Frequent exposure to the atmosphere as the Moenkopi beds were forming is indicated by the almost universal presence of sun-baked surfaces and ripple marks. Plant impressions are common and appear to represent several different species. The fragments which could be brought to camp belong to a species resembling *Walchia gracilis*.

MOENKOPI OF THE LITTLE COLORADO VALLEY.

Topographic expression.

As displayed in the Little Colorado Valley, the Moenkopi forms banded buttes or narrow terraced mesas scattered as outliers over the Pennsylvanian limestone floor or developed within the formation itself. The extreme irregularity in composition and attitude of beds has given rise to fantastic erosion forms—"hoodoos," "stone babies," fragmental shells, and irregular cavernous structures lined with honeycombed rock. Vigorous wind abrasion has added many picturesque details. The sandstone beds undermined by the erosion of less resistant strata break into lenticular or flat blocks 10 feet or more in diameter and cover the mesa sides with a slab talus which gives Moenkopi erosion remnants a unique appearance. North and east of Box Springs gypsiferous amorphous shale or "marl" weathers into badland domes with ash-gray, maroon, black, and light-red colors.

Stratigraphy.

Except in the locality at which the section given on page 24 was measured, the full thickness of the Moenkopi is not exposed along Little Colorado River, but the formation was examined and a number of incomplete sections were obtained in the 125-mile stretch from Government Bridge to Adamana. At the Warner ranch, 4 miles above Tanner Crossing, 30 feet of Moenkopi is exposed immediately beneath a conglomerate cap. The strata comprise 24 feet of ripple-marked, sun-baked imbricated chocolate-red shales, followed upward by 6 feet of chocolate-colored sandstone broken by shale partings and lenses of red-clay pellets into three to five irregular beds. Immediately at the contact with the overlying Shinarump conglomerate the shale is sandy and muscovitic and assumes a gray and purple tone, streaked and blotched with white. Mud cracks are well displayed in it, and impressions of twigs, branches, and leaves are common. Between Black Point and Black Falls the Moenkopi buttes consist of alternate bands of light-red and dark-red shales and shaly sandstone interbedded with thin layers of gypsum and capped by a 20-foot bed of light-red sandstone. At Grand Falls the following section was measured, with the assistance of Mr. Heald:

Section of the lower part of the Moenkopi formation at Grand Falls, Ariz.

[Dip, 1° E.]

	Ft.	in.
1. Sandstone; microscopic grains of quartz with calcareous cement; one massive bed......	4	0
2. Shales, arenaceous, paper-thin, interrupted by beds of sandstone one-half inch to 1 inch thick, like No. 1....................	4	0
3. Sandstone like No. 1.......................		8
4. Arenaceous shales, shaly sandstones, and arenaceous limestone composed of grains of quartz with some calcite fragments and with mica on bedding planes; calcareous cement; in beds one sixty-fourth inch to 2 inches thick; some lenses of larger quartz and limestone pebbles	5	0
5. Sandstone like No. 1.......................		6
6. Shales like No. 2..........................	5	0
7. Sandstones like No. 1......................		6
8. Shales and argillaceous sandstones, in beds less than 1 inch thick, like No. 4; shale thinnest and best developed at the base..	16	0
Unconformity.		

	Ft.	in.
9. Conglomerate, buff, composed of flattened pebbles of limestone, the largest 2 inches in length (70 per cent), and minute grains of quartz (30 per cent)		6
Unconformity.		
10. Kaibab limestone, buff, fossiliferous, in beds 6 inches to 2 feet thick; 130 feet exposed in the canyon wall.		
	36	2

All the beds in the foregoing section thicken and thin or disappear along the strike. Some of the sandstone strata, imbricated and cross-bedded at high angles, include chunks of clay at the base. Mud cracks are prominent in the shale and occur also in the sandstone. Sun-baked surfaces are common, and even, regular, or lozenge-shaped ripple marks are abundantly displayed. The joint cracks are occupied by calcite and by gypsum. Short curved or straight sand cylinders (worm casts and borings?), plant impressions, and footprints (?) were observed.

Near the mouth of Canyon Diablo 40 feet of the middle Moenkopi is exposed as chocolate-colored shales in beds less than an inch thick, alternating with beds of red sandstone 4 to 6 inches thick, and including a 10-foot bed of cream-white sandstone not elsewhere noted. (See Pl. V, *A*, p. 21.) The sandstone slabs are beautifully ripple marked, twenty or thirty beds, one above another, being marked on their upper surfaces by choppy or parallel waves, and many of them on their under surfaces by mud cracks and flattened mud fragments. (See Pl. V, *B*.)

At Wolf Crossing and at Tolchico the lowest beds of the Moenkopi are exposed, and their character is indicated in the following section:

Section of Moenkopi formation 1½ miles east of Tolchico, Ariz.

	Feet.
1. Sandstones and sandy shales in thin, uneven, overlapping beds, with ripple-marked, sun-baked, mud-cracked surfaces; forms caps of intricately eroded buttes	10+
2. Sandstone, dark to light red, massive at the base, composed of quartz with muscovite grains united by calcareous cement and containing lenses of clay and lime fragments; surface of stratum mud cracked; rock used for building	10
3. Shales and thin-bedded sandstones, dark chocolate-red, composed of quartz with abundant muscovite grains; calcareous cement. The overlapping imbricated flasky beds, particularly the paper-thin shale layers, reveal ripple-marked, sun-baked, mud-cracked surfaces and pockets filled with wind-blown (?) sand	15
Unconformity.	
Limestone (Kaibab), buff, fossiliferous.	
	35+

The top of the Moenkopi at Tucker Spring consists of 20 feet of dark-red, green, and ash-colored sandy shale, in irregular beds and overlapping lenses. These shales are traversed along joint and bedding planes by bands of green, green-white, yellow-green, and violet, apparently due to leaching. Beneath the shales are dark-red sandstones including conglomerate composed of gray, green, and brown calcareous clay fragments and concretionary limestone balls arranged as broken strings or singly in lenses one-eighth inch by 1 inch to 2 by 15 inches. Fifty feet below the top of the Permian (?) is a 10-foot bed of red-brown massive sandstone, composed of red, black, and brown quartz and tiny shale fragments cemented by lime. Cross-bedding, both tangential and angular, is revealed by alternate light-red and dark-red laminae.

Section of Moenkopi formation 2 miles east of Holbrook, Ariz.

	Ft.	in.
1. Sandstone, brown, unevenly thin bedded and cross-bedded, composed of very fine quartz with some muscovite; calcareous cement; brown coat largely superficial; contains lenses of conglomerate like bed No. 3	1	0
2. Shale, chocolate-colored, arenaceous, in wavy and curled beds with wedges of eolian (?) sand	3	0
3. Sandstone, irregularly blotched and banded brown and light gray, very irregularly bedded and cross-bedded; includes lenses of conglomerate composed of flattened clay pebbles, limestone concretions, and bone fragments. The gray rock consists of quartz grains of microscopic size, together with abundant flakes of biotite and muscovite and rarely gypsum, producing a pepper and salt appearance. Cement calcareous	6	0
4. Shales, chocolate-colored, argillaceous, calcareous, and arenaceous, and thin, very fine grained sandstones in beds 1 to 4 inches thick	20	0
5. Sandstone, gray, like No. 3	1	0
6. Sandstone and arenaceous shales, very thin bedded, friable, lenticular, minutely cross-bedded, composed of quartz grains with some mica and cemented by lime; includes lenses of greenish-white and brown mud fragments	15	0

	Ft.	in.
7. Sandstone, shale, and "marl," in irregularly alternating chocolate-colored, red, and green-gray bands; include some gypsum...	27	0
8. Sandstone, chocolate-colored, red, and green-white, shaly, in beds about one-half inch thick; highly lenticular, cross-bedded; bedding planes sun baked and cracked.......	8	0
9. Shale, chocolate-colored, argillaceous and arenaceous, in paper-thin beds, interleaved with sheets of green-white sandstone, averaging one-half inch in thickness; gypsum abundant as sheets and apophyses which have disturbed the bedding...............	27	0
10. Shale, green-white, arenaceous and calcareous, imbricated, unevenly cross-bedded; composed of fine quartz and muscovite...		3
11. Shales and "marl" in beds averaging about 4 inches in thickness; green-white gypsum in seams, sheets, spherical masses, and individual crystals...........................	10	0
12. Shale and "marl," red, calcareous..........		4
13. Gypsum, greenish-white, with some clay....		3
14. Shale and "marl," dark red, seamed along joints and bedding planes by sheets of gypsum less than one-half inch thick, displayed like fine lace mesh................	5	0
	123	10

All the beds in this section decrease and increase within short distances along their strike, and most of them retain their individuality only for a few tens or a few hundreds of feet. It is difficult to locate equivalent strata in two sections measured a mile apart. Bed No. 3 is an exception; with considerable variation in thickness and composition it forms the caps of mesas in the Holbrook region. The conglomerate in Nos. 1, 3, and 5 forms in places the larger part of those beds. Where best developed the pebbles of shale and of concretional limestone range from half an inch to 2 inches in long diameter. Vertebrate remains in the conglomerate are abundant but fragmentary; plants are represented by impressions and undeterminable remnants. Some of the gypsum beds, 1 inch to 6 inches in thickness, may be traced continuously for 20 to 150 feet and appear to have been deposited in place, but most of the gypsum is plainly of secondary origin. Cross-bedding, in large part tangential, is a persistent feature. Sun-baked, rippled surfaces are common, but mud cracks are relatively rare.

Structure and composition.

The Moenkopi formation of the Little Colorado Valley is prevailingly quartzitic with calcareous cement. Lenses and beds of arenaceous limestones are common, but in bulk are much less than the sandstones, and the argillaceous materials are relatively unimportant. Cross-bedding, ripples, and mud cracks are found at all horizons, and sun-baked surfaces are characteristic. Calcite and dolomite serve as cement and occur also in seams and as crystals and tiny clusters. The "calcareous strata," which in general are most numerous in the upper middle portion of the formation, contain from 30 to 80 per cent of material insoluble in hydrochloric acid. Gypsum is apparently disseminated throughout the formation but occurs in large quantity at only two points in the Little Colorado Valley—between Aztec and Winslow and between Grand Falls and Black Falls. It is best developed near the middle of the formation. Near Holbrook the gypsum is most abundant about 200 feet below the top, where it is interstratified and also appears as an interlaced network of white and pink seams traversing the strata in all directions. (See Pl. V, *C*, p. 21.) Below Grand Falls selenite fragments strew the surface, and beds and lenses of amorphous gypsum 1 inch to 6 inches thick project from mesas and form compact road surfaces. The most extensive bed observed has a continuous outcrop of about a mile. Salt crystals were found with gypsum at a few places, and in the vicinity of Sunset Crossing (Winslow) there are several salt springs that were utilized by the Hopis long before the advent of the Spaniards. That salt is unevenly distributed in the Moenkopi is indicated by records of wells along the Santa Fe Railway. The borings at Manila and at cattle ranches northeast of Holbrook yielded fresh water, but the water from the deep well at Adamana contains 3 per cent of sodium chloride.

MOENKOPI OF DEFIANCE PLATEAU.

Stratigraphy.

On the uplifted dome of Defiance Plateau a number of streams have sunk their channels through the resistant cap of Shinarump conglomerate, revealing the Permian below. At most localities only the De Chelly sandstone is exposed, but in Canyon Bonito, at Buell Park, and at the mouth of Black Creek Valley the Moenkopi beds are brought to view. They are well displayed for study 2 miles west of Fort Defiance, where branches of Bonito Creek have dissected the Moenkopi into intricately carved mesas and buttes. The shaly red beds of this locality, together with all the sandstones and conglomerates between Ganado and Fort Defiance, were included by Newberry[1] in his Saliferous series. Howell[2] assigned these beds to a horizon "so near the base of the Trias that a canyon anywhere, a few hundred feet deep, would expose the Carboniferous."

The contact of the Moenkopi with the underlying Carboniferous formations is not revealed at Fort Defiance; the upper part is exposed along the west front of the hogback cut from the Defiance monocline, and the middle beds are well displayed in the walls of Quartzite Canyon. In an east-west section across Bonito Valley Mr. Heald measured 200 feet of shales and sandstones just below a massive stratum of De Chelly sandstone 115 feet thick. This part of the upper Moenkopi consists of chocolate-red shaly beds, varying from sandstone composed of well-rounded fine quartz grains to argillaceous shale; the cement is calcareous. Ripple marks and sun-baked surfaces are characteristic. The beds weather into boardlike slabs. A number of sections measured in the middle part of the Moenkopi are fairly represented by the following section:

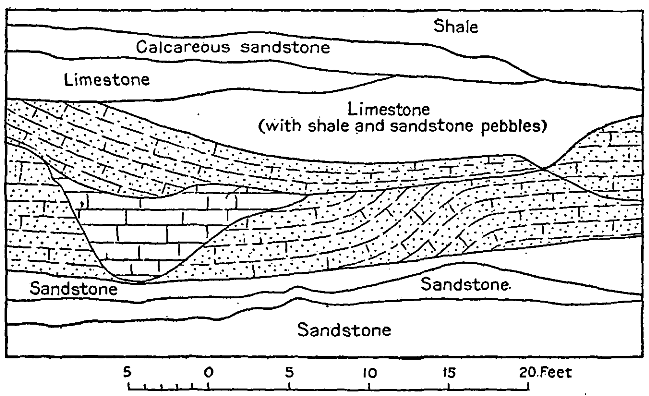


FIGURE 1.—Detailed structure of Moenkopi formation in Bonito Valley.

Section of middle part of the Moenkopi formation 3 miles west of Fort Defiance, Ariz.

	Feet.
1. Shales, chocolate-colored, arenaceous and argillaceous, with calcareous cement, in wavy laminae, less than one-half inch thick; foliation surfaces smooth, sun baked, ripple marked, sun cracked; beds thin and thicken along strike and overlap as lenses	10
2. Limestone, calcareous, sandstone, and shales, chocolate-colored, gray, and white, in beds 6 inches to 3 feet thick, arranged as fat, short lenses, overlying one another with wavy scalloped surfaces; waves 4 to 15 feet from crest to crest; all cross-bedded. A few of the limestone lenses are conglomeratic and contain pea-sized pebbles of concretionary gray limestone and chocolate-colored shale	22
3. Sandstone, gray, calcareous, in beds 3 to 10 feet thick, with lenses of chocolate-colored calcareous shale, forming beds which meet at various angles; shale broken into minute bits horizontally and vertically; sandstone imbricated on small scale with wavy one-sixteenth to 4 inch flakes; plant impressions	40
	72

In a stratum in the wall of Quartzite Canyon, considered the equivalent of bed No. 3 of this section, Permian plants were obtained. (See p. 31.)

At Buell Park the massive De Chelly sandstone is underlain by 140 feet of chocolate-red shale with laminae one-sixteenth to 1 inch thick, interstratified with thin shaly sandstones. Fine-grained red quartz is the chief constituent, but muscovite is generally disseminated and also concentrated on bedding planes. Brown, glistening clay surfaces were observed on many shale fragments and indicate exposure to the air.

Lithologic features.

Arenaceous shales and thin-bedded sandstones constitute about 95 per cent of the Moenkopi strata exposed in the canyons on Defiance Plateau. The beds of limestone in the middle part of the formation are impure; in only one specimen tested did the material insoluble in hydrochloric acid fall below 50 per cent. Rock from these beds has been found unsuitable for the manufacture of lime. Calcite and dolomite, however, are present in disseminated grains and tiny geodes in the calcareous beds, and siliceous pseudomorphs of salt are found on sun-baked foliation surfaces. Specks of gypsum are common, but seams of gypsum are exceedingly rare, and the waters of Bonito Creek are unusually free from alkali. The beds are prevailingly chocolate-colored to red, owing to the ferric pigment and disseminated red quartzes; the more calcareous layers

[1] Newberry, J. S., op. cit. (Ives expedition), p. 91.
[2] U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 286, 1875.

and lenses are light gray to cream. Gray and blue-green spots dot the surfaces of certain beds and may represent centers of organic leaching. In places foliation is well developed, but intricate lens structures are common, and some of the shales or "marls" are as structureless as adobe. (See fig. 1.) Cross-bedding, both angular and tangential, on a minute scale is present in nearly all parts of the formation, and ripple-marked, sun-dried, and sun-cracked surfaces, in many places coated with mica, are characteristic features.

MOENKOPI OF THE SAN JUAN VALLEY.

Stratigraphy.

Permian (?) beds are exposed along the south side of San Juan River between the mouth of the Chinle and the mouth of Copper Canyon, where they form the floor of Monument Valley and the drainage area of Gypsum Creek. Both the Moenkopi formation and the De Chelly sandstone are present in this area. The Moenkopi formation overlies the Goodridge formation (Pennsylvanian) and rises above the limestone floor in mesas, buttes, and towers intricately and fantastically carved by water and by wind.

In general aspect the Moenkopi formation of the San Juan Valley resembles strata of equivalent age in the Little Colorado Valley. The beds are calcareous and consist of alternate layers of arenaceous shale and sandstone with dark-red, light-red, and chocolate hues. The stratigraphic boundaries of the formation, however, are very unlike in the two regions. Along the Little Colorado the Moenkopi is set off from adjoining formations by unconformities and its chocolate-red color contrasts strongly with the buff of the underlying Kaibab limestone and the gray of the overlying Shinarump conglomerate. On the San Juan red beds continue downward for 300 feet into strata carrying characteristic Pennsylvanian fossils. The bottom of the Moenkopi formation is drawn on the surface of the uppermost bed of hard massive blue-gray limestone containing *Bellerophon crassus*, and its top is arbitrarily set at the base of the lowermost heavy bed of sandstone (De Chelly). As thus limited the Moenkopi in the San Juan Valley has an average thickness not far from 500 feet. It should be noted, however, that 845 feet of strata at the mouth of Chinle Creek were assigned by Woodruff to the Moenkopi—475 feet of "shale, light pink, sandy, and sandstone, slightly darker," overlying 370 feet of "shale, sandy, and brick-red argillaceous sandstone."[1] The character of the Moenkopi of the San Juan Valley may be judged from the following section:

Section of Moenkopi formation 4 miles northwest of Oljeto ranch, Utah.

	Feet.
Massive De Chelly sandstone.	
1. Arenaceous shales and shaly, very fine grained sandstones in alternating strata 6 inches to 10 feet thick, chocolate-colored to dark red; top of many beds coated with mica and marked by ripples and mud cracks and glistening sun-dried surfaces	126
2. Shales, chocolate-colored, arenaceous, calcareous, in thin, uneven lenticular beds	15
3. Sandstone, light red, friable, with calcareous cement, interbedded with argillaceous and arenaceous shale traversed by seams of gypsum; all beds lenticular; foliation surfaces are ripple marked and scarred by plant impressions	55
4. Shales, chocolate-colored, arenaceous, and shaly sandstones in alternating lenticular beds weakly cemented with lime; sun-baked surfaces and lenses of flattened mud pebbles common; gypsum rare	145
5. Sandstone, gray, concretionary, imbricated	2
6. Shale, chocolate-colored, arenaceous, mud cracked, ripple marked	5
7. Sandstone, red, in two beds separated by a 6-inch stratum of shale; cross-bedded; bedding surfaces sprinkled with mica	10
8. Sandstone composed of well-rounded quartz grains of microscopic fineness and covered with green blotches	9
9. Shale like No. 4	10
10. Sandstone like No. 3	4
11. Shale like No. 4	8
12. Sandstone, dark red, massive, very fine grained.	3
13. Shales, light red, with bands of ash-gray and lavender, arenaceous and highly calcareous; two 3-foot bands of sandstone with ripple marks and sun-dried surfaces	40
14. Sandstone like No. 12	5
15. Shales, bright red, arenaceous, highly calcareous, spotted with yellow-gray; includes three 2-inch lenses of conglomerate composed of concretionary fragments of blue-gray limestone and flattened mud pebbles	28

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

	Feet.
16. Dark-red sandstones and light-red, ash-gray, and purple sandy shales, in thin alternating beds; foliation surfaces are ripple marked and sun dried and coated with mica; a little gypsum present	25
17. Sandstone, red, fine-grained, cross-bedded, containing irregular concretionary lumps exposed by weathering	18
18. Shale, gray, arenaceous, calcareous	2
Limestone, probably the topmost bed of the Goodridge formation.	
	487

The Moenkopi strata exposed in the shallow meandering canyon of Gypsum Creek include at their base about 100 feet of very thin bedded friable dark-red sandstones alternating with argillaceous, arenaceous, and highly calcareous shales seamed with gypsum; within the next 100 feet the sandstones become firmer and lighter red, and occur as beds 10 to 15 feet in thickness separated by thin shale partings. Throughout this 200 feet lenses of limestone conglomerate are common. These lenses consist of pebbles of gray, dark-blue, and black limestone with scattered fragments of shale and of sandstone. The pebbles average about half an inch in size; some are 2 to 3 inches in long diameter. Both round and angular shapes were noted; most of them are flattened and a few are thin slabs. One conglomerate lens about 200 feet from the base of the Moenkopi is over 400 feet long and 10 feet thick at the center; it contains rounded fragments 4 to 5 inches in diameter and pencil-like forms 6 to 8 inches long.

The picturesque group of mesas, needles, fingers, and towers 200 to 600 feet high which stand on the summit of the Mitten Butte anticline and dominate the landscape in Monument Valley (Pl. VI, *A*) rest on a base of Moenkopi shales and sandstone with interbedded gypsum, and the beautiful Organ Rock of Moonlight Valley (Pl. VI, *B*) is composed entirely of banded Moenkopi strata.

No fossils other than fragmentary plants were obtained from the Permian of the San Juan area.

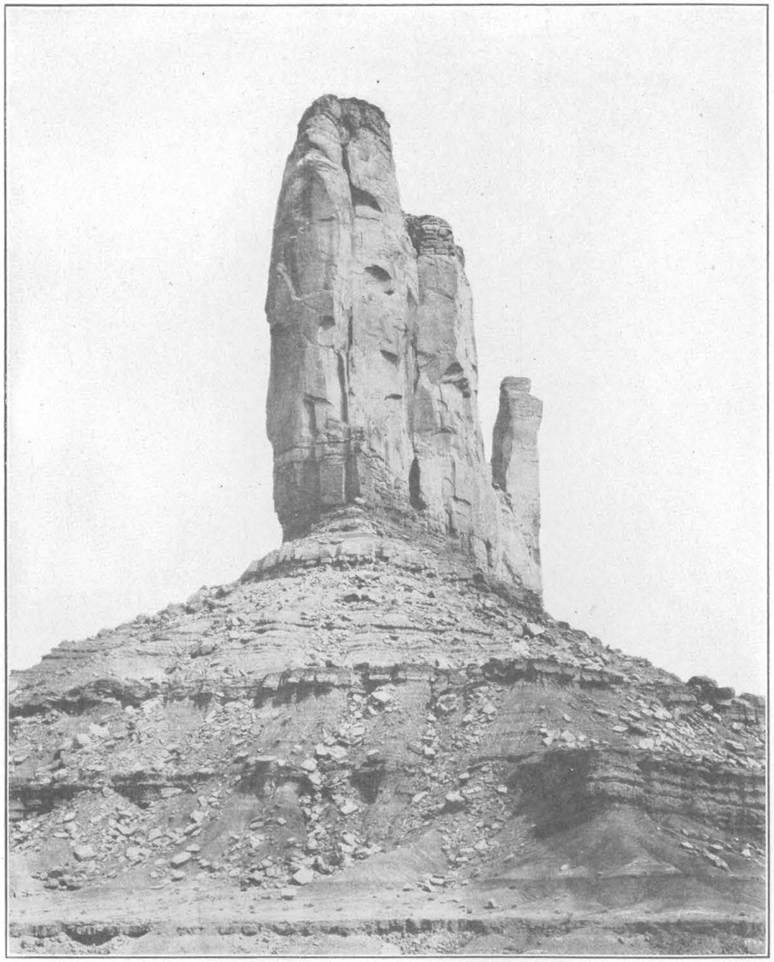
Lithologic features.

The structure and composition of the Moenkopi formation in the San Juan Valley as observed at a number of places both south and north of the river is summarized below.

The lower beds of the formation, consisting of alternating strata of sandstone and shale, present similar features throughout. The upper part of the formation changes rapidly along the strike, becoming more arenaceous toward the north and consisting not of continuous, uniform beds, but of huge lenses of sandstone embedded in shale. The formation as a whole is made up of arenaceous shale and shaly calcareous sandstone rather than argillaceous shale and siliceous sandstone. All beds so far as observed have calcareous cement, and lenses of limestone conglomerate are widely distributed, particularly in the lower halves of the beds. Cross-bedding in sandstone strata and ripple-marked, sun-baked shales are characteristic features. Gypsum and scattered grains of salt are widely disseminated throughout the formation, occurring as individual crystals and lumps and also as stringers and veins intersecting the beds at various angles. In a few places beds of gypsum 2 to 6 inches in thickness and 40 to 200 feet in horizontal extent were observed, and along Gypsum Valley sparkling selenite fragments are so abundant that the surface appears to be covered with ash or crusted snow and so thick and so loosely compacted as to make travel tedious. Water from the Moenkopi in the streams and springs of Gypsum Valley is wholly unfit for use by man or beast. In large part at least the gypsum seems to be a secondary accumulation.

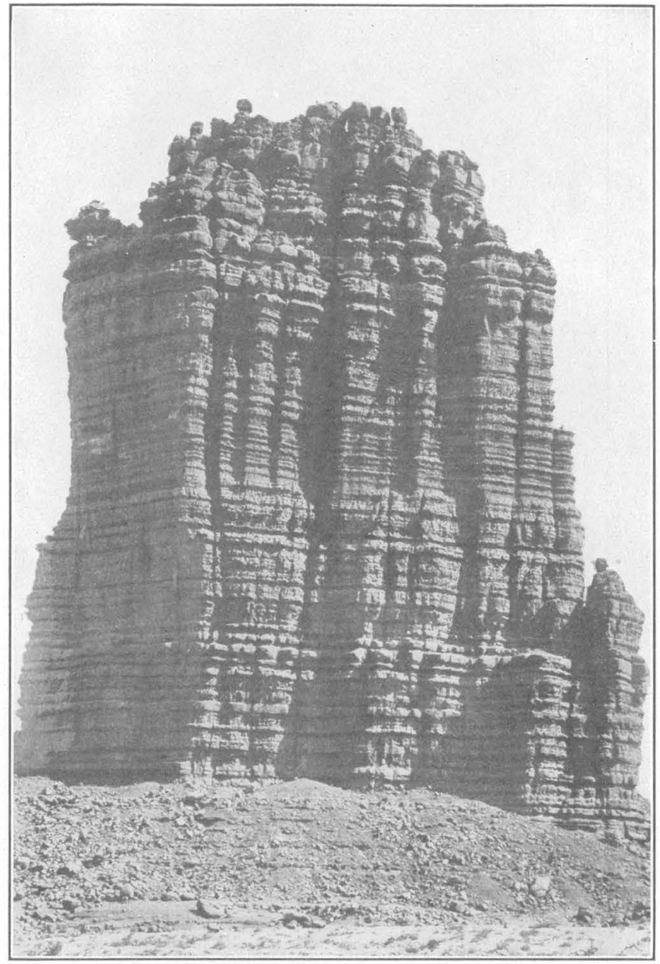
Age and correlation.

The Moenkopi formation is assigned to the Permian (?) on both stratigraphic and paleontologic evidence. It possesses essential unity in structure, texture, color, composition, and conditions of sedimentation. An erosional unconformity with the Kaibab limestone marks its lower limit in the Little Colorado Valley of Arizona; and though clear evidence of such relation has not been obtained in the San Juan region, the fossiliferous Goodridge beds are separated from the Moenkopi by a sharp lithologic break. The Shinarump conglomerate (Triassic) unconformably overlies the Moenkopi or the De Chelly sandstone, which is also assigned to the Permian (?). The paleontologic evidence obtained both within the Navajo Reservation and along its borders is conflict-



A. MITTEN BUTTE, MONUMENT VALLEY, UTAH.

Towers composed of De Chelly sandstone; pedestal of shales of Moenkopi formation.



B. ORGAN ROCK, MOONLIGHT VALLEY, UTAH.

Strata of Moenkopi formation; typical for San Juan Valley. Photograph by Charles Goodman.

CANYON DE CHELLY, ARIZ.

Walls of massive De Chelly sandstone. Height may be judged from apparent size of horse in middle distance. Photograph by W. C. Mendenhall.

ing. Fossils collected on the rim of the Little Colorado Canyon by Mr. Pogue include many fragmentary bivalves and some gastropods. Prof. Schuchert [1] reports:

I see *Bakewellia*, *Pinna*, *Schizodus*, and *Bellerophon*. The horizon is clearly above the Pennsylvanic and is the Permic molluscan fauna devoid of brachiopods. The horizon may be high in the Permic, that is, above Lower Permic, as the term is understood in America, say about Middle Permic.

Fragmentary plant remains including species of *Walchia* were collected at a number of localities and in 1913 E. C. Case and W. B. Emery, of my party, obtained determinable plant fossils from the middle Moenkopi beds 3 miles west of Fort Defiance. Regarding this collection David White [2] writes:

One of the fossil plants from the Moenkopi formation * * * is a *Walchia*, which, though badly smeared with mud, appears to be identical with *Walchia piniformis*. The large fragment with closely placed lateral twigs belongs to another *Walchia* resembling *Walchia hypnoides*. It is perhaps identical with that described by Dawson as *Walchia gracilis*. One or two small fragments in one of the loose rock pieces agrees still more closely with *Walchia gracilis*. These forms of *Walchia* are characteristic of the Permian and are present in Oklahoma and in the Wichita formation of Texas.

Walcott [3] has described 23 genera represented by 34 species of fossils in beds in Kanab Valley, that are believed to be the equivalent of the Moenkopi. He remarks: "The Permian character of the fauna, taken with the evidence afforded by the stratigraphy, clearly establishes the Permian as a well-defined and distinct group in the Colorado Valley." On the other hand Girty [4] states:

It seems all but certain that the "Permian" of the Grand Canyon area, the "Permo-Carboniferous" of the Wasatch Mountains and the Lower Triassic of southern Idaho are a single series of strata originally continuous from one region to the other and having essentially identical faunas. The whole group therefore must be either Permian or Triassic.

In a personal communication of later date (Oct. 18, 1915) Girty concludes: "There no longer seems substantial reason to doubt that Walcott's Permian is the Lower Triassic (Meekoceras zone) of Idaho and the 'Permo-Carboniferous' of Utah."

[1] Personal communication.

[2] Personal communication, Mar. 14, 1914.

[3] Walcott, C. D., The Permian and other Paleozoic groups of the Kanab Valley, Ariz.: Am. Jour. Sci., 3d ser., vol. 20, pp. 221-225, 1880.

[4] Girty, G. H., New species of fossils from the Thaynes limestone of Utah: New York Acad. Sci. Annals, vol. 20, pt. 2, pp. 239-242, 1910.

On the northern flanks of the Zuni Mountains, near Fort Wingate, Dutton [5] found "several specimens of *Bakewellia* and an attenuated form of *Myalina* corresponding to the forms of the latter genus which are common in the Permian." The description of the strata from which these fossils were obtained indicates their equivalency with the Moenkopi at Fort Defiance and elsewhere. S. W. Williston [6] states that "there are genuine Permian red beds" in the Zuni Mountains and that "a Paleozoic brachiopod was obtained by Mr. Miller in the [Moenkopi] cliffs at Holbrook."

In its stratigraphic position the Cutler formation of the San Juan Mountains [7] corresponds to the Moenkopi formation, and the two are lithologically somewhat similar.

DE CHELLY SANDSTONE.

DISTRIBUTION.

Overlying the Moenkopi formation and terminated upward by the Shinarump conglomerate are massive cross-bedded sandstones which so far as known are peculiar to the Permian (?) of the Navajo country. These sandstones have little or no expression in the Little Colorado Valley but are exposed in Monument Valley and in many canyons of Defiance Plateau. Canyon de Chelly, famous for its scenery and its records of an ancient race, is bounded by vertical walls of this sandstone, and the term De Chelly sandstone is proposed for that part of the Permian (?) lying above the Moenkopi. The sandstones forming the magnificent red walls of Canyon de Chelly and Canyon del Muerto have heretofore been considered the equivalent of the Vermilion Cliff (Triassic) or the Wingate sandstone (Jurassic).[8]

The outcrops of the De Chelly sandstone are numerous, but their position, usually in canyon walls and on faces of buttes and mesas, is such that their horizontal expanse is slight, and on the geologic map (Pl. II, in pocket) the Moenkopi and De Chelly are represented by a single color.

[5] Dutton, C. E., Mount Taylor and the Zuñi Plateau: U. S. Geol. Survey Sixth Ann. Rept., p. 134, 1885.

[6] Personal communication, Nov. 2, 1913.

[7] Cross, Whitman, U. S. Geol. Survey Geol. Atlas, Rico folio (No. 130); Ouray folio (No. 153).

[8] Dutton, C. E., op. cit., pp. 136-137. Darton, N. H., A reconnaissance of parts of northwestern New Mexico and northern Arizona: U. S. Geol. Survey Bull. 435, p. 43, pl. 9, 1910.

DE CHELLY SANDSTONE OF DEFIANCE PLATEAU.

The floor of Defiance Plateau is in large part a gigantic cameo in which the gray Shinarump conglomerate has been irregularly cut away and the red De Chelly sandstone exposed. Along the lines of canyons the engraver's tool has cut deeply into the block, revealing the character of the material. Where Bonito Canyon crosses the Defiance monocline the De Chelly strata are exposed in section, affording favorable opportunity for observing the stratigraphic arrangement of the beds.

Section of De Chelly sandstone at west entrance of Bonito Canyon, near Fort Defiance.

[Measured by K. C. Heald. Dip, 16° E.]

	Feet.
Shinarump conglomerate.	
Unconformity.	
1. Sandstone, light red, fine grained; clear-white and red rounded quartz grains; calcareous and ferritic cement; contains rare pebbles one sixty-fourth to one-sixteenth inch in diameter; massive, cross-bedded in places; weathers into rounded knobs; in two beds, 13 and 15 feet thick	28
2. Sandstone, tan to brown, fine grained; clear, well-rounded quartz; calcareous cement; many specks of limonite; even bedded to slightly cross-bedded; hard; forms nearly vertical cliff; in three beds, 7, 3, and 6 feet thick	16
3. Sandstone, chocolate-colored to gray-brown, fine to medium grained; clear, well-rounded quartz; massive; parts of the bed show no structure; other parts cross-bedded with curved laminae tangential to a horizontal surface; weathers in rounded bosses	77
4. Sandstone, chocolate-colored, shaly, largely concealed by talus	27
5. Sandstone, light red, fine grained; clear to red rounded quartz grains; bottom 5 feet thin bedded; in the center gray, cross-bedded, resistant sheet, 1½ feet thick; remainder massive, inconspicuously cross-bedded	115
Moenkopi shales.	
	263

The cliff wall of the Defiance hogback at Carson Monument consists of 8 feet of massive cross-bedded light-red to tan sandstone at the bottom, overlain by 120 feet of tangentially cross-bedded massive friable sandstone, between which and the cap of Shinarump conglomerate is about 100 feet of thick-bedded light-red firm sandstone in which cross-bedding is slightly developed. Two sections taken by W. B. Emery in Buell Park include 466 feet and 585 feet, respectively, of red sandstone, cross-bedded in both straight and curved laminae averaging about 4 inches in thickness and having a prevailing southeast dip. In the lower part of Black Creek canyon 240 feet of dark-red fine, even-grained sandstone, apparently massive but in reality consisting of beds about 2 feet thick, is overlain by 45 feet of thin-bedded, cross-bedded medium-grained light-red sandstone and 27 feet of thick-bedded sandstone of the same general character. This locality appears to mark the southern extension of the massive De Chelly sandstone as represented on the Navajo Reservation. In Nazlini Canyon 200 feet of the De Chelly sandstone is in view, and several canyons trenching the west slope of Defiance Plateau, tributary to Pueblo Colorado and Wide Ruin washes, expose the De Chelly sandstone in walls 50 to 150 feet high. In all these places the De Chelly is in beds 2 to 15 feet thick, each bed strongly cross laminated. In Canyon de Chelly the strata are in general massive and attain thicknesses of more than 100 feet, and the separation of the 800-foot wall into beds is in some places indicated only by change in the dominant direction of cross-bedding. (See Pl. VII.)

DE CHELLY SANDSTONE OF MONUMENT VALLEY.

In another connection Woodruff [1] and I [2] have called attention to the existence of thick beds of massive sandstone at the top of the Permian (?) in San Juan Valley. These sandstones and grits appeared so out of place in the Permian and Triassic sections previously studied in Arizona and Utah that they were set off as a subdivision of the Moenkopi without an attempt to differentiate between portions of unlike lithologic aspect. At the Oljeto ranch 200 feet of these rocks are displayed in section, and the term "Oljeto sandstone member" of the Moenkopi formation was proposed for them. The strata designated by this term are sandstones, grits, and conglomerates and include all beds between the Chinle (Triassic) shales and the typical Moenkopi sediments. Further study of the Permian (?) and Triassic has led me to discard the term "Oljeto sandstone member," for the coarse sediments at its top are equivalent to the Shinarump conglomerate, and the lower part of the "Oljeto sandstone mem-

[1] Woodruff, E. G., Geology of the San Juan oil field, Utah: U. S. Geol. Survey Bull. 471, p. 87, 1912.

[2] Gregory, H. E., The San Juan oil field, San Juan County, Utah: U. S. Geol. Survey Bull. 431, pp. 16-20, 1911.

ber," together with the massive bed previously considered as the topmost stratum of the Moenkopi, occupies the stratigraphic position of the De Chelly sandstone.

The De Chelly sandstone in Monument Valley is a fine-grained cross-bedded light-red sandstone, 250 to 400 feet thick. In some places it is massive throughout; in others it is separated into strata 10 to 40 feet thick. It shows little variation in color and composition but much variation in degree and quality of cross lamination. The remarkable display of erosion features which have aroused the enthusiasm of visitors to this little-known region is due chiefly to the De Chelly sandstone. In the lower Chinle Valley the sandstone in the Comb monocline stands as a smoothed, domed ridge which at Moses Rock consists of a single massive bed 380 feet thick; south of Meridian Butte it forms a mesa bordered by unscalable walls and dissected by a maze of canyons; and on the crest of the Monument upwarp towers capped by the De Chelly sandstone resting on banded pedestals of the Moenkopi shale rise to heights of 600 to 800 feet above the desert sands at their base. (See Pl. VI, *A*, p. 30.)

STRUCTURE, TEXTURE, AND COMPOSITION.

With the exception of the Navajo and Wingate sandstones, which it resembles in many physical features, the De Chelly sandstone presents the most massive strata of all the red beds. In the wall of Canyon Bonito beds 5 to 10 feet thick are found near the top; but in the same locality 60 to 70 feet of strata with most obscure bedding stand vertically in the wall. At Oljeto a single bed is 85 feet thick, and in Canyon del Muerto and Canyon de Chelly there are massive beds 200 to 300 feet thick, with no definite planes of separation. Here and in Monument Valley giant slabs of rocks splitting off from the massive beds leave clean, smooth faces hundreds of square feet in area, marked only by the delicate tracery of cross-bedding laminae.

The De Chelly sandstone is fine grained throughout and remarkably uniform in texture. It consists essentially of grains of two sizes—spherical grains of quartz, averaging about 0.19 millimeter in diameter and making up the bulk of the rock and less well-rounded grains 0.5 to 0.6 millimeter in diameter. In places grains of the two sizes are intermingled, but commonly the larger grains are sprinkled over the surfaces of cross-bedding laminae. Here and there slightly larger grains are found as lenses or strings marking cross-bedding division planes, and rarely scattered pebbles one-sixteenth to one-eighth inch in diameter are seen. White rounded quartz grains constitute about 95 per cent of the rock; red and amber quartz grains are also found, but the prevailing light-red to red-yellow hue of the strata is maintained chiefly by the ferritic pigment which, with calcite, constitutes the cement. Light-colored specks of kaolin are present in the hand specimen and in places give the rock an appearance of a mixture of salt and cayenne pepper. Mica and black quartz are also sparingly distributed.

Cross-bedding is a characteristic feature of the De Chelly sandstone. Here and there the entire wall of a canyon consists of interlocking curved beds; elsewhere massive cross-bedded strata are replaced along the strike by horizontally foliated sandstones. The cross laminae may be a foot or more in thickness, but usually they measure less than an inch and in many places the division planes are so closely spaced that the structure is concealed, the rock surface being completely overspread by a lacework of intricate curves. Typically the canyon walls in the De Chelly sandstone are marked by sweeping curved bands 20 to 200 feet long, tangential to a horizontal surface and flatly convex upward. This structure is illustrated in Plate VIII, *A* and *B* (p. 38).

The De Chelly sandstone is traversed by wide-spaced joints which together with the curved cross-bedding foliation allow the agents of erosion to carve alcoves, recesses, and tunnels in great variety and on a scale that ranges from ornamental pockets to great arched-roof alcoves in which, high on the canyon walls, are tucked away single houses or whole villages of cliff dwellings. (See Pl. XXIX, *B*, p. 134.)

PHYSIOGRAPHY OF PERMIAN TIME.

Gilbert[1] conceived the whole plateau country as "covered by an inland sea entirely separate from the ocean * * * from the close of the Carboniferous to the beginning of the

[1] Gilbert, G. K., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 187, 1875.

Cretaceous." As a result of studies in the Grand Canyon region Walcott[1] reached the conclusion that

> It is probable that the era of the deposition of the Permian was one of slow movement of the sea bed. Elevation and depression are indicated strongly by a marked unconformity, by erosion, in the lower portion of the upper Permian. * * * The sediments are mostly detrital in character, and ripple marks and other indications of a littoral deposit are also seen at several horizons.

Robinson[2] considered the Moenkopi of the San Francisco Mountain volcanic area as "fluviatile or lacustrine" in origin. Huntington and Goldthwait[3] concluded that "the Moenkopi series was probably laid down in a shallow sea where estuarine conditions may possibly have prevailed." In a later paper Huntington[4] ascribed these beds to alternate lacustrine and subaerial deposition incident to the expansion and contraction of waters of a lake contained within an inclosed desert basin. These authors make no mention of the marine fossils from Kanab described by Walcott.

The Plateau province during Permian (?) time was probably a region of low relief bordering the sea and having an arid climate. Over the long slopes and into the flat-floored depressions sediments were carried from surrounding lands and deposited on flood plains, Piedmont slopes, and the floors of fresh and alkaline lakes. The remarkable banding of subequal dimensions displayed in certain localities and so vividly described by Dutton indicates cycles of change of roughly equal length. In some places the sediments suggest change from subaerial to lacustrine deposition; in others marine strata are interbedded with materials of flood slopes. Deposits of gypsum alternating with ripple-marked beds of lenticular sand point to fluctuation in volume of the water contained by ephemeral lakes. Ancient playas, deltas, and flood plains are suggested by rain prints, mud cracks, and the almost universal presence of shining films of clay and mica and halite pseudomorphs that coat the planes of foliation. The general absence of fossils, other than fragments of vertebrates and xerophilous plants, is suggestive of continental conditions. Aridity is suggested by the presence of feldspars and by the prevailing reds and browns of the rock, which are inconsistent with the presence of ground water near the surface. The cross-bedding also points to aridity, for while angular cross-bedding of types common on alluvial plains and even on the seashore occurs in many strata, tangential cross-bedding of the eolian type is prevalent. (For a further discussion of cross-bedding, see p. 58.)

Toward the end of the Permian epoch aridity reached a stage where sand dunes became a prominent feature. These are best preserved along the east and northeast sides of the area, where the De Chelly sandstone displays the record of wind work during late Permian (?) time. The walls of Canyon de Chelly consist in part of overlapping heaps of wind-blown sand now weakly cemented into rock. In the picturesque Navajo language they are "frozen dunes."

The exact sequence of events during Permian (?) time has not yet been made out, but the final explanation must allow for extensive subaerial sedimentation under arid conditions and for two or more invasions of the sea. It is not necessary, however, to assume that all parts of the great area in which Permian deposits occur had the same physiographic history.

PERMIAN(?)-TRIASSIC EROSION INTERVAL.

The Moenkopi formation or the De Chelly sandstone in places where the Moenkopi is absent, is succeeded by beds assigned to the upper part of the Triassic system. The plane of separation in most places is a maturely eroded surface that represents in the time scale a long period during which vast amounts of material were weathered, corraded, and redistributed. The agents of erosion during this epoch may have been at work only on Paleozoic strata; or Lower and Middle Triassic sediments may have been deposited and wholly or partly involved in the regional denudation. Neither the duration of the period of erosion nor the place of deposition of the transported sediments is known. The field evidence merely shows that the conditions of sedimentation were markedly dissimilar before and after the erosion interval.

[1] Walcott, C. D., Study of a line of displacement in the Grand Canyon of the Colorado in northern Arizona: Geol. Soc. America Bull., vol. 1, p. 64, 1890.

[2] Robinson, H. H., The San Franciscan volcanic field, Ariz.: U. S. Geol. Survey Prof. Paper 76, p. 28, 1913.

[3] Huntington, Ellsworth, and Goldthwait, J. W., The Hurricane fault in the Toquerville district: Harvard Coll. Mus. Comp. Zool. Bull., vol. 42, p. 210, 1904.

[4] Huntington, Ellsworth, Some characteristics of the glacial period in nonglaciated regions: Geol. Soc. America Bull., vol. 18, pp. 386–387, 1907.

The unconformity at the top of strata assigned to the Permian (?), first noted by Gilbert [1] on the West Fork of Paria Creek, has been found at many localities, and I have discussed its relations somewhat fully elsewhere.[2]

In addition to localities previously described, this erosion interval was noted during the field seasons of 1911 and 1913 along the lower Little Colorado,[3] near St. Joseph, on the headwaters of Pueblo Colorado Wash, in the lower Chinle Valley, and at other points. The wide extent of the unconformity in southern Utah and northeastern Arizona suggests that it is coextensive with the Plateau province and may extend beyond its borders.

At some localities the plane of unconformity between Permian (?) and Triassic strata has not been recognized. At Red Butte Ward [4] found an uninterrupted transition from Permian to Triassic. At Tucker Springs, where conglomerate, sandstones, and shales are intricately interlaminated, vertebrate bones were collected by E. C. Case,[5] who found in the material an interclavicle fragment of *Metoposaurus* closely allied to *Metoposaurus frassi*, a distinctly Triassic species. The bed from which this fossil was obtained was considered at the time to be 20 feet below the Triassic strata. At Oljeto similar conditions prevail. S. W. Williston [6] reports that he found a Paleozoic brachiopod near Fort Wingate in beds associated with those containing phytosaur and labyrinthodont bones of Middle or Upper Triassic age.

These interesting puzzles, which appear to involve redeposition, can be solved only by detailed stratigraphic field work.

TRIASSIC FORMATIONS.

HISTORICAL SKETCH.

Between the Pennsylvanian and the Upper Cretaceous formations of the Plateau province there is a series of beds, 2,000 to 5,000 feet thick, of unusual expression, elaborately sculptured and wonderfully colored. As far as his eye can reach the traveler can draw lines separating the buff-gray Pennsylvanian limestone below and the dull gray Cretaceous beds above from the red, purple, yellow, and green strata between, and even one ignorant of geology can readily distinguish within this zone of color a zone of brown-striped buttes and a higher series of variegated badland deposits capped by a magnificent red wall whose top is banded with green. But although the boundaries of the formations may be drawn with lines so bold, the problem of establishing the precise limits of formations and of determining their ages or positions in the time scale is unusually difficult because of variations in structure and composition and of the extreme scarcity of fossils. The published descriptions and classifications of the sedimentary beds of the Plateau province are therefore widely dissimilar, and correlations based on conclusions of workers in this field can not be made with assurance.

Marcou's threefold division of the strata between the Sierra Madre (Zuni Mountains) and the Rio Colorado Chiquito (Little Colorado) [7] is chiefly of historic interest, for though he referred all the strata to the Triassic, he presented no evidence for his conclusion. Newberry [8] divided all the strata between the Cretaceous and the Carboniferous into a "red sandstone" or "Saliferous group" and a group of "variegated marls." The massive Wingate sandstone he described as "indurated marls." In his classification the "variegated marls" were considered Triassic and the Jurassic was represented by a few feet of coal-bearing shales found north of the Hopi Buttes. The strata below the Dakota exposed along the San Juan, considered in the present report as Jurassic, were assigned by Newberry [9] to the Lower Cretaceous and the Trias, a classification accepted by Holmes,[10] working in the same area. Within the Mesozoic, thus roughly subdivided by Newberry, the Permian was set apart by Walcott,[11] and the geologists of the Wheeler

[1] Gilbert, G. K., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 160, 1875.

[2] Gregory, H. E., The Shinarump conglomerate: Am. Jour. Sci., 4th ser., vol. 35, pp. 424–438, 1913.

[3] Gregory, H. E., A reconnaissance of a portion of the Little Colorado Valley, Ariz.: Am. Jour. Sci., 4th ser., vol. 38, pp. 498–501, 1914.

[4] Ward, L. F., Geology of the Little Colorado Valley: Am. Jour. Sci., 4th ser., vol. 12, pp. 401–413, 1901.

[5] Personal communications, Sept. 18 and 23, 1913.

[6] Personal communication, Nov. 3, 1913.

[7] Marcou, Jules, Geology of North America, pp. 10-13, 1858.

[8] Newberry, J. S., Geological report, in Ives, J. C., Report upon the Colorado River of the West, pt. 3, pp. 79, 93–97, 1861.

[9] Newberry, J. S., Geological report, in Report of the exploring expedition * * * under command of Capt. J. N. Macomb, p. 63, 1876.

[10] Atlas of Colorado and portions of adjacent territory, pl. 15, U. S. Geol. and Geog. Surveys Terr., 1877.

[11] Walcott, C. D., The Permian and other Paleozoic groups of the Kanab Valley, Ariz.: Am. Jour. Sci., 3d ser., vol. 20, pp. 221-225, 1880.

Survey separated the remainder into Jurassic and Triassic with undefined limits. In the Navajo country, Howell[1] noted strata of Jurassic age in Moenkopi Wash and 20 to 30 feet of "red marl" belonging to this system between Keams Canyon and Ganado. These beds, considered as McElmo in the present paper, are called Jurassic, Triassic, and Lower Cretaceous in different parts of the area, and Howell remarks that "it is not an easy matter to separate the Cretaceous from the Triassic." In the Triassic Howell included the "variegated marl series" (Chinle formation) and the overlying soft massive sandstones (the La Plata group and McElmo formation). On the geologic map of Gilbert, Marvine, and Howell,[2] the northwest border of the Navajo country is colored as Triassic, Jurassic, and Cretaceous, the boundaries being drawn on the surface of what is here described as the La Plata group. Gilbert's measured section[3] from Fort Wingate northward, involving 2,738 feet of sediments, gave the true relations of the Mesozoic strata in northwest New Mexico and further studies in this region by Dutton[4] resulted in dividing the beds between the Dakota and the Permian into (1) Lower Trias, 1,600 feet of shales with a sandstone "equivalent to Powell's Shinarump conglomerate" at the base; (2) Wingate sandstones, Triassic, 450 feet; (3) Zuni sandstones, Jurassic (?), 1,100 feet.

A desire to establish a paleontologic basis for the subdivision of the red beds of northern Arizona led to the expeditions of Ward[5] in 1899 and 1901. His field studies in the lower valley of the Little Colorado resulted in dividing the Triassic as follows:

Triassic formations in Little Colorado Valley.

	Feet.	
Painted Desert formation:		
White sandstone	100	
Brown sandstone	200	
Variegated sandstone	800	
Orange-red sandstone	100	
		1,200
Shinarump formation:		
Leroux member:		
Calcareous marls	200	
Mortar beds	80	
Limestone ledge	20	
Sandstones	100	
Variegated marls	400	
Lithodendron member	800	
		1,600
Moencopie [Moenkopi] formation, Triassic in large part		700
		3,500

The most valuable result of Ward's work was the discovery of vertebrate fossils in the "Leroux member," which determined the age of these beds as Upper Triassic.

The stratigraphic boundaries of the three Triassic formations recognized by Ward are not drawn at any particular horizon marker. The "Lithodendron member of the Shinarump formation" was so designated because it contained all the fossil wood and was believed to pass by transition into the underlying Moenkopi formation. To the "Leroux" were assigned all the marls in which petrified wood was not found, and the term "Painted Desert formation" was proposed for all the sandstones overlying the variegated marls. The two upper formations are thus seen to be substantially the equivalent of the "variegated marls" of Newberry. To my mind it is undesirable to retain the subdivisions and nomenclature adopted by Ward, for the following reasons: The "Shinarump group" as used by Powell and others has always included the beds below the Shinarump conglomerate—that is, the Moenkopi and De Chelly (Permian?). The "Lithodendron member" is assumed to be the equivalent of Powell's Shinarump conglomerate, but Powell used this term for a particular conglomerate rarely exceeding 100 feet in thickness, a bed which has been repeatedly recognized by field workers and which I have traced from Utah to New Mexico. Moreover, the term "Lithodendron" (fossil tree) is not distinctive, for wood occurs at several horizons above the Shinarump conglomerate. The "Leroux formation" as defined is too indefinite for comparison, its boundaries can not be traced in the field, and its relation to the Shinarump conglomerate is undeterminable. According to my interpretation the "Painted Desert for-

[1] Howell, E. E., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, pp. 280-285, 1875.

[2] U. S. Geog. and Geol. Surveys W. 100th Mer. Geol. Atlas, sheets 6 and 76, 1874.

[3] Gilbert, G. K., op. cit., pp. 551-552.

[4] Dutton, C. E., Mount Taylor and the Zuñi Plateau: U. S. Geol. Survey Sixth Ann. Rept., pp. 135-138, 1885.

[5] Ward, L. F., Geology of the Little Colorado Valley: Am. Jour. Sci., 4th ser., vol. 12, pp. 401-413, 1901; Status of the Mesozoic floras of the United States: U. S. Geol. Survey Mon. 48, pt. 1, pp. 13-46, 1905.

mation" is the stratigraphic equivalent of the Wingate and "Zuni" sandstones of northwestern New Mexico, of the Vermilion Cliff and White Cliff (?) sandstones of Utah, and of the La Plata group and McElmo formation of Colorado; and although these beds along Moenkopi Wash present features not usually found elsewhere, it seems desirable to correlate them with formations previously established by students of the stratigraphy of the Colorado Plateau. (See pp. 66–68.)

As defined in the present report the Triassic embraces all the strata between the Permian(?)-Triassic erosion interval and the base of the massive red cross-bedded sandstone which is included in all the Mesozoic sections in southern Utah, northern Arizona, northwestern New Mexico, and southwestern Colorado so far described. The lower limit of the Triassic as thus defined is readily traced throughout the Colorado Plateau province, and the sandstone overlying it (Wingate of Dutton and of this report; Lower La Plata of Cross; all or part of the sandstone at the top of the Vermilion Cliff series of Powell and Dutton) is unmistakable, for it is one of the most conspicuous formations known to geology.

The Triassic is subdivided into two formations—the Shinarump conglomerate and the Chinle formation. The basis of separation is lithologic, as the fossils obtained, including petrified wood and vertebrate and invertebrate remains, are common to both formations.

SHINARUMP CONGLOMERATE.

PREVIOUS DESCRIPTIONS.

The presence of a "firmly cemented conglomerate containing many fragments of silicified wood" capping the cliffs composed of "variegated sandstones and marls" overlying the Carboniferous was noted by Powell[1] in 1873. The geologists of the Wheeler Survey repeatedly mention a conglomerate in the midst of "variegated clays" or "shales" or "saliferous and gypsiferous clays," and the sections published by Gilbert, Howell, and Marvine leave no doubt as to the position of the conglomerate in the Mesozoic formations. Marvine[2] found above Sunset Crossing (Winslow) "dark-red and chocolate-colored shaly sandstones, * * * capped with a conglomerate of siliceous pebbles, the Shinarump Triassic conglomerate of Powell." Newberry[3] had previously noted below Winslow 20 feet of "conglomerate, a coarse light-brown sandstone with white, bluish, red, and black quartz pebbles, varying in size from that of a pea to an egg * * * quite indistinguishable from much of the Carboniferous conglomerate in Ohio and Pennsylvania." The conglomerate at Fort Defiance was also recognized as the equivalent of that in the Little Colorado Valley.[4] In 1876 Powell[5] proposed the term "Shinarump group" for all the strata between the "Upper Aubrey" (Kaibab) and the Vermilion Cliff sandstone and considered the entire group of which the conglomerate forms the middle part as Triassic in age. Dutton[6] and Gilbert[7] use "Shinarump group," in harmony with Powell's definition, Dutton ascribing the strata to Permian and Triassic and Gilbert to the Jura-Trias. The middle member of the "Shinarump group" of the Henry Mountains is described by Gilbert as "gray conglomerate with silicified wood—the Shinarump conglomerate"; and in the High Plateaus Dutton found "a singular conglomerate * * * of fragments of silicified wood embedded in a matrix of sand and gravel" in the midst of "transitional shales," leading "up to the base of the Vermilion Cliff sandstone." For the Grand Canyon district as a whole Dutton[8] remarks:

> Wherever we encounter a cliff which discloses the upper Permian bed we find at the summit of the escarpment a band of pale-brown sandstone of coarse texture, often becoming a conglomerate. Its thickness is usually from 40 to 75 feet. In a few places it is wanting from its proper horizon, and in some others its thickness becomes more than 100 feet.

The Shinarump conglomerate was recognized by Dutton also at Fort Wingate.[9] In

[1] Powell, J. W., Some remarks on the geological structure of a district of country lying to the north of the Grand Canyon of the Colorado: Am. Jour. Sci., 3d ser., vol. 5, pp. 456–465, 1873.

[2] Marvine, A. R., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 215, 1875.

[3] Newberry, J. S., Geological report, in Ives, J. C., Report upon the Colorado River of the West, pt. 3, p. 75, 1861.

[4] Idem, p. 93.

[5] Powell, J. W., Report on the geology of the eastern portion of the Uinta Mountains, pp. 53, 68–69, U. S. Geog. and Geol. Survey Terr., 2d div., 1876.

[6] Dutton, C. E., Report on the geology of the High Plateaus of Utah, pp. 144–148, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1880.

[7] Gilbert, G. K., Report on the geology of the Henry Mountains, 2d ed., pp. 5–6, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1880.

[8] Dutton, C. E., Tertiary history of the Grand Canyon district: U. S. Geol. Survey Mon. 2, pp. 43–44, 1882.

[9] Dutton, C. E., Mount Taylor and the Zuñi Plateau: U. S. Geol. Survey Sixth Ann. Rept., p. 134, 1885.

contrast with the views of Powell, Dutton, Marvine, Howell, and Gilbert, who treated the conglomerate member of the "Shinarump group" as a bed usually less than 100 feet thick and of essential uniformity of character throughout a wide area, Ward [1] defines the Shinarump conglomerate, which he later called the "Lithodendron member" of his Shinarump formation, as a series of conglomerates, sandstones, argillaceous shales, and variegated marls 800 feet thick.

Because of its value as a datum plane for stratigraphic work in the Plateau province, I have elsewhere [2] discussed the limits and character of the Shinarump conglomerate and propose to give to this unique stratum the rank of a formation.

AREAL EXTENT AND THICKNESS.

The Shinarump conglomerate has been recognized in southern Utah, northern Arizona, and northwestern New Mexico at almost every place where the base of the Triassic is exposed. In Utah Dutton found this rock at Pine Valley Mountain, near St. George, "throughout the great circuit of cliffs south of the High Plateaus," within the High Plateaus, in the San Rafael Swell, and near the junction of Grand and Green rivers. Gilbert found the Shinarump conglomerate in the Henry Mountains, and I have observed it at Lees Ferry, Ariz., and at Kanab, Toquerville, Water Pocket Canyon, White Canyon, Elk Ridge, and other points in southern Utah. In Arizona the conglomerate has been found by Robinson [3] in Sycamore Canyon, 20 miles southwest of Flagstaff, and at other points south and west of the Little Colorado and Puerco valleys. In New Mexico it is exposed by the erosion of the Zuni upwarp. The distance from Fort Wingate, N. Mex., to Toquerville, Utah, is about 300 miles, and from Sycamore Canyon to San Rafael Swell, 290 miles, and within those limits the Shinarump conglomerate is to be found at nearly every locality where this portion of the Triassic is exposed. In Colorado this bed has not been recognized. (See p. 41.)

In the Navajo country the Shinarump conglomerate is displayed as a mammoth horseshoe with tips on Colorado River and Lukachukai Creek. Along the Echo Cliffs, up the Little Colorado and Puerco valleys, and across the length of Defiance Plateau the outcrops are nearly continuous. In Monument Valley many ridges and mesas owe their preservation to a cap of this resistant stratum. The thickness of the Shinarump conglomerate in the Grand Canyon district, according to Dutton, is usually from 40 to 75 feet, and in the High Plateaus it rarely exceeds 50 feet. Howell reports 50 feet at Last Bluff and a maximum thickness of 100 feet at St. George; and Gilbert records 30 feet in the Henry Mountain district. Robinson measured at Cedar ranch, north of San Francisco Mountain, 35 feet of "yellowish to white medium to coarse grained sandstone containing rounded pebbles up to 3 inches in diameter, many angular fragments of petrified wood," and at Anderson Mesa, south of Flagstaff, "5 feet of fine-grained red conglomerate."[4] In the Navajo country the Shinarump conglomerate is 45 feet thick at Lees Ferry, 50 feet near Willow Springs, 30 to 60 feet at the mouth of Moenkopi Wash, 30 feet 4 miles southeast of Black Falls, 30 feet north of Tolchico, 40 to 50 feet at Tucker Springs, 30 feet at Hardy, 25 feet at Querino, 20 to 40 feet at Fort Defiance, 80 feet at Buell Park, 20 to 60 feet at Chinle, 40 to 60 feet at Sehili, and 45 feet at Olieto.

TOPOGRAPHIC EXPRESSION.

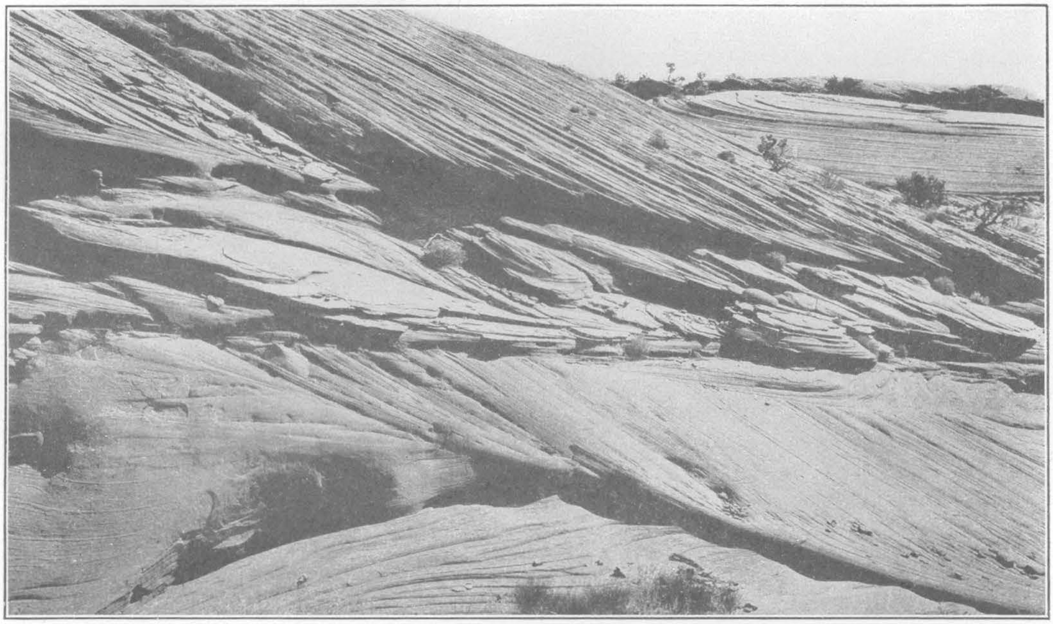
Because of the relative softness of the beds above and below it, the Shinarump conglomerate is a cliff maker and caps erosion remnants. Along the Little Colorado from Adamana westward to Winslow it has preserved the cliffs of the Moenkopi from destruction. The vertical walls of Canyon de Chelly, Canyon del Muerto, and Canyon Bonito are made possible by this resistant cap, which in certain places overhangs as an ornamental molding. In Monument Valley, as at Toquerville, the conglomerate forms domes or canoe-shaped ridges in harmony with the type of structure; where the dips are steep the upturned edge of the stratum is carved into series of pinnacles and teeth. Over the Defiance Plateau it forms the

[1] Ward, L. F., Status of the Mesozoic floras of the United States: U. S. Geol. Survey Mon. 48, pt. 1, p. 45, 1905.

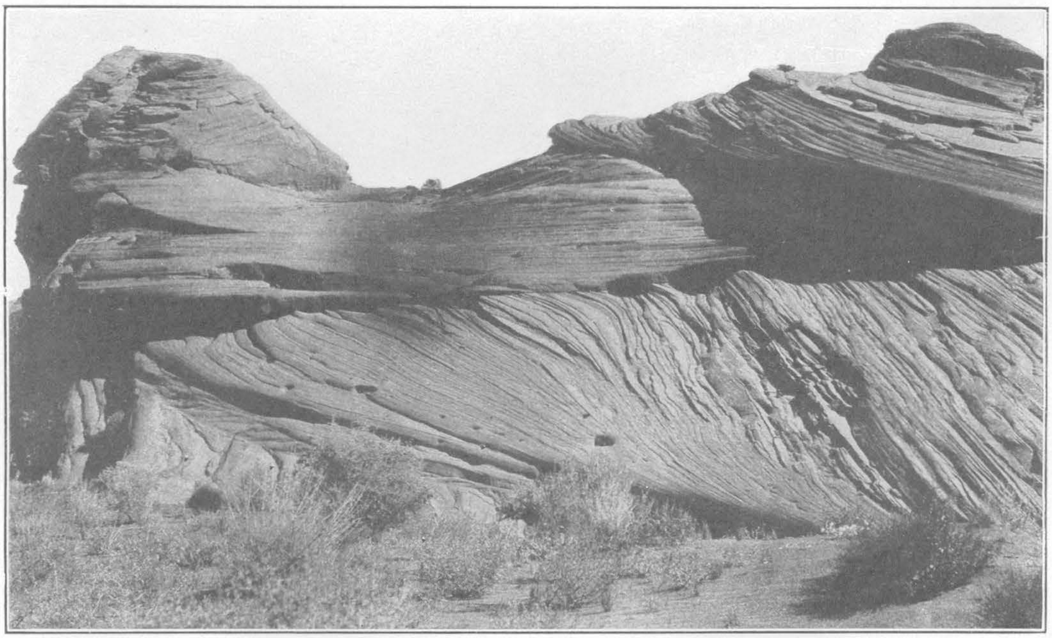
[2] Gregory, H. E., The Shinarump conglomerate: Am. Jour. Sci., 4th ser., vol. 35, pp. 424-438, 1913.

[3] Robinson, H. H., The San Franciscan volcanic field: U. S. Geol. Survey Prof. Paper 76, p. 27, 1913.

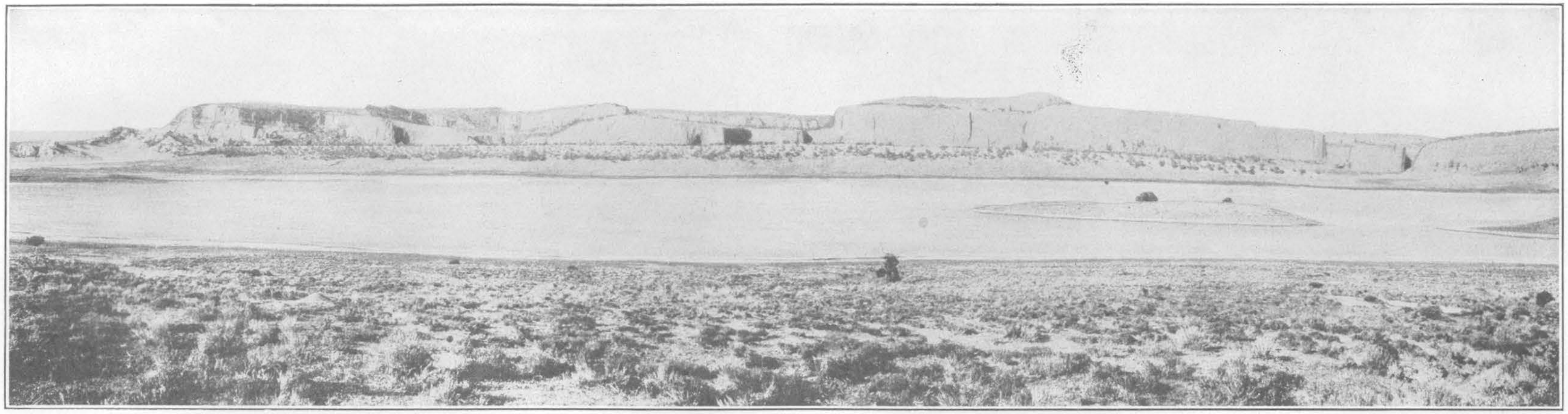
[4] Robinson, H. H., op. cit., p. 27.



A. CROSS-BEDDED DE CHELLY SANDSTONE NEAR HEAD OF GYPSUM CREEK, ARIZ.
Wind-swept surface; cavities formed by solution.

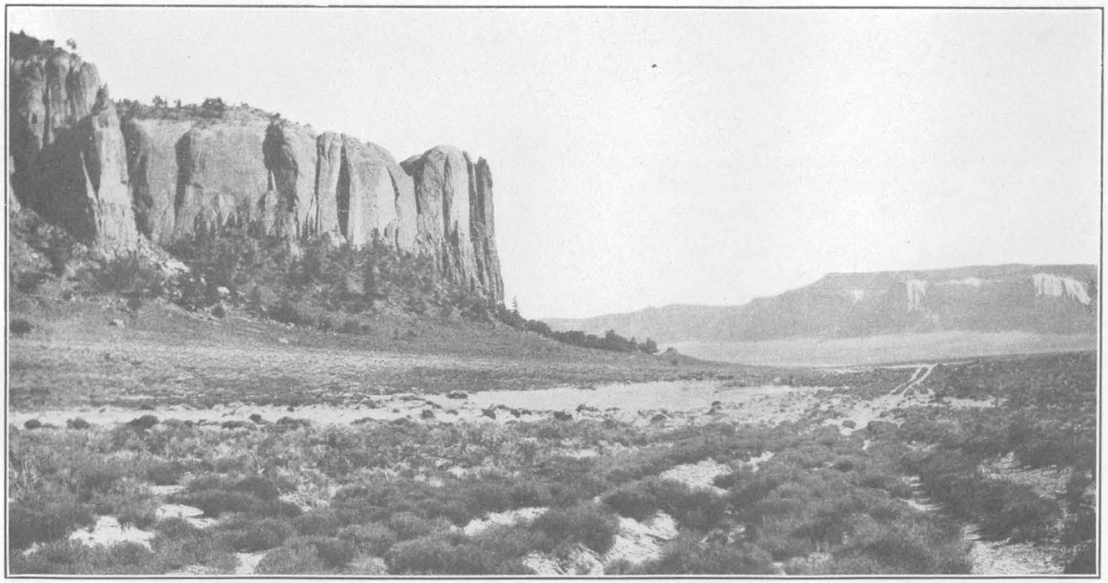


B. CROSS-BEDDED DE CHELLY SANDSTONE 10 MILES EAST OF THE VOLCANIC NECK AGATHLA, ARIZ.



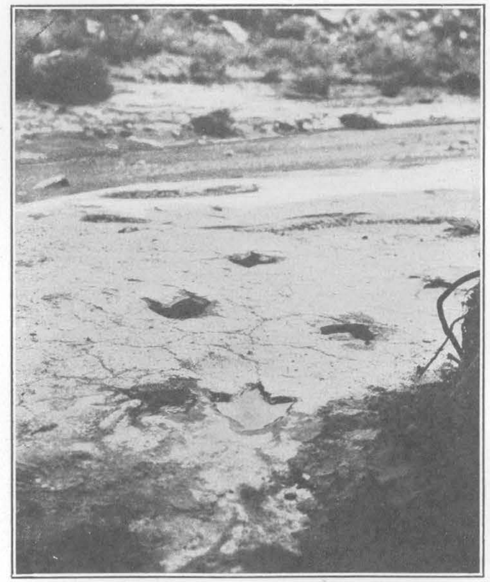
A. CLIFFS AT RED LAKE, N. MEX.

Wall composed of Wingate sandstone, 200 feet thick, underlain by Chinle formation.



B. BUTTRESS AND RINCON OF WINGATE SANDSTONE 6 MILES SOUTH OF CRYSTAL, N. MEX.

Photograph by K. C. Heald.



C. DINOSAUR TRACKS IN NAVAJO CANYON, ARIZ.

Strata of Todilto formation.

surface or rests as patches on both the steep eastern face and the gently inclined western face of the Defiance monocline. As reported by Mr. Pogue the conglomerate forms an almost continuous cover of the flat upwarp west of Willow Springs. Pebbles from the Shinarump are widely distributed.

UPPER CONTACT.

The plane of unconformity at the base of the Shinarump conglomerate is well exposed, but its contact with the overlying Chinle formation is in most places concealed by talus. Ward[1] says that "the lower marls ["Le Roux"] are often separated by beds of sandstone and true conglomerate, showing that it is all one great system of Shinarump sandstones," a conclusion in harmony with the views of Powell, Dutton, and Gilbert. Woodruff states: "It is probable that there is an unconformity at the top of the bed" ("Oljeto" includes Shinarump conglomerate). At Fort Defiance and Chinle the beds immediately overlying the Shinarump conglomerate were examined. In a branch of the Canyon de Chelly near Chinle 4 feet of purple-gray lumpy ripple-marked micaceous sandy shale rests on a wavy, eroded surface of the conglomerate. Weathered fragments of quartz and of wood are included in the shale. Two miles farther north Mr. Heald noted similar relations. On the back slope of the cuesta at Fort Defiance the upper wavy, scalloped surface of the conglomerate is immediately overlain by 2 feet of paper-thin drab, highly muscovitic shale, followed by irregularly foliated cross-bedded purple shale and sandstone. These typical exposures indicate that unconformities of at least local extent mark the upper limit of the Shinarump conglomerate, and in any case the abrupt change in lithologic character in passing into the Chinle formation is significant.

STRUCTURE, TEXTURE, AND COMPOSITION.

The geologists of the early Government surveys were evidently impressed by the persistence and constancy of character shown by the Shinarump conglomerate in widely separated localities. Dutton, in speaking of the cliff exposures of the "Shinarump group," including the conglomerate, says: "As we pass from one of these localities to another not a line seems to have disappeared, not a color to have deepened or paled. * * * The constancy, so far as known to me, is without a parallel in any other region."[2] "The Shinarump conglomerate keeps its aspect unaltered wherever it spreads."[3] After examining this formation at more than 40 localities, I recognize a considerable range of differences in structure and composition. The likenesses, however, are much more numerous than the differences, and outcrops separated by 200 miles resemble each other more closely than they resemble any parts of other Mesozoic formations. The Shinarump is everywhere lenticular; lenses of conglomerate overlap lenses of coarse or fine sand, and plasters of pebbles many square feet in area or long, narrow cobble pavements appear and disappear within the formation in a capricious manner. (See Pl. XI, *A*.) Cross-bedding is characteristic; short laminae meet each other at large angles, and longer beds form smaller angles with the horizon. Angles between 3° and 24° with a prevalent dip of N. 30° W. were measured on the Little Colorado. In many places pebbles are irregularly grouped like raisins in a pudding, and here and there lines of pebbles one-sixteenth inch to 2 inches in diameter simulate strings of beads. Again, a single cobble may be set in the midst of several cubic yards of finer-textured rock.

At the mouth of Canyon de Chelly 1 foot of chocolate-colored shale, 1 foot of red-gray fine sandstone, and a thin bed of carbonaceous matter are included in 40 feet of conglomerate exposed in the wall of the canyon. At Tanner Crossing an otherwise massive bed includes several thin lenses of chocolate-colored shale. Near Winslow, at Oljeto, at St. Michaels, and elsewhere patches of gray clay shale are plastered on the under side of the lowest bed of conglomerate. At Tucker Spring the conglomerate is abnormally variable and sustains unusual relations with the underlying formations, as is shown in the following section:

[1] Ward, L. F., field notebook, June 22, 1901.

[2] Dutton, C. E., Report on the geology of the High Plateaus of Utah, p. 144, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1880.

[3] Dutton, C. E., Mount Taylor and the Zuñi Plateau: U. S. Geol. Survey Sixth Ann. Rept., p. 34, 1885.

General section of Shinarump conglomerate at Tucker Spring, Ariz.

	Feet.
1. Conglomerate and coarse sandstone, gray at top; consists of pebbles of brown and white quartz, gray-brown and black quartzite, chert, and limestone one-half inch to 3 inches in diameter; pebbles smoothed or subangular, some faceted; abundant wood impressions. Conglomerate traversed by irregular bands of black sand. The middle portion includes lenses of friable iron-stained sands and gravels, chunks of clay, and fragments of wood. The bottom 5 feet is a massive bed of coarse, cross-bedded lenticular sandstone, traversed by strings of quartz pebbles 2 inches or less in diameter	35
2. Sandstone, coarse, composed of subangular white quartz and quartzite, chert, and clay pellets, the largest one-half inch in diameter.	1
Unconformity, local (?).	
3. Shales, banded green-white and red, arenaceous, arranged as overlapping lenses	20
4. Sandstone, brown, calcareous, cross-bedded, friable; contains lenses of conglomerate consisting of clay pellets and calcareous concretions	15

In color the Shinarump conglomerate is gray to white, rarely brown. In texture it varies from a conglomerate with pebbles as much as 3 inches in diameter to coarse grit or sandstone and in a few places to fine sandstone. The sandstone phase appears in all the outcrops observed, and conglomerate and sandstone do not appear to be geographically segregated. The outcrops along the Little Colorado between Holbrook and Leupp show about 50 per cent of conglomerate with pebbles 1 to 3 inches in diameter. North of Tolchico 90 per cent of the outcrop consists of clean-washed subangular quartz pebbles less than half an inch in diameter. East of Black Falls few of the pebbles exceed 1 inch in diameter, but below Tanner Crossing the outcrops again contain 30 to 50 per cent of pebbles averaging 2 inches in diameter. Along the Puerco at Querino and Houck the conglomerate, arranged in irregular masses, lenses, and stringers, is composed of pebbles one sixty-fourth to 3 inches in diameter. It is also coarse in the lower part of Black Creek canyon, at Chinle, at Agathla, and at Oljeto. At Fort Defiance about 10 per cent of the pebbles in the conglomerate lenses exceed 3 inches in length, and 50 per cent are longer than 1 inch. The largest pebbles noted are elongated quartzites 5 to 7 inches in length. Probably more than 95 per cent of the pebbles are subangular to round siliceous fragments of great variety; red, white, black, and topaz-colored quartz and black and gray quartzite are everywhere present; chert and chalcedony are occasionally found. Three miles north of Tolchico 5 per cent of the rock consists of banded quartzite and 3 per cent of limestone and chert fragments. Scattered pebbles of limestone were also found in the Shinarump at Warner Wash, near the Government bridge across the Little Colorado, and at a few other localities. Pellets of clay shale and of sandstone were observed at Oljeto and Sehili. In general matrix, pebbles, and cement are alike in composition and the rock is therefore firm and in places becomes a glistening hard quartzitic conglomerate. In the Little Colorado Valley above Grand Falls the cement is partly calcareous and the rock crumbles so readily that its presence is scarcely discernible. Iron oxide in several places forms part of the cement. Petrified wood is universally present, commonly as chunks several inches to several feet in length, but also as logs. The blocks of silicified wood are not waterworn except some of the smallest particles, which exhibit rounded surfaces. Indeterminable fragments of bones and teeth were found at Warner Wash, at Oljeto, and in Buell Park.

CONDITIONS OF DEPOSITION.

The geologists of the Wheeler Survey concluded that the Shinarump was a marine deposit.[1] Dutton[2] states that the conditions under which the Shinarump conglomerate "accumulated would seem to have been remarkably uniform and may have been similar in some respects to those attending the formation of coal." Gilbert thought that an inland sea covered this region during Triassic time and speaks of "logs and leaves drifted from the shore." Huntington and Goldthwait[3] considered the origin of the Shinarump conglomerate an open question, but to these authors the weight of evidence seemed to indicate that "in part, at least, it is nonmarine"—a conclusion based, however, on erroneous assumptions, including marine origin of the Moenkopi, the

[1] U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, 1875.
[2] Dutton, C. E., op. cit. (Geology of the High Plateaus), p. 147.
[3] Huntington, Ellsworth, and Goldthwait, J. W., The Hurricane fault in the Toquerville district, Utah: Harvard Coll. Mus. Comp. Zool. Bull., vol. 42, pp. 210-213, 1904.

limitation of petrified wood to a definite horizon, the thinning of the conglomerate toward "the great central plateau region," and the invasion of the sea at the end of Shinarump time. The descriptions given above of the structure and composition of the Shinarump conglomerate apply to strata deposited on land rather than those laid down under the sea. Features of particular significance are great and sudden variation in texture and mode of stratification; numerous intraformational unconformities, bands and patches and trains of pebbles embedded in sandstone, and sharply marked lateral unconformities, presumably bounding braided channels of ancient streams. It is difficult to conceive of conditions under which strings of pebbles 1 to 2 inches in diameter would be carried seaward for distances of 200 miles and deposited with chunks and logs of wood without any definite indication of marine life. Moreover the Shinarump conglomerate was laid down upon a surface of subaerial erosion.

A relatively rapid transgression of the sea over a nearly base-leveled surface would furnish conditions favorable for the deposition of thin sheets of conglomerate and sandstone, and a disturbing fact in this connection is the presence of pelecypods in the Shinarump at Beautiful Valley, one of which, according to T. W. Stanton,[1] "is almost certainly marine." If marine conditions prevailed during the deposition of the conglomerate, the visit of the sea was brief, for no marine forms appear among the Triassic fossils from beds immediately overlying it.

But the problem is by no means solved even if we exclude the ocean as the agent of deposition. We have still to determine how a stratum of conglomerate and coarse sands, in most places less than 70 feet in thickness, may be spread almost continuously over more than 50,000 square miles of territory. Streams of fluctuating volume and ephemeral character are involved, and long piedmont slopes appear to be necessary. But the position of the streams and the direction in which they were running are not known.

There is no regular gradation in size or shape of pebbles and little change in composition between Winslow and Oljeto, 140 miles, or between Fort Defiance and Toquerville, 250 miles. The pebbles in the conglomerate in the San Francisco volcanic field represent rocks exposed in the Bradshaw Mountains;[2] those in Black Creek Valley may have come from the strata in Quartzite Canyon.

[1] Personal communication, July 15, 1912.

It is not improbable that the pebbles of Shinarump conglomerate were transported from several centers within and around the Plateau province. The presence of a remnant of pre-Cambrian quartzite protruding through Moenkopi shales at Fort Defiance suggests that other ancient land masses now concealed may have been exposed during the erosion interval between the Permian (?) and the Triassic. One fact stands out prominently: No considerable amount of material in the Shinarump has been derived from the underlying Permian (?) and Pennsylvanian strata. The solution of this interesting problem waits upon detailed mapping.

AGE AND CORRELATION.

The Shinarump conglomerate unconformably overlies the Permian (?) of the Navajo country; the fossil wood and fragments of bones in the conglomerate are believed to have Upper Triassic affinities, and fossils of Upper Triassic age appear in the strata above. Among its constituent pebbles are well-rounded chert fragments containing Permian fossils. Similar fragments have not been found in the Moenkopi formation or the De Chelly sandstone of this region. Thin sections were studied by G. H. Girty, who reports as follows:

> These sections show a form clearly belonging to the Fusulinidae. The silicification has made the structure a little hard to interpret, but I think that you have a species of the genus Fusulina itself, a large elongated form related to *F. elongata* of the Guadalupe group (Permian). A species very similar to *F. elongata*, possibly identical with it, occurs in the Nosoni formation of California, which has been regarded as of Pennsylvanian age, but which, there is some reason to believe, may be Permian.

Within the Plateau province the outcrops of the Shinarump conglomerate occupy the same horizon and have remarkable lithologic similarity. Beyond the borders of the Colorado Plateau no beds are known which may be considered equivalent. A tentative correlation of the limestone conglomerate of the Dolores formation with the Shinarump conglomerate was proposed by Cross,[3] but later abandoned.[4]

[2] Robinson, H. H., op. cit., p. 30.

[3] Cross, Whitman, The Triassic portion of the Shinarump group: Jour. Geology, vol. 16, pp. 97-123, 1908.

[4] Personal communication, Feb. 10, 1913.

CHINLE FORMATION.

DEFINITION AND AREAL EXTENT.

The name Chinle formation is proposed for the group of shales, "marls," thin, soft sandstones, and limestone conglomerates lying between the Shinarump conglomerate and the Wingate sandstone. The strata composing the formation are highly varied in structure and in composition, but as a whole they constitute a stratigraphic unit of unmistakable individuality.

The Chinle is widely distributed. The entire formation is present in Chinle Valley, from which its name is derived. It may be continuously traced from Colorado River at Lees Ferry southward along the Echo Cliffs, across the Painted Desert, eastward past Monument Point, through the Hopi Buttes, thence northward along the Pueblo Colorado and Chinle valleys to the mouth of Lukachukai Creek. Another belt of the Chinle formation follows Black Creek Valley and the west base of the Chuska Mountains. In Monument Valley it forms a band at the base of Comb Ridge, and in Dutton Plateau it constitutes the pedestal on which rest the towering walls of Wingate sandstone. The upper part of the formation is exposed in San Juan, Piute, and Navajo canyons. Where the dip is steep, as in Black Creek Valley, the belt of Chinle strata is less than 1 mile wide; on the gently sloping west limb of the De Chelly upwarp and on the slopes of Zuni Mountain and in Monument Valley its width is 3 to 10 miles. South of the Hopi Buttes, where the strata are essentially horizontal, the Chinle crops out at the surface as a band over 20 miles wide.

FIELD APPEARANCE.

The Chinle is the most beautifully colored formation in the Navajo country. Where limestone conglomerate is prominent, the cliff faces are striated with bands of purple, pink, and gray; the friable marls and shales constitute a painted landscape with patches and bands of yellow, ash-gray, drab, lavender, rose, pink, slate, maroon, sienna, lilac, cream, and various shades of red and brown. Patches of blue, of white, and even of black are seen, and chocolate-colored shales predominate toward the base. Travelers on the Santa Fe Railway find in the Chinle beds at the base of Dutton Plateau and between Pinta and Adamana a sample of the brilliantly colored rock fabric that covers large parts of the Navajo country. The formation is displayed in all its beauty north of Fort Defiance, in the vicinity of Chinle, at Ganado, in the Painted Desert, and north of Winslow. Between Holbrook and Indian Wells the painted beds are in sight along the road for 20 miles, and a view of the landscape of vivid and changing color from one of the lava-topped buttes of this region is long to be remembered.

Erosion has carved the less resistant parts of the Chinle formation into badland forms—mounds and domes and short, low ridges, isolated or in groups, separated by trenchlike valleys of intricate pattern. Where sandstone beds are present the resulting erosion forms are mesas and buttes and towers, hats and inverted cups; where limestone is present flat-topped mesas or long lines of cliffs reached by a stairway of shale risers and limestone treads make up the landscape. The Chinle formation is a valley maker, in contrast to the overlying sandstones of the La Plata group which form a red frame for the varicolored pictures developed in the shales.

STRATIGRAPHY.

MAJOR DIVISIONS.

During my first season's work in the Navajo country the Chinle formation appeared to be unusually complex and to vary in texture, color, and composition both vertically and horizontally to so great a degree as to preclude the possibility of subdivision. As the work progressed it became apparent that groups of strata with persistent features could be differentiated, and as an aid for those geologists who are to follow my reconnaissance by detailed studies I have thought it advisable to outline four divisions of the Chinle formation as follows:

Division A, the highest strata: Red, brown, pink, or rarely gray calcareous shales and shaly sandstones, with a few thin beds of limestone and limestone conglomerate; form banded walls at the base of the overlying massive Wingate sandstone; intricately carved into buttes or distributed as a patchy floor over the topmost limestone stratum of division B. Type localities, Mesa de Ventana and Todilto Park.

Division B: Gray, pink, and purple cherty limestone and light to dark red shale, in alternating bands. Limestone is massive or conglomeratic, in beds 1 to 6 feet thick, is highly resistant, and forms the caps of mesas and local plateaus; shales are thin, calcareous, mottled, and friable. Type localities, Carson Mesa, Leroux Wash. (See Pl. X, *A*, p. 46.)

Division C: Shales and "marls," with rare calcareous sandstone, all lenticular, exceedingly friable, variegated with tones of pink, red, ash, and purple; limestone conglomerate in lenses, short beds, and irregular masses is characteristic; gypsum is common, and petrified wood almost universal; weathers into mounds, buttes, and immature mesas with typical badland expression. Type localities: Cottonwood Wash, Black Creek Valley, and Beautiful Valley and Round Rock fossil forest. (See Pl. X, *C*.)

Division D: Dark-red, light-red, chocolate-colored, or rarely gray shales (70 per cent) and shaly sandstones (30 per cent); ripple marked, imbricated; brown conglomerate of lime and clay pebbles occurs in lenses; gypsum common; petrified wood in small amounts; bone fragments abundant; weathers into buttes and mesas divided by sharply cut miniature canyons, producing very rough topography. Rests unconformably (?) on the Shinarump conglomerate. Type locality, Chinle.

TYPICAL SECTIONS.

The following sections selected from 27 that were measured indicate the character of the Chinle formation as shown in different parts of the field:

Section of Chinle formation in Chinle Valley, combined from sections at Carson Mesa, Round Rock fossil forest, and Lukachukai.

	Feet.
Wingate sandstone, light red, massive, cross-bedded.	
1. Sandstone in beds 3 inches to 4 feet thick and arenaceous shales; light-red to yellow-red, mottled with green-white spots; very fine white or rarely red quartz; cement calcite stained with iron; weathers into miniature flat-topped mesas. Thickness, average of three sections	315
2. Limestone, gray-green to pink, massive; abundant chert fragments 1 to 2 inches in diameter; very hard; forms mesa cap over large areas	4
3. Shale, light red, arenaceous, calcareous	6
4. Limestone, green-gray to pink, massive, cherty.	3
5. Shale, light red, calcareous	17
6. Limestone, pink, massive, conglomeratic	3
7. Shale, dark red, calcareous	7
8. Limestone, pink, massive, cherty	2
9. Shale, red, highly calcareous	27
10. Limestone, gray-pink, massive; much chert; prominent cliff maker	3
11. Shale, light red mottled, calcareous, with lenses of limestone conglomerate 2 to 4 inches thick.	45
12. Limestone, pink, cherty; bone fragments	1
13. Shale, light red mottled, calcareous	11
14. Limestone, red mottled, massive	2
15. Shale, light red mottled	10
16. Limestone, pink, with limestone and chert nodules in two bands	6
17. Shale, yellow-red, calcareous	30
18. Limestone, pink, cherty	5
19. Shale, light red, calcareous	28
20. Limestone, mottled, cliff maker; includes teeth and bones of *Metoposaurus*	4
21. Shales and shaly limestone, variegated, irregular foliation; include concretionary pebbles of limestone, mud pellets, and a little gypsum.	30
22. Shales and "marls," brightly colored red, purple, gray, rarely yellow and blue; structure and composition widely and abruptly variant; series of short overlapping lenses of calcareous shale, arenaceous limestone, limestone conglomerate, fine and coarse sandstone, and amorphous clays; contain concretions of limestone, mud lumps, clay pellets, and balls of coarse sand; gypsum common in veins and disseminated fragments; petrified wood in chunks and trees abundant, especially near top; all beds calcareous and friable; forms badland topography	420
23. Sandstone, gray, friable, lenticular, with chunks of mud shale and petrified wood	6
24. Sandstone, light green, evenly thin bedded	14
25. Brown fine-grained sandstone and gray-brown conglomerate in overlapping lenses; conglomerate of gray limestone pebbles one-sixteenth inch to 3 inches and quartz one-sixteenth to one-fourth inch in diameter; gypsum and abundant plant fragments	23
26. Shale, dark red, arenaceous	20
27. Brown fine-grained thin-bedded sandstone and arenaceous shale; lenticular; ripple marked; gypsiferous; contain many thin lenses of sandy mud flakes and conglomerate of concretionary limestone pellets; petrified wood, teeth, and bones in small amounts; estimated thickness.	140
Shinarump conglomerate.	
	1, 182

Bed No. 1 in the above section is classed as division A; beds 2 to 20 as division B, beds 21 and 22 as division C, beds 23 to 27 as division D. A complete section of division D was not measured at this locality.

The walls forming Leroux Wash terminate abruptly with a bed of limestone conglomerate which forms the cap of an extensive mesa. (See Pl. X, *A*.) The cliffs between the limestone and the floor of the wash are formed of divisions B and C of the Chinle, displayed as follows:

Section of Chinle formation, Pueblo Colorado Wash, 12 miles southeast of Twin Buttes.

	Feet.
1. Limestone conglomerate, green-gray; nodules of gray, green, black, dark-red, and brown limestone and chert one sixty-fourth inch to 2 inches in diameter; very resistant; forms top of extensive mesa	4
2. Shale, yellow-red, dark red at base, calcareous and gypsiferous; forms banded cliffs	55

	Feet.
3. Limestone, purple, thin bedded, crumbly, specked with green-gray; forms slight scarp and makes color band on cliff	1
4. Shale, bottom light red, upper part pink and ash-gray; gypsiferous; friable	50
5. Limestone, pink, light red in upper parts, thin bedded; blotched with green-gray spots and bands; concretions of chert and limestone	8
6. Shale, dark to light red, friable, gypsiferous	60
7. Limestone, gray, thin bedded, somewhat concretionary	6
8. Shale and "marls," variegated, gypsiferous, contain gray or rarely red concretions of limestone about half an inch in diameter; bottom 20 feet ash-gray to pink and contains sand concretions; next 25 feet purple to pink; remainder bright brick-red; weathers into badland slopes	120
9. Limestone, concretionary; abundant chert in nodules and stringers constitutes about half the rock; rare red nodules of lime; forms cliffs.	2
10. Shales or "marl," light red below, dark purple above; contains abundant chert in nodules and irregular bands; also much gypsum	57
11. Limestone, purple, with pebbles of concretionary limestone, quartz, and chert	1
12. Shale, dark red, purple below, crumbly, friable, gypsiferous, marly; some petrified wood; largely covered	100+
	364+

The beautiful banded cliffs facing the Painted Desert in the escarpments of Ives Mesa, Newberry Mesa, and Ward Terrace are cut from strata of the Chinle formation. In this region erosion has largely removed the sandstones of division A, and the beds of division D are in most places buried by alluvium and wind-blown sand. Divisions B and C are displayed on Ward Terrace as shown in the following section:

Section of Chinle formation on Ward Terrace east of Black Point.

[Measured with the assistance of K. C. Heald.]

	Feet.
1. Limestone conglomerate, green-gray, with chert; resistant, bone fragments and gastropods in loose blocks; forms top of plateau	5
2. Shale, pink, light and dark chocolate-red, and ash-gray, argillaceous, paper-thin, highly calcareous, gypsiferous; contains short lenses of limestone conglomerate and of sandstone; forms slope with knife-edge spurs	195
3. Sandstone, brown, calcareous cement; at top is a 2-inch sheet of gray and yellow limestone pebbles	2
4. Shale, red and ash-gray, calcareous, argillaceous, and arenaceous	6
5. Sandstone, brown; calcareous cement; black, red, and white angular quartz; fine; gritty; some gypsum	2
6. Shale, pink, red, and ash-colored, splotched with white and green-gray, calcareous, argillaceous, paper-thin	12
7. Limestone, green-gray and purple; a knobby, rough bed; irregular concretionary masses of limestone containing other limestone concretions; set in pink and pink-purple shales or marls, which are spotted with greenish-white blotches; few tiny subangular grains of quartz and fragments of dark-red shale distributed throughout; all highly calcareous; erodes in grotesque forms	15
8. Shale like No. 12	33
9. Limestone conglomerate of concretions half an inch or less in diameter; contains thin beds of sandstone	3
10. Shale like No. 12; forms slope	15
11. Conglomerate of light-green and purple-red shale fragments, with limestone and a few tiny grains of quartz; forms bench; is a lens	4
12. Sandstone and argillaceous shale or "marl"; very thin bedded, friable, flaky, cross-bedded, highly lenticular, gypsiferous; includes limestone concretions	60
13. Conglomerate of limestone concretions, red and white quartz, biotite, gypsum, and muscovite; contains bones and teeth and specimens of *Unios* converted into gypsum; calcareous and gypsiferous cement; strongly cross-bedded	1
14. Shale and sandstone in irregular beds; sandstone gray, fine grained, of white and red quartz, biotite, and lenses, thin beds, and single lines of limestone pebbles; shale dark red, purple, and ash-colored, markedly cross-bedded, in laminae of paper thickness; cement calcareous; irregular limestone concretions common; in places dark purple-red clay shales predominate and develop as lenses 30 to 80 feet long and 3 to 10 feet thick; gypsum in seams and scattered specks; petrified wood common; weathers into badland knobs, rounded divides, and box canyon heads	50
	403

Along the borders of Monument Valley the Chinle formation is almost continuously exposed, and along the east edge of Skeleton Mesas the deeply cut canyons reveal all or parts of the formation. A typical section including divisions A and B and the upper part of division C was measured as follows:

Section of Chinle formation at mouth of Segihatsosi Canyon.

	Feet.
Wingate sandstone.	
1. Sandstone and sandy shale, dark red, in beds 2 to 5 feet thick	190
2 Limestone, pink, arenaceous, shaly; contains small concretions and six bands of fine-grained greenish limestone conglomerate	10
3. Limestone, green-white, nodular and conglomeratic	12

		Feet.
4.	Shale, red and green banded, calcareous.......	50
5.	Arenaceous red shale and light-green nodular conglomeratic limestone; limestone strata 6 inches to 2 feet thick; shale 1 foot to 6 feet thick..	45
6.	Covered..	15
7.	Limestone, like No. 9........................	5
8.	Shale, bright red, sandy........................	10
9.	Limestone conglomerate, red-gray; pebbles of quartz, calcareous sandstone, and limestone; fossil bones and teeth........................	5
10.	Calcareous sandy shale, calcareous sandstones, and impure limestones, very irregular in bedding, poorly consolidated; locally called "marls"; brilliantly colored in bands and patches, red, brown, pink, purple, lavender, ash, and green; include many lenses of limestone conglomerate, balls of chalcedony, veins of gypsum; much petrified wood, rare bones, teeth, and *Unio* shells; weather in badland mounds with furrowed slopes; base not exposed..............................	250
		592

FEATURES OF OTHER SECTIONS.

At the base of Dutton Plateau continuous exposures of the Chinle may be traced from San Antonio Springs to the hogback east of Gallup. In this area the red sandstones and shales of division A and the shales and marls separated by thin beds and lenses of limestone conglomerate (division B) differ in no essential from corresponding portions of the Chinle formation analyzed above. The same may be said of exposures in Navajo, Piute, and Copper canyons, and of the variegated shales exposed between Moenkopi Wash and Lees Ferry and in the petrified forests north and south of the Puerco at Adamana. At all these places sections were measured. In Black Creek Valley between Fort Defiance and Red Lake nearly 1,000 feet of the Chinle is exposed, about half of which is assigned to division C. The strata include an unusual amount of mica on bedding planes, and many of the sandstones of division D are tangentially cross-bedded and rippled. Massive limestone was not found at this locality and the numerous lenses of limestone conglomerate are thin and impure. The strata are so variable in extent and composition that in two sections 1 mile apart only the sandstones of division A could be correlated with confidence. In Todilto Park, where all of division A is exposed, the regular alternation of red sandstone and shale is a noticeable feature, the couplet sandstone 4 feet and shale 4 feet being repeated 13 times. The lava caps of many of the Hopi Buttes preserve parts of the formation. In this area the strata are unusually friable; thin dikes of gypsum and of calcite are more resistant to erosion than the "marls" and "mortar beds" of concretionary limestone. The "marls" of division C on Newberry Mesa are almost without structure; they form long, even slopes uninterrupted except for protruding logs of petrified wood and pillows of concretionary limestone. East of Tanner Crossing Mr. Heald found the limestone conglomerate at the top of division D to contain over 50 per cent of quartz pebbles and to change abruptly along the strike into sandstone containing pellets of shale and nodules of chert.

GENERAL FEATURES OF STRATIGRAPHY AND LITHOLOGY.

Vertebrate or invertebrate fossils were found in the limestone conglomerates of divisions B, C, and D, and petrified wood was obtained from all the subdivisions. In the beds overlying the Shinarump conglomerate wood is not common except immediately at the bottom; in division B it occurs irregularly and is wanting in many localities, and the only wood observed in division A was a few impressions of twigs. Division C is the principal wood zone, and in it occur the newly discovered fossil forests at Round Rock, Beautiful Valley, Willow Springs, and elsewhere, as well as the forests north of Adamana, first described by Whipple.

The peculiar limestone conglomerate was found at all exposures where divisions B, C, and D were examined, and at a few localities small lenses were observed in division A. In the lower beds the conglomerate is exceedingly variable in thickness and extent of lenses and in size of constituent pebbles. At Chinle five overlapping beds with a combined thickness of 10 feet were measured by Mr. Heald, and 5 miles farther north seven lenses ranging in dimensions from 6 inches by 6 feet to 20 by 200 feet and consisting of loosely cemented pebbles one sixty-fourth inch to 3 inches in diameter were observed. At the Fort Defiance school 10 feet of conglomerate with pebbles varying in shape from rounded pellets the size of a pea to shaly limestone fragments 4 inches in length caps a hogback. In the Oljeto region lenses of conglomerate 300 to 400 feet long and 5 to 30 feet thick are interbedded with shales of division D. In the marls and friable shales and sandstone of division C the conglomerate occurs with extreme irregularity in thin bands, in fat, short lenses, and at many places in detached balls, pellets, and lozenges displayed without apparent relation to stratification. In the upper beds 2 miles southeast of Tunnel Springs, 100 feet below the Wingate sandstone, the limestone occurs as pebbles one sixty-fourth to 1 inch in diameter scattered through lenses of green-gray sandstone and associated with reddish fragments of chert reaching 4 inches in longest diameter. The limestone conglomerates of divisions C and D are commonly associated with gray, greenish-gray, and purple blotched lenticular cross-bedded sandstone. In division B limestone attains its greatest development and becomes a persistent stratigraphic member. As shown in the sections on pages 43–45, the strata range in thickness from 1 foot to 10 feet and occur as gray, drab, or pink lenses or as thin beds of wide extent. At no place were less than three beds noted; five to seven beds are commonly present in the Hopi Buttes area; and 2 miles north of Tyende eight bands of limestone separated by shale retain their individuality for 5 miles, a mode of occurrence more or less typical for division B but quite unlike that of the conglomerate lenses in divisions C and D. (See Pl. XI, *B*.) Many of the limestone beds are compact and so resistant as to determine the topography; part of them are loosely cemented. Pebbles of lime constitute over 90 per cent of the conglomerate, and in certain places there is no other ingredient. Chert, however, is a common constituent; shale fragments and tiny well-rounded grains of quartz also occur in the limestone.

The shales throughout the Chinle formation are arenaceous and calcareous. They have a noticeable argillaceous content only in division C, and even here fine shaly sandstone and even coarse sandstone with pebbles of quartz and quartzite are found. In this division all the beds are highly irregular and change markedly in character within a distance of a few feet along the strike. In a branch of Pueblo Colorado Wash, 3 miles north of Tanner Spring, is a group of calcareous beds consisting of balls of limestone, grains of quartz, and slabs of brown sandy hardened mud, all arranged in laminae whose surfaces show mud cracks. Gypsum is widely disseminated in the shales of division D and particularly in division C, where stringers and lenses and balls of gypsum are of common occurrence. The cement of all the shales examined is calcareous.

The materials called "marl" in the reports of Marcou, Newberry, Ward, and others are highly calcareous shales and sandstones with microscopic grains of quartz and lime, and practically without structure except for closely packed concretionary masses. The "marls" appear to be accumulations of lime silt that attain thicknesses of 5 to 60 feet. (See Pl. X, *C*.) They are spotted and streaked with a variety of color in a capricious manner. On weathering they cover the surface with flakes and crumbs into which the foot sinks deeply. Climbing a slope of water-soaked "marl" is a precarious undertaking.

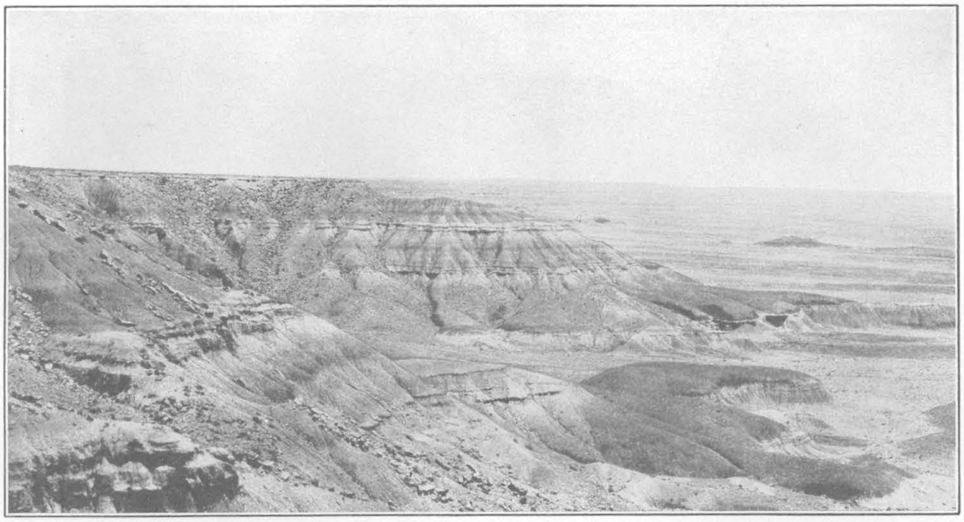
Division A, though in general light or dark red, in many places takes on orange or even yellow tones. In many places along the base of the Chuska Mountains, in Pueblo Colorado Wash, near Bidahochi, along Chinle Wash, and elsewhere the thicker beds are beautifully banded with white in long parallel or divergent lines or short lenses or even dots. Near Zilditloi Mountain and at Indian Wells the material appears amorphous, like chunks of dark-red clay squeezed together. At these localities the beds weather into pillows and spools and bobbins of fantastic shape unlike typical exposures of the Chinle.

Cross-bedding and ripple marks in sandstones, sun-baked surfaces and rare mud cracks, rain prints, and worm casts are features of many beds.

AGE AND CORRELATION.

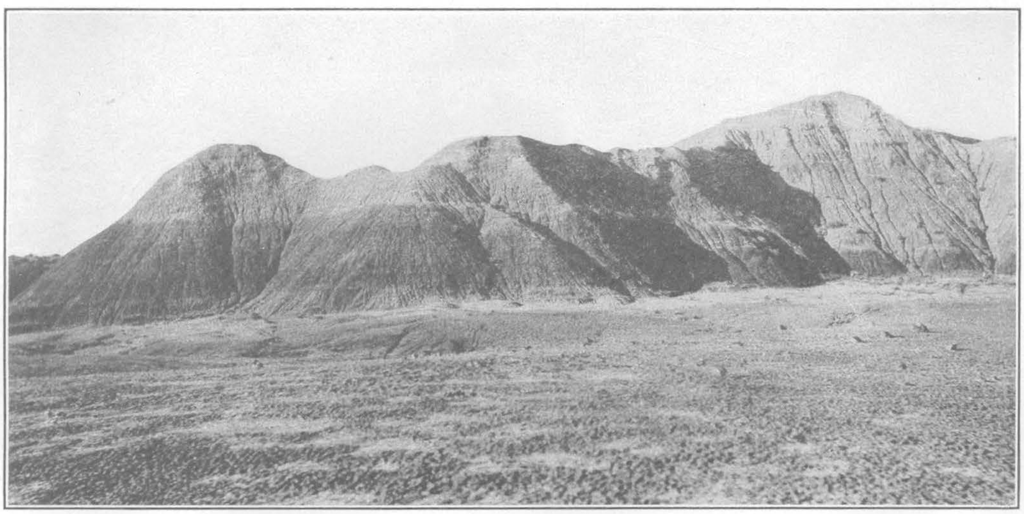
The age of the Chinle formation is determined by small collections of fossils from several places within and near the Navajo country. The fossils obtained from the "Leroux" (part of Chinle) at Tanner Crossing by Ward and Brown were described by Lucas, who determined the species *Episcoposaurus* sp.?; *Heterodontosuchus ganei*, *Metoposaurus frassi*, *Placerias hesternus*, *Palaeoctonus* sp.? These forms were assigned by Lucas [1] to the

[1] Lucas, F. A., Vertebrates from the Trias of Arizona: Science, new ser., vol. 14, p. 376, 1901; A new batrachian and a new reptile from the Trias of Arizona: U. S. Nat. Mus. Proc., vol. 27, pp. 193-195, 1904.

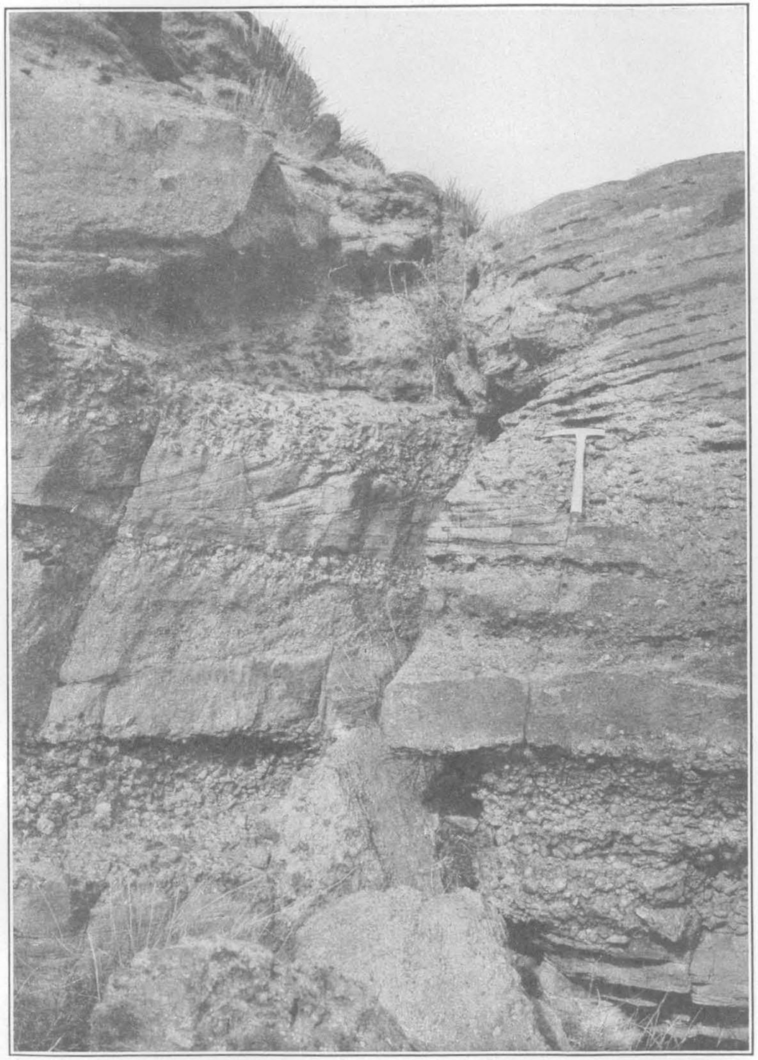


A. BLUFFS BORDERING LEROUX WASH, ARIZ.
Strata of Chinle formation, division B.

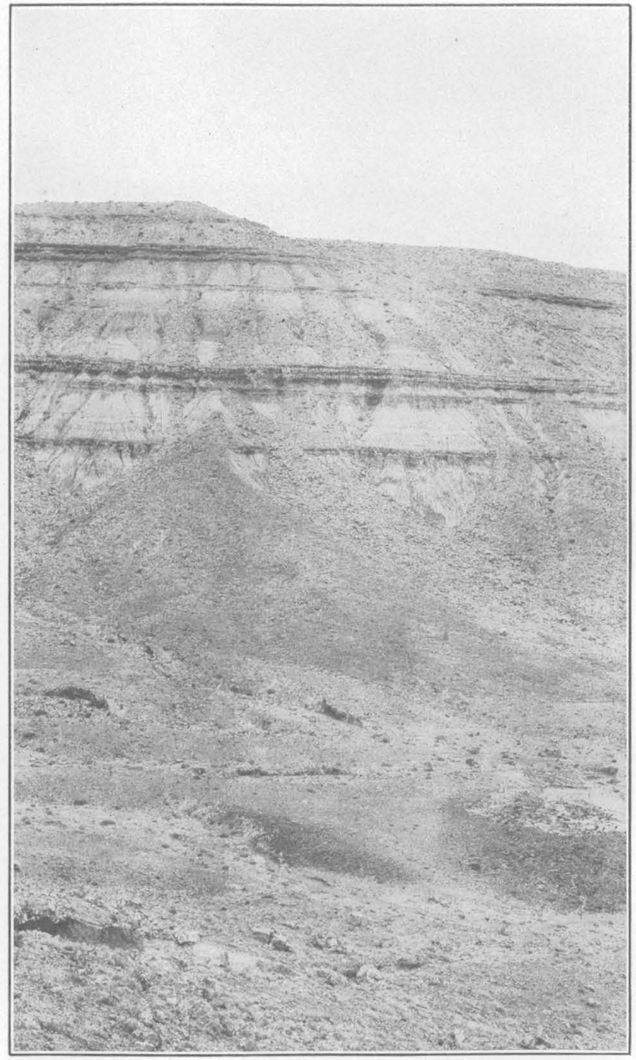
B. PETRIFIED TREE, LITHODENDRON WASH, ARIZ.



C. VIEW IN BEAUTIFUL VALLEY, ARIZ.
Buttes carved from Chinle formation, division C; boulders are fragments of petrified wood.



A. SHINARUMP CONGLOMERATE NEAR FORT DEFIANCE, ARIZ.



B. CHINLE FORMATION 2 MILES NORTH OF TYENDE, ARIZ.

Upper Triassic with the remark: "We have in these Triassic beds of Arizona * * * the same combination of belodont and labyrinthodont as in the Keuper." *Metoposaurus*, probably *Metoposaurus frassi*,[1] was obtained at Tucker Springs, and undescribed phytosaur and labyrinthodont bones were collected by Williston [2] on the flanks of Zuni Mountain. The Triassic crocodile *Heterodontosuchus ganei* was also found 10 miles north of San Juan River and is common in the Dolores formation of Colorado.[3] *Unio cristonensis*, considered by Stanton [4] as probably Triassic, was obtained from divisions B and C, and the invertebrates collected by Woodruff near the top of the Chinle formation in San Juan Valley are considered also by Stanton as "probably Triassic." [5] Collections of vertebrate fragments from the Chinle beds (divisions C and D) at Copper Canyon and at Chinle have not been identified, but according to Prof. Lull [6] they have Triassic affinities. The petrified wood of the Chinle of the Navajo country has not been specifically determined.

In the course of my field work I have become familiar with the Mesozoic formations studied by previous workers in the Plateau province south of Colorado River and to a lesser degree north of that river and north of the San Juan and have found little difficulty in recognizing the Chinle formation in Arizona, New Mexico, Utah, and Colorado. Its position between the Shinarump conglomerate and the Wingate sandstone and its assemblage of varied but persistent features warrants the making of lithologic correlations with confidence.

The Chinle includes portions of Newberry's "Red Sandstone series" and "Variegated marls." Just what portions of these series are equivalent to the Chinle formation it is impossible to state, for the lower limit of the "Variegated marls" is set at 115 feet above the Shinarump conglomerate [7] and its upper part includes the La Plata and McElmo sandstones. The "Leroux member" of Ward's "Shinarump formation," [8] consisting of 800 feet of "argillaceous and calcareous marls," sandstones, limestones, and "mortar beds," is apparently equivalent to division B and part of division C of the Chinle. Division A of the Chinle is represented in Ward's section by 100 feet of "red-orange sandstones," assigned to the "Painted Desert formation." Division D and part of division C of the Chinle are included by Ward in that remarkably heterogeneous assemblage of strata, the "Lithodendron member." The "upper Shinarump" "shales" and "clays" of Dutton, Gilbert, Howell, and Marvine are substantially the equivalent of the Chinle. Dutton makes no mention of limestone conglomerate in the strata exposed north of Wingate station, but Gilbert noted 6 feet of purplish limestone at this locality. Beds of limestone and limestone conglomerate are not described by the geologists of the Wheeler Survey, and no such strata are included in the "section of Jurassic and Triassic formations in the Kanab Valley" studied by Walcott in 1879.[9]

Huntington and Goldthwait [10] found at Toquerville, Utah, beds corresponding in position to the Chinle, consisting of 250 feet of soft purple and red shale capped by 100 feet of "mauve sandstone." To these strata they applied the name "Painted Desert" in a sense unknown to Ward, the originator of the term.

Many years of detailed study of the Mesozoic of southwestern Colorado by Cross has resulted in delimiting the Dolores formation,[11] which occupies the stratigraphic position of the Chinle. The Dolores unconformably underlies the lowest La Plata sandstone (Wingate sandstone) and rests unconformably on the Cutler (Permian?), the Rico (Permian?), or the Hermosa (Pennsylvanian). About 400 feet of Dolores strata are exposed in the Rico quad-

[1] Determined by E. C. Case, personal communication.
[2] Williston, S. W., personal communication.
[3] Cross, Whitman, The Triassic portion of the Shinarump group, Powell: Jour. Geology, vol. 16, p. 116, 1908.
[4] Stanton, T. W., personal communication.
[5] Woodruff, E. G., Geology of the San Juan oil fields, Utah: U. S. Geol. Survey Bull. 471, p. 85, 1912.
[6] Lull, R. S., personal communication.
[7] Newberry, J. S., Geological report, in Ives, J. C., Report upon the Colorado River of the West, pt. 3, p. 79, 1861.
[8] Ward, L. F., Status of the Mesozoic floras of the United States: U. S. Geol. Survey Mon. 48, p. 45, 1905.
[9] Quoted by Cross, Whitman, and Howe, Ernest, Red Beds of southwestern Colorado and their correlation: Geol. Soc. America Bull., vol. 16, pp. 484-485, 1905.
[10] Huntington, Ellsworth, and Goldthwait, J. W., The Hurricane fault in southwestern Utah: Jour. Geology, vol. 11, pp. 46-63, 1903; The Hurricane fault in the Toquerville district, Utah: Harvard Coll. Mus. Comp. Zool. Bull., vol. 42, pp. 201-259, 1904. The stratigraphic units proposed in these publications—Upper Verkin, Lower Verkin (changed in the second paper to Moencopie), Shinarump, Kanab, and Colob—are described briefly and without measured sections. It has been found unprofitable to attempt to correlate them with the subdivisions established by Dutton, Gilbert, Walcott, Ward, or Cross.
[11] Cross, Whitman, U. S. Geol. Survey Geol. Atlas, La Plata folio (No. 60), 1899; Rico folio (No. 130), 1905.

rangle and 1,700 feet in the La Plata quadrangle. The lower portion of the Dolores consists of "reddish sandstones, more or less shaly, with conglomerate consisting chiefly of very small limestone pebbles."[1] "The upper memmember of the Dolores is commonly a very even, fine-grained reddish sandstone free from conglomerate but variably shaly."[2] The upper part of the Dolores as described by Cross appears to be the equivalent of division A of the Chinle; the lower part may represent division B or D or even an abbreviated form of divisions B, C, and D combined. The variegated shales and "marls" of division C, with their wealth of fossil wood, have not been found in Colorado, and the 1,000 feet or more of "arkose sandstone and conglomerate" at the base of the Dolores in the La Plata quadrangle were not found in the Navajo country. From published descriptions supplemented by a small amount of field work along Dolores River I have gained the impression that the Dolores is to be correlated with the upper half (divisions A and B) of the Chinle. The statement of Cross[3] "that the Shinarump (as defined by Powell) may include important divisions not represented in the Dolores" is verified, and among those divisions is part, at least, of division C of the Chinle formation and the Shinarump conglomerate, which, as I have elsewhere shown,[4] occurs at a lower horizon than the fossiliferous limestone conglomerates ("Saurian conglomerate") of the Chinle and the Dolores.

CHINLE-WINGATE CONTACT.

Wherever the contact between the red or orange-red shales of the upper Chinle and the massive Wingate sandstone was observed care was taken to search for evidence of unconformity. The strata are well displayed for such an examination, as along cliff bases and in canyon walls the contact may be traced without interruption for distances of 1 to 5 miles. No channeling or other conspicuous evidence of a break in sedimentation was observed, but at many places the contact is marked by a thin band of leached material and a disturbance of the otherwise regular stratification. In lower Piute Canyon 5 to 15 feet of irregularly curved, highly varied strata resting unevenly on shales and limestone conglomerates mark the base of the Wingate. East of Tanner Crossing Mr. Heald found at the top of the Chinle a 2-foot bed of "conglomerate" consisting of well-rounded pebbles of quartz with rare limestone, gray shale, and red quartzite fragments arranged as stringers, cross-bedded, and with ripple-marked and mud-cracked surfaces. A slight change in direction of strike and dip was also noted. Six miles southwest of Tuba a similar stratum forms the top of the Chinle formation. In Laguna Canyon, at Azansosi Mesa, and at the east base of Carrizo Mountain the Wingate sandstone rests on a slightly irregular knobby surface of calcareous shales on which are spread sheets of gray sandstone containing white and black quartz and chunks of gray shale. In Piute and Copper canyons similar relations were noted. In Todilto Park an irregular bleached band at the base of the Wingate sandstone rests on wavy, knobby, imperfectly bedded layers of Chinle shale into which project strings of white sandstone like the filling of mud cracks.

Although such features are proofs only of local unconformity, I am inclined to consider them of greater significance, in view of the fact that an erosion interval at this horizon has been noted beyond the borders of the Navajo Reservation. Thus Gilbert[5] states:

> In the region of the Virgin River and Kanab Creek the change from the variegated shales of the Upper Shinarump to the homogeneous sandstone of the Vermilion Cliff is gradual, * * * but in one locality, at least, there is direct evidence that the surface of the clay was exposed to the air before it was covered by the sand. On the northern flank of Mount Ellsworth are the vestiges of a system of mud cracks, such as form where wet clays are dried in the sun. Where the under surface of the Vermilion sandstone is exposed to view it is seen to be marked by a network of ridges, which once occupied the sun cracks of the Shinarump clay; and where the clay is seen in juxtaposition, tapering fillets of sand can be traced from the ridges downward 10 feet into the clay.

Dutton[6] remarks: "The contact [of the Triassic Vermilion Cliff sandstone] with the shales [Shinarump] below is usually conformable, but in the vicinity of Hurricane fault * * * the junction is often unconformable." Cross[7] indicates an unconformity between the Dolores and the La Plata sandstone.

[1] Cross, Whitman, and Howe, Ernest, op. cit., p. 467.

[2] Idem, p. 468.

[3] Cross, Whitman, and Howe, Ernest, op. cit., p. 496.

[4] Gregory, H. E., The Shinarump conglomerate: Am. Jour. Sci., 4th ser., vol. 35, p. 437, 1913.

[5] Gilbert, G. K., Report on the geology of the Henry Mountains, p. 9, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1880.

[6] Dutton, C. E., Report on the geology of the High Plateaus of Utah, p. 148, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1880.

[7] Cross, Whitman, U. S. Geol. Survey Geol. Atlas, Ouray folio (No. 153), 1907, and elsewhere.

SILICIFIED WOOD OF THE TRIASSIC.

Fossil wood was first noted in northern Arizona by Capt. Sitgreaves[1] in 1851, 6 miles northwest of the mouth of Zuni River, on the border of the area set aside in 1906 as the Petrified Forest National Monument. The so-called North Forest was discovered by Whipple[2] and Marcou in their traverse of northern Arizona in 1853. The unusual abundance of fossil wood at this locality suggested the name Lithodendron Creek for the northern tributary to Rio Puerco, along whose banks silicified logs were strewn in profusion. The fossil wood discovered by the Ives expedition of 1857–58 on Ives Mesa, in the Pueblo Colorado Valley, and at Fort Defiance is described by Newberry.[3] As the work of the Powell and Wheeler surveys progressed it was found that accumulations of petrified wood were not localized, but were coextensive with the Plateau province.

The abundance of fossil wood both north and south of Colorado River is almost incredible, and its presence has made a profound impression on the native tribes. To the Navajos the logs are yeitsobitsin, the bones of yeitso, a monster who was destroyed by the sun and whose blood was congealed in lava flows. In the Piute mythology the broken trunks are the spent weapons of Shinárav, the great Wolf God; the accumulated masses mark the sites of battle fields.

In the Navajo country fossil wood constitutes a characteristic feature of the Triassic sedimentary beds; it is found wherever the Shinarump conglomerate or Chinle formation is exposed by erosion. On Lithodendron Creek, in Beautiful Valley, at Round Rock, and at Willow Springs petrified logs and chips are sufficiently abundant to justify the term fossil forests. At those localities solid logs exceeding 50 feet in length may be counted by the dozen, blocks 3 to 10 feet long occur in hundreds, and the scattered chips are innumerable. At other localities the wood is only slightly less abundant. In the North Forest, on Lithodendron Creek, where the trees are best displayed within an area of about 1,200 acres, a number of logs have lengths of 30 to 40 feet, and diameters of 3 to 4 feet; the largest seen is about 70 feet long and measures 6½ feet at its flattened butt. The Beautiful Valley Forest, covering about 3 square miles, contains 10 logs between 50 and 80 feet in length and averaging about 3 feet in diameter, in addition to hundreds of smaller dimensions. The floor of the valley in places is literally paved with blocks of fossil wood. In the Round Rock or Senakahn Forest the trees are as abundant as at any other place known. Trunks 30 to 60 feet in length, with diameters of 1 foot to 5 feet, were measured. The Willow Springs Forest, about 5 square miles in area, includes dozens of silicified trees in the midst of chips so abundant as to conceal the strata beneath. At this locality Mr. Pogue measured a trunk 4 feet in diameter at the butt and 150 feet long, the largest tree so far reported from the Navajo Reservation. At Lees Ferry logs 60 feet long are not uncommon.

The tree trunks are very unevenly distributed. They usually occur in widely spread groups of unassorted large and small trees, all lying flat and trending in parallel or diverse directions, or overlying one another, like fallen timber in the path of a tornado. In Nokai Canyon a nicely laid pile of eight logs, 7 to 15 feet long and 3 to 4½ feet in diameter, occupies an isolated position, and at certain localities only a single log is to be found within an area of several acres. No complete trees were seen; most of the logs terminate abruptly, with worn surfaces at both ends. A few trees are still attached to their upturned stumps, and at several places stumps with root bases attached were noted. There is a singular scarcity of small branches and twigs, and a somewhat careful search for cones and needles resulted in finding none.

The logs are not confined to a single horizon. Their lowest stratigraphic position is the base of the Shinarump conglomerate, from which they protrude in places like projecting roof beams of houses. Some of the largest logs seen are lying directly on the old erosion surface separating the Permian (?) from the Triassic. Throughout the Shinarump conglomerate the wood occurs—in the coarser materials usually as angular pebbles, in the sandstone lenses as blocks and logs. Tree trunks are common in

[1] Sitgreaves, L., Report of an expedition down the Zuni and Colorado rivers, p. 7, 33d Cong., 1st sess., Senate Ex. Doc., 1854.

[2] Whipple, A. W., U. S. Pacific R. R. Expl., vol. 3, pt. 1, p. 74, 1856.

[3] Newberry, J. S., Geological report, in Ives, J. C., Report upon the Colorado River of the West, pt. 3, pp. 79–80, 91, 1861.

the uppermost part of the Shinarump conglomerate and in the immediately overlying Chinle shales—a horizon that includes the Willow Springs Forest and the largest logs at Lees Ferry, Nokai Canyon, and Copper Canyon and in Middle Moonlight Valley. To judge from the descriptions by Ward [1] and by Merrill,[2] the trees in the Petrified Forest National Monument occur at this horizon. The Beautiful Valley Forest and the Senakahn (Round Rock) Forest are in division C of the Chinle formation, and the trees in the forest on Lithodendron Creek lie among the limestone conglomerates of division C or the lower part of division B.

The logs are usually incrusted with sand or gravel tightly held in place by siliceous cement; less commonly the inclosing mantle is formed of limestone conglomerate, and in the badlands along Cottonwood Wash, in Chinle Valley, and elsewhere imperfectly preserved trunks and logs are embedded in argillaceous "marls."

As exposed on the surface the logs are generally broken into segments a few inches to several feet long, arranged in proper sequence. Some trunks are split lengthwise into rails and slivers. The surface of fracture is commonly smooth and even, as if cut by saws. Most of the trees are composed wholly of silica in the form of jasper and chalcedony; a few consist chiefly of copper, and the wood of one log noted is now represented by iron. Coal and lignite were obtained from the interior of two logs embedded in marl, and carnotite was found in the carbonized wood of Monument Valley. Some of the logs are colored in harmony with the gray sands in which they are embedded, but most of them are colored by iron and manganese and assume beautiful tones of red, brown, yellow, and blue. Superoxidation has added brilliancy to colors on the surface of broken blocks, making the varicolored jasper, a much prized semiprecious gem stone.

The conditions under which the large amount of fossil wood was accumulated in the Triassic sediments are not clearly understood. That the trees grew in the spots where they are now found is highly improbable. Of the standing trees reported one has its roots in the air, the others so far as I have observed are wedged among other logs in a manner common to driftwood. (See Pl. X, *B*, p. 46.) The few stumps noted are in proper position, and Ward[3] is of the opinion that a group of stumps near Tanner Crossing is in place. Mr. Heald, who studied these stumps, considers this conclusion to be open to doubt. No roots extending downward have been found attached to stumps.

It is believed that the tree trunks now turned to stone were carried by streams during floods. Many of them have worn ends and battered sides, and most of them are without bark. Trees of various sizes and ages are huddled together; the blunt end of one log abuts against the side of its neighbor; and collections of trunks are wedged tightly together with different angles of inclination. The sandstone in which most of them occur is cross-bedded and lenticular, is laterally unconformable, and has other features suggestive of fluviatile deposition. The accumulations of trunks in the fossil forests are closely similar to piles of driftwood now seen along Colorado, Little Colorado, and San Juan rivers—piles of trunks and branches, some much worn, some still retaining the bark, crowded together and overriding one another; stumps attached to trees or separate in various positions, some upright, some lying on the surface, others buried in alluvium or wind-blown sand. The logs now stranded on the surface of the lava at Black Falls are about equal in number to the fossil trees in Beautiful Valley. Most of the wood, particularly the logs, must have become silicified in its present location, the process being favored by rapid burial, a water table fluctuating through short periods, and the presence of alkaline solutions.

As seen in the field, the logs appear to represent a number of different kinds of trees, and Knowlton [4] reports that several species are present in the fossil forests at Adamana. The species so far described, *Araucarioxylon arizonicum* and *Woodworthia arizonica*, were obtained in the valley of Lithodendron Wash, along the southern border of the Navajo country.

JURASSIC FORMATIONS.

HISTORICAL SKETCH.

Strata assigned to the Jurassic system have been reported from the Navajo country and from regions beyond its borders. Marcou [5]

[1] Ward, L. F., Status of the Mesozoic floras of the United States: U. S. Geol. Survey Mon. 48, p. 32, 1905.

[2] Merrill, G. P., The fossil forests of Arizona, 1911.

[3] Ward, L. F., op. cit. (Mesozoic floras), pp. 33–34.

[4] Knowlton, F. H., The fossil forests of Arizona: Am. Forestry, vol. 9, p. 214, 1913.

[5] Marcou, Jules, U. S. Pacific R. R. Expl., vol. 3, pt. 4, pp. 150–151, 1856.

speaks of Jurassic rocks along Puerco River, but it is impossible to determine what portion of his "Gypsum formation" is assigned to this age. On the evidence supplied by fossil plants Newberry[1] regarded a 12-foot bed of carbonaceous shale near Oraibi as Jurassic, "the sole representative of the Jurassic series." These beds were regarded by Howell[2] as Lower Cretaceous and in the present report are mapped as Dakota (Upper Cretaceous). Howell assigned "20 or 30 feet of red marl" between White Rock Spring [in Steamboat Canyon?] and Pueblo Colorado [Ganado?] to the Jurassic and stated that "Beds evidently belonging to this series were seen near the Moenkopi. * * * To the eastward it [the Jurassic] thins out rapidly, until in eastern Arizona and in New Mexico it probably disappears entirely. Dutton[3] uses the term Jura-Trias to include all beds between the Permian (?) and Cretaceous of northwestern New Mexico and says: "General considerations, however, strongly favor a Jurassic age for those beds which lie above the Wingate sandstone." Ward assigns no strata to the Jurassic.

Gilbert[4] states:

In the Plateau region of Utah beds referable to the Jura are always found beneath the Cretaceous, but they are not everywhere fossiliferous. Upon both forks of the Virgin River and upon Kanab Creek I found Jurassic forms (including *Camptonectes bellistriatus* and *Pentacrinus asteriscus*) in a cream-colored arenaceous limestone, and they appeared to be restricted to a brief vertical range. Farther east, in the basins of the Paria and Dirty Devil, Mr. Howell found the same species in gray shales overlying the cream-colored beds, which are there sandstones.

The list of fossils from Kanab Valley was increased in number by Walcott,[5] who found the following species in cream-colored magnesian limestone 770 feet below the Cretaceous: *Myalina* sp.?, *Camptonectes bellastriatus*, *C. extenuatus?*, *C. stigius*, *Pecten* n. sp., *Myophoria ambilineata*, *Astarte?* sp.?, *Trigonia?* sp.?, *Ostrea strigilicula*, *Solarium?* sp.?

[1] Newberry, J. S., Geological report, in Ives, J. C., Report upon the Colorado River of the West, pt. 3, pp. 82–83, 129–131, 1861.

[2] Howell, E. E., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 281, 1875.

[3] Dutton, C. E., Mount Taylor and the Zuñi Plateau: U. S. Geol. Survey Sixth Ann. Rept., p. 138, 1885.

[4] Gilbert, G. K., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 174, 1875.

[5] Quoted by Cross, Whitman, and Howe, Ernest, Red Beds of southwestern Colorado and their correlation: Geol. Soc. America Bull., vol. 16, p. 448, 1905.

The La Plata group in southwestern Colorado is assigned by Cross[6] to the Lower Jurassic on the basis of unconformable relations with the Dolores formation (Chinle formation in part), of Upper Triassic age, and a general stratigraphic equivalence with the White Cliff sandstone of Powell, which lies beneath marine Jurassic beds. Higher strata of Jurassic (?) age (McElmo formation) in the San Juan Mountain district are substantially the equivalent of the Morrison in structure, composition, and fossil content.

Reconnaissance surveys of the Navajo country included preliminary studies of the beds between the Chinle formation and the Dakota sandstone. Many sections were measured, the lithologic character of the strata was determined, and fossils and footprints were obtained from the La Plata group (Jurassic) and shells and fragmentary vertebrate material from the McElmo formation (Jurassic?).

PRESENT KNOWLEDGE OF THE JURASSIC OF THE PLATEAU PROVINCE.

The present knowledge of the Jurassic of regions bordering the Colorado and San Juan is in an unsatisfactory state. Although the beds assigned to this system are the most conspicuous members of the stratigraphic column of the Plateau province, their correlation and place in the time scale rests on poorly established assumptions. The unconformity at the base of the La Plata group noted by Cross can not be extended with confidence, and the division plane between the upper La Plata and the McElmo is somewhat arbitrarily drawn on lithologic evidence. The Jurassic beds throughout this region are in large part of continental origin, but the only definite horizon markers are the marine fossils obtained by Gilbert, Howell, and Walcott; and though it is probable that the invasion of the sea followed the deposition of the La Plata sandstones and extended beyond the High Plateaus, no marine sediments of Jurassic age are known south and east of Colorado River. The only fossils found in the La Plata group are those reported from the Navajo Reservation—dinosaur tracks, bone fragments, worm trails, unios, and bits of

[6] Cross, Whitman, U. S. Geol. Survey Geol. Atlas, Engineer Mountain folio (No. 171), 1910.

wood that have Triassic as well as Jurassic affinities. On the other hand, the McElmo formation may be found to belong among Cretaceous rather than Jurassic strata. In general aspect the sequence of Jurassic beds is uniform throughout the Navajo country; the different members, however, thicken and thin, split up or coalesce, and change in color, in response to causes whose significance is not understood. Under the circumstances it seems advisable to record observations rather than to formulate assumptions and draw conclusions. The subdivisions proposed and the descriptions which follow are therefore presented as an introduction for those who may wish to write the Jurassic history of this fascinating region.

MAJOR DIVISIONS OF THE JURASSIC.

In the present report all strata between the Chinle formation and the Dakota sandstone are included in two large subdivisions which are readily recognized in the field by color contrast and lithologic dissimilarity:

1. The La Plata group, Jurassic. Topographically this is the most conspicuous assemblage of strata in northeastern Arizona and southeastern Utah. In a general way it corresponds with the La Plata sandstone as described by Cross. It consists essentially of two massive cross-bedded cliff-making sandstones with smaller amounts of shaly sandstone and of limestone. For the upper formation of the La Plata group the term Navajo sandstone is proposed; the Wingate sandstone of Dutton is the lower massive bed; and the intermediate strata of thin-bedded sandstone and limestone will be described as the Todilto formation.

2. The McElmo formation, Jurassic(?). The name McElmo was proposed by Cross for a series of beds on McElmo Creek. From the type locality I have traced the beds southward to Puerco River and southwestward to White Mesa. The formation consists of sandstones and shales of predominant gray and greenish tints.

LA PLATA GROUP.

DISTRIBUTION AND TOPOGRAPHIC EXPRESSION.

Strata assigned to the La Plata group are nearly coextensive with the Navajo country. They underlie Dutton Plateau and constitute the terraced platform at the west edge of the Chuska Mountains. Lukachukai Mountain overlooks a sea of red Jurassic sandstone extending down the Chinle across the Gothic Mesas to the San Juan. Diminished representatives of the La Plata group are found in the southern part of the reservations and in the walls of the Painted Desert. The group reaches its maximum development on Kaibito, Shato, and Rainbow plateaus and in the Segi Mesas province. This area presents a continuous field of massive red rock trenched by Navajo, Piute, Laguna, Glen, and San Juan canyons.

In architectural features the sandstones of the La Plata group take first rank. Where the strata are horizontal, precipitous cliffs 200 to 800 feet high extend for miles; where dips are steep, as in the Echo Cliffs and Comb Ridge, the serrate edges of the sandstone members project high in air as unscalable pinnacles or stand against the eroded limbs of monoclines like giant flatirons. Round Rock, Los Gigantes, Monument Point, Edna Needle, Echo Peaks, and the less conspicuous "haystacks" east of St. Michaels are examples of innumerable pinnacles and cathedral towers carved from these strata. The most unusual features of the architecture are the caves and alcoves—deep recesses carved out of solid rock, with floor and roof and sides all made of La Plata sandstone. Many hundreds of these cavities were observed, varying in size from pockets a few feet deep occupied by birds and bats to gracefully formed rock shelters whose broad floor and arched roofs provide a home for the cliff dweller. The windows, which pierce the massive walls at Fort Defiance, Mesa de Ventana, Round Rock, and elsewhere, and the natural bridges, which reach their highest development in the magnificent Rainbow arch, give to the La Plata group still greater scenic value.

Considered as a whole, the La Plata group is readily distinguished from the formations which lie above and below it. As displayed in canyon walls and in long cliff faces, the La Plata forms a band of red between a variegated base and a green-white cap. Its beds are usually massive and quite unlike the underlying shales of the Chinle formation and the overlying strata of the McElmo formation. In a few places, however, its massive character is not maintained, its color fades, and the La Plata becomes a less conspicuous feature in the landscape. Moreover, the shaly and thin-bedded Todilto formation varies widely in thickness, and the Wingate and Navajo sandstones are almost identical in composition and structure, so that unless the whole group is exposed in section its subdivisions are in places difficult to establish.

The La Plata group is best displayed through a zone extending northwestward from New Mexico to the High Plateaus of Utah. In the walls of Dutton Plateau it is about 500 feet thick. It maintains or exceeds this thickness in Black Creek and Chinle valleys. In the Segi Mesas province three measured sections include 790, 848, and 930 feet of strata. In the Rainbow Plateau the La Plata exceeds 1,000 feet in thickness, and Mr. Pogue found that the upper massive bed (Navajo sandstone) alone was 800 feet thick at Nasja Canyon.

As the La Plata is traced through southeastern Utah into Colorado it is found to become thinner, and at its type locality, the La Plata Mountains, the total thickness rarely exceeds 400 feet. In the Hopi Buttes region the La Plata sandstone is distinguished with difficulty, and in the formations south and west of the Little Colorado, so far as known, the group is not represented.

TYPICAL SECTION.

The arrangement of beds in the La Plata group is fairly well represented in the following section, measured with the assistance of Mr. Pogue. Beds 1 to 6, inclusive, are the Navajo sandstone, beds 7 to 11 constitute the Todilto formation, and bed 12 is the Wingate sandstone.

Section of La Plata group at northwest edge of Tyende Mesa, Ariz.

	Feet.
1. Sandstone, light brick-red, uniformly fine grained, clear, well-rounded white quartz with rare red quartz; ferric and calcite cement; massive, tangentially cross-bedded, becoming thinly divided in upper half; forms top of plateau set with low mesas	115
2. Limestone, gray-blue, massive, lenticular; forms a bench	3
3. Sandstone, light red, massive, like No. 1	12
4. Limestone, gray-blue, interleaved with thin-bedded, red, shaly sandstone	2
5. Sandstone, light red to terra cotta, fine grained, even textured, slightly calcareous, massive, cross-bedded in long, sweeping curves; the laminae marked by an accumulation of grains slightly larger than normal; forms nearly perpendicular canyon wall decorated with niches and arched roof alcoves	345
6. Sandstone, light red, fine to medium grained, with a thin lens of limestone conglomerate; cross-bedded in part; separated from No. 5, with which it might be included, by a plane along which cross-bedding disappears	70
7. Limestone conglomerate and limestone in overlapping lenses	6
8. Sandstone, light red, in two massive beds	8
9. Shales, light red to purple, arenaceous and calcareous, with greenish mud lumps	10
10. Limestone conglomerate; a lens composed of weathered limestone ranging from grains the size of grass seed to pebbles as large as walnuts. Within 1,000 feet of the section measured this bed ranges in thickness from 3 inches to 20 feet and includes lenses of sandstone and of shale	2
11. Sandstone, light red and dark red, in strata 2 to 6 feet thick, very irregularly deposited	30
12. Sandstone, dark red to orange-red, uniformly fine grained, calcareous cement; upper 50 feet thick bedded; remainder massive and tangentially cross-bedded; forms inner canyon wall marked by curved roof recesses, the sites of cliff dwellings	245
	848

WINGATE SANDSTONE.

In his report on the Zuni Plateau Dutton [1] describes the massive bed above his so-called Lower Trias (Chinle formation of present report) in the following terms:

> Next in order comes the conspicuous stratigraphic member of the whole region. It is a massive bright-red sandstone. Out of it have been carved the most striking and typical features of those marvelous plateau landscapes which will be subjects of wonder and delight to all coming generations of men. It is in reality a group or subgroup of sandstone, in which the lines of bedding are generally but not always effaced. Sometimes, however, the partings are wholly obliterated, so that the edge of the entire subgroup is presented as a single indivisible member. Sometimes a portion of the partings is effaced and a part is so presented. Sometimes partings are seen to divide the whole of it into a series of beds varying in thickness from a yard or two to 20 feet. Most frequently there will be at least 250 feet presented without subdivision and as a vertical wall. This formation is without much doubt the equivalent of the Vermilion Cliff series in southern Utah, but its aspect is somewhat different. We can, however, trace the transition of its outward features by a slow gradation over the intervening country. The thickness of this subdivision, which I have named provisionally in my field notes the Wingate sandstone, varies much from place to place. In the immediate vicinity of the Zuni Plateau its thickness averages about 450 feet.

As displayed at the type locality in the wall of Dutton Plateau the Wingate sandstone presents the following features:

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

Section of Wingate sandstone 1½ miles north of Wingate station, N. Mex.

	Feet.
Todilto formation with thin sandstones deposited on uneven surface of No. 1.	
1. Sandstone, light red, composed of very small quartz grains weakly cemented by iron and lime; massive; highly cross-bedded in straight lines intersecting at various angles, also in curves of several different radii; with No. 3 forms cliff face from the Gallup hogback eastward for 25 miles	225
2. Sandstone, white, fine grained, friable; differs from No. 1 in color only; forms conspicuous band extending for some miles	1
3. Sandstone, dark to light red, uniformly fine grained, calcareous cement; massive; cross-bedded in varying amounts; marked throughout by specks and ribbons and by thin lenses of white; near the base is an irregular white band 6 inches to 1 foot in thickness	40
Shaly sandstones and limestone conglomerates of Chinle formation.	
	266

The thickness assigned by Dutton to the Wingate is considerably greater than any measurements obtained by me and raises a doubt regarding correlation. But the description quoted applies to the Wingate as the term is used in this report, and Darton[1] records a thickness of 400 feet near Guam. Gilbert's section[2] at Bear Springs showing 220 feet of "massive cross-bedded sandstone, red and compact, with white band near base," overlain by 2 feet of crystalline limestone, is almost identical with the one here given.

At widely separated localities between the Zuni Mountains and Kaiparowits Plateau the Wingate sandstone differs in no essential from the type beds at Dutton Plateau. Except in the Moenkopi region it is thick and massive, fine grained, and commonly red.

At the base of the Lukachukai Mountains the Wingate has the following expression:

Section of Wingate sandstone near Lukachukai.

	Feet.
Todilto formation.	
1. Sandstone, light red, fine grained, calcareous cement, massive	12
2. Sandstone, light red, in beds 1 to 5 feet thick, with a 3-inch white band at base	85
3. Sandstone, yellow-red, massive, cross-bedded, in overhanging cliffs	140
4. Sandstone, light red, in thin beds	30
5. Sandstone, light to dark red, thin bedded at bottom, massive at top; in places appears to be succession of shale and sandstone; elsewhere shale forms huge lenses extending for a few hundred feet along the strike	200
Chinle formation.	
	467

[1] Darton, N. H., A reconnaissance of parts of northwestern New Mexico and northern Arizona: U. S. Geol. Survey Bull. 435, p. 46, 1910.

[2] U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 552, 1875.

The Wingate sandstone of Mesa Ventana is a single stratum, light red, massive, intricately cross-bedded, 375 feet thick. South of Crystal it is 200 feet thick. (See Pl. IX, *B*, p. 39.) On the eastern edge of Todilto Park, where 210 feet of the Wingate is exposed, the upper 100 feet is a massive bed with strong vertical jointing and no banding, the lower 100 feet marked with subregular ribbons and discontinuous patches of white. Three miles farther west this bed is 150 feet thick and forms a wall nearly 2 miles long. (See Pl. IX, *A*.) At the west base of Chuska Mountain, where 150 feet of the Wingate stands as a nearly vertical cliff, the upper half is massive and light red, and the lower part is dark red banded with narrow white lines. In Piute Canyon the Wingate is represented by 270 feet of light-red massive cross-bedded sandstone; in Laguna Canyon 200 feet is exposed, and in Segihatsosi Canyon 275 feet; in the Moenkopi region the thickness decreases to 30 feet at Willow Springs; and at Cottonwood Tank the stratum might be described as a series of sandstones in beds 3 to 20 feet thick, separated by sandy shales. At the mouth of the San Juan the Wingate is estimated as 300 feet thick.

It will be seen from the above descriptions that the thickness of the Wingate is variable. Its massiveness is also subject to change, and although in distant views the bed appears as a wall unbroken by horizontal planes, close examination reveals the presence of thin-bedded shaly sandstone at several horizons. These beds so far as noted are not persistent. Two features are of particular significance—cross bedding and texture. Cross-bedding is almost universal and is more prominent near the top. Part of the laminae are straight and meet one another at angles as great as 30°. The prevailing type, however, is tangential, the laminae extending at curves with various radii. (See p. 58.)

The texture of the Wingate sandstone is fine and singularly uniform. The grains range from those of microscopic size to some as large as millet seed, are rounded or subangular, and are loosely held together by lime and iron cement. Only at two localities were grains exceeding one-tenth of an inch in diameter noted. The ledge 1 mile south of Tunnel Springs, considered as typical in composition, consists of clean-washed, scoured grains of translucent white quartz, and a few of red and black quartz, with inconsiderable amounts of feldspar, calcite, and iron. The larger grains which mark the divisions between cross-bedding laminae appear glued to the surface. Microscopic examination of specimens from three localities shows that the rock is composed of grains of translucent quartz, with some plagioclase feldspar, and a little zircon, iron, and garnet. The grains in the body of the rock average about 0.16 millimeter in diameter; those on foliation surfaces 0.45 to 0.60 millimeter. All have imperfect oblong shapes with rounded or broken corners. The cement is calcite or rarely silica but is almost completely concealed by the abundant ferric iron which gives the rock its color. The bounding walls of joints and tiny faults that traverse the sandstone are more resistant than the body of the rock and project as ridges above the surface, and in many places nets of thin quartz seams are etched from the surface and cover the ledge as a lace pattern of irregular detail.

The Wingate sandstone was recognized by Dutton [1] as the equivalent of the Vermilion Cliff sandstone of the Paria Plateau and assigned by him to the Triassic. In my opinion the massive sandstones of the Vermilion Cliff sections are Jurassic and include the Wingate and also part at least of the Navajo. The Wingate is also to be correlated with the lower member of the La Plata sandstone of Colorado and not with the upper portion of the Dolores, as suggested by Cross and Howe.[2] The assumed absence of cross-bedding and the red color of the Wingate of Dutton's type locality—criteria on which the correlation of Cross is based—are not diagnostic, for cross-bedding is present and in the Navajo country the equivalents of the La Plata group are generally red.

[1] Dutton, C. E., Mount Taylor and the Zuñi Plateau: U. S. Geol. Survey Sixth Ann. Rept., p. 137, 1885.

[2] Cross, Whitman, and Howe, Ernest, Red Beds of southwestern Colorado and their correlation: Geol. Soc. America Bull., vol. 16, p. 479, 1905.

TODILTO FORMATION.

CHARACTER AND DISTRIBUTION.

Gilbert's section on the north flank of Zuni Mountain includes a bed of crystalline limestone intervening between two bodies of "massive, cross-bedded sandstone" 220 and 200 feet thick, overlying red and variegated shales [Chinle formation].[3] Near the locality mentioned by Gilbert this bed, 2 feet in thickness, consists of massive, dense, pure limestone, blue-gray on the surface, gray to pinkish on fresh fractures, forming a cap for the lower cliff bench. It appears singularly out of place wedged in between two heavy sandstones. Twelve miles farther east the limestone is 11 feet thick and made up of beds 2 to 4 inches thick of hard compact rock containing pockets filled with calcite and so resistant as to form the flat top of Powell Mountain. For this stratum I propose the name Todilto formation, from Todilto Park, where I first studied it. At this locality it caps an eastward-sloping mesa of Wingate sandstone, and consists of 10 feet of resistant compact blue-gray limestone separated into two parts by a few inches of red sandy lumpy shale containing flattened calcareous mud pebbles. Near the top are well-worn fragments of black, white, and gray quartz and chert in quantities sufficient to form irregular bands embedded in the limestone. At the Lukachukai Mountains the Todilto formation appears as a bed 3 feet thick. In the area west of Chinle only thin detached limestone lenses were noted, and at Round Rock it was not seen. In Laguna Canyon the Todilto is represented by thin layers of limestone conglomerate with fragments of red and gray shale. On Carrizo Mountain the formation was not observed by Emery, but 12 miles west of the mountain, near Hogansaani, he measured the following section:

Section of Todilto formation at Hogansaani, Ariz.

	Ft.	in.
1. Sandstone, calcareous, in beds a quarter of an inch thick, with minute layers of limestone	1	0
2. Limestone, arenaceous		8
3. Limestone, blue-gray, dense		4
4. Sandstone, reddish white, calcareous, contains pebbles of limestone	1	0
	3	0

[3] Gilbert, G. K., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, pp. 351-552, 1875.

Along the San Juan southwest of Bluff, Utah, a group of bedded sandstone, limestone, and shales 30 to 50 feet in thickness separates the two massive sandstones of the La Plata group. From Marsh Pass northward and northwestward the middle part of the La Plata, corresponding to the Todilto formation, thickens and includes increasingly large amounts of shale and thin-bedded sandstone. In the walls of Segihatsosi Canyon the following section was measured:

Section of Todilto formation in Segihatsosi Canyon, Ariz.

	Feet.
Massive Navajo sandstone.	
1. Limestone conglomerate	6
2. Sandstone, calcareous, cross-bedded	8
3. Shales, very thin bedded, calcareous, with purple and green-white mud lumps	10
4. Limestone conglomerate, consisting of flattened limestone pellets. This bed is lenticular and within half a mile varies in thickness from 3 inches to 20 feet through a vertical range of 50 feet	4
Massive Wingate sandstone.	
	28

The rim of lower Piute Canyon is cut in 100 feet of bedded light-red calcareous sandstone with many lenses of calcareous shale and sandstone, limestone, and limestone conglomerate, and the same thickness of bedded strata is shown in a talus-covered slope at the mouth of the San Juan. At Navajo Mountain the corresponding group of sediments is 200 feet thick and contains inconsiderable beds and lenses of limestone. The position of these beds between two massive sandstone strata, Wingate and Navajo, is the basis for their assumed equivalence with the Todilto formation. Their expression, however, is so different from that in the type locality that this correlation must be considered only as a working field hypothesis.

AGE AND CORRELATION.

No fossils were obtained from the Todilto formation, but dinosaur tracks were noted in these beds in Navajo Canyon and at Willow Springs. In Navajo Canyon the tracks occur in a 3-inch bed of highly calcareous sun-cracked sandstone 100 feet below the massive cross-bedded Navajo sandstone. Measurements were taken of size of track, length of stride, and alignment. On the basis of these data supplemented by photographs (see Pl. IX, *C*, p. 39), Prof. Lull[1] has kindly submitted the following report:

The footprints are comparable to those of the Connecticut Valley, the larger one resembling *Eubrontes giganteus* but it is larger and more robust. *E. giganteus* reaches a size of 15 by 10 inches (footprint), while the Navajo form is 22 inches long by 14 inches wide, with an immensely thick middle digit and a stride of 79 inches. No claw nor phalangeal impressions are indicated in the figures, doubtless owing to the character of the sediment.

The lesser track compares most nearly with the Connecticut type known as *Anchisauripus minusculus*, though the latter is slightly longer, averaging 12 inches to 10 inches for the western form, the width in each instance being the same. The Navajo specimen shows a well-defined heel pad similar to that in the eastern species, but aside from this the claws and phalanges are not indicated in the sketch, so that one can hardly judge of affinities. The stride of the lesser Navajo form is 41 inches, to 39 for *A. minusculus*. The tracks are both clearly those of bipedal carnivorous dinosaurs, the larger indicating a form as large if not larger than any known in the Connecticut Trias. They are not older than the latest Triassic.

I have found it impossible to recognize the Todilto formation in Ward's description of the "Painted Desert formation." The Todilto, however, appears to be the same as the middle member of the La Plata of Cross,[2] which is described as follows:

The limestone is often bluish black, of conchoidal fracture and destitute of fossils. The shales which replace it are also dark, some sandy, others grading into limestones. Adjacent to these shales the sandstones are inclined to become thinly bedded and so the complex between the more massive sandstones sometimes exceeds 50 feet in thickness.

TODILTO-NAVAJO CONTACT.

In many localities the Navajo sandstone rests with apparent conformity on shales and limestones of the Todilto formation, and at two places the calcareous shales are increasingly arenaceous toward the top and the limestone lenses are accumulated at the bottom. Elsewhere the Todilto is capped by crumpled lenticular cross-bedded shales with balls and lozenges of amorphous clay and segregated limestone pellets, associated commonly with mud cracks and rarely with ripples whose surfaces are strewn with clean quartz grains. At these places the typical cross-bedded Navajo sandstone is either directly superposed on a wavy surface of calcareous shale or marked

[1] Lull, R. S., personal communication.
[2] Cross, Whitman, U. S. Geol. Survey Geol. Atlas, La Plata folio (No. 60), p. 4, 1899.

at the base by gray lenticular sandstone. Whether these indications of unconformity have more than local significance has not been determined.

NAVAJO SANDSTONE.

DISTRIBUTION AND TOPOGRAPHIC EXPRESSION.

The upper formation of the La Plata group is widely displayed in the Navajo country and is appropriately termed the Navajo sandstone. It is exposed in Black Creek and Chinle valleys and in the Gothic Mesas area, and it forms the surface of Kaibito, Shato, and Rainbow plateaus and of the Segi Mesas. Nearly complete sections are revealed in the walls of Navajo and San Juan canyons, in Glen Canyon of the Colorado, and in the scores of deep, short canyons heading in Navajo Mountains. (See Pls. XXXI, *B*, and XXXII, *B*, pp. 134, 135.) Like the Wingate sandstone, the Navajo sandstone is everywhere a cliff maker, but the absence of resistant cover and the friable nature of the rock results in the production of rounded forms, composing a landscape of remarkable variety and beauty. About Navajo Mountain vertical red walls of deep canyons are terminated by a series of domes, and the intercanyon spaces are covered with overlapping mounds 10 to 500 feet in height. Throughout this area the topography is most inhospitable; many canyons have probably never been traversed by Indians or white men, and the towering buttes have not been climbed.

STRATIGRAPHY.

Sections measured at a number of localities demonstrate the general massive character of the Navajo sandstone and reveal also the presence of beds of shale and limestone. The upper part of the walls of Segihatsosi Canyon, Tyende Mesa, consist of the following strata:

Section of Navajo sandstone in Tyende Mesa, Ariz.

	Feet.
1. Sandstone, yellow to red, cross-bedded, more or less calcareous, massive near bottom, finely divided near top; massive part much like No. 5; forms top of plateau	115
2. Limestone, gray-blue, persistent over wide areas; forms definite bench	3
3. Sandstone, red, massive, calcareous	12
4. Limestone, blue-gray, lenticular, interleaved with thin beds of red sandstone	2
5. Sandstone, yellow to red, even grained, of fine texture, slightly calcareous; more massive, cross-bedded, and redder toward top; forms nearly vertical canyon wall with rounded rincons and overhanging cliff-house coves	345
6. Sandstone, light-red, medium to coarse grained, with one thin lens of limestone conglomerate; conformable with heavy sandstone above	70
Todilto formation.	
	547

Near the head of Piute Canyon Mr. Pogue measured the following section:

Section of Navajo sandstone in Piute Canyon, Ariz.

	Feet.
Limestone, blue to white	5
Sandstone, purplish red, medium grained, calcareous	30
Limestone, bluish gray, in thin beds interleaved with red sandstone	10
Sandstone, yellow-red, cross-bedded	120
Limestone, bluish gray, arenaceous	1
Sandstone, yellow-red, fine to medium grained, bedded to massive, cross-bedded, calcareous; in places weathers with mammillary forms	320
	486

On the mesas west of Piute Canyon the eroded remnants of Navajo sandstone are light red and cross-bedded and contain thin bands of limestone about 150 feet above their base. A much thicker bed along the lower San Juan has been cut down to 300 feet; 800 feet is exposed in a dome near Cha Creek. At no point on Rainbow Plateau was an entire stratum of the Navajo sandstone seen, but it is believed to have attained thicknesses exceeding 1,000 feet. Mr. Pogue found 600 feet of the Navajo in a branch of Navajo Canyon. The upper part of Tyende Creek (Laguna Canyon) is cut entirely in the Navajo sandstone; 400 feet is shown in the canyon walls, but a much greater thickness occurs on the dissected divides westward toward Piute Canyon and eastward over Skeleton Mesa. The surfaces of Segi Mesas and Shato Plateau are dotted with flat-topped buttes and rounded knobs, such as Zilnez, which owe their existence to bands of blue cherty limestone 2 to 4 feet thick, made up of lenses 4 to 8 inches thick. On Kaibito Plateau, 3 miles south of Red Lake, the Navajo sandstone, here 135 feet thick as determined by Mr. Pogue, contains two bands of limestone. At Willow Springs, where 365 feet of fine-grained cross-bedded calcareous sandstone is exposed, a band of cherty blue limestone 1 foot thick was found 165 feet above the base. Along the lower Chinle the Navajo sandstone, 400 to 600 feet thick, is traversed by ribbons of nodular limestone 8 inches to 1 foot wide. In Todilto Park only 200 feet of sandstone has been assigned to the Navajo.

South of Zilditloi Mountain the massiveness of the Navajo sandstone decreases, and the formation becomes thinner. Between Ganado and Leupp no unmistakable Navajo sandstone was seen; but certain outcrops in this area have been assigned tentatively to the La Plata group, as indicated on the geologic map.

STRUCTURE, TEXTURE, AND COMPOSITION.

The Navajo sandstone is nearly everywhere cross-bedded on a scale which for extent and perfection of detail is difficult to exaggerate. Angular cross-bedding was observed, but the prevailing type is tangential; curved laminae become tangent to adjoining surfaces. Starting as highly inclined arcs of small radii the cross-bedding laminae gradually decrease in curvature until they merge into contact with the underlying strata. In some places the arcs are tangent to horizontal surfaces or meet them at angles of 1° or 2°; elsewhere arcs of various radii are tangent to one another. (See Pl. XII, *A*.) Many groups of curved laminae are sharply truncated along horizontal or inclined surfaces. In places the curved laminae have uninterrupted sweeps of 200 to 300 feet; commonly their length is measured in tens of feet, and many cliff faces are decorated by close-set loops and arabesques comparable with the lathe work in steel engraving. In general the cross-bedding laminae are outlined by layers of weakly cemented quartz grains that determine planes of fracture, but in places major joints exert a stronger control and furnish erosion remnants decorated on all sides by intersecting curved lines.

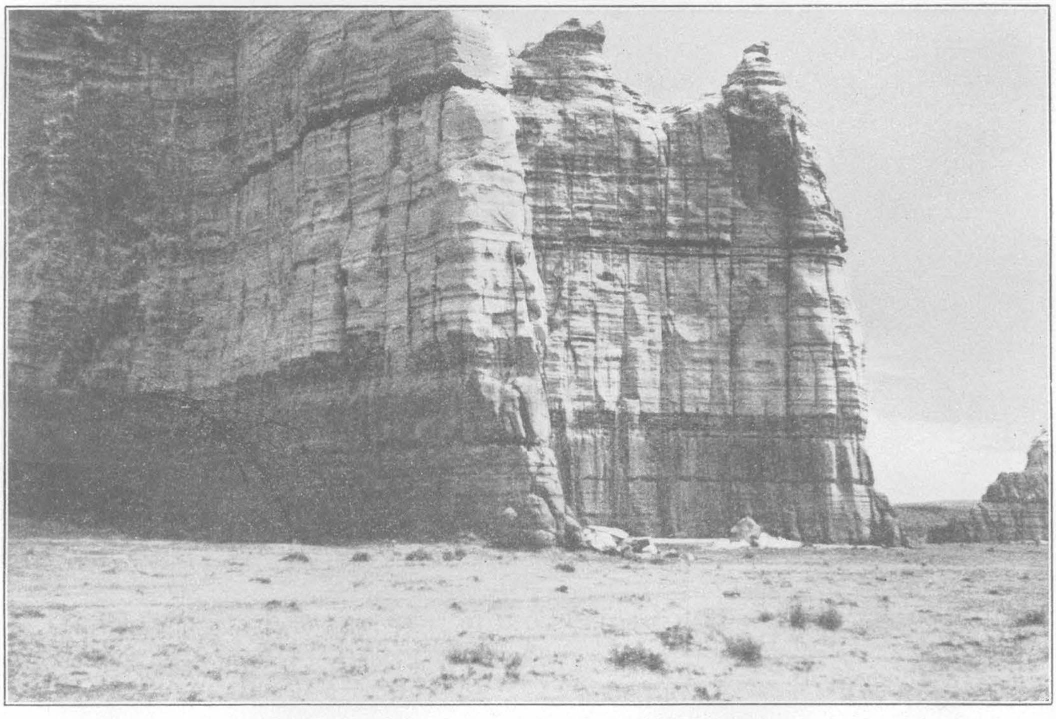
To the tangential cross-bedding are due the exceptional erosion features of the Navajo sandstone—the innumerable pockets, recesses, and alcoves bounded by curved planes which characterize this formation. Overhanging cliffs are common, and the beautiful arc of the Rainbow Bridge is only an unusually perfect example of the control exerted by curved lamination.

The prevailing color of the rock is light red and is surprisingly constant over large areas. Among the Segi Mesas and on the Rainbow Plateau the red tint is so boldly applied that no other color appears in the view. In places, however, dark reds and maroons are seen, and not uncommonly orange and even tan colors add variety to the landscape, and patches of white are not unusual. In the Echo Cliffs the rich red tints of the Navajo sandstone fade into yellow gray and become nearly white in the vicinity of Bitter Springs but the Wingate and the Todilto retain their dominant tones. It is interesting to note that all parts of the La Plata in Colorado are described as white and that the White Cliff sandstone of east-central Utah has been correlated with the La Plata.

The Navajo sandstone is composed of translucent quartz grains, with small amounts of feldspar, rare fragments of zircon, magnetite, garnet, pyroxene (?), and tourmaline (?). In two thin sections examined the grains are imperfectly rounded but without sharp edges; a third specimen consists of almost perfect spheres. The grains are of two sizes; probably 90 per cent of the rock consists of grains ranging between 0.15 and 0.25 millimeter in diameter; the other grains, formed as an interrupted coat on cross-bedding laminae, average about 0.65 millimeter. Only at a few localities were much larger pebbles of quartz, of shale, and of sandstone noted. In general the cement is calcite, with large or small amounts of iron oxide, which is reflected in the varying color of the rock. Hand specimens from the Echo Cliffs and the Chinle Valley have siliceous cement. In places the cement is stained green by copper, and in the White Mesa copper district the original cement is partly replaced by malachite and chrysocolla. Much of the cement is weak and grains of calcite and of kaolin are disseminated; the rock is consequently friable, and even where continuously swept by the wind crumbles under foot. It was found possible to trail a man who had strayed from camp by the hobnail prints he made on a bare ledge. In many places the joints in the Navajo are lined with quartz, and their position is indicated by a tracery of thin white ridges intersecting at various angles. In Copper Canyon, on Shato and Kaibito plateaus, and to a less extent elsewhere, some joints are lined with chrysocolla and other copper minerals. (See p. 141.)

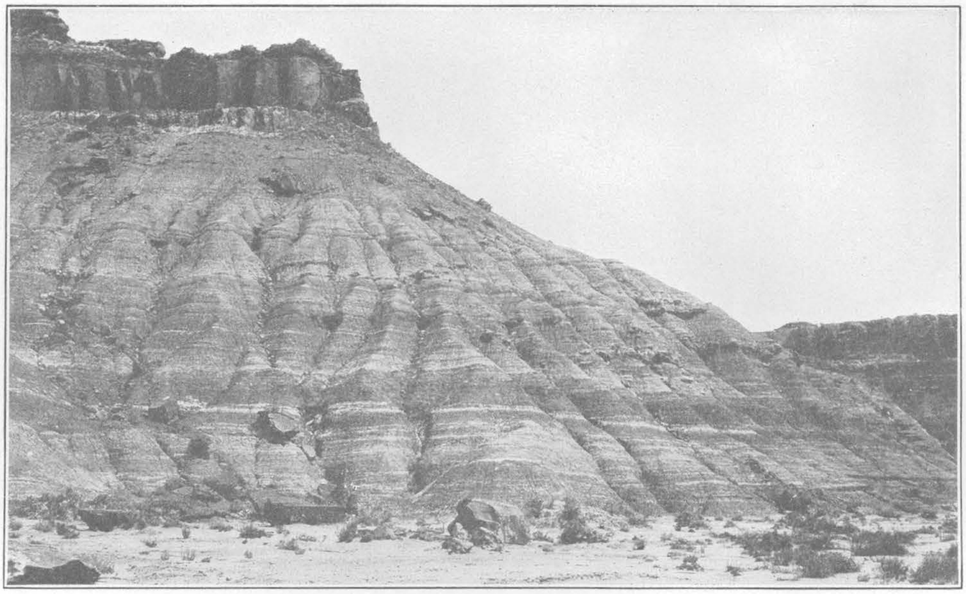
The limestone, which is an almost universal feature near the top of the Navajo sandstone, is in lenses. The thin outcrops rarely extend more than a few hundred feet, and most of them are measured in tens of feet. The lenses are usually less than 1 foot thick and break up

A. CROSS-BEDDED NAVAJO SANDSTONE, GLEN CANYON, UTAH.

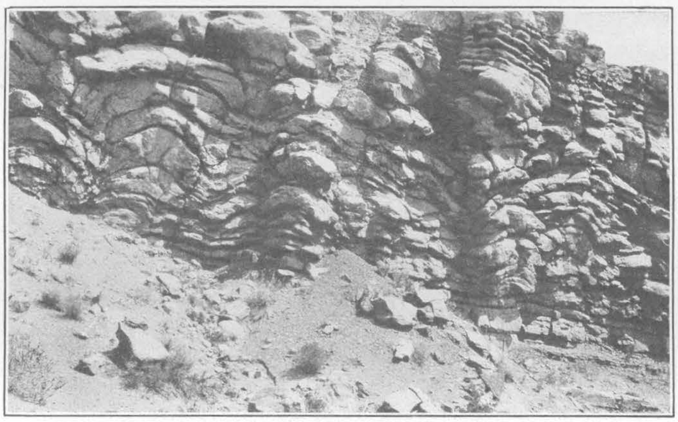


B. THEATER ROCK, NEAR LOHALI, ARIZ.

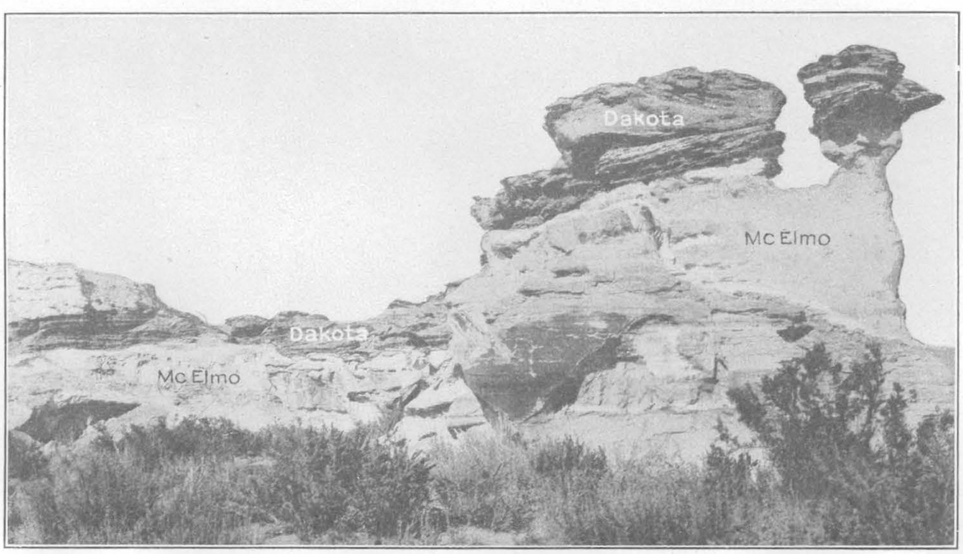
Sandstone of McElmo formation; dark bands are deep red, light bands greenish white.



A. SLOPE AND CLIFF AT MOA AVE, ARIZ.
Undifferentiated La Plata and McElmo formations.



B. DETAIL OF STRATIFICATION, McELMO FORMATION, GARNET RIDGE, ARIZ.



C. CLIFF NEAR BLUE CANYON, MOENKOPI VALLEY, ARIZ.
Showing unconformable contact of Dakota sandstone and McElmo formation.

into shaly beds including sandstone. They are exceedingly resistant, however, and form the caps of low mesas and buttes, irregularly distributed over the otherwise smooth surfaces of Navajo sandstone exposures. The two specimens submitted to analysis proved to be dolomite. Chert and chalcedony are commonly found with the limestone.

CONDITIONS OF DEPOSITION.

The significant features of the Navajo sandstone are uniformity of grain, cross-bedding, and red color. Specimens taken from ledges 200 miles apart are indistinguishable in the laboratory by texture or composition or color; tangential cross-bedding is persistent. The structure and composition of the rock suggests aridity and the uninterrupted control of the winds, and the "live dunes" now being formed on the floor of Chinle Valley differ only in color from the "frozen dunes" displayed in the bordering rock walls. There is little doubt that desert conditions prevailed in this region during part of Jurassic time, but the boundaries of this ancient Sahara and its relations to highlands and oceans are unknown. The thin lenses of dolomitic limestone and limestone conglomerate in the upper part of the Navajo sandstone probably represent local bodies of water of ephemeral character. It should be borne in mind, however, that these calcareous beds are in the stratigraphic position of the marine limestone of Kanab, described by Gilbert.[1]

AGE AND CORRELATION.

No fossils have been found in the Navajo sandstone, and its age, like that of other formations of the La Plata group, is determined by stratigraphic position and lithologic similarity. It is the equivalent of the upper La Plata sandstone [2] of the La Plata Mountains, from which it differs in no essential except color and thickness.

On Dutton's geologic map and sections [3] the massive "white sandstone" (Jurassic) is extended to cover the western edge of Kaibito Plateau. He says: "The extension of the Jura south of the Colorado and its exposure in the line of Echo Cliffs has been traced for nearly 60 miles." In my view the sandstones forming the crest and escarpment of Echo Cliffs and the walls of Glen Canyon, mapped by Dutton as Triassic, belong in the La Plata group and Dutton's descriptions and illustrations of the "Jurassic white sandstone" suggest lithologic equivalence with the Navajo and also with the massive phase of the McElmo. The upper limit of the La Plata along the southern base of Kaiparowitz Plateau has not been established. Sections on Warm Creek and Sentinel Creek include more than 100 feet of calcareous and gypsiferous shales and thin sandstones between typical Navajo sandstone and massive strata assigned to the McElmo.

I have been unable to recognize with assurance the Navajo sandstone in the Lower Cretaceous and Jura-Triassic strata along the San Juan described by Newberry,[4] or in the Lower Dakota, Upper Dakota, and Triassic mapped by Holmes [5] in the Carrizo Mountain area.

McELMO FORMATION (JURASSIC?).

HISTORICAL SKETCH.

All the strata in the Navajo country between the Dakota sandstone and Navajo sandstone are included in the McElmo formation, of Jurassic (?) age, a subdivision not previously recognized in the region south of San Juan and Colorado rivers. These beds are included in the "variegated marls" ("Triassic") of Newberry [6] and the "Painted Desert formation" ("Triassic") of Ward and were mapped by the geologists of the Wheeler Survey as Triassic on Dutton Plateau and as Cretaceous at White Mesa and in Moenkopi Wash.[7]

Under the name "Zuni sandstone" Dutton [8] included all the strata in western New Mexico between the Wingate sandstone and the Dakota sandstone. These beds, which were provisionally assigned to the Jurassic, include not only

[1] Gilbert, G. K., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 174, 1875.

[2] For a discussion of the correlation of the formations in the San Juan Valley, see Cross, Whitman, and Howe, Ernest, Red Beds of southwestern Colorado and their correlation: Geol. Soc. America Bull., vol. 16, pp. 447-498, 1905, and Emery, W. B., Geology of Carrizo Mountain, Ariz.: U. S. Geol. Survey Bull. — (in preparation).

[3] Dutton, C. E., Tertiary history of the Grand Canyon district: U. S. Geol. Survey Mon. 2, pls. 3 and 4, 1882.

[4] Newberry, J. S., Geological report, in Report of the exploring expedition * * * under the command of Capt. J. N. Macomb, 1876.

[5] Holmes, W. H., U. S. Geol. and Geog. Survey Terr. Ninth Ann. Rept., for 1875, pp. 237-276, 1877.

[6] Newberry, J. S., Geological report, in Ives, J. C., Report upon the Colorado River of the West, pt. 2, p. 77, 1861.

[7] U. S. Geog. Surveys W. 100th Mer. atlas sheets 67 and 76, 1875.

[8] Dutton, C. E., Mount Taylor and the Zuñi Plateau: U. S. Geol. Survey Sixth Ann. Rept., p. 137, 1885.

the McElmo formation as defined in the present report but also a portion of the La Plata group.

In Newberry's measured section of "Lower Cretaceous" in the San Juan Valley,[1] the McElmo beds are readily recognized. The Lower Dakota of the Hayden Survey[2] as mapped between the Colorado line and the mouth of Montezuma Creek is substantially the McElmo. The strata displayed on McElmo Creek, the type locality of the McElmo formation as defined by Cross, have been traced southward across the San Juan, and this formation name has been retained for the beds in the Navajo country. However, the McElmo strata in northeastern Arizona are prevailingly sandstones and in lithologic features resemble the "Zuni sandstone" of the Navajo Church (Dutton Plateau) more closely than the variegated shales of the McElmo Valley.

DISTRIBUTION AND TOPOGRAPHIC EXPRESSION.

The McElmo formation is well exposed in the Navajo country. It encircles Black Mesa as a broad band and is involved in the Defiance monocline and the laccolithic uplifts of Navajo and Carrizo mountains. On Dutton Plateau it stands high on the cuesta wall and forms the picturesque Navajo Church. Protected by a cap of Dakota sandstone, it forms White Mesa and the magnificent buttes overlooking Glen Canyon of the Colorado. In spite of its friability the massive parts of the McElmo are cliff makers. Sheer walls of intricately cross-bedded sandstone 100 to 200 feet high may be seen at Yale Point, and at Lohali the McElmo is carved into a group of towers and needles 150 to 300 feet in height. Theater Rock is a fluted mass of sandstone in which is carved an alcove with vertical walls 280 feet in height, banded dark red and green-white. (See Pl. XII, *B*.) Square Butte, at the head of Pinneettin Canyon, is a tower 370 feet in height, and the 400-foot walls of White Mesa are practically unscalable. Where unprotected the McElmo beds rapidly disintegrate and give rise to broad valleys, as seen at Klethla, at Red Lake, and along the middle San Juan. Where large amounts of shale are present and the Dakota cap is absent, the McElmo formation weathers into a maze of irregular buttes and bobbins and dolls, known to the Navajos as saowa, or stone babies. The variety of badland forms produced in favorable localities rivals the topography of the Chinle formation. At Blue Canyon the delicacy of coloring and intricacy of carving in the McElmo formation combine to produce a landscape not exceeded in beauty by any other scenic feature of the Plateau province. (See Pl. XXIV, p. 113.)

NAVAJO-McELMO CONTACT.

Although the McElmo formation is readily distinguished as a whole from the underlying Navajo sandstone, the plane of separation has not been established with confidence. In some places shaly green-white McElmo beds rest unconformably upon the massive red Navajo. At a number of localities thick-bedded red Navajo sandstone becomes at the top less red and more shaly and appears to pass by gradations through greenish and irregularly bedded shale into typical McElmo sandstone. The problem is further complicated by the presence of one or more unconformities within the McElmo, usually at no great distance from its base. So far as my observations extend, it is not practicable to locate the contact with an error of less than 100 feet and the boundary has accordingly been mapped at the base of the lowest stratum that shows features unmistakably characteristic of the McElmo formation. On the flanks of Navajo Mountain, where both Navajo and McElmo are altered by metamorphism, the basal McElmo is distinguished from the upper Navajo by the presence of numerous pebbles of baked clay, lighter hue, and more regular banding. At the east base of Navajo Mountain the typical Navajo is unconformably overlain by 5 to 15 feet of green-gray sandstone or grit. At White Mesa the contact is shown by a 2-foot band of concretionary sandstone, including lenses of conglomerate and of green shale. In Blue Canyon the transition beds between red-stained white Navajo sandstone and green-white McElmo consist of 5 feet of red friable lenticular sandstone and shale overlying 8 inches of imbricated arenaceous shales containing mud lumps and quartz pebbles. In the Navajo Church section of Dutton Plateau the relation between the McElmo beds and those assigned to the La Plata is as follows:

[1] Newberry, J. S., op. cit. (Macomb expedition), p. 105.

[2] U. S. Geol. and Geog. Survey Terr. Atlas of Colorado, sheet 15, 1877.

Section of transition beds between McElmo sandstone and Navajo sandstone at Navajo Church, N. Mex.

McElmo sandstone.	Feet.
Unconformity; 200 feet exposed, marked by many channels, by quartz sand and mud pellets strewn on the surface, and by fragments of red sandstone incorporated in lowest green beds.	
1. Sandstone, red, green, and white intermixed, in lenticular beds less than 1 foot thick; beds irregularly channeled and coated with pebbles	14
2. Sandstone, bleached white, very fine grained, lenticular	12
3. Six highly irregular lenticular beds of pure and impure gray limestone, arenaceous and calcareous shale, and argillaceous and calcareous sandstone. Top and bottom surfaces channeled	12
Navajo sandstone.	

This arrangement is duplicated at Sunrise Springs and in the Tyende Valley and indicates an unconformable contact of at least local significance. At Zilditloi Mountain an unconformity is again apparent, and in the wall of Pueblo Colorado Wash, below Sunrise Springs, an unconformity was observed between a fine-grained bright-red sandstone (La Plata ?) and an overlying thinly stratified white sandstone containing lenses of conglomerate. The plane of separation is indicated by an eroded surface truncating the lower strata. A duplicate of this occurrence was noted by Mr. Emery 6 miles west of Carrizo Mountain.

M^cELMO-DAKOTA CONTACT.

At all places where the Dakota is found the McElmo is also present, and the upper surface of the McElmo wherever observed is a plane of erosion. Along the northeast base of Black Mesa the McElmo surface is beveled, channeled, and weathered. In Moenkopi Canyon the relief of the contact surface exceeds 80 feet in a distance of a quarter of a mile. (See Pl. XIII, *C*.) On a wavy erosion surface of the McElmo 2 miles north of Tunnel Springs fragments of wood, shale, sandstone, and quartz lie in irregular position. The McElmo-Dakota unconformity is prominently exposed on the low mesas south of Salahkai, and in Steamboat and adjoining canyons the white McElmo beds, irregularly overlain by gray conglomerate with petrified wood and impure coal, are visible for distances of several miles. In the cliffs 4 miles west of Manuelito the unconformity is marked by color (white below, gray above), texture (fine, even-grained sandstone below, conglomerate with wood and coal above), and channels in the McElmo into which the Dakota is nicely fitted.

The time interval represented by this plane of erosion is not known. The McElmo and Dakota beds usually have the same attitudes, and at certain localities the phenomena require for their explanation only a slight change in conditions of deposition. Elsewhere the deeply eroded soft and fine-grained McElmo strata are immediately overlain by conglomerate composed of quartz and quartzite pebbles entirely unlike any materials known from the McElmo. The impression gained from the whole field is that mature planation with the removal of considerable thickness of strata preceded the deposition of the Dakota.

SELECTED SECTIONS.

The composition and arrangement of strata assigned to the McElmo formation are shown in the following sections measured in the central part of the Navajo country:

Section of McElmo formation at Todokozh, on east face of Black Mesa, between Lohali and Yale Point, Ariz.

Dakota sandstone.	
Unconformity.	Feet.
1. Thin-bedded sandstone and green-white and yellow shale; top very white, powdery, as if exposed to weathering before Dakota was deposited; very fine grained, calcareous and slightly gypsiferous	17
2. Shales, yellow-gray, argillaceous and calcareous.	6
3. Sandstones, yellow-gray, thin bedded, cross-bedded, with streaks of gravel consisting of pebbles the size of B shot	8
4. Shales, alternating green, white, and yellow-gray, friable; at bottom is 6 feet of soft thin-bedded dark-green coarse sandstone interleaved with lenses of dark-red shales	18
5. Sandstone, white to yellow-green, massive, cross-bedded, fine grained except for thin lenses of coarse sand; consists of clear quartz cemented by lime, with disseminated grains of gypsum	66
6. Shale, banded white and yellow-green, with streaks of dark red; argillaceous and highly gypsiferous; consists of series of thin lenses	4
7. Sandstone, green-gray streaked with pink and yellow, massive, cross-bedded, lenticular; mostly fine grained but contains lenses of subangular quartz and green clay pellets as large as buckshot; includes flakes of gypsum and pancake concretions of brown sandstone.	60

	Feet.
8. Shales, dark red, with green-white bands and one 2-foot bed of fine-grained sandstone; argillaceous and calcareous; contains many flat flakes of gypsum	14
9. Sandstone, gray-green, soft, massive, in irregular beds and overlapping lenses; mostly very fine grained but includes short thin lenses consisting of white and pink rounded and subangular grains of quartz the size of bird-shot	18
10. Shales, dark red, with broken pinched-out lenses of green-white shale and a 4-inch bed of dark-green and red mottled sandstone; arenaceous and gypsiferous	3
11. Sandstone, light green, soft, massive, cross-bedded; consists of very fine well-rounded quartz grains; near the top are two 3-inch bands of resistant dark-green sandstone	40
12. Shale, banded dark red and green, gypsiferous, irregularly bedded, nodular, includes broken fragments of No. 13	5
13. Sandstone, white to green-gray, in places yellow or red, soft, semimassive, cross-bedded; extremely irregular in deposition; includes thin lenses of green and red shale; prevailingly fine grained but lenses of conglomerate consisting of red mud lumps and rounded grains of quartz the size of buckshot are present; gypsiferous, noncalcareous	36
14. Shale, light green at top, dark red at base; nodular within a distance of 100 feet; ranges in thickness from 4 inches to 3 feet; arenaceous, gypsiferous	2
15. Sandstone, green-gray, friable, massive, cross-bedded with pronounced vertical jointing, poorly exposed	
16. Interval not exposed; estimated	200
Navajo sandstone.	
	497

Section of McElmo formation at Blue Canyon, Ariz.

[Measured by J. E. Pogue.]

	Feet.
Dakota sandstone.	
Unconformity.	
1. Sandstone, pale greenish white, massive, cross-bedded, very fine grained, dense, tough, probably argillaceous	100
2. Sandstone, white, pure, fine grained, mostly friable and cross-bedded	110
3. Sandstone, dark red, massive, fine grained, argillaceous; weathers to remarkable irregularly spherical forms; contains streaks of white sandstone	50
4. Alternating red shales and white sandstones; could not be measured very accurately; begins third cliff	150
5. Sandstone, white, fine, argillaceous in places; seams of grayish-white shales	20
6. Shales, dark red, arenaceous	10
7. Sandstones, white, fine, in places somewhat calcareous; contain thin bands of red shales	15
8. Shales, dark red, arenaceous; 2-foot band of purple shale; contains seams and bands of white sandstone	10
9. Sandstone, white, fine; some bands somewhat calcareous	10
10. Shales, red, with sandstone seams and bands	10
11. Sandstone, white, fine grained, slightly calcareous in places; contains few thin seams of gray shales	25
12. Shales, dark red, arenaceous, thin bedded; seams of white friable sandstone and white calcareous sandstone; begins second cliff	25
13. Sandstone, white, fine, calcareous	1
14. Sandstone, white, very friable, pure, fine grained; some seams appear to be slightly calcareous; composed almost exclusively of clear, well-rounded small grains of quartz	12
15. Shales, dark red, arenaceous	10
16. Sandstone, white, fine, calcareous, in resistant band; weathers to dirty color	5
17. Shales, dark red, arenaceous, in fairly thin beds; contains some thin bands of red and white sandstone	32
Navajo sandstone.	
	595

Section of McElmo formation on north face of White Mesa, Ariz.

[Measured by J. E. Pogue.]

	Feet.
Dakota sandstone.	
Unconformity.	
1. Sandstone like No. 2 but massive	20
2. Sandstone, light yellow to white, fine grained; clear, well-rounded quartz grains; thin bedded and cross-bedded, speckled or mottled appearance due to deposition of material between grains	65
3. Sandstone, light yellow, thin bedded, cross-bedded, fine grained, lower 50 feet layers of red sandstone; remainder contains lenses and narrow bands of light-green sandstone and sandy shale with a few bands of dark-green sandstone, forms great mesa wall which appears at a distance to be greenish white	240
4. Sandstone, white, more resistant than other members	5
5. Sandstone like No. 7 but with bands of white sandstone; Nos. 5, 6, and 7 form badland topography	40
6. Sandstone, white, fairly coarse grained, bedding oblique to that of No. 7	5
7. Sandstone, red, fine grained, thin bedded, cross-bedded, with seams and bands of white sandstone	75
8. Sandstone, gray, resistant	15
9. Sandstone, gray, like No. 10 but more resistant	75
10. Sandstone like No. 11 but with fewer resistant bands; forms gentle slope between steeper slopes of Nos. 9 and 11	40
11. Sandstone, light yellow to grayish white, pure, fine grained, friable, occasionally reddish on exterior; weathers to a slope; contains several more resistant bands (6 inches) and at the top a 4-foot layer of rather coarse calcareous grayish-white sandstone	40
Interval not exposed, estimated	50
Navajo sandstone.	
	670

FEATURES OF OTHER SECTIONS.

Three sections of McElmo beds in Dutton Plateau include thicknesses of 550, 640, and 600 feet. Fully 80 per cent is sandstone in massive beds 30 to 150 feet in thickness, white to green-white in tone, with lesser amounts of red. About half of the beds are beautifully banded and cross-bedded in the manner made familiar by the frequent reproduction of Hillers's photograph of Navajo Church.[1]

The seven beds exposed near Manuelito, in all 340 feet thick, are white, green-white, and yellow fine-grained and cross-bedded sandstones, with inconsiderable amounts of red and green shales. In Todilto Park the McElmo formation has been reduced, presumably by pre-Dakota erosion, to 230 feet of yellow, greenish, and red sandstone, in two beds separated by 8 feet of red shale. The top 4 feet is little more than a white powder of minute quartz grains; the bottom bed is a conglomerate of pebbles of quartz, sandstone, and clay balls. The McElmo near Bitsihuitsos Butte, where nearly the whole formation is exposed, was divided by Mr. Pogue into seven beds with a total thickness of 500 feet. Three green-white to yellow-white sandstone strata, each containing lenses and sheets of red, purple, green, and mottled shales, measured together 460 feet.

East of the Haystacks at St. Michaels the McElmo beds are not readily separable from the underlying La Plata group. At this point the McElmo formation consists of greenish-yellow sandstone with bands and lenses of green and dark-red shales and lenses of fine conglomerate in its upper portion. Lenses of red and green shale are included even in massive cross-bedded sandstone. In the cliffs at Red Lake Store, on the Kaibito Plateau, 65 feet of white thin-bedded cross-bedded sandstone is traversed by numerous short, thick lenses of green sandstone and shale, below which is 75 feet of sandstone, white at the top but passing through a banded yellow, white, and red portion to a lower part that is red banded with green-white. Lying on the surface near this locality the centrum of a carnivorous dinosaur like that of *Creosaurus* was found. Two miles south of Red Lake Mr. Pogue found the massive cross-bedded McElmo sandstone, greenish yellow in tone, displayed as a cliff 600 feet in height, below which was 40 feet of mottled and banded thin-bedded sandstone. On the edge of Black Mesa, 6 miles west of Ganado, there is 200 feet of red fine-grained sandstone in beds 2 to 10 feet in thickness, banded with ribbons of white 6 inches to 2 feet thick. The white strata increase in number and thickness upward, and near the top the cliff wall is composed entirely of greenish-white sandstone. Along the upper part of Pueblo Colorado Wash the typical La Plata is not present and the sections display features somewhat unlike the McElmo of other localities. The region has not been carefully studied, and the strata of the following section are assigned to the McElmo with hesitation. The lower beds may represent equivalents of part of the La Plata group.

Section of McElmo formation (?) 2 miles west of Cornfield School, in Pueblo Colorado Valley, Ariz.

	Feet.
1. Sandstone, yellow-green, firm, cross-bedded; forms top of mesa wall	50
2. Sandstone, greenish white, well stratified, poorly cemented, crossed by three red bands in lower 40 feet; the upper band compounded of several irregular red lenses	200
3. Sandstone, red to dark brown, banded at base by six to eight white layers about 2 inches in thickness; erodes along joints into picturesque remnants, of which "Neubert's Organ" is an example	200
4. Shales, brown and blue-white	30
5. Sandstone, white, of clean quartz pebbles marked by black spots and dendritic figures.	2
6. Shales, yellow-red, white, green-white, and light blue, arenaceous; include three beds 1, 4, and 5 feet thick, which weather with honeycomb structure along ancient sun-cracked surfaces	150
7. Sandstone, white, cross-bedded	3
8. Sandstone, yellow-brown, much cross-bedded, friable, marked near top by eight bands of green-white and red-brown shale one-half inch to 3 inches thick	50
9. Shales, arenaceous; yellow-brown 10 feet, dark red and purple 5 feet, brown 10 feet, white and red 5 feet, brown 30 feet	60
10. Sandstone, red, massive, friable, terminated above and below by white bands	20
	765

The 300 to 400 feet of McElmo beds that crop out along San Juan River in the Gothic Mesas province are identical in appearance with those at the type locality, McElmo Creek. They are essentially shales, banded green, white, red, and brown; sandstone beds

[1] U. S. Geol. Survey Sixth Ann. Rept., fig. 12, 1885; Bull. 435, pl. 11, 1911.

over 5 feet in thickness constitute probably less than 20 per cent of the outcrops. Their expression is therefore quite different from that of exposures farther south. In place of the massive white sandstone cliffs of the Navajo country, there is a wilderness of columns, spools, and buttes beautifully colored and so elaborately carved and dissected that a passage through them is possible only by carefully selected routes.

Along the Tusayan washes the McElmo is represented by greenish-white friable sandstone with subordinate amounts of arenaceous shale. At Burro Spring 300 feet of intricately cross-bedded green-white sandstone is capped by a 4-foot bed of cherty limestone, the fragments of which are widely spread over the floor of Oraibi Wash. Near Flat Rock Mr. Pogue found the following strata:

Section of McElmo formation (?) on east side of Oraibi Wash, 5 miles south of Big Burro Springs, Ariz.

	Feet.
1. Sandstone, green-white, wholly quartzose, cross-bedded, friable	85
2. Shales and sandstone, banded red and gray	25
3. Sandstone, gray-white, fine grained; forms vertical wall	50
4. Shale, horizontally banded, interstratified with thin beds of white and red calcareous sandstone	100
	260

MCELMO FORMATION IN TYENDE VALLEY.

Along the trails and wagon road from Tyende (Kayenta) eastward toward Chinle the McElmo sandstone is exposed for a distance of 30 miles and the canyons tributary to Tyende Creek furnish many sections well displayed for study. The cliffs and chains of "hoodoos," mounds, buttes, and minor fantastic erosion remnants are striped with red, orange, green, and white bands and specked with lenses and spots of white. At Tyende and along the base of Black Mesa the strata retain their common greenish or white hues, but the sandstone members rarely exceed 10 feet in thickness and are interleaved with red shale at irregular intervals. Farther northeast calcareous and gypsiferous thin-bedded sandstone and gypsiferous, calcareous, and arenaceous shales replace massive sandstones. Shades of red and yellow predominate over the green and white of the typical McElmo. North of Bitsihuitsos Butte the landscape is dotted with red cliffs capped by bands of white, composed of the following beds:

Section of McElmo formation in cliff 5 miles north of Bitsihuitsos Butte, Ariz.

	Feet.
1. Sandstone, alternating red and white, in beds 2 feet thick	10
2. Sandstone, white, thin bedded	15
3. Sandstone, dark red, decorated by irregular, disconnected, horizontal blotches and bands of greenish white; weathers into rough columns, cushions, knobs, and stone babies	70
4. Shale, dark red, sandy	2
5. Sandstone, white, friable, with lenses of red shale	2
6. Shale, light red, sandy	10
	109

North of lower Tyende Creek the mesas of Garnet Ridge present a series of steps of prevailing brown color rising above the massive cross-bedded Navajo sandstone, in which is cut the meandering Sahotsoidbeazhe Canyon. The mesas are formed of strata so unlike the typical McElmo of White Mesa and Dutton Plateau, so poorly consolidated, and so recent in general appearance that they were indicated as Tertiary (?) in field notebooks. These beds are tentatively assigned to the McElmo on the basis of their relation to the Navajo sandstone and their supposed connection along the strike with undoubted McElmo strata at Tyende.

Section of McElmo formation (?) in Garnet Ridge, Ariz.

	Feet.
1. Sandstone, gray to white, of fine uniform grain, except for millet-seed grains cemented on bedding planes and cross-bedding laminae; ripple marks and mud cracks present; round grains of clear quartz, white, with a few red and black; poorly cemented; cross-bedded at low angles, rarely tangential; intersected by seams of calcareous sand 0.01 inch to 2 inches in width; prominent joints trending N. 40° E. and N. 40° W.	25
2. Shales and sandstone, light red, dark red, and brown in alternating bands, 1 to 3 feet thick; arenaceous and calcareous; cross-bedding poorly defined, but bedding planes irregular and wavy and rock traversed by undulating streaks and minute faults and folds	30
3. Sandstone, gray, white, and variegated, calcareous, friable, irregularly bedded, imbricated, and cross-bedded	10
4. Shales, arenaceous and argillaceous, with variable amounts of sandstone; dark red, light red, green-white, ash-gray, or variegated; within a few feet along the strike shale is locally replaced by lenses of calcareous sandstone built of overlapping short laminae	15
5. Sandstone, light red, white on fresh fracture, calcareous, irregularly bedded, ripple marked.	2
6. Shales, various shades of red and brown, also ash gray and green, argillaceous, calcareous, and arenaceous, with beds and lenses of white and light-red sandstone 2 to 14 inches thick	35

	Feet.
7. Conglomerate, igneous, large pebbles, set in igneous paste	4
8. Sandstone, light red, fine, even grained, lenticular; replaced along the strike by white sandy shales	1
9. Shale; banded white, green, ash-gray, dark red, light red, and chocolate-colored; bands in places continuous for several hundred feet, elsewhere distributed as discontinuous stripes or dots; arenaceous beds paper-thin to one-eighth inch thick; uneven, wavy, and in places imbricated	42
10. Sandstone, red-brown, fine; well-rounded quartz grains, calcareous cement	5
11. Shale, dark red to light brown, with scattered patches of black, white, and green; arenaceous; irregularly bedded; where shale partings are not developed by weathering strata assume appearance of thick-bedded, variegated sandstone	28
12. Sandstone, dark red, with white patches; many curved beds; massive or irregularly bedded; friable; fine quartz, even grained; weathers to knobs, hoodoos, stone babies, and bobbins	30
Sandstone, light red, massive, cross bedded (Navajo sandstone).	
	227±

The curved strata in bed No. 12 of the section are shown in Plate XIII, *B* (p. 59); the peculiar conglomerate forming No. 7 of the section has been fully discussed elsewhere.[1]

West of Navajo Mountain the strata assigned to the McElmo formation present features similar to those in Tyende Valley. On both sides of Glen Canyon 150 to 200 feet of red sandy shales and thin red sandstones lie between the Navajo sandstone and the green-white McElmo strata. In the present report these beds are classed with the McElmo, but they may represent a formation that has not previously been recognized and is more fully developed north and west of Colorado River.

LITHOLOGIC FEATURES.

Shales in the McElmo formation are much less abundant than sandstone; they are nearly all highly arenaceous and might reasonably be classed as thin-bedded calcareous or argillaceous sandstones. True argillaceous shales are rare. Some of the sandstone beds are massive; others appear massive because of inconspicuous parting planes or because of elaborate cross-bedding tracery. The sandstones are variable in texture; the thick cross-bedded strata and many of the thinner beds are composed of round grains of clean quartz, mostly white in color and of microscopic dimensions; about half of the beds examined are medium to coarse in texture and are made up of grains of subangular quartz and rare feldspar and chalcedony of the size of B to BB shot. Lenses of sandstone with white quartz, black quartz, and jasper, in angular to subangular fragments of the size of buckshot, are irregularly distributed in thin and thick beds alike. They are more abundant in the upper beds. Calcareous and siliceous concretions are prominent features at Navajo Church and a few other places; in general they are rare. At a point 2 miles north of Tunnel Springs, where 320 feet of the McElmo is exposed, a massive bed contains several chunky lenses of very resistant dark-green sandstone. At this locality five lenses of conglomerate, 1 to 6 feet long, consisting of subangular pebbles of quartzite and chert half an inch to 2 inches in diameter were observed, in addition to pebbles arranged as strings or embedded as individuals. A persistent feature is the presence of fragments of green clay pebbles either singly or, rarely, grouped as short, fat lenses. The cement of the McElmo is prevailingly lime and green ferrous iron. Gypsum is widely disseminated as grains, rarely as stringers and lenses, but no gypsum beds were observed. Springs in the McElmo are commonly "todokozh" to the Navajos—that is, heavily charged with calcium sulphate and calcium and magnesium carbonates. Petrified wood was noted at a few places, both as worn pebbles and as fragments that apparently had suffered little or no erosion.

Much of the sandstone is clear white to gray in color, but many cliff faces and hand specimens appear green or delicate white-green to blue-green. The shales are of various tones of red, yellow, and green. The color is produced by a coating of ferrous iron on individual grains or whole strata. The disseminated green shale pellets also act as a pigment. The local belief that the green shales carry copper is not borne out by microscopic analysis.

UNDIFFERENTIATED LA PLATA AND McELMO OF THE HOPI BUTTES PROVINCE.

Neither the McElmo formation nor the La Plata group attains its typical development

[1] Gregory, H. E., The igneous origin of the "glacial deposits" on the Navajo Reservation, Arizona and Utah: Am. Jour. Sci., 4th ser., vol. 40, pp. 97-115, 1915.

in the region between Black Mesa and Little Colorado River. If the La Plata in its threefold form was ever present, it has now been largely removed, and the McElmo has had a like experience.

The Wingate (?) sandstone forms Monument Point, and typical McElmo beds are exposed in the lava-capped mesas facing Jadito Wash, but in the region as a whole it was found impossible in a reconnaissance survey to assign the highly colored sediments to different formations with confidence. Erosion and outflows of lava have destroyed the continuity of the beds, and a deep coating of alluvium conceals many contacts.

The character and arrangement of the undifferentiated La Plata and McElmo strata in the Hopi Buttes province are shown in the following section measured with the assistance of Mr. Heald:

Section of undifferentiated La Plata and McElmo beds at Bidahochi, Hopi Buttes volcanic field, Ariz.

	Feet.
1. Basalt	50
Unconformity.	
2. Shales, banded green, pink, and gray, and thin sandstone; partly covered by talus	210
3. Sandstone, very dark red or chocolate-colored, spotted with white; so calcareous as to weather like marl	33
4. Conglomerate; body of the rock is sandy shale or sandstone; pebbles are strung irregularly in rows and consist of white, gray, pinkish, and black subangular quartz ranging from one sixty-fourth to 1 inch in long diameter, arranged as lenses 1 to 6 feet thick; lime cement has allowed conglomerate to crumble to a sand bank of light-red color and full of pebbles	4
5. Sandstone, yellow-red, crumbly, highly cross-bedded; erodes into rounded knobs; resembles poorly consolidated La Plata sandstone	55
6. Sandstone, light red, consisting of fine quartz grains, with several irregular bands of white, also white blotches; irregularly bedded and jointed; erosion produces biscuits, spools, lozenges, etc	143
7. Shales, chocolate-red; calcareous cement; regularly bedded; contain spherical fragments of sandstone	13
8. Sandstone, very light red, with band of white, probably the result of bleaching; fine quartz, calcareous cement	4
	512

UNDIFFERENTIATED LA PLATA AND McELMO OF MOENKOPI PLATEAU.

From the vicinity of Tuba southward across Ward Terrace the La Plata group and the McElmo formation present features not seen elsewhere. The La Plata usually massive is divided here into relatively thin beds, and the lower part of a series of strata equivalent to the McElmo contains large amounts of red and orange-colored sandstones and limestone conglomerates in addition to white sandstones and shales. These beds were described by Ward as the "Painted Desert formation" and separated by him into four members, which, beginning at the top, are as follows: White sandstones, 100 feet; brown sandstones, 200 feet; variegated sandstones, regularly stratified and brilliantly colored, 800 feet; orange-red sandstones, 100 feet; total, 1,200 feet.[1] Views of the "Painted Desert" beds are presented in Plates XIII, *A* (p. 59), and XIV, *C* (p. 82).

The nature of the work engaging the attention of my party did not permit a thorough study of these interesting sediments. The boundaries of subdivisions recognized in the field were not traced, and the manner of gradation of the beds along strike remains to be determined. On the geologic map therefore the strata between the Chinle formation and the known Cretaceous of the Moenkopi region are assigned positions in a more or less arbitrary fashion. However, sections were measured at a number of points, fossils were collected, and various lithologic features were examined. A part of these observations are here recorded as a contribution to the geology of an area worthy of careful study.

Section of undifferentiated La Plata and McElmo strata on Ward Terrace, about 16 miles south-southwest of Tuba, Ariz.

[Beds Nos. 7 to 16 measured by K. C. Heald.]

	Feet.
1. Sandstone, green-white on exposed surfaces, light red in wall; remarkably uniform in texture, composed of clear white or rarely red and black round grains of quartz about 20 millimeters in diameter; poorly cemented with lime and ferrous iron; massive stratum tangentially cross-bedded on an elaborate scale; at 70 feet from the base there is an irregular bed of cherty limestone conglomerate which averages about 5 feet in thickness; carved with overhanging alcoves;	

[1] Ward, L. F., Status of the Mesozoic floras of the United States: U. S. Geol. Survey Mon. 48, pp. 44-45, 1905.

	Feet.
forms top of east wall of Ward Terrace; separated from Cretaceous above by unknown thickness of thin-bedded sandstone........	105
2. Shales, red, friable, calcareous, lenticular....	20
3. Sandstone, gray, shaly, imbricated, cross-bedded; forms cliff, variable in thickness..	3
4. Shale, red, banded white and pink, containing lenses of sandstone of same color; all calcareous....................................	50
5. Sandstone, light red, cross-bedded; in places forms massive wall; elsewhere contains lenses of shale and concretionary nodules..	20
6. Sandstone and shale, gray streaked with red, pink, and white, in alternating beds or lenses of highly irregular form and dimensions; uniformly fine grained......................	50
7. Shale, light red, with 10-foot maroon band at top, arenaceous, calcareous..................	30
8. Sandstone, brown-purple, medium-grained, hard, calcareous cement; weathers to rounded forms....................................	25
9. Shale, banded dirt-gray, light red, white, and purple, gypsiferous, argillaceous.............	25
10. Sandstone, light red, very fine grained, calcareous, thin bedded; one hard 3-foot bed.....	10
11. Brown-purple sandstone and chocolate-colored shale....................................	80
12. Shale, chocolate-colored, arenaceous, micaceous....................................	10
13. Sandstone, white, medium-grained; well-rounded grains of quartz, mostly white, a few green, red, and yellow...........................	8
14. Sandstone and shale, light to dark red; many concretions of cherty limestone in sandstone beds....................................	70
15. Sandstone, yellow-red; lower 2 feet and upper 90 feet dark red, with a few thin, gray-white bands; microscopic grains with stringers of coarse sand; about half the beds are 15 to 40 feet thick; others much thinner; all cross-bedded in short irregular laminae; has many lenses of red cherty limestone; about 20 feet from the bottom is a dark lens full of worm tracks; the sandstone is soft and weathers into dolls, spools, bobbins, and rounded forms....................................	270
16. Conglomerate, gray-white, made up of medium-grained, well-rounded quartz, 95 per cent white, 5 per cent black, green, red, and yellow; some larger pebbles of limestone, gray shale, and reddish quartzite; top few inches very fine grained, with thin stringers of heavier grains; ripple marked, mud cracked, cross-bedded, with laminae dipping 22° N..	2
Unconformity indicated by change of dip and strike and channeled surface.	
Shale with petrified wood (Chinle formation).	
	778

Section of undifferentiated La Plata and McElmo strata in north wall of Moenkopi Canyon, from a point 4 miles east of Moenkopi village to the Government Farm.

[Condensed from descriptions by K. C. Heald. Average dip, 2° NE.]

	Feet.
1. Limestone, blue-gray, hard, dense, with red, black, and white chert.....................	2
2. Sandstone, gray-white, becoming vermilion in a short distance; very fine round grains of quartz with calcareous cement; massive, cross-bedded, the laminae dipping 25° E.; contains dark round sand concretions about half an inch in diameter....................	20
3. Shale, chocolate-colored, dense, argillaceous; includes flakes of muscovite; partly covered by talus..................................	22
4. Sandstone, white, coffee-colored, light red, or vermilion, very fine grained, calcareous, friable; in three beds, including oblong and round concretions; contains plant fragments and is ripple marked and mud cracked......	54
5. Sandstone, red-purple, with two gray bands, argillaceous...............................	8
6. Sandstone, calcareous cement, friable; weathers into irregular knobs........................	99
a. 3 feet gray; medium-grained, well-rounded quartz; 95 per cent white, rest mostly red; inclusions of drab shale.	
b. 1 foot bright vermilion; fine grained, uniform, well-rounded quartz.	
c. 1 foot white; fine grained, uniform, well-rounded quartz.	
d. 8 feet gray-purple; medium-grained, rounded quartz; 90 per cent white, rest mostly red; carries biotite.	
e. 1 foot white; like 6b in composition and texture but well cemented.	
f. 50 feet red-purple; like 6d but has much higher percentage of red and vermilion quartz.	
g. 35 feet gray-purple, like 6d; makes steep, soft slope.	
7. Shale like No. 19............................	45
8. Sandstone; white when fresh; weathers dirty gray; made up of microscopic quartz grains; high percentage of lime; hard; weathers rough, raspy, like limestone; on heavy bed.	8
9. Shale like No. 19............................	9
10. Sandstone, like No. 23, but color is bright red-purple....................................	10
11. Shale like No. 19............................	55
12. Sandstone, like No. 23, but color is bright, light red..	3
13. Shale like No. 19............................	7
14. Sandstone like No. 23.........................	6
15. Shale like No. 19............................	22
16. Sandstone like No. 23.........................	12
17. Shale like No. 19............................	4
18. Sandstone, gray, fine-grained, calcareous......	2

	Feet.
19. Shale, red and gray banded; at bottom a thin-bedded sandstone; grades upward into dense, slightly calcareous, argillaceous shale; includes three lenses of red and gray sandstone, 2 to 6 inches thick, and a 4-inch lens of cherty limestone	52
20. Sandstone, white to light red; microscopic grains; calcareous cement; thin bedded	1
21. Shale, brown, arenaceous, micaceous, calcareous	6
22. Sandstone, mottled red and gray, calcareous, fine grained; well-rounded white quartz; uniform size; weathers with concretionary structure	3
23. Sandstone, purple, fine grained; rounded grains of red and white quartz; uniform size; calcareous cement; hard, dense, concretionary weathering; shaly at top; carries biotite	14
24. Shale, variegated, prevailing color purple-gray, with bands of white argillaceous, noncalcareous rock; alternating hard and soft bands; much mica on foliation surfaces; hard bands cross-bedded; contains three thin lenses of white hard fine-grained, highly calcareous sandstone, marked by worm tracks	56
25. Concealed by dunes; probably like No. 27	40
26. Sandstone like No. 30b	3
27. Shale, banded dark red and gray with red and white sandstone lenses; shale arenaceous, slightly calcareous, micaceous, hard; shows mud cracks and ripple marks; sandstone of microscopic grain, cross-bedded	45
28. Sandstone like No. 30b	9
29. Sandstone, dark red-brown, mottled with gray, thin bedded, very fine grained; calcareous cement; has one 2-inch band of chocolate-colored argillaceous shale	6
30. Sandstone	10
a. 2 feet white and maroon banded; extremely fine grain, with sprinkling of grains one thirty-second of an inch in diameter; calcareous, cross-bedded, with thin planes.	
b. 8 feet light yellowish red; mostly microscopic grains, but has strings and patches of pebbles one thirty-second of an inch in diameter, making up perhaps 15 per cent of the rock; grains all quartz and mostly translucent, but some opaque white, yellow, red, and black; calcareous cement; top of rock is gray and ripple marked on horizontal surfaces; cross-bedded.	
31. Conglomerate, gray, with lenses of red; varies from a limestone conglomerate like that common in the Chinle formation to gray sandstone consisting of round red, white, black, and yellow quartz grains one thirty-second to one-eighth of an inch in diameter; soft calcareous cement	1
32. Shale, chocolate-brown, argillaceous but with scattering of tiny quartz pebbles; calcareous cement; lowest bed exposed	4
	638

The top of the section just given is probably as much as 300 feet below the typical green-white McElmo sandstones and shales lying 8 or 10 miles farther south and east; the bottom of the section is perhaps 200 feet above the Chinle formation. About 6 miles west of Moenkopi village, where the Triassic-Jurassic contact is exposed, the Chinle consists of dark-red and purple "marls," calcareous sandstone, and limestone conglomerates with accumulations of broken unios, considered by T. W. Stanton [1] as close to *Unio cristonensis*. Above the unconformable contact are beds 1 to 10 feet thick of light-red and yellow-red cross-bedded ripple-marked sandstone closely resembling the Wingate except in massiveness. The beds of the section just given are extremely irregular in color, composition, and structure; they thicken and thin along the strike, split up, or coalesce, and the number and dimensions and position of lenses of limestone change in a capricious manner. Two sections taken 500 feet apart exhibit considerable differences. In many respects the top beds of the section are similar to the upper part of the Navajo sandstone of the Kaibito, Shato, and Rainbow plateaus, with which they have been tentatively correlated in this report. The fossils collected from beds of limestone conglomerate on Ward Terrace at a horizon about midway up in the section were studied by W. I. Robinson, who assigned them to the middle or late Jurassic.[2] In the collection are two species new to science, *Valvata gregorii* and *Limnea hopii*.

CRETACEOUS FORMATIONS.

HISTORICAL SKETCH.

The presence of strata of Cretaceous age in the Navajo country was announced by Marcou, who based the determination chiefly on lithologic comparison with Cretaceous formations observed on the Llano Estacado of western Texas. The distribution of the Cretaceous as indicated on the geologic map by W. P. Blake,[3] accompanying Marcou's report, is, however, quite unlike that determined by later observers. Newberry [4] noted Cretaceous strata in one of the Hopi Buttes and recognized the existence

[1] Personal communication.
[2] Robinson, W. I., Two new fresh-water gastropods from the Mesozoic of Arizona: Am. Jour. Sci., 4th ser., vol. 40, pp. 649-651, 1915.
[3] U. S. Pacific R. R. Expl., vol. 3, pt. 4, 1856.
[4] Newberry, J. S., op. cit. (Ives expedition), pp. 80-96.

of a large area of sandstones and shales assignable to this system along the southern border of Black Mesa.

In a measured section of "Lower Cretaceous" strata at one of the Hopi villages (Mishongnovi ?) Newberry found *Gryphaea pitcheri*, *Ammonites percarinatus*, and *Inoceramus crippsii?*. The strata northwest of the Hopi villages, including White Mesa, assigned by Newberry to the "Upper Cretaceous," are classed as Jurassic (?) (McElmo) in the present report. In the absence of a geologic map, it is difficult to determine the location of the Cretaceous outcrops described by Newberry along his route from the Hopi villages to Fort Defiance, but it is evident that strata on Defiance Plateau were erroneously assigned to that age. East of Fort Defiance Newberry found the "Lower Cretaceous" overlying "variegated marls" (Chinle, La Plata, and McElmo) extending to the "hogback" (Nutria monocline) east of Gallup.

In Howell's traverse of the Navajo Reservation from Tuba, Ariz., to Fort Wingate, N. Mex., the route of Newberry was in part duplicated.[1] Like Newberry, Howell mapped as Cretaceous large areas now classified as Jurassic and Triassic, but he obtained much additional information regarding the succession of strata. The subdivisions established at the Hopi villages—100 to 300 feet of "cream-colored sandstone" overlying 300 to 500 feet of "dark shale, in part carbonaceous"—correspond roughly to the Mesaverde and Mancos formations as defined in the present report. East of Fort Defiance Howell recognized the Dakota sandstone (No. 8 of his section) and noted that "the main divisions of the Cretaceous retain their distinctive characters throughout."[2] In the "general sections" published by Howell the Cretaceous is for the first time shown to extend from a point near Fort Defiance eastward to the base of Mount Taylor.[3] After the reconnaissance of Howell, no studies were made of the great Cretaceous island in the center of the Navajo country until 1909, when, in conjunction with M. R. Campbell, I undertook a preliminary study of the southern border of the coal field.[4] During subsequent seasons I traced the boundaries of this Cretaceous outlier, as shown in recent Survey publications.[5]

The Cretaceous of the Zuñi Mountain region was first described by Gilbert[6] as follows:

> The Cretaceous rocks are an alternating series of sandstones and shales in which the sandstones are yellow and the shales gray and yellow, with bituminous layers and coal; * * * with the utmost variability of individual beds there is combined a marked uniformity of the series as a whole. * * Lithologically it is a single series, offering no criteria for subdivision. In its entire depth of 2,000 feet fossil animals have been found, in this particular field, only in the lower 850 feet.

Strata believed by me to represent the Dakota are placed by Gilbert at the base of the Cretaceous in the Stinking Springs (Mineral Springs) section and near that horizon on the south edge of Dutton Plateau. The studies of Gilbert in northwestern New Mexico were continued by Dutton,[7] who established boundaries between the Cretaceous and Jurassic (?) systems and noted that the Cretaceous is in "all essential respects equivalent to the Cretaceous as described by the geologists of the Hayden Survey." Dutton[8] gives the following generalized section:

Cretaceous system.	Feet.
Laramie group	800
Massive sandstones (upper)	125
Shales and marls	550
Massive sandstones	175
Shales and marls	900
Massive sandstones	125
Shales and marls	1,200
Dakota sandstone	250
	4,125

Because of their economic importance, the Cretaceous beds between the Santa Fe Railway and San Juan River, extending over Dutton, Manuelito, and Chaco plateaus and flooring Chuska Valley, have been studied more than any other strata exposed in the Navajo country. The following papers combine stratigraphic studies with a discussion of the occurrence of coal:

Schrader, F. C., The Durango-Gallup coal field of Colorado and New Mexico: U. S. Geol. Survey Bull. 285, pp. 241–258, 1906.

[1] Howell, E. E., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, pp. 227–301, 1875.

[2] Idem, p. 276.

[3] Idem, p. 288.

[4] Campbell, M. R., and Gregory, H. E., The Black Mesa coal field, Ariz.: U. S. Geol. Survey Bull. 431, pp. 145–163, 1911.

[5] Darton, N. H., A reconnaissance of parts of northwestern New Mexico and northern Arizona: U. S. Geol. Survey Bull. 435, 1910. See also Geologic map of North America, U. S. Geol. Survey, 1911.

[6] Gilbert, G. K., U. S. Geog. and Geol. Surveys W. 100th Mer., vol. 3, p. 545, 1875.

[7] Dutton, C. E., op. cit. (Mount Taylor, etc.), pp. 113–198.

[8] Idem, p. 139.

Shaler, M. K., A reconnaissance survey of the western part of the Durango-Gallup coal field of Colorado and New Mexico: U. S. Geol. Survey Bull. 316, pp. 375–426, 1907.

Gardner, J. H., The coal field between Gallup and San Mateo, N. Mex.: U. S. Geol. Survey Bull. 341, pp. 364–378, 1909.

Kirk, C. T., The geology of the Gallup basin, N. Mex.: New Mexico Univ. Bull. 76, pp. 28–68, 1914.

Additional information regarding the coal-bearing beds of the Gallup region has been supplied by Darton.[1]

Cretaceous strata were recognized by Newberry[2] along the northern border of the Navajo Reservation in the San Juan Valley and distinguished as Upper, Middle, and Lower Cretaceous; the last is now known as the McElmo formation (Jurassic ?). The well-known "hogback" at Jewett, composed, as shown by Shaler, of Mesaverde and Lewis formations, was first described by Newberry and correctly assigned to the Upper Cretaceous. On the atlas of the Hayden Survey (Sheet XV) the strata composing the "Creston"[3] are mapped as Fox Hills, those in the lower Chuska Valley as Colorado, and those in the vicinity of Carrizo Mountain as Upper and Lower Dakota.

My studies of the Cretaceous in New Mexico were limited to the region south and west of Chaco River, and the geologic map accompanying this report includes the map of Shaler[4] in so far as the coal-bearing beds and the uppermost Cretaceous shales are concerned. I have also followed Shaler and Gardner in subdividing the Cretaceous into the Dakota sandstone, Mancos shale, and Mesaverde formation, a procedure justified by the fact that the Cretaceous formations were continuously traced by these authors southward from their type localities in Colorado. Strata classed as Lewis shale and Laramie formation in Shaler's report are included on the geologic map (Pl. II, in pocket) with "Mesaverde and later formations" and are but briefly described in the text (p. 75).[5]

[1] Darton, N. H., op. cit., pp. 55–58.

[2] Newberry, J. S., op. cit. (Macomb expedition), pp. 104–109.

[3] The term "Creston," which was assigned to this portion of the Defiance monocline ("hogback") and which Newberry states was derived from the Mexicans, is probably a misinterpretation of the familiar Spanish term cuesta.

[4] Shaler, M. K., op. cit., pl. 22.

[5] Field work done by C. M. Bauer since this report was prepared has shown that in the Chaco River valley the "Mesaverde and later formations" up to the base of the Tertiary should be subdivided as follows: Kirtland shale, including Farmington sandstone member, 836 to 1,635 feet; Fruitland formation (coal-bearing), 194 to 292 feet; Pictured Cliffs sandstone, 49 to 275 feet; Lewis shale, 76 to 475 feet; and Mesaverde formation, 1,980 feet.

My knowledge of the Dakota, Mancos, and Mesaverde in the areas studied by Shaler and also at Black Mesa is the basis for using these terms to include all Cretaceous beds in the Navajo country. The age of the formations is established by collections of fossils determined by Mr. Stanton and Mr. Knowlton.

AREAL EXTENT AND GENERAL APPEARANCE.

As indicated above, the Cretaceous strata crop out in the Navajo country in two areas—on Black Mesa, in Arizona, and in the area including Manuelito, Dutton, and Chaco plateaus and Chuska Valley, in New Mexico. In addition to these extensive exposures smaller areas may be seen on the Moenkopi Plateau, at White Mesa, at Navajo Mountain, at Carrizo Mountain, and beneath the lavas of the westernmost Hopi Buttes. Where the rocks attain considerable thickness, the Cretaceous is readily distinguished as far as the eye can reach. The Jurassic below is brilliantly colored with reds, purple, orange, green, and white; the Cretaceous sandstones are gray, yellow-gray, and brown-gray, and the shales blue-gray to iron-gray. Compared with the scenery of all other series displayed in the Plateau province that of the Cretaceous is dreary and monotonous. The fascinating variety of brilliant colors and bewildering range of erosion forms shown by the other formations are lacking. No surprises await the lover of landscape effects who travels among these strata, and the imagination is not stimulated by unexpected vistas. In a scenic sense the lofty Cretaceous mesas serve their best purpose in furnishing viewpoints from which the marvelous panorama of the lower Mesozoic may be leisurely examined.

At every point where all the members of the Cretaceous are displayed in horizontal position the topographic expression is identical—a low gray or brown cliff (Dakota) at the base, followed by a long slope of blue-gray shale (Mancos), capped by high cliffs of sandstone interrupted by slopes of shale (Mesaverde). Where the lower sandstones alone are present, the Cretaceous merely serves as a cap for cliffs of the McElmo formation, from which it is distinguished by color. Where the middle member forms the surface, mounds and mesas abound, and where only the upper sandstones are displayed sheer walls of buff or yellow-gray sandstone rise above the widened valley floors.

The combination of friable shale and resistant sandstone furnishes ideal conditions for the formation of mesas impressive in size and variety of form—features characteristic of the Cretaceous of the Plateau province. The long finger mesas on which the Hopi villages are securely placed and the outliers Howell Mesa and Padilla Mesa are but portions of Black Mesa, a Cretaceous erosion remnant about 2,400 square miles in area, preserved by the Tusayan downwarp. On Dutton Plateau, where the strata dip gently northward, a southward-facing series of steps are developed—the treads in shale, the risers formed of broken sandstone cliffs or strings of mesas. The first step is a broad valley floor cut in the Mancos shale; the succeeding steps, determined by thinner shale beds, are narrower. The culminating points, such as Pyramid Butte and Hosta Butte, are carved from successively higher strata in the Cretaceous. On the Chaco Plateau mesas 10 to 100 feet in height dot the surface. The Manuelito Plateau, which serves as a divide for streams flowing north, west, and south, is intricately dissected into a tangle of mesas and flat-topped ridges carved from Cretaceous beds. In the Chuska Valley, where the strata dip eastward at angles between 2° and 70°, the dominant features are cuestas rising sharply above the valley floors.

DAKOTA SANDSTONE.

PREVIOUS DESCRIPTIONS.

In the area under discussion, the presence of the Dakota sandstone was first recognized by Dutton.[1] The formation was briefly discussed by Schrader and by Shaler. Gardner[2] describes the Dakota sandstone, 200 feet in thickness, as follows:

> Light-gray hard sandstone at top and bottom; alternating thin beds of sandstone and shale with bituminous shale and a few irregular coal beds of no commercial importance.

In the hogback east of Gallup Darton[3] found 60 to 100 feet of basal Cretaceous, "a hard buff sandstone, in part coarse and massive, lying unconformably on soft white Zuni sandstone." Eight miles southeast of Gallup Darton recognized 250 feet of the Dakota sandstone. In the Navajo country the strata assigned to the Dakota range in thickness from nearly 300 to less than 20 feet. In places this formation is lacking altogether and shale carrying *Exogyra columbella* Meek ? lies directly upon the McElmo formation.

[1] Dutton, C. E., op. cit. (Mount Taylor, etc.), p. 138.

[2] Gardner, J. H., The coal field between Gallup and San Mateo, N. Mex.: U. S. Geol. Survey Bull. 341, pp. 365–366, 1909.

[3] Darton, N. H., U. S. Geol. Survey Bull. 435, pp. 55–57. 1910,

STRATIGRAPHY.

The Dakota includes the sandstone and conglomerate beds with small amounts of shale and coal lying between the McElmo formation and the thick beds of fossiliferous shale of Benton age. The invertebrate fossils collected from the Dakota were found to be of little value in placing this formation in the time scale; the plants however include well-known Dakota species.

Strata assigned to the Dakota are included in many sections measured on the Navajo Reservation. The following are considered typical:

Section of lowest Dakota at Pyramid Butte, N. Mex.

	Feet.
1. Sandstone, buff, coarse, cross-bedded, in 3-foot beds; forms top of butte	15
2. Shale, carbonaceous, with many plant fragments.	5
3. Sandstone, buff-yellow, coarse, cross-bedded, lenticular	15
4. Coal, impure	1
5. Shales; alternating thin beds of yellow arenaceous shale and black carbonaceous shale	15
6. Conglomerate of overlapping lenses of gravel and coarse sand with undeterminable plant and shell fragments	5
Unconformity.	
McElmo sandstone.	
	56

Section of Dakota sandstone in Steamboat Canyon, Ariz.

	Feet.
1. Sandstone, yellow, in irregular lenticular beds 1 foot to 4 feet thick; full of plant fragments, especially near bottom; few shells near top; species identified: *Phyllocladus subintegrifolius*, *Ficus inaequalis*, *Ilex* sp.?, *Ostrea* sp., *Corbula* sp.; forms cap of mesa	15
2. Shales and coal, with lenses of sandstone. Shales yellow and sandy at base and drab and argillaceous near the top. Coal in ten to twelve thin seams, three of them over 1 foot thick. Coal, shale, and cross-bedded sandstone replace one another along the strike. Contains fragments of wood and of shells	65
3. Sandstone, yellow, cross-bedded, with lenses of shale and of coal, conglomerate at base; contains impressions of plants; bedding extremely irregular	22
Unconformity.	
Sandstone, white, fine, even grained (McElmo).	
	102

Section of Dakota sandstone in Todilto Park, N. Mex.

	Feet.
Mancos shale.	
1. Sandstone, yellow-gray, cross-bedded, in irregular beds from a feather edge to 3 feet thick; forms top of hogback	25
2. Shale and thin-bedded sandstone, mud cracked.	10
3. Sandstone, yellow-gray, fine to coarse, very irregular, full of unconformities; bands, lenses, and individuals of gray, yellow, and drab mud chunks; appears only partly consolidated	0
4. Shale, yellow, carbonaceous and arenaceous, and thin-bedded sandstone	8
5. Shale, carbonaceous and argillaceous, with seams of impure coal	2
6. Sandstone, gray-yellow, with bands of brown, cross-bedded; foliation surfaces sun baked; many concretions; plant fragments and clay chunks	4
7. Shales, black, carbonaceous and argillaceous, with three bands of coal 2 to 4 inches thick, and plant fragments, including *Salix* sp. and *Ficus*	10
8. Sandstone, coarse to fine, glistening, conglomeratic in places; brown gravel concretions; abundant plant fragments	80
9. Shale, yellow and red, sandy, lenticular	5
10. Sandstone, yellow, coarse, cross-bedded, highly lenticular, with lenses, strings, and single pebbles of quartz, quartzite, chert, dense limestone, and sandstone, half an inch to 2 inches in diameter, all worn but not well rounded	85
Unconformity.	
Sandstones and shales, green-white and red (McElmo).	
	245

Section of Dakota sandstone in east face of Black Mesa, 6 miles north of Lohali, Ariz.

	Feet.
1. Sandstone, yellow-gray, thin bedded, ripple marked with worm burrows, etc.; forms top of wide bench above which rise slopes of dark and drab Mancos shale, capped by vertical wall of Mesaverde	3
2. Coal, of good quality; separated by thin shale partings; carries sulphur	5
3. Shale, yellow-gray, with two 10 and 14 inch coal seams	6
4. Sandstone, yellow, fine, lenticular	1
5. Coal of good quality	2
6. Shale, yellow-gray, with two bands of coal, 8 and 12 inches thick	10
7. Sandstone, yellow-gray, with brown-black concretionary bed, containing fossil leaves, as in No. 10; thin-bedded shales at top	3
8. Shale, yellow and drab, with many lenses of coal, some of good quality	11
9. Sandstone, yellow, hard, fine grained, evenly bedded, and mud full of plant fragments	1
10. Shales, yellow and drab, with abundant plant fragments and two 8-inch beds of impure coal; contains two beds of fine-grained clayey sandstone, from which were obtained *Salix* sp.; *Andromeda pfaffiana* (?), and *Juglans* cf. *J. crassipes*	8
11. Sandstone, yellow, hard, coarse, cross-bedded, unevenly bedded; contains numerous small red-brown concretions	4
Unconformity.	
Sandstone, green, yellow, and white, fine grained; gypsiferous (McElmo).	
	54

Near Lohali Mr. Pogue found only 45 feet of the Dakota, about half of which is coal and carbonaceous shale in beds ranging in thickness from 4 to 18 inches. Twelve miles farther north the 80 feet of sandstone and shale representing the Dakota contains only inconspicuous seams of impure coal. The formation is 210 feet thick 6 miles southeast of Marsh Pass and 295 feet at the mouth of Laguna Canyon, and it is believed by Mr. Pogue to attain considerably greater dimensions along the northwest face of Black Mesa, but in Moenkopi Canyon it is represented only by 15 feet of sandstone indurated by iron cement. White Mesa is capped by 10 feet of yellow-gray sandstone, underlain by 5 feet of blue carbonaceous shale and 23 feet of lenticular buff sandstone with plant impressions and iron concretions. In upper Steamboat Wash 40 feet of coarse sandstone in beds 6 to 8 feet thick separated by lenses of shale forms the canyon rim. The lava-capped mesas on the northwest edge of the Hopi Buttes volcanic field include various amounts of the Dakota, and the maximum of 160 feet is shown in an isolated mesa 3 miles north of Comar Spring. Boulders of conglomerate believed to be Dakota were found along the north base of Navajo Mountain. The 170 feet of the Dakota at Carrizo Mountain is predominantly sandstone.

LITHOLOGIC FEATURES.

The Dakota sandstone is highly variable in structure, texture, and composition. It is characterized more by a persistent combination of features than by the persistence of any given bed. The base is commonly but by no means universally marked by conglomerate, and the top is in many places a coarse brown or gray sandstone bed but may be a group of interbedded sandstones and shales or wholly sandy shale of yellow or gray tones. Coal lenses occur prevailingly in the middle of the Dakota but are found in all positions from top to bottom. The formation is everywhere lenticular; lenses and wedges of sandstone, of or a few inches thick overlap, appear, and disconglomerate, of shale, and of coal tens of feet appear along the strike and vertically in a most capricious manner. In a branch of Steamboat Wash the Dakota immediately overlying the McElmo sandstones presents four phases within a distance of 1 mile—(1) conglomerate with quartz and shale pebbles, half an inch to 1½ inches in diameter; (2) drab mud shale, poorly bedded; (3) brown sandstone, irregularly bedded and cross-bedded, usually with much black carbonized wood; (4) coal with drab shale. At one locality a 15-foot bed of conglomerate is replaced by shale within a distance of 200 feet along the cliff face. The sandstones are commonly cross-bedded, straight laminae meeting one another at high and low angles. In the finer sandstones curved laminae occur.

The material composing the coarser phases of the Dakota varies widely in composition and relative abundance. Along the south side of Todilto Park, the pebbles of white (90 per cent), red, and black quartz, quartzite, chert, and hardened shale (yellow and brown) are one sixty-fourth to one-half inch in diameter, and lenses 6 inches by 10 to 100 feet, made up of subangular quartz in bunches or strings or individuals, traverse the strata. Kaolinized feldspar and rolled pebbles of shale and sand lumps occur, and at some localities the fragments of shale make up the bulk of the rock. At Chilchinbito pebbles of quartz, quartzite, and chert one thirty-second of an inch in diameter are mingled with broken chunks of sandstone, lumps of mud, and poorly consolidated balls of sand, making a mixture identical with that on the floor of a wash after a sudden shower. On the flanks of Navajo Mountain Mr. Heald found blocks of gray hard cross-bedded sandstone, believed to be Dakota; they contain round to subangular pebbles one-third to one-half inch in diameter, of which 95 per cent are gray and white and 5 per cent red and black. On the southwest side of Navajo Mountain, at an altitude of 9,000 feet, the Dakota (?) is represented by an arkose breccia consisting of angular fragments of brown, gray, and red quartzitic sandstone, black slate, white quartzite, and abundant feldspar, both fresh and partly decomposed. The sandstone fragments are from 3 inches to 2 feet in diameter. At nearly all localities impressions of leaves, stems, and tree trunks are found, and fossil wood was observed at a few places. Dark-brown ferruginous concretions are abundant in the Dakota. They are commonly small and rounded and weather out as knobs and "boltheads." In places they take the form of pancakes, balls, or lozenges—irregular masses 6 to 10 feet in long diameter.

The cement of the Dakota is calcareous, ferruginous, and siliceous. Where calcareous cement occurs the rock is readily crumbled and is highly porous. Hydrous iron oxide is the most common cementing material and permits the formation of resistant ledges which stand as cliffs. In places the rock is so firmly united as to form a quartzite conglomerate. The removal of cement and of clay pellets and the decomposition of the vegetable remains has produced a porosity which makes the Dakota an excellent water carrier.

MANCOS SHALE.

GENERAL RELATIONS.

The Mancos shale includes all the strata between the Dakota sandstone and the Mesaverde formation. It is essentially a thick accumulation of drab sandy clay shales, with a relatively small percentage of sandstone, impure limestone, and coal. The beds are gypsiferous, and they carry many fossils of Benton age. The Mancos strata are conformable with the sediments above and below, but are lithologically unlike them. The contact with the Dakota is established with a fair degree of approximation, for shale carrying Benton fossils lies within 25 to 50 feet of characteristic Dakota beds, and at nearly all localities an "oyster bed" with hundreds of broken shells of *Ostrea* and *Gryphaea* is found within the lowest 200 feet of the Mancos. The Mancos-Mesaverde contact in a few sections measured was located with little difficulty, for a slate-colored shale immediately underlies massive yellow-buff sandstone. At most localities, however, the upper limit of the Mancos must be arbitrarily drawn in the midst of 100 to 300 feet of strata, for the Mancos passes into the Mesaverde by a series of transitional beds of shale and sandstone possessing features of both formations.

LOCAL FEATURES.

In the valley of Simpson Creek, where the Cretaceous section has been greatly reduced by pre-Tertiary erosion, the Mancos is represented by about 200 feet of paper-thin drab shale with thin beds of yellow-gray sandstone and a layer of coal 1 to 1½ feet thick. At 220 feet above the Dakota the following Benton fossils were found in abundance: *Ostrea* sp., *Camptonectes*, *Inoceramus labiatus*, *Prionotropis?* sp., and scales and bones of fishes.

The southern wall of Salahkai Mesa includes 550 feet of shale between the typical Dakota and the heavily bedded Mesaverde cap. About midway up in a section measured at this locality is a 1-inch bed of black calcareous sandstone from which were obtained *Lingula* sp., *Ostrea* sp., *Prionotropis* sp., and shark teeth—an assemblage of Benton forms. The 428 feet of clayey, gypsiferous shale exposed near Jadito Springs contains three thin beds of gray sand shales in which are embedded *Inoceramus labiatus* and *Prionotropis* sp. The long mesas of Tusayan, on which are perched the seven Hopi villages, are composed of Mesaverde sandstone underlain by Mancos shale. The 295 feet of Mancos strata exposed at Shongopovi include many brown-gray sand bands in addition to the normal dark-blue and slate-colored rocks, giving to the cliff a general gray tone. The rocks range from thin-bedded sandstones to sandy limestones and include lenses of coal and much gypsum. Crinkled ammonites, *Prionotropis*, were collected at one horizon, and in this general locality Newberry[1] collected *Ammonites percarinatus*, *Inoceramus crippsii*, *Pinna?*, *Lingula* sp., and *Gryphaea pitcheri* var. *navia*.

At Oraibi Butte and Padilla Mesa the Mancos is exposed for vertical distances of 270 and 130 feet respectively; it lies low on the cliffs and extends outward beneath alluvial slopes. The lower boundary of the Mancos is concealed also at Howell Mesa, where 310 feet of gray, drab, and black shales are visible in the Mesa wall. In the section measured at Chilchinbito the upper contact of the Mancos was drawn at the base of the lowest thick bed of sandstone. As thus limited, the gray and drab argillaceous shales with sandy carbonaceous and calcareous beds have a thickness of 565 feet. About 100 feet from the base is a shell heap including hundreds of specimens of *Ostrea* and *Inoceramus labiatus*. Beneath the sandstone cap of Lolomai Point is 620 feet of Mancos shale, and at 60 feet from the bottom there is a 3-foot bed of coquina consisting entirely of one species determined by Prof. Charles Schuchert as *Exogyra laeviuscula*, of Colorado age. In the Blue Canyon section 490 feet of the Mancos was measured by Mr. Pogue, who found "oyster beds" at 45, 75, and 95 feet from the base and "numerous crinkled ammonites" at 195 and 230 feet. Vertebrate bones found on the slope justified further search for fossils, and accordingly Mr. Heald returned in 1911 and made a collection of bones which proved to be the larger part of a dinosaur. On these bones Prof. R. S. Lull[2] reports:

> Very largely a plesiosaur skeleton, identified by teeth, vertebrae, and the presence of gastroliths, genus not to be determined without extensive development of the material. A marine form. Invertebrates associated with the skeleton are of Benton or Niobrara age, which agrees approximately with the level at which the plesiosaur might occur.

In Red Wash, near the Carrizo Mountains, Mr. Emery measured 335 feet of the lower part of the Mancos, in which *Ostrea congesta* and *Gryphaea newberryi* were found in abundance. The sandy strata capping the dome of Navajo Mountain have been converted into resistant quartzite by the addition of a siliceous coating to the quartz grains. Only a small part of the lower Mancos is exposed on the mountain summit, but search resulted in finding a few shells, among which Prof. Schuchert recognized *Exogyra laeviuscula* and *Mactra emmonsi*, of Colorado age.

The shell bed near the base of the Mancos of Black Mesa is exposed 4 miles east of Fort Defiance, also in the "Haystacks" region along the road between St. Michaels and Gallup and at other points in Black Creek Valley. It consists essentially of irregularly shaped accumulations of *Exogyra*, *Ostrea*, and *Gryphaea*, closely packed in a sandy calcareous matrix. At the Tuba coal mine *Ostrea petina*, identified by Prof. Schuchert, constitutes about 90 per cent of the shell heap; on the north slope of Black Mesa *Ostrea pellucida?* and *Exogyra* are about equally abundant. At Defiance Mesa the only other fossils found among bushels of *Ostrea lugubris* were fragmentary fish remains, and at Round Top Butte, in the Hopi volcanic field, the whole shell stratum appears to consist of *Exogyra columbella*. The Mancos formation is analyzed in the combined sections on pages 76–79.

[1] Newberry, J. S., op. cit. (Ives expedition), pp. 117-132.

[2] Personal communication.

MESAVERDE FORMATION.

GENERAL RELATIONS.

The Mesaverde of the Navajo country differs in no essential respect from strata of this age at the type locality in Colorado. At its base are one or more heavy beds of sandstone 30 to 50 feet thick; these are succeeded by strata consisting of about equal amounts of thin sandstone and shale with many beds of coal. The top of the formation includes three or more beds of massive sandstone attaining thicknesses of 40 to 100 feet. It is a prominent cliff maker, forming in many places unscalable walls. Mesaverde strata constitute the cap and the encircling wall of Black Mesa and the precipitous north front of Dutton Plateau and rank with the La Plata sandstone in boldness of topographic expression.

In the present report the Mesaverde is the most recent formation described, as I have not studied Cretaceous beds higher in the stratigraphic column. The Lewis shale and later Cretaceous deposits are known to be present on the Chaco Plateau and along the San Juan,[1] and beds younger than the Mesaverde occupy an undetermined area on the northern part of Manuelito Plateau. Massive sandstones along the Fort Defiance and Tohachi road are overlain by a series of soft sandstones and shales eroded into capped columns and irregularly shaped buttes which carry fossils that may belong to a formation younger than the Mesaverde. *Sphaerium*, *Planorbis* (*Bathyomphalus*) sp., and *Viviparus* sp. were obtained in a cliff 5 miles south of Tohachi, and in strata 200 feet below there were found an abundance of plant fossils, including *Ficus* cf. *F. speciosissima*, *Ficus* sp., *Juglans*, and two undescribed species of *Carpites*. Near Tohachi a turtle, *Baena* sp., considered by Prof. Lull[2] as not older than Judith River, was found by Mr. Emery. This locality is worthy of detailed study by those interested in the Mesaverde. Nearly all of the formation is believed to be present along the north rim of Black Mesa, but elsewhere it has suffered diminution by erosion.

[1] Shaler, M. K., A reconnaissance survey of the western part of the Durango-Gallup coal field of Colorado and New Mexico: U. S. Geol. Survey Bull. 316, pl. 22, 1907.

[2] Lull, R. S., Personal communication.

LOCAL FEATURES.

The arrangement of strata shown by the Crown Point section (p. 77) is typical for the lower part of the Mesaverde formation of northwestern New Mexico. Sections measured at several points on Manuelito, Dutton, and Chaco plateaus exhibit substantially the same features, their differences relating chiefly to the position, number, and thickness of shale and coal beds. As shown by Shaler,[3] coal of commercial value occurs in the Gallup region at two horizons separated by about 500 feet of barren strata. The portion of the Mesaverde involved in the Defiance monocline, on the west side of the Chuska Mountains, is analyzed in the section on page 77.

In the Black Mesa area the thickness of the Mesaverde and the proportionate amounts of shale, sandstone, and coal vary widely; the formation is nearly twice as thick along the northeast rim of Black Mesa as in the zone extending from Salahkai to Oraibi. This difference is probably the result of erosion, but no definite statement can be made until the strata have been traced across the 50-mile stretch from Lolomai Point to Jadito Wash or Padilla Mesa. At Salahkai Mesa, where 330 feet of the Mesaverde is exposed, the top 117 feet is coarse cross-bedded sandstone in two massive beds separated by 22 feet of thin-bedded sandstone with many plant impressions. Below these upper sandstones are five groups of strata about equal in thickness consisting of alternating clayey and sandy shales and thin-bedded sandstones. Gypsum is abundant in the clayey shale beds; coal was found only at the bottom. In Keams Canyon the Mesaverde strata present the following features:

Section of Mesaverde formation at mouth of Keams Canyon, Ariz.

[Measured with the assistance of K. C. Heald.]

	Feet.
1. Sandstone, yellow-gray, coarse grained, with lenses 2 to 4 inches thick of pebbles, mostly white and gray quartz, one-fourth to 1 inch in diameter and chunks of shale; cross-bedded; abundant ironstone concretions; forms top of mesa	23
2. Sandstone, yellow to white, thin bedded, cross-bedded, fine grained; surfaces of strata coated with brown films and ripple marked; underlies as wavy surface the conglomeratic part of No. 1, a relation repeated between Nos. 4 and 5 and Nos. 5 and 6	22

[3] Shaler, M. K., op. cit., p. 410 and sections.

	Feet.
3. Sandstone like top of No. 6, brown, thin bedded, with shiny foliation surfaces	15
4. Shale, drab-gray, argillaceous; bottom is 3 inches of yellow earthy limonite and a 6-inch lens of coal; plant fragments in mud shale; top forms wavy surface on which rests irregular band of coarse brown-red sandstone, forming bottom of No. 3	14
5. Sandstone like No. 6; contains irregular lenses of very fine, crumbly sandstone or mud shales; many brown-black concretions at top	27
6. Sandstone, coarse, conglomeratic; pebbles of white quartz as much as one-sixteenth of an inch in diameter; highly cross-bedded; coarse material in streaks; top 5 feet thin bedded, of greenish tone; many brown sun-dried surfaces on thin concretionary bands and lenses	25
7. Sandstone, gray-white, thin bedded, soft, crumbly; irregular in thickness and character; mostly medium grained but very fine or microscopic toward the top; thin, smooth, wavy brown bands with sun-dried surfaces occur near top; unconformable with No. 6	14
8. Sandstone, yellow-gray, cross-bedded, thin bedded; forms little cliff	13
9. Shale, yellow-gray, with two coal seams partly covered but probably 2 and 3 feet thick	11
10. Sandstone, yellow-gray, medium grained, cross-bedded in part; at top is black concretionary bed 5 to 6 feet thick; few plant remains	13
11. Shale, yellow-gray, with concretionary nodules of limonite and streaks of hematite; coal in thin lens at top; this bed varies much in thickness and character within a short horizontal distance	3
12. Sandstone, brown-gray, thin bedded, cross-bedded, unevenly stratified; some gypsum; rare plant stems	2
13. Shales, black, yellow, and drab; three beds of coal, 1 to 3 feet thick, interleaved with gypsiferous shale; at top is irregular lens of hematite and limonite inclosing leaves of *Sequoia reichenbachi*, *Ficus* sp., fragments of dicotyledons of Montana age	22
14. Sandstone, yellow, weathering gray; fine grained, well-rounded quartz grains, cross-bedded; at top are irregular lenses of coarse brown sandstone	25
15. Coal with some shale; good quality	9
16. Shale, sandy, and thin sandstone; yellow and white	5
17. Sandstone, yellow-gray; top two-thirds massive, cross-bedded; bottom third irregularly thin bedded, with lenses of shale, coal, and brown ironstone concretions; upper part of massive bed is softer and slightly greenish in hue; contains pellets of clay; weathers to a slope	45
	288

At Second Mesa the Mesaverde formation, as determined by Mr. Pogue, is 285 feet thick. The bottom sandstone is 80 feet thick, and the top of the mesa is formed of a massive cross-bedded stratum of coarse-grained sandstone, 55 feet thick, unevenly conglomeratic, with pebbles of quartz and of shale, cemented by lime and by iron oxide. Yellow and dark-purple shales with thin seams of coal constitute most of the remaining portion of the cliff. Sections measured 3 miles northeast of Oraibi Butte and at Padilla Mesa are almost identical. At the top is 95 feet of yellow-gray coarse-grained sandstone, with lenses and strings of cross-bedded conglomerate, consisting of subangular fragments of quartz with chert and shale and rare kaolinized feldspar cemented with lime and with yellow iron oxide. Shales and thin sandstones with lenses of impure coal make up the next 100 feet; then follows 65 feet of thick-bedded to massive yellow-gray sandstone displayed as a cliff face. At Howell Mesa only about 200 feet of the Mesaverde remains. In Moenkopi Valley 6 miles east of Blue Canyon, where 220 feet of the Mesaverde is exposed, the section includes three strata of coarse sandstone or grit—two, 45 and 12 feet thick at the bottom and a 25-foot bed at the top. Clayey shale and coal constitute 70 per cent of the remaining 138 feet. Along the northern rim of Black Mesa the Mesaverde attains a greater thickness than is known at any other place in northern Arizona. In this region the top sandstones are unusually thick and massive and the number of thin coal beds is abnormally large. At Chilchinbito the mesa rim is a vertical wall 320 feet high, of yellow-gray sandstone with inconspicuous lenses of shale, and six coal beds in addition to eight or ten seams of matted plant fragments occur below the sandstones.

The typical arrangement of Mesaverde strata for the northeast face of Black Mesa is shown in the section on page 78.

COMBINED SECTIONS.

For comparison of the Cretaceous of the Navajo country with that of other localities, three sections are presented below. The Crown Point section includes part of the Mesaverde and, possibly, the top of the Mancos as represented in northwestern New Mexico; the Black Creek section includes the Dakota and Mancos and part of the Mesaverde; and the Yale Point section embraces the entire Cretaceous system as displayed in northeastern Arizona.

Section of Cretaceous rocks at Crown Point, $1\frac{1}{2}$ miles south-southwest of Pueblo Bonito Indian School, N. Mex.

	Feet.
1. Sandstone, yellow-gray, slightly cross-bedded; few brown iron and sandstone concretions, ammonites and shark teeth; forms vertical cliff at top of mesa	85
2. Sandy shale or thin-bedded sandstone	4
3. Sandstone, yellow, massive, cross-bedded; stand as wall; very even grained, without shale partings	24
4. Drab argillaceous shales and thin-bedded sandstones; rare carbonaceous layers one-sixteenth inch thick near top	20
5. Sandstone, yellow-gray, thin-bedded	6
6. Shales, drab and black, with white blossom (gypsum?) in places; thin-bedded sandstones toward the bottom	50
7. Sandstone, yellow-gray, forming vertical cliff; separated into several irregular beds by thin lenses of sandy shale; fairly uniform in texture but contains many lenses, usually 3 to 30 feet long, of concretionary iron and brown sandstone, full of fossils, including the following Montana species: *Lingula* sp., *Ostrea* sp., *Inoceramus sagensis*, *Cucullaea* sp., *Leda* sp., *Cardium bellulum*, *Cyprimeria* sp., *Lucina* sp., *Tellina* sp., *Corbula* sp., *Dentalium* sp., *Gyrodes* sp., *Spironema?* sp., *Fasciolaria?* sp., *Placenticeras* sp.; besides the fossils collected clams 10 inches in length and ammonites 8 inches in diameter were seen	80
8. Shale, drab, with thin coal lenses	5
9. Sandstone, yellow-gray, friable	12
10. Shales, argillaceous and arenaceous, with three beds of coal (6 inches, $1\frac{1}{2}$ inches, and 3 feet) and thin sheets of white-gray sandstone; contains many round and pancake concretions of gray limestone coated with iron; much vein calcite and gypsum	38
11. Drab shale and gray-yellow sandstone	3
12. Coal and shale in thin beds, about equal amounts	9
13. Sandstone, yellow-gray, fine grained, even bedded	2
14. Coal, of good quality, with four shale partings	10
15. Sandstone, gray-white, shaly, fine grained; well-rounded quartz; many sheets of carbonaceous shale near top	18
16. Sandstone, gray, yellow stained, medium grained, gritty, with abundant iron concretions, 1 inch to 1 foot in diameter; at top is 1 foot of yellow limestone mottled with concretionary pellets one-eighth to one-half inch in diameter	40
17. Shale, carbonaceous, and coal; probably 4 feet of good coal	12
18. Shale, drab, sandy, with 2 feet of sandstone at top, capped by a thin sheet of iron concretions	22
19. Coal, nearly pure, with thin shale partings	8
20. Shale, drab, sandy, in lower part; alternations of coaly shale and impure coal in upper part	19
21. Sandstone, gray-white, yellow stained, unevenly bedded; inclusions of clay and nodules of hematite, capped by 3 to 6 inches of black-brown concretionary sandstone	4
22. Coal, with small fragments of shale and thin shale bands; near top a 2-foot bed of drab shale weathering into knobs and balls on vertical surface; four coal beds 6 inches to 2 feet thick, of good quality; others impure	19
23. Shale, gray, argillaceous, gypsiferous, with bands of impure coal and lenses of concretionary limonitic sandstone	27
24. Sandstone, gray, subangular; medium-sized quartz grains; irregularly bedded, full of coal and plant fragments; in places sandy shale	7
25. Shales, gray, purple, and drab; full of plant fragments, with three seams, probably 4 feet in all, of good coal; gypsum abundant	16
26. Sandstone, yellow to gray-white, coarse to conglomeratic; subangular quartz with many small chalklike lime fragments; even bedded; few plant impressions	16
27. Coal; much sulphur	1
28. Sandstone, mottled gray-white and brown, with yellow streaks, fine grained; well-rounded quartz; firm; cliff maker	20
29. Shale, brown, argillaceous; much gypsum	13
30. Sandstone in five beds	64
a. 10 feet gray-brown; massive, thin bedded at top.	
b. 4 feet white; thin bedded, fine grained, soft.	
c. 20 feet gray-brown; massive, coarse, well-rounded quartz, friable.	
d. 10 feet like 30a, but darker and harder; forms terrace front.	
e. 20 feet gray-white; massive, fine grained, well-rounded quartz, lime cement, friable.	
Beds c, d, and e include layers of calcareous sandstone with numerous fossils, including *Cardium* and *Mactra?* sp.	
	654

Section of Cretaceous rocks in upper Black Creek Valley, Chuska Mountains, Ariz.

Tertiary.

Unconformity.

	Feet.
1. Sandstone, brown and yellow-gray, in massive beds 15 to 30 feet thick, uniformly medium grained; fossils in brown calcareous bands include *Avicula?* sp., *Inoceramus sagensis?*, *Liopistha* (*Cymella*) sp., *Mactra formosa*, of the Montana group	140
2. Gray sandstones and yellow shales	10
3. Shales, drab and yellow-gray, argillaceous and in part arenaceous and calcareous; top 30 feet sandstone in beds 4 inches to 1 foot thick; contains many sheets of mashed plant fragments and four lenses of impure coal; fossils: *Inoceramus*, *Cardium*, *Ammonites*	134
4. Gray to brown sandstone, in irregular very thin beds, and drab-gray sandy shale in about equal	

	Feet.
parts; about 15 per cent of shale is argillaceous and 5 per cent calcareous; fossils in brown sand bed at bottom: *Inoceramus* sp., *Cardium* sp., *Tellina* sp., *Mactra* sp., *Fasciolaria* sp., *Baculites* sp	90
5. Drab-gray clayey and sandy shales (about 70 per cent), thin-bedded yellow-brown sandstone (about 26 per cent), and calcareous layers (4 per cent); abundant plant fragments; fossils in sandstone bed 80 feet from base include *Ostrea* sp., *Anomia* sp., *Inoceramus* sp., *Plicatula* sp., *Cardium* sp., *Tellina* sp., *Mactra* sp., *Gyrodes* sp., *Cinulia?* sp., *Baculites* sp.; limestone 60 feet from base contains *Mactra* sp	110
6. Shales, drab, argillaceous and highly carbonaceous	20
7. Yellow-brown thin-bedded sandstone and shale.	5
8. Shale, drab, with numerous plant fragments and 6-inch bed of shaly coal	14
9. Sandstone, brown to yellow; fine subangular quartz with stringers of coarse sand; cross-bedded, with laminae 2 to 8 feet thick	130
10. Shale, blue-gray, with a thin band of red and two of white; uniformly argillaceous, except for a 2-foot bed of sandstone and three calcareous bands; Benton fauna in impure limestone 165 feet from base: *Ostrea lugubris*, *Inoceramus fragilis*, fish bones	437
11. Sandstone, brown, thin, irregularly bedded; clay pellets and ironstone concretions common; foliation surfaces lumpy, sun dried, and covered with worm tracks; appears like successive layers of sand exposed between showers	40
12. Brown thin-bedded sandstone and drab shale; numerous plant fragments and six thin seams of impure coal	75
13. Sandstone, brown, cross-bedded, consisting of medium-sized, well-washed quartz; weakly cemented, very lenticular and stringy	6
Unconformity.	
McElmo sandstone, massive, 70 feet thick.	
	1,211

Section of Cretaceous rocks near Yale Point, on Black Mesa.

[Measured by J. E. Pogue.]

	Ft.	in.
1. Sandstone, yellow, fine to medium grained, calcareous, fossiliferous; forms a sheer cliff capping Black Mesa	200±	
2. Sandstone and shale alternating	20	0
3. Sandstone, light gray, fine grained, with seams and bands of gray shale; includes near center two coal beds each 4 to 5 feet thick	50	0
4. Sandstone, light gray, fine grained; includes bands of gray shale and iron oxide	10	0
5. Clay, indurated with iron oxide		6
6. Shale, gray, containing band of gray sandstone	2	0
7. Coal	1	5
8. Shale, gray	1	5
9. Coal, good	1	1
10. Shale, drab to bluish gray	1	7
11. Coal, good		9
12. Shale, gray, thin		9
13. Coal, good	2	0
14. Shale, gray to slate-colored, with seams and bands of light-gray sandstone	1	6
15. Coal, good	1	0
16. Shale, gray, sandy	4	8
17. Coal, good		9
18. Shale and sandstones, gray, thin bedded.	7	6
19. Coal, pure	6	2
20. Shale, gray, thin, sandy, alternating with beds of sandstone as much as 8 inches thick	6	7
21. Coal	1	0
22. Shale, light gray, sandy; near bottom is 1-foot band of dense, hard fine-grained sandstone indurated with iron oxide	6	0
23. Coal, good; selenite in joints		11
24. Shale, gray, with 2-inch seam of fair impure coal near top	6	0
25. Coal; some selenite		9
26. Shale, dark gray, thin; contains few thin coal seams a fraction of an inch thick, also few thin layers of gray sandstone.	7	9
27. Coal, good	1	4
28. Shale, gray, sandy; seams of sandstone near bottom	9	4
29. Sandstone, yellow, mostly massive but locally thin bedded, with seams and a few stout lenses of dark-colored shale.	25	0
30. Drab to blue shale, alternating with beds of yellow sandstone; lenses of lignite scattered throughout	3	6
31. Shale, drab	4	0
32. Coal, pure		6
33. Sandstone and shale, yellow; upper 11 feet drab shale	16	0
34. Sandstone, light yellow, fine to medium grained, speckled, friable but stands up prominently in cliff; contains bands with clay pellets, surrounded by crusts of iron oxide like kernels in nut; also lenses of greenish shale and lenslike masses of coal several inches thick	41	0
35. Gray shale and grayish-yellow sandstone, in alternating thin beds	20	0
36. Sandstone, yellow	2	0
37. Shale, purple and gray, thin	16	0
38. Shale, gray, sandy, dense, massive, indurated, with a few wavy carbonaceous sheets	3	2
39. Coal, pure, with a few thin shale partings.	1	8
40. Shale, gray, thin; much selenite	20	0
41. Sandstone, yellow, calcareous, medium grained, forming vertical cliff; massive except for narrow lenses carrying kaolinized fragments and a very few small subangular quartz pebbles; fossils include *Ostrea*, gastropods, several species of pelecypods, and belemnite-		

	Ft.	in.
like forms; species determined: *Ostrea pellucida*, *Inoceramus proximus*, *Gervillia*, of Montana age	80	0
42. Sandstone, light gray, very thin bedded, very fine grained, breaking in thin sheets of large diameters; contains ammonites	44	0
43. Sandstone, yellow, massive, medium grained, with kaolinized feldspar and subangular quartz fragments	10	0
44. Shale, gray, dense, sandy, in beds 1 foot thick	9	0
45. Sandstone, white to yellow, fine to coarse grained, in beds 1 inch to 2 feet thick; areas of iron oxide; seams of shale as much as 3 inches thick	8	0
46. Gray sandstone, alternating with thin seams of dark-colored shale carrying gypsum	1	8
47. Sandstone, yellowish white, shaly, dense, massive, carrying carbonaceous streaks	1	9
48. Shale, banded purple, black, and gray, highly carbonaceous, gypsiferous	2	0
49. Sandstone, dense, fine grained, almost a quartzite; wavy lenses stained with iron oxide and thin seams of coal	1	8
50. Shale, purple	4	0
51. Sandstone, white, massive, coarse grained, essentially a grit; thin lens of purplish shale 3 feet from top	14	0
52. Shale, purple, with seams of impure coal.	1	7
53. Sandstone, white, medium to coarse grained, calcareous, cross-bedded, with lenses of fine conglomerate and of coal.	60	0
54. Shale, bluish gray, thin, sandy	2	0
55. Sandstone, white to yellow, fine grained, calcareous, massive to thin bedded; few seams and bands of yellow and light-gray sandy shales; upper 100 feet not well exposed	145	0
56. Shale, dense, hard, containing some gypsum and thin beds of coal; bottom 8 feet overlapping lenses of gray-yellow sandstone	21	0
57. Shales, blue to slate colored, crumbly, mostly very thin bedded; carrying much selenite both as crystals and as a coating on foliation surfaces and joint cracks; badland topography; occasional seams of grayish and brownish shales; no carbonaceous phases	470	0
58. Sandstone, gray-yellow, medium grained, calcareous; conglomeratic lenses with kaolinized fragments; fossiliferous layer near top	35	0
59. Shales, purplish, friable, crumbly, with coal and leaf impressions, grading at top to grayish-green more massive sandy shales; bed thins and thickens along strike	17	0
60. Sandstone, yellow brown, fine grained, cross-bedded, with lenses of conglomerate consisting of quartz pebbles and clay fragments	30	0
Unconformity (?).		
Sandstone, green-white, fine grained, calcareous, with purple, red, and green shale lenses (McElmo).		
	1,462	0

TERTIARY FORMATIONS.

PREVIOUS MENTION.

Deposits of "fresh-water Tertiaries, probably of Miocene age, parallel to those of the 'Badlands' of Nebraska," were noted by Newberry[1] along his route from Walpi to Ganado, and the Tertiary strata on the Chuska Mountains were mapped by Dutton[2] and by Shaler,[3] both of whom considered them of Eocene age. My reconnaissance surveys show that Tertiary sediments are coextensive with the limits of the Chuska, Tunitcha, and Lukachukai mountains, occupy considerable areas on the Defiance Plateau, and are interbedded with volcanic deposits on the southeastern edge of Black Mesa and within the Hopi Buttes province.

TERTIARY DEPOSITS OF THE CHUSKA MOUNTAINS.[4]

GENERAL FEATURES.

The cap rock of the Chuska Mountains is a quartz sandstone of widely variable texture, structure, and degree of consolidation. On Chuska Mountain and the outlying mass of Defiance Mesas and along the west rim of Tunitcha and Lukachukai mountains the cap rock is firm, and its eroded edge forms a bordering wall; at other points it is friable and produces a talus which conceals bedrock. The thickness of this capping sandstone is in few

[1] Newberry, J. S., op. cit. (Ives expedition), p. 88.

[2] Dutton, C. E., op. cit. (Mount Taylor, etc.), pp. 130, 140.

[3] Shaler, M. K., op. cit., pl. 22.

[4] The Chuska Mountains as defined by the United States Geographic Board extend from Tohachi to Redrock Valley and include the Chuska (Choiskai) Mountains, Tunitcha Mountains, and Lukachukai Mountains, shown on the Chaco and Canyon de Chelly reconnaissance topographic maps of the United States Geological Survey. These three names, applied to well-marked subdivisions of a range, are commonly used by Navajos and whites. In the text of the present report the term Chuska Mountain is used with its local meaning, indicating that portion of the Chuska Mountains southeast of Wheatfields Creek, whose culminating point is Chuska Peak. By definition the term Chuska Mountains replaces Boundary Mountains, previously applied to the whole range (Gregory, H. E., The Navajo country: Am. Geog. Soc. Bull., vol. 47, pp. 561-577, 652-672, 1915).

places less than 800 feet and at Deza and View Point probably exceeds 1,000 feet. The sandstone lies in a horizontal position and rests in most places on the eroded edges of Mesozoic strata—Chinle, La Plata, Mancos, or Mesaverde. At Chuska Mountain, however, it is underlain by a group of shales which in turn are underlain by truncated beds of Cretaceous age. Both the shales and the sandstone are assigned to the Tertiary and for purposes of description are distinguished as Tohachi shale and Chuska sandstone. These Tertiary beds are unimportant factors in the ground-water problem with which I was chiefly concerned; they were therefore not studied in detail, and my conclusions regarding them are subject to radical revision.

TOHACHI SHALE.

The Tohachi shale as exposed in sections 2 miles north and 3 miles west of Tohachi Indian School consists of alternating beds of poorly consolidated clays and sands with a few strata of impure lignite. It closely resembles the alluvium in the banks of the present streams. The stratification is very irregular; the shales and sandstones and carbonaceous layers are little more than lenses of moderate dimensions that overlap and interleave; few of them retain their individuality for distances greater than 200 feet. The sandstone beds are 10 to 30 feet thick and include lenses of drab and red-brown shale, irregular chunks of clay, balls of pyrite, and concretionary masses of manganese and iron displayed as irregular bands and flattened spheres. The sandstone layers are brown, yellow, gray, and white and are composed of well-rounded quartz grains poorly cemented with lime. They are cross-bedded and appear to occupy eroded channels.

As the name implies, the Tohachi shale consists predominantly of argillaceous strata, arranged in groups 10 to 60 feet in thickness. The bedding of the shale, like that of the sandstone, is extremely irregular; sheets of sandstone and of earthy peat are included, and the beds replace one another within short distances along the strike. Fragments of carbonized and of petrified wood, sandstone concretions, flakes of gypsum and of sulphur probably of secondary origin, and lumps of mud are not uncommon. The shales are black, drab, blue, yellow, brown, and red in unevenly distributed streaks, some of which are continuous for several hundred feet and at a distance produce the effect of regular banding.

Fragments of bone and *Unio* shells were collected from the sandstone bands of the Tohachi shale, and a variety of leaves and stems were found in the clay layers. On examination by T. W. Stanton, W. H. Dall, and F. H. Knowlton, the fossils proved to be not of diagnostic value beyond the fact that they indicate probable early Tertiary time. In composition and manner of deposition the Tohachi shale closely resembles the strata included in the Nacimiento group (basal Eocene) as described by Gardner.[1]

CHUSKA SANDSTONE.

Overlying the Tohachi shale at Chuska Peak is about 700 feet of sandstone. At this point the top of the shale is concealed by talus, but 3 miles farther east an unconformable contact is revealed. This formation, for which the name Chuska sandstone is proposed, extends northwestward to View Point, forming a resistant cover throughout the extent of the Chuska Mountains. Viewed as a whole the Chuska sandstone is thinly foliated, beds exceeding 10 feet in thickness are rare, and at some localities—for example, on Lukachukai Creek— the strata in a vertical exposure of 200 or 300 feet average less than 1 foot in thickness. On the other hand, at a point on the east edge of Chuska Mountain a massive bed 60 feet thick was noted. The rock is mostly gray with a pinkish cast; some beds are as white as chalk, and brown beds are also included. Cross-bedding is common, particularly in the upper strata, and lenticular arrangement of beds was observed at several points. The rock is medium to fine grained and consists of fairly well rounded bits of clean white quartz with lesser amounts of red and of black quartz, volcanic ash, and rare muscovite. At a point 2 miles northeast of Tohachi the base of the Chuska sandstone is a bed of gray conglomerate with pebbles of quartz, sandstone, and shale one sixty-fourth to one-half inch in diameter. Over large areas the rock has the consistency of quartzite; elsewhere it is only

[1] Gardner, J. H., The Puerco and Torrejon formations of the Nacimiento group: Jour. Geology, vol. 18, pp. 702-744, 1910.

moderately firm; at a few places beds about 100 feet below the top are exceedingly friable. At the head of Spruce Brook the surface of the sandstone is marked by pits, rounded cavities, and tubes half an inch or less in diameter. No fossils were found in the Chuska sandstone, and its age is unknown. Its position and lithology suggest correlation with the Wasatch formation of north-central New Mexico.

TERTIARY DEPOSITS OF DEFIANCE PLATEAU.

Along the southwestern edge of Defiance Plateau from Beautiful Valley nearly to the Santa Fe Railway Tertiary sediments form the surface rock. Ganado Mesa consists of tilted beds of the Chinle formation truncated and overlain by 20 to 35 feet of Tertiary strata in horizontal position. These capping strata consist of sandstone weakly held together by calcareous cement. The bedding and texture are very uneven; lenses of conglomerate composed of small fragments of white quartz and chunks of sandstone and chert overlap and replace lenses of fine-grained sandstone. Cross-bedding is common. Within the lower beds and at the contact with the Chinle shales are narrow bands of nodular siliceous limestone containing fragments of chert one-eighth inch to 2 inches in long diameter, and beds of pure-white volcanic ash are found at two horizons.

Strata assigned to the Tertiary crop out at a number of points between Ganado and Wide Ruin Wash. In a canyon 6 miles northwest of Tanner Spring 80 feet of yellow and brown banded sands are eroded into badland slopes. In a butte rising from the floor of Wide Ruin Wash 4 miles east of Tanner Spring 60 feet of light-green, dark-red, and gray arenaceous shales are overlain by 2 feet of white volcanic ash. The butte is capped by 12 feet of thin-bedded yellow-gray friable sandstones composed of black, white, and red quartz grains. The Tertiary sediments of Padres Mesa, resting unconformably on Chinle strata, are analyzed in the following section:

Section of Tertiary strata in north face of Padres Mesa, Ariz.

	Feet.
1. Sandstone, cream-gray, thin bedded, composed of quartz and ash; calcite cement	50
2. Sandstone, gray, fine grained, calcareous; cross-bedding laminae coated with white, red, and black quartz and bits of volcanic ash	1
3. Sandstone, cream-colored, thin bedded, calcareous	5
4. Sandstone like No. 2	1
5. Sandstone, cream-colored, thin bedded, fine grained, in part shaly, but with a little argillaceous matter	18
6. Sandstone like No. 2	1
7. Gray, fine-grained calcareous sandstone and sandy shales, including ash	9
8. Sandstone, cream-colored, cross-bedded; laminae of alternating sheets of coarse and fine sand; includes well-rounded pebbles of quartz and ash	8
9. Sandy shale or thin sandstone, banded dark brown, red, and cream-colored, calcareous, exceedingly friable	35
10. Sandstone, gray, made of white and black quartz and ash; calcareous cement	4
11. Shale and thin-bedded sandstone, yellow-gray, calcareous	20
12. Sandstone and ash, white, banded red; irregularly bedded with curved laminae	6
13. Sandstone, cream-colored to pink, peppered with black and red grains of quartz and ash, highly calcareous	27
14. Shale or marl, red-brown, with minute grains of quartz	12
15. Sandstone, gray to white; microscopic grains of clean, rounded quartz and rhyolitic ash; calcareous cement; forms cliff face	27
	224

The age of the Tertiary sediments of Ganado Mesa and Padres Mesa is not known. Lithologically they resemble the Tohachi shale, from which they differ in the larger proportion of calcareous beds and the greater abundance of volcanic ash.

TERTIARY SEDIMENTS ON THE SOUTHEAST EDGE OF BLACK MESA.

From Sunrise Springs westward nearly to Jadito Wash Tertiary sandstones and volcanic ash unconformably overlie strata of Mesozoic age. In Sabito Wash 240 feet of partly consolidated sediments are exposed. At the base are fine-grained dark-colored cross-bedded sandstones containing fragments of ash. Toward the top the beds become more calcareous and include porous chalk and irregular masses of lime-incrusted plant stems. A section studied at Sunrise Springs contains the following strata:

Section of Tertiary sediments at Sunrise Springs, Ariz.

	Feet.
1. Sandstone, massive, like No. 3, except for thin bands of rhyolitic ash; 3 miles below Sunrise Springs Nos. 1 and 2 form a single bed, 95 feet thick, of thin-bedded calcareous sandstone containing much ash overlying 15 feet of dark-red shale	40

	Feet.
2. Sandstone or ash, olive-colored, cross-bedded, very thin bedded; well-rounded black, white, and red quartz, olivine, augite, and feldspar	6
3. Sandstone, conglomerate, and tuff, cream-gray; at bottom 4 to 6 inches of tuff of various colors; grades into 1-foot bed of microscopically fine ash, followed by 2 to 6 feet of resistant sandstone, including lenses of limestone	55
Unconformity.	
Sandstone, light red (pre-Tertiary).	
	101

TERTIARY OF THE HOPI BUTTES REGION.

The lavas and clastic igneous materials of the Hopi Buttes volcanic field (see p. 85) are associated with shales and sandstones of Tertiary age. In some places these water-laid sediments underlie lavas; elsewhere they are interbedded with volcanic ash. (See Pl. XIV, *A*.) A typical section is afforded by White Cone, which rises above a floor of pre-Cretaceous rock. (See Pl. XIV, *B*.)

Section of Tertiary strata at White Cone, Ariz.

	Ft.	in.
1. Sandstone and ash, white, in beds 2 to 6 inches thick; very fine grained, with pellets of clay one-sixteenth inch in diameter; calcareous cement; friable	20	0
2. Reddish-pink shale and white cross-bedded fine to coarse grained sandstone; fragments of ash	50	0
3. Sandstone, white to gray, cross-bedded; few shell fragments	5	0
4. Shales and amorphous marls, pink	5	6
5. Sandstone and ash, white, fine; weathers into balls	2	0
6. Shales, gray, gypsiferous, calcareous, unconsolidated; has band and nodules of gray-yellow iron concretions; shells near base	25	0
7. Sandstone, yellow, poorly consolidated, fine grained		8
8. Shales or marls, banded dark brown, pink, and green; upper 5 feet is a crumbling gypsiferous band containing numerous shells of *Unio*, *Physa*, and *Planorbis*	55	0
9. Sandstone, yellow-gray, cross-bedded, fine, very soft; includes ash and specks of muscovite	5	0
10. Shale or marl, banded, gray, red, white, pink, and green, poorly consolidated, evenly bedded; includes films of muscovite and sheets of ash	30	0
11. Volcanic ash, gray; pebbles of augite and olivine and clay pellets		4
12. Shale or marl like No. 10	14	0
13. Volcanic ash, banded; pebbles chiefly augite and fragments of basic lavas intermingled with clay	5	6
14. Shale or marl like No. 10	12	0
15. Volcanic ash, white, of microscopic grain, firm, slightly calcareous		1
16. Shale or marl like No. 10	15	0
	245	1

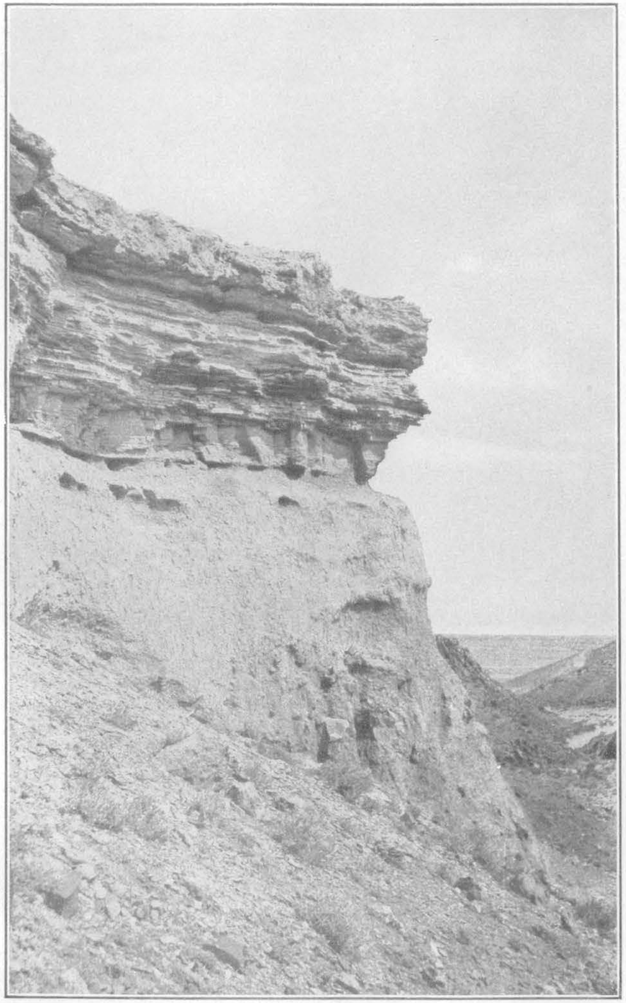
The age of the Tertiary of the Hopi Butte province, as well as of that coating the southeast edge of Black Mesa, is undetermined. The fossils collected belong to species not available for the determination of geologic time. The shells are considered by Stanton as probably Tertiary, and fragments of an alga, probably *Chara* sp., are assigned by Knowlton to Tertiary or Recent time.

QUATERNARY FORMATIONS.

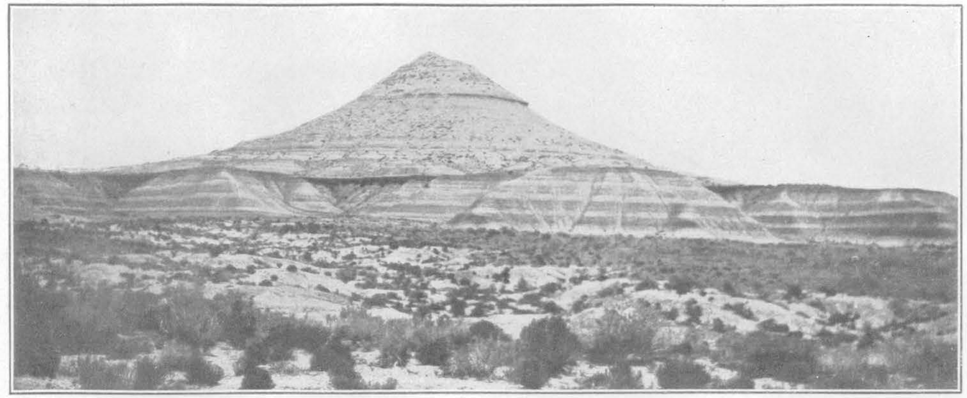
The sediments in the Navajo country that date from Quaternary time include alluvial deposits of the valleys and slopes and eolian sands. (See p. 136.) Certain accumulations on Navajo Mountain suggest incipient ice work, and miniature embankments on this mountain and also on the Chuska Mountains are ascribed to nivation, operating at a time when a perennial snowcap occupied the highland. No undoubted evidence of glaciation, however, has been obtained within the limits of the Navajo Reservation; 30 miles beyond its border, on San Francisco Mountain, the moraine of a glacier 2 miles in length is found at an elevation of 9,200 feet.

Vertebrate bones taken from a dissected terrace at Shato Springs were found by Prof. Lull[1] to belong to the Pleistocene genera *Elephas*, *Megalonyx*, *Equus*, and *Bison?*.

[1] Lull, R. S., Personal communication.

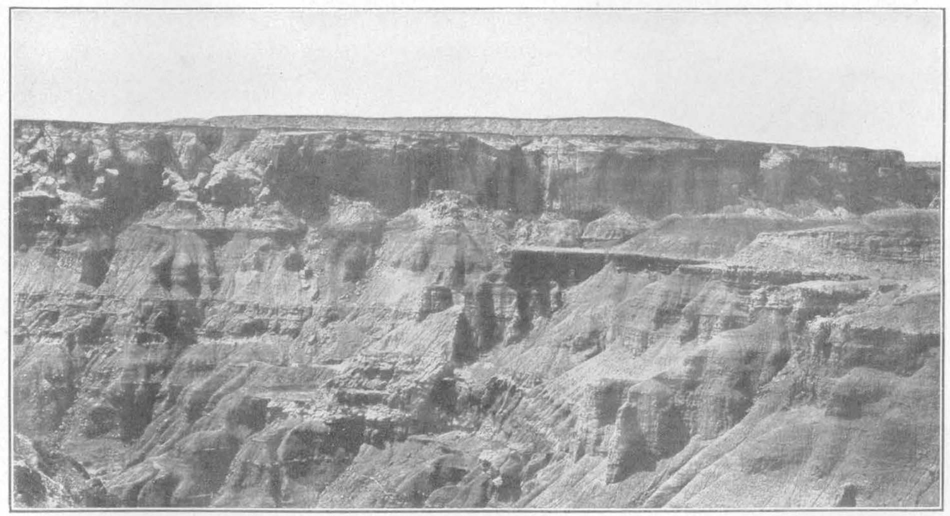


A. INTERBEDDED TERTIARY SHALES AND VOLCANIC TUFF NEAR BIDAHOCHI, ARIZ.



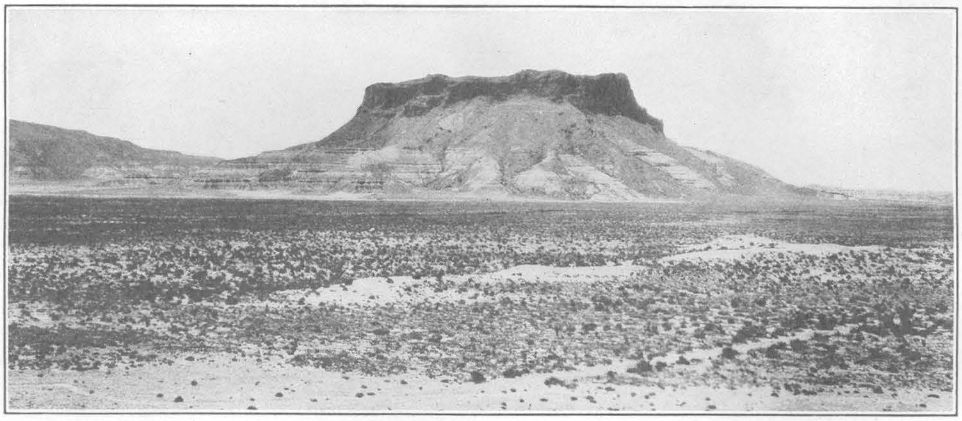
B. WHITE CONE, HOPI BUTTES VOLCANIC FIELD, ARIZ.

Tertiary clays and sand interbedded with volcanic ash.

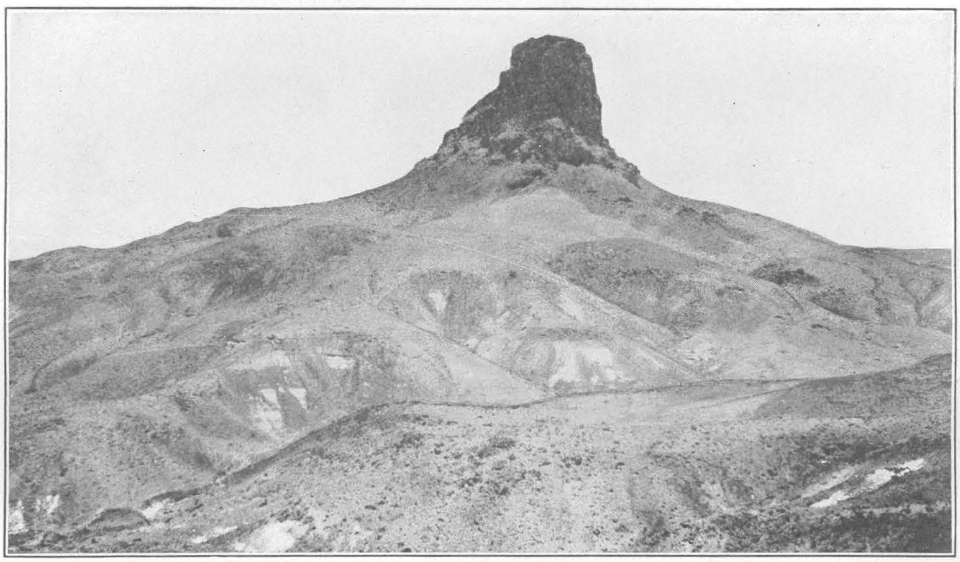


C. CLIFF FACING WARD TERRACE, 12 MILES SOUTH OF TUBA, ARIZ.

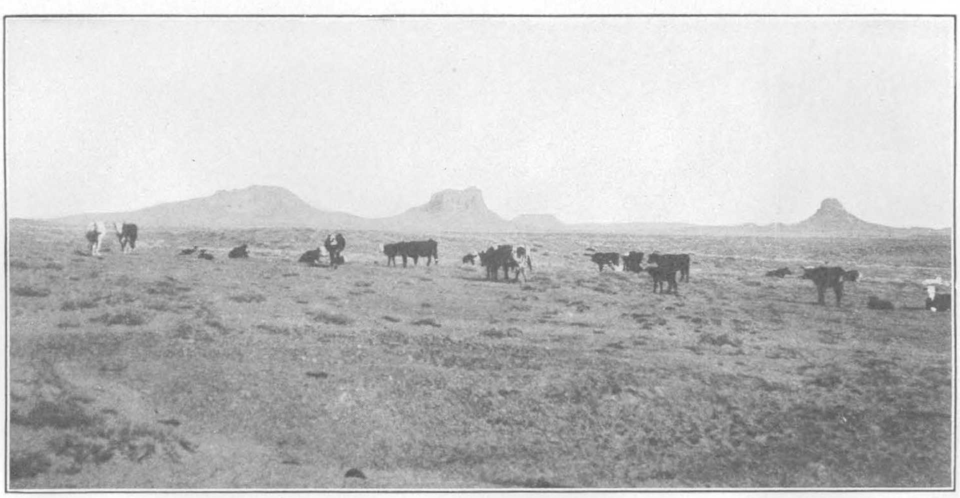
Undifferentiated La Plata and McElmo formations.



A. TYPICAL MESA, HOPI BUTTES VOLCANIC FIELD, ARIZ.
Analcite basalt overlying shales of Chinle formation.



B. MONTEZUMAS CHAIR, ARIZ.
A volcanic neck of teschenite rising through Mesozoic strata.



C. VOLCANIC NECKS AND LAVA-CAPPED MESAS, WEST EDGE OF HOPI BUTTES VOLCANIC FIELD, ARIZ.

CHAPTER IV.—IGNEOUS ROCKS.[1]

GENERAL CHARACTER.

Extrusive and intrusive igneous rocks are widely distributed within the Navajo country. As compared with the sedimentary beds they are resistant masses developed by erosion as mesa caps, volcanic necks, and dikes—dark forms in striking contrast with the brightly colored walls of sandstone. In the clear air of the Plateau province black igneous spires are visible at great distances and for centuries have served as landmarks on the long Indian trails. "Dzil zhin" (black mountain), here and there qualified by terms indicative of form or geographic position, is a recurring word in Navajo descriptions and in the history and legends of the tribe. On his excursion to Hopi villages Newberry[2] was guided by the "blue peaks," which "rose up in front like ships approached at sea—some in cones and symmetrical castellated slopes and others in irregular masses." Howell[3] noted a dike at Moenkopi and some "basaltic buttes" near Fort Defiance, and Loew[4] speaks of a dike of basalt near the Hopi villages. Approaching the reservation from the opposite direction Holmes[5] examined the "trachyte" of Carrizo Mountain.

The igneous rocks of the Navajo country have been subjected to erosion, but not to an extreme degree. Only in the Little Colorado Valley were recent lavas seen, and no areas of deep-seated igneous rocks have been exposed by erosion. Necks, dikes, fragments of ancient flows, and fields of buried ash are the prevailing forms. Carrizo and Navajo mountains are laccoliths, the latter not sufficiently dissected to reveal its intrusive core.

Of the 22 geographic provinces into which the Navajo country has been divided, only six (Chaco Plateau, Manuelito Plateau, Black Mesa, Segi Mesas, and Rainbow Plateau) are without igneous masses. One or more intrusions have been mapped within the other subdivisions, and the Hopi Buttes, Monument Valley, the lower Chuska Valley, and the eastern border of Defiance Plateau may properly be classed as centers of volcanism.

Not all the igneous outcrops shown on the map were visited, and the time allotted for examination of some of them was insufficient to determine their nature. It is believed, however, that with few exceptions the lavas in the areas of extrusive rocks are correctly indicated on the map. The large deposits of tuff on Palisade Creek and along the southeastern edge of Black Mesa are also mapped as extrusives.

Typical dikes have been distinguished from well-defined necks, but intrusions, including volcanic agglomerate, which may or may not have given rise to volcanoes, are mapped as dikes.

HOPI BUTTES VOLCANIC FIELD.

Within the area between Jadito and Pueblo Colorado washes, comprising about 1,100 square miles, practically all the prominent features of the landscape are of volcanic origin. During the course of field work 19 lava-capped mesas, 23 necks, and 16 dikes were examined without exhausting the list. About half of the igneous mesas and buttes are of sufficient height to be represented on the Tusayan and Fort Defiance topographic maps; the others are not shown by 200-foot contours.

LAVA FLOWS.

EXTENT AND THICKNESS.

The lava flows of the Hopi Buttes are detached masses—the protective caps of mesas isolated by erosion. (See Pl. XV, *A*.) Hauke Mesa, the largest of the scattered remnants, extends with unimportant interruptions from Indian Wells to the edge of Jadito Wash, a distance of 19 miles. Its surface, outlined by a scalloped border, has a relief of over 600 feet and is roughened by uneven accumulations of lava as well as by dissection according to a wide-spaced pattern. An unnamed mesa south

[1] Including petrographic notes by L. V. Pirsson.
[2] Newberry, J. S., op. cit. (Ives expedition), p. 118.
[3] Howell, E. E., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, pp. 299, 638, 1875.
[4] Loew, Oscar, idem, p. 639.
[5] Holmes, W. H., U. S. Geol. and Geog. Survey Terr. Ninth Ann. Rept., for 1875, pp. 274-276, 1877.

of White Cone is 12 miles long and is capped, except for short stretches, with a continuous sheet of basalt. The mesa at Malpais Spring, two mesas at Maddox, two at Cedar Springs, and two northwest of Cottonwood Spring complete the list of lava remnants exceeding 2 square miles in area. From masses of such size the fragments of ancient flows grade downward to buttes whose lava tops measure but a few hundred square feet. The total area of lava exposed in the Hopi Buttes field is roughly estimated at 135 square miles.

In thickness the lavas are widely variant. East and north of Bidahochi the fragmentary sheets exceed 50 feet in thickness in only a few places. Twin Mesas are coated by 16 feet of lava; the section at Cottonwood Springs includes only 10 feet. The detached mesas on the south and southwest borders of the volcanic field are terminated by 20 to 80 feet of basalt. The flows forming Hauke Mesa range in thickness from 50 feet at the southern margin to 240 feet at the northwest edge, and Egloffstein Butte, according to Mr. Pogue, is a remnant of a single flow 400 feet thick. This lack of uniformity is well shown in the vicinity of Cedar Springs, where within a distance of 3 miles measurements of 20 to 200 feet were obtained.

TEXTURE AND COMPOSITION.

Viewed from a distance the black basaltic caps of the Hopi Buttes contrast sharply with the brightly colored sediments beneath. Nearer at hand the lava beds are conspicuous for their numerous small caves and pits, resulting from the erosion of irregular lenses of ash and tuff. Lines of flow, indicated by bands of color and accentuated by differential weathering, determine the form of talus slabs, and widely spaced joints outline unsymmetrical blocks. The lavas lack homogeneity of structure and of texture, both on large and small scales. Lenses of vesicular lava are interleaved with sheets of fine-grained rock and with irregular masses of ropy slag. Embedded in the flows are thin slabs of basalt, a few tens of feet in length, lenses of tuff and of ash in various attitudes, and also fragments of sandstone and of shale. Where fresh surfaces are exposed, the lava at some localities is uniformly dense; amygdaloidal texture is, however, more common.

A preliminary study of a selected list of thin sections of the Hopi Buttes lavas was made by Prof. L. V. Pirsson, who reports as follows:

These lavas may be roughly divided into two groups, the classification depending on the compactness of the groundmass as seen under the microscope. One group is represented by the rock from Hauke Mesa at Indian Wells, which in the section is seen to be composed of larger augite and olivine phenocrysts in a dense groundmass. The augites are well formed, unaltered, and of a grayish-brown color with a darker outer shell of a more purplish brown. The olivines are somewhat altered to serpentine along cracks. The groundmass consists of a thickly crowded mass of small, well-formed augite prisms of the darker color seen in the shells of the phenocrysts, together with grains of iron ore and a colorless mineral as cement. In numerous areas the minute augites are crowded aside, leaving clear, more or less rounded areas of the colorless mineral. This mineral is isotropic, having no effect on polarized light; its index of refraction is definitely lower than that of balsam, and it has well-defined cubic cleavage. It contains no arranged inclusions and only slender minute needles of apatite, which abound in the groundmass, project into it. The mineral must be analcite, and the rock is to be classed as an analcite basalt, or monchiquite, in lava form. With the exception of a few minute groups of a circular radial zeolite with feeble polarization and the serpentine in the cracks in the olivine the rock is remarkably fresh and unchanged, especially the groundmass minerals. It resembles the analcite basalts of the Highwood Mountains, in Montana, and the monchiquites of Brazil. The upper part of the lava-capped mesa 8 miles northeast of Comar Springs is very similar to the rock just described but is considerably altered and of finer grain. The lava under the tuff at Lokasakad is similar but is also altered and contains in addition a little plagioclase. That 1 mile south of Cedar Springs, where the flow is compact, is rather finer and not so fresh; it also contains some feldspar and chalcedony in the pores. The lava at Bidahochi also belongs here but incloses a larger amount of plagioclase in the groundmass. These are transition forms between analcite basalts and common plagioclase basalts.

The very dense types constituting the other group are represented by the presumed older lava from the occurrence 1 mile east of Cedar Springs, which, though vesicular, is extremely dense. Its compactness is so great that even with a high power little can be discerned save that the rock for the most part is composed of minute granules of iron ore and brown augite cemented by a colorless substance. A very few small, much or completely altered olivines and augites occur as phenocrysts. The rock is reddened by a ferritic substance apparently due to the oxidizing action of the steam which produced the vesicles. The vesicles are filled with secondary zeolites and calcite. The rock might well be a denser form of a magma similar to that of the rock from Indian Wells, but this can not be definitely proved without chemical analysis, as it is so compact. It may be provisionally classed as analcite basalt.

The lava 100 feet from the top of Egloffstein Butte is similar to that described above but contains also numerous phenocrysts of augite and olivine, the latter completely altered to a green fibrous serpentine, and has chalcedony and carbonates in the pores of the rock.

The lava capping the mesa 3 miles northeast of Comar Spring is a vesicular basaltic pumice or scoria. The cell walls are too black and dense for determination of any microlites of the component minerals; here and there an augite phenocryst is embedded in the mass. The pores or cells are everywhere filled with carbonates. The general appearance indicates a rock like that east of Cedar Springs but even denser. Here also may be placed the presumed older lava which occurs as inclusions in the flows along the southwest base of Hauke Mesa.

ASH AND TUFF ASSOCIATED WITH LAVAS.

Lenses or beds of ash or tuff were noted at nearly every outcrop of lava within the Hopi Buttes province. On the border of the volcanic field deposits of this character were found interbedded with Tertiary sediments. Scattered lenses of ash were noted in the sandstones of Wide Ruin Wash, and along the southeast border of Black Mesa ash beds are persistent members of the Tertiary deposits. Near Sunrise Springs volcanic ash and tuff intermingled with fragments of shale and sandstone occur in lenses 4 to 15 feet thick. The position of these ash deposits is to the leeward of the ancient volcanoes, a fact which doubtless explains their location. On the west and southwest borders of the Hopi Buttes volcanic field—that is opposite to the direction of the prevailing winds—ash from this source, so far as my observation extends, is absent.

The clastic volcanic materials irregularly interstratified with the lavas were studied at a number of localities. In the Bidahochi-Lukasakad region, along the southern border of Hauke Mesa, a generalized section shows the following relations:

Generalized section of volcanic rocks on south border of Hauke Mesa, Ariz.

1. Analcite basalt, scoriaceous; forms caps of mesas.
2. Tuff, bedded, with variable dip, in places cross-bedded, here and there interstratified with layers of fine white ash and mud shales.
3. Sandstone and ash, chalk-white, with bands and lenses of thinly laminated impure buff-yellow and greenish-white limestone.
4. Tuff, very coarse, containing chunks of lava and holocrystalline igneous rock 1 inch to 5 feet in diameter and small amounts of red sandstone and shale.
5. Lava, coarsely crystalline or porphyritic, with prominent augite phenocrysts.

At a point 2 miles southeast of Indian Wells the red (Jurassic?) sandstone is covered by 200 feet of cross-bedded tuff, containing in places blocks of sandstone and fragments of lava 2 to 6 feet in diameter. Above the tuff lie finely foliated cream-yellow shales alternating with soft chalklike ash beds. (See Pl. XIV, *A*, p. 82.) In a cliff 1 mile northwest of the Stiles ranch (Maddox) thin bands of tuff are intercalated between red-brown and greenish-white shales and a lava flow capping the mesa. South of Cedar Springs a measured section includes the following beds:

Section of igneous materials in mesa wall on Holbrook trail about 1 mile southeast of Cedar Springs, Ariz.

	Feet.
1. Analcite basalt, bluish gray, dense, at top, porphyritic at base	20
2. Ash, regularly banded dark gray, yellow-white, pink, and dark yellow; bands are cross-bedded and range in composition from fine volcanic dust through ash to tuff with fragments of black, dense lava half an inch to 3 inches in diameter; augite crystals and clay pellets and thin layers of yellow mud are included; top surface much weathered	15
3. Volcanic conglomerate consisting of groundmass of yellow-gray volcanic mud in which are embedded chunks of lava 1 inch to 5 feet in diameter; usually scoriaceous lava with bomb and flow structure	60±
	65±

Four miles east of Bidahochi 195 feet of variegated red, green, white, and brown shales are overlain by 8 feet of ash. The lower 5 feet of the ash bed is coarse and thinly foliated and contains black pebbles of lava; the upper 3 feet is fine-grained unstratified red ash. Above the ash is 16 feet of porphyritic lava. At Cottonwood Springs brown ash interstratified with thin beds of limestone and of chalky shale forms a group of strata 100 feet thick.

Four miles south of Cedar Springs sediments that are probably of Tertiary age overlie the highest lavas, as shown in the following section:

Section of a butte 4 miles south of Cedar Springs, Ariz.

	Feet.
1. Limestone, yellow, very thin bedded, porous, with rare layers of fine ash, apparently a lacustrine deposit	5
2. Tuff, composed of coarse ash and chunks and bombs of basaltic lava	30
3. Augite basalt, amygdaloidal, with well-developed flow structure	10
4. Yellow thin-bedded porous sandy limestone and yellow paper-thin shales, probably lacustrine in origin	40
Unconformity.	
5. Sandstone and sandy shales, red (Jurassic?).	
	85

The relation of volcanic ash to the associated nonvolcanic sediments is typically shown at two inconspicuous knobs 4 miles north of White Cone, where 15 feet of lenticular cross-bedded ash lies on an unevenly eroded surface of red shale. At the bottom the ash is almost microscopic in texture and includes lenses of paper-thin mud shales and of siliceous silts. The top of the stratum consists of angular fragments of lavas and sandstone as much as 1 foot in diameter. Above the ash, resting in hollows, are fine porous cream-white shales and limestones with abundant impressions of plants, including *Chara*. The relations suggest the presence of a lake basin in which ash was deposited directly and also by streams.

In the Hopi Buttes province in general pure volcanic ash is usually interstratified with water-laid sediments, and where two strata of lava occur in the same section the ash occupies an intermediate position. In total quantity the coarse tuff exceeds the fine; it also forms the thickest beds. Although presumably the coarser tuff lies nearer its point of origin, the source of the fragmental volcanic material was not satisfactorily determined. Tuff with blocks of basalt and bombs exceeding 5 feet in long diameter was observed at a few places, but most exposures reveal material composed of worn and rounded fragments the size of peas and smaller. Certain beds consist of chalklike powder displayed as ancient dunes. Three thin sections of tuff were briefly examined by Prof. Pirsson, who writes as follows:

The chalky-appearing layer in the strata of the red wall about 3 miles southwest of Sunrise Springs is a volcanic tuff, very fine in texture and showing under the microscope a typical vitroclastic structure [1] and composed entirely of colorless glass shards without any crystalline material. This does not suggest that it came from any teschenitic magma; on the contrary, it appears like a fine wind-sorted rhyolitic dust which has been transported a considerable distance.

The red tuff occurring about 1 mile south of Cedar Springs is composed of glassy ash and fine lapilli of a mafic character, such as might have come from a basaltic magma, mixed intimately with finely comminuted material whose nature indicates that it was derived from sedimentary rocks; thus it contains much angular quartz. Its iron content has been altered by oxidation to the ferric state, which explains its red color. It also contains much calcite.

The black tuff from Sunrise Springs is similar to that near Cedar Springs, but the particles are much larger and generally so well rounded as to suggest that they must have been rolled, washed, and laid down in water. It contains olivines and augites like those in the teschenite described above and was evidently derived from a similar magma.

[1] Pirsson, L. V., Microscopical characters of volcanic tuffs: Am. Jour. Sci., 4th ser., vol. 40, p. 198, 1915.

VOLCANIC NECKS.

GENERAL APPEARANCE.

The time elapsing since volcanoes were active in the Hopi region has been sufficient to allow not only for the mutilation of lava flows and fields of ash but also for the destruction of craters and cones. Centers of eruption are, however, indicated by numerous volcanic pipes in various stages of preservation. Some of them protrude from mesas formed of brightly colored sediments; others form the cores of buttes and are exposed to view only in gorges cut deeply into the flanking walls. A few necks rise directly from the surrounding plain, towers of lava and agglomerate reaching heights of 400 to 800 feet, without a protective cover. Each neck has individual features and presents a separate problem. Some consist largely of massive rock; in others agglomerate predominates. The pedestals on which they stand are formed of massive and brilliantly colored shales of the Triassic and Jurassic (?) periods or the gray-toned strata of the Upper Cretaceous. Some are conical in form; others rise as massive vertical walls; still others are cut in terraces that rise as giant steps. Chimney Butte, Haystack, Pyramid Butte, Elephant Butte, Round Top, Twin Butte, and Montezumas Chair are local features whose names suggest the variety of topographic form. (See Pl. XV, *B*, p. 83.) The abundance of these columns and needles and their individuality, size, grouping, and color give to the Hopi Buttes field an unusual scenic expression. (See Pl. XV, *C*.)

COMPOSITION.

The material of which the necks are composed consists of two classes, agglomerate and massive igneous rock. The proportion of agglomerate to homogeneous, massive lava is highly variable, but at all localities visited the material exposed is, in part at least, an aggregate of broken fragments. Some necks—for example, the butte 7 miles south-southeast of Maddox—consist entirely of fragments firmly bound together. Several of the necks consist of agglomerate penetrated by unmodified igneous rock in the form of dikes, sheets, and apophyses connected to form an irregular framework within and upon which the agglomerate had been laid.

The agglomerate is prevailingly igneous in composition, being made up of fragments of lava usually angular in outline and reaching 30 or 40 feet in long diameter. In nearly all places fragments of country rock are constituent parts of the agglomerate. Blocks of sandstone and shale 2 inches to 4 feet in diameter are common, and in places large portions of the mass consist essentially of sedimentary fragments held together by a paste of igneous and sedimentary material.

The massive igneous rock is in most places dense and fine grained, but coarse granitic texture and porphyritic texture have also been developed. Amygdaloidal texture may be observed in the midst of an otherwise dense mass, and at two localities isolated crystals of augite exceeding half an inch in length were seen embedded in fine-grained intrusive rock.

A specimen from a small neck on the trail between Sunrise Springs and Indian Wells is a dense, minutely brecciated porphyritic limburgite, the weathered surface of which has an appearance resembling oolite. In thin section the phenocrysts of olivine are seen to be only slightly larger than the slender needles of augite, which, as an interlacing mesh, constitute the bulk of the rock, exclusive of the glassy groundmass. Iron ore is present, as are also serpentine and calcite as alteration products.

A hand specimen from Montezumas Chair has minute, short, black crystals of augite weathered out on the surface, which give to the rock a porphyritic appearance. On fresh fracture the augites are inconspicuous, as their color is identical with that of the microcrystalline groundmass. Prof. Pirsson states:

The section of rock from Montezumas Chair shows zonally built augite phenocrysts, the inner portion of a pale purplish brown, the outer shell similar but of a much stronger color and perceptibly pleochroic. The angle of extinction of c on C is 42° within and 39° in the outer shell and shows no marked dispersion, indicating only a moderate content of TiO_2. The crystals are fairly idiomorphic, are strongly built, and run to 1.5 millimeters in length. Associated with them are poorly crystallized olivines of irregular form, which are very fresh, with here and there a little serpentine. The groundmass is made up of abundant iron ore, a little biotite, and a second generation of similar augite in minute prisms poikilitically inclosed in large, stout, irregular laths of labradorite with associated grains of orthoclase, analcite, and probably nephelite.

In spite of the two generations of augite, which produce a somewhat porphyritic character, this rock is clearly to be referred to the teschenites. A striking feature is the freshness of all the minerals, which raises the question whether the analcite is primary or an alteration product of nephelite, as has been held by Rosenbusch for other occurrences of this type. In the present case one would be inclined to consider it an original mineral.

DIKES.

The number of igneous intrusions having the texture, dimensions, and field relations usually ascribed to dikes is relatively small in the Hopi Buttes volcanic field. Few of the masses called dikes consist of homogeneous rock; most of them are composed in part of a conglomerate of igneous and sedimentary rocks and differ little except in form from the clearly defined volcanic necks. Most of them, in fact, are riblike protrusions from mesas and buttes whose cores are ancient volcanic conduits now filled by consolidated breccia. It was found impracticable to map all the dikes and to study their structure. Their general character may be judged from the following descriptions of a few examples:

From the west edge of a mesa facing French Butte a dike with an average width of 4 feet extends in a N. 30° W. direction for a distance of 900 feet. The crest of the serrate wall stands 3 to 16 feet above the surface. The contact with the inclosing shales is sharp, the usual intervening paste of agglomerate being absent. Horizontal columnar structure, largely obscured by strong jointing parallel with the walls of the dike, is well developed. In this same locality a dike about 500 feet long extends as a wall across the flank of French Butte, and in the adjoining valley disconnected fragments of another dike traverse the lowland as a row of teeth and elongated mounds, composed largely of agglomerate. The material composing the massive igneous part of the dikes in the French Butte area consists of phenocrysts of augite and olivine in a ground mass of augite and glass and may be called limburgite.

Two dikes were noted in connection with a volcanic neck 7 miles south-southeast of Maddox. The south dike, which may have genetic relations with a mound of agglomerate 500 feet distant, is about 200 feet long and scarcely more than 1 foot in width. It is composed of porphyritic diabase in which crystals of augite, biotite, and rare olivine are prominent. About 600 feet west of this dike is another which extends as a ridge for a distance of over 100 feet.

The large butte on the bank of Jadito Wash 8 miles below Jadito Spring owes its preservation to a dikelike mass of augitite (?) 300 feet long and 70 feet wide, which rises 200 feet above the surrounding plain. Along its contact walls polygonal jointing is developed and columns of large diameter in horizontal, oblique, and even vertical position were noted.

On the west side of Pueblo Colorado Wash 6 miles south of Twin Mesas a dike only 2 feet wide and cut down nearly to the level of the plateau extends for 200 feet. The limburgite forming the dike presents a zonal arrangement. The borders, about 4 inches on each side, consist of cryptocrystalline material; the rock forming the center is amygdaloidal in texture and abundantly supplied with jet-black phenocrysts of augite one-sixteenth to one-third inch in long diameter. This dike is associated with two necks of volcanic agglomerate consisting of angular chunks of limburgite, shale, and limestone, 1 to 2 feet in diameter, forming a giant pudding. A few hundred feet west of these necks are deposits of coarse and fine ash arranged in beds, which dip away from the volcanic pipe.

Immediately east of Twin Buttes is a remnant mass of agglomerate consisting of fragments of igneous rock of various sizes and blocks of sandstone 2 inches to 6 feet in diameter. Westward from this low mesa extends a dike having a width of 1 to 3 feet. Throughout its extent of 400 feet it forms a wall with a maximum height of 20 feet. (See Pl. XVI, *A*.) The main mass of the dike consists of finely porphyritic and slightly amygdaloidal augitite or limburgite, but included within it and in places constituting a large part of the mass are fragments of shale and of other sedimentary rocks, apparently incorporated during the process of intrusion. The microscope reveals phenocrysts of augite and of olivine set in a groundmass composed of augite, biotite, grains of iron ore, and glass.

At a few localities the country rock in contact with dikes is baked and in part recemented. In general, however, contact metamorphism is inconspicuous.

VOLCANIC ROCKS ON THE BORDER OF THE HOPI BUTTES FIELD.

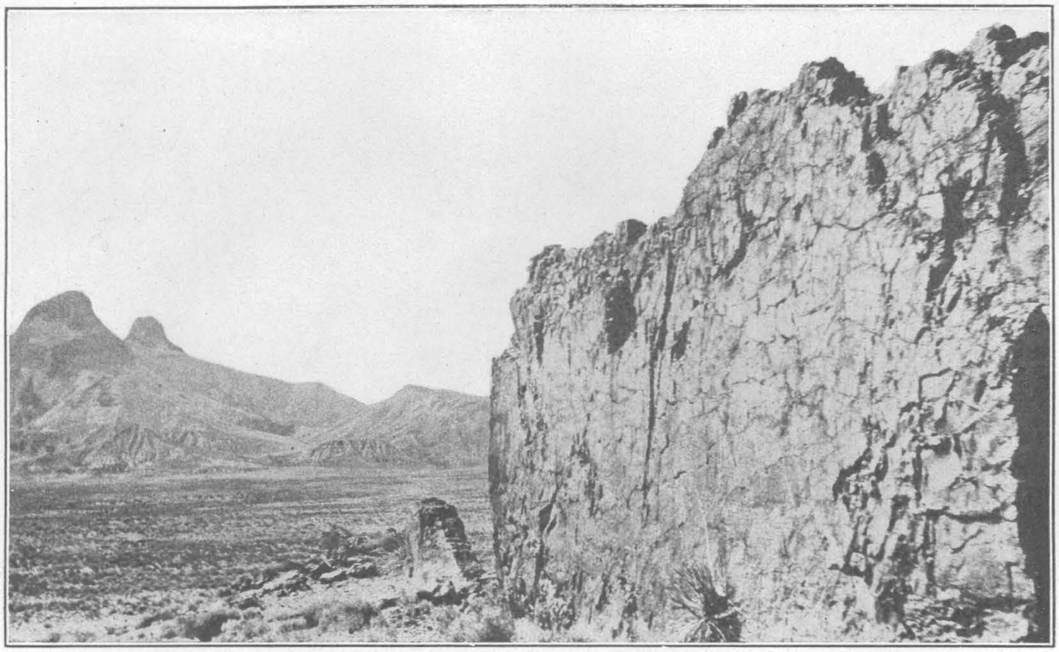
In the bed of Leroux Wash, 16 miles northeast of Holbrook, are two small outcrops of mixed augitite and agglomerate. On the mesa east of the wash are two finlike ridges of igneous rock which form conspicuous landmarks. The south ridge is 300 feet long and 80 feet high; the north ridge is 500 feet long and 125 feet high. The cores of both ridges are dikes of homogeneous rock in which columnar structure has been developed. Bordering the dikes are masses of agglomerate consisting of chunks of both dense and vesicular igneous rock and of lesser amounts of baked sandstone and shale. These outcrops are believed to mark the site of an ancient volcano.

Pilot Knob, which rises 800 feet above the platform separating Wide Ruin and Lithodendron washes, was not examined, but the descriptions given by the Navajos indicate that this well-known landmark is the remnant of a former isolated volcano. Eight miles northwest of the Hopi Buttes field is an igneous mass known as the Giant's Chair. This is probably the feature mentioned by Loew[1] as "a dike of basalt 25 feet in width and many hundred feet in length, which protrudes from a mesa of Cretaceous age, about 12 miles southeast from the seat of the Moqui Pueblo."

GEOLOGIC HISTORY.

The Hopi Buttes volcanic field is an isolated area of volcanism. No outlying extrusives or intrusives were found between Montezumas Chair and the lavas of the San Franciscan field, along Little Colorado River, 30 miles farther west. To the east no igneous rock is found in place between Twin Mesas and Fort Defiance, and the nearest igneous mass on the north is beyond Black Mesa, 70 miles distant. Among the Hopi Buttes there is no topographic feature which might represent a volcano of large dimensions, and the relations of the volcanic material in the San Franciscan and Mount Taylor fields—a large central volcano with peripheral flows and cones—are not duplicated here. Numerous independent sources are indicated by the well-defined and widely dispersed necks and many of the dikes are of a character which suggests that the forces that produced them

[1] Loew, Oscar, U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 638, 1875.

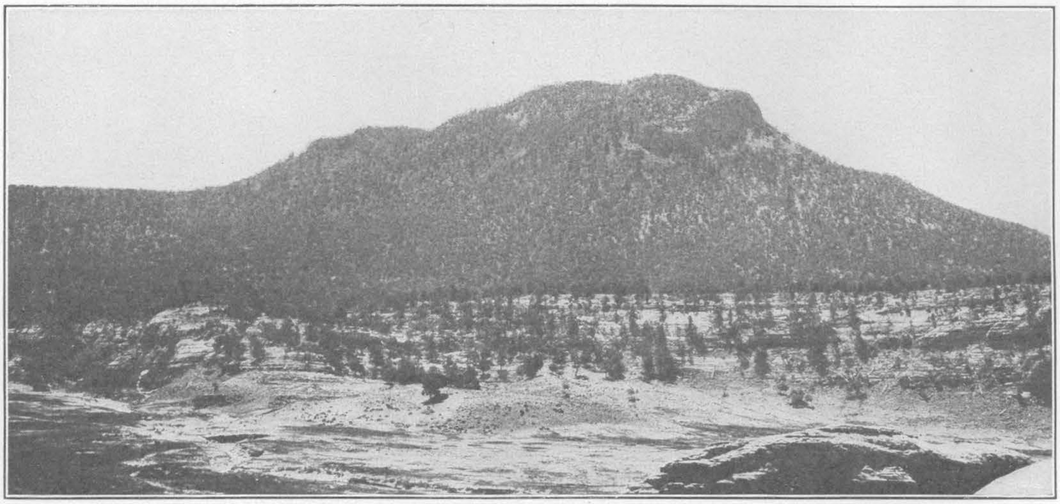


A. TWIN BUTTES, ARIZ.

Volcanic neck in background; dike of limburgite coated with agglomerate in foreground.

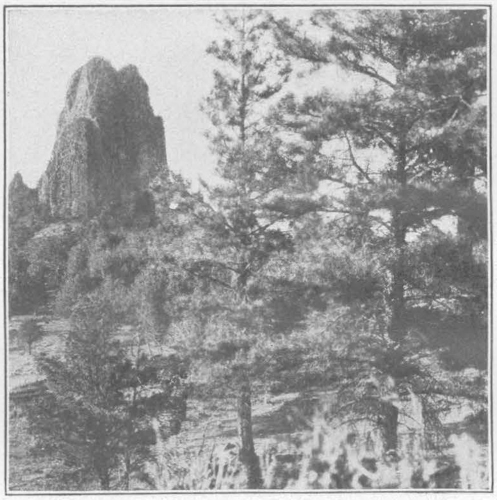
B. OUTLET NECK, FOOT OF RED LAKE, N. MEX.

A volcanic neck. Photograph by K. C. Heald.



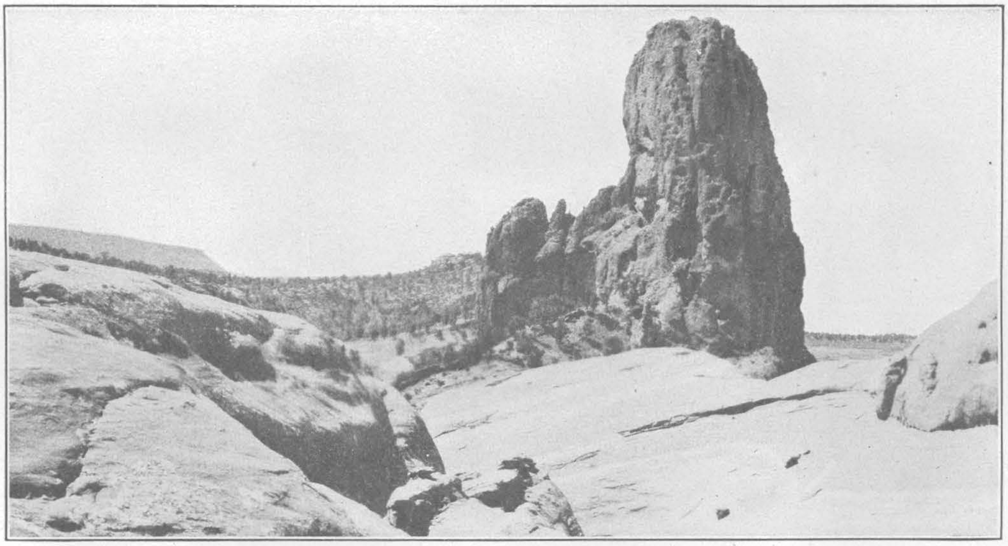
A. ZILDITLOI MOUNTAIN, N. MEX., FROM THE WEST.

Sheet of nephelinite overlying Jurassic and Cretaceous strata.



B. BEELZEBUB, A VOLCANIC NECK IN TODILTO PARK, N. MEX.

Monchiquite and agglomerate.



C. THE BEAST, BLACK CREEK VALLEY, N. MEX.

A volcanic neck of monchiquite rising through sandstones of La Plata group.

may also have given rise to flows or ash. Whether or not the whole area was at one time floored with volcanic material is unknown, but the highly irregular distribution of the lavas and their abrupt variation in thickness lead one to assume that the flows did not form a continuous mantle. The largest area of lava in the field, Hauke Mesa, is a series of lenses of different thicknesses interrupted by and interbedded with ash and tuff and agglomerate, and the topography indicates that several feeding dikes and necks are concealed beneath its surface.

The character of the floor on which the lavas and clastic volcanic materials were deposited is indicated by measured sections. South of Cedar Springs thin-bedded arenaceous limestones assigned to the Tertiary period underlie 10 feet of lava. At Egloffstein Butte the underlying strata consist of shales and coal of the lower part of the Mancos formation. The lava at Round Top rests on strata believed to be of Dakota age. The banded chocolate-colored, green, pink, and red shales and sandstones capped by 50 feet of lava at Bidahochi have been assigned to the McElmo (?) formation. The lava and tuff at Five Buttes rest on beveled strata containing limestone conglomerates of the Chinle formation. The floor on which the lava was poured out is thus seen to consist of strata ranging in age from Tertiary to Upper Triassic, and yet the prevolcanic surface has slight relief. If the elevations shown on the reconnaissance topographic map of the Tusayan quadrangle are taken as correct, the surface underlying the lavas stands at 6,400 feet on the northwest edge of the field and at 6,000 feet in Five Buttes, 32 miles to the southeast. The base of the lava at Round Top is also at 6,400 feet, and at Twin Mesas, 32 miles east, it is at 5,900 feet. The ancient floor has therefore a southeasterly slope of 12 to 15 feet to the mile. At a few places the lava is slightly lower and at a few other places somewhat higher than the figures given. The floor is obviously not flat, neither is it deeply dissected. In physiographic terms a stage of late maturity had been reached.

The arrangement and distribution of volcanic materials and the nature of the floor on which the lavas and tuff were laid down are bits of evidence available for the restoration of the landscape during the period of maximum volcanism. The area of the field dominated by cones and flows was about 1,100 square miles. Bordering the field on the north, a plain of moderate relief formed of Cretaceous strata extended beyond the line of vision; toward the south, and between the volcanoes, Triassic formations made up the bedrock floor. The presence of ash at various horizons and of sediments separating flows indicates lapses of time between eruptions of the same and of different cones. Doubtless active and inactive volcanoes existed in close proximity. Lava flows from cones and fissures were probably intermingled in the center of the area, and individual flows 10 to 20 miles long were to be seen on the slopes and valleys leading to Little Colorado River. Obstruction of the normal drainage by dams of lava and of ash gave rise to local water bodies in which were deposited the shales and chalk-white ash now so widely distributed. That some of the lakes were long-lived is indicated by the presence of beds of lacustrine muds and clean ash 10 to 40 feet thick and of fresh-water shells and plants. That most of the lakes were ephemeral is suggested by the facts that the yellow lacustrine shales are sun-baked and cracked on foliation surfaces and that the films of mud are curled and wrinkled and retain rain prints. Fluctuating stream flow is necessary to account for the extreme coarseness of much of the tuff and the abrupt alternation of coarse and fine deposits in both vertical and horizontal directions. Individual cones and short lava flows were most numerous in the southwestern part of the field, and it is probable that during the period of volcanic activity an observer at Lokasakad could have included 20 or 30 volcanoes within a single view. Of existing landscapes comparable with the Hopi Buttes during the time when topographic features due to volcanism were still preserved the southern edge of the Uinkaret Plateau affords the best example that has come under my observation. A sketch of the view looking south from the summit of Mount Trumbull included 18 recent cones, and more than 50 are grouped at the mountain's base. Among them are several flows of fresh lava connected with cones or fed by dikes. The floors of the intervening valleys are white with the silt and clay of ephemeral lakes and streams, and the valley sides are mantled with coarse débris. A similar view may be obtained from a good lookout east of San Francisco Mountain.

The relative age of the flows and tuff deposits within this field is a problem awaiting solution. That many of the remnant flows belong to one general period of volcanic activity is suggested by the following observations: The topography of the remnant flows and necks is consistent with the assumption that dissection of the volcanic materials began at approximately the same time throughout the field. On the borders of the field the mesas are more isolated and their lava caps perched higher and the necks are more denuded than in the center. On the southwest border, where the easily eroded Chinle shales are exposed and where the slopes to the Little Colorado are steepest, the greatest amount of dissection has taken place. Moreover, the lavas where similarly exposed have about the same degree of freshness. On the other hand, the presence in a number of places of two or more sheets of lava separated by deposits of tuff of considerable thickness and the erosional unconformities between consecutive lava flows indicate considerable lapse of time between periods of active volcanism. The presence of blocks of lava included in flows of lava of a different type and the separation of ash deposits by 5 to 20 feet of water-laid sediments lead to the same conclusion.

The geologic period during which volcanoes were active in the Hopi Buttes area has not been determined. The deposits are obviously older than the flows and ash of the Little Colorado Valley (p. 104), which have experienced an insignificant amount of erosion. Unfortunately, neither the date of the most recent flows in the Plateau province nor that of the period during which the mature topography underlying the lavas was developed can be set with assurance. Lavas of substantially the same age, as indicated by degree of weathering and of dissection, and resting on a similarly eroded surface at Black Point are assigned by Robinson[1] to the Pliocene. It was hoped that the date of the volcanic outbursts in the Hopi Buttes field could be directly proved by paleontologic evidence. Many fossils were collected from the strata interbedded with ash and tuff, but unfortunately they are of species common to all parts of the Tertiary (p. 82). The lavas can not, however, be early Tertiary; the floor on which most of them rest has been developed by the removal of the entire thickness of Cretaceous and Jurassic strata involved in the Tusayan downward, which is believed to date from the beginning of Tertiary time.

[1] Robinson, H. H., The San Franciscan volcanic field, Ariz.: U. S. Geol. Survey Prof. Paper 76, pl. 3, 1913.

ZILDITLOI VOLCANIC FIELD.

SALIENT FEATURES.

With Zilditloi Mountain as a center, a volcanic field embracing a variety of features may be examined. The mountain itself is a lava-capped dome overlooking Black Creek Valley from a height of 1,400 feet. At its western base, on the borders of Red Lake, are volcanic plugs and weathered masses of agglomerate admirably displayed for study. North of Zilditloi the upper canyon of Black Creek, whose waters have been diverted to feed Red Lake, leads eastward into the picturesque Todilto Park, where there are two volcanic necks and several dikes. Four miles west of the mountain a short canyon affords access to Buell Park, whose floor is dotted with masses of igneous rock. Treated as a unit, the Zilditloi field includes an area of about 24 square miles, arranged as a belt 8 miles long and 3 miles wide. Throughout this field the activity of the volcanic vents is believed to have produced cones of ash as well as lava flows.

The major structural features of the field are two in number—the Defiance monocline, which involves Permian (?) sandstones, the strata in which Buell Park has been cut, and the maturely dissected quaquaversal fold represented by Todilto Park. The crustal movements that produced these structural features are believed to antedate the period of volcanic eruptions. The distribution of the volcanic remnants in an east-west line, as shown on the map, suggests a zone of fracture crossing the Defiance monocline nearly at right angles. If the position of Fluted Rock, 8 miles west of Buell Park, is also taken into consideration, a roughly linear arrangement for eight or nine vents is indicated. No independent evidence of such a line of crustal weakness was obtained.

During the time since the lavas were poured out and the ash carried eastward by the prevailing winds the forces of erosion, guided by the massive La Plata and De Chelly sandstones and the resistant Shinarump conglomerate, have removed fully 1,500 feet of strata from the vicinity of Red Lake and probably 1,000 feet from Todilto Park and an equal amount from Buell Park.

ZILDITLOI MOUNTAIN.

Viewed from Red Lake, Zilditloi Mountain is a flat dome of lava resting on a platform of Mesozoic sedimentary rock. (See Pl. XVII, *A*.) Ascent from the west involves scaling the wall of La Plata sandstone, traversing a dissected bench about half a mile wide, ascending a steep slope cut in McElmo and Cretaceous sediments, and finally climbing a cliff of lava columns 150 feet in height. On the east and north sides of the mountain the platform, cut in beds below the base of the lava, is nearly a mile in width. The floor on which the lava rests has slight relief and truncates edges of sedimentary rock which dip southeastward at a low angle. The thickness of the lava cap of Zilditloi was not determined. At two points 150 and 160 feet of columnar lava is exposed. The lower contact is concealed by talus at the several localities visited, and it is probable that the greatest thickness is about 200 feet. The source of the lava also was not determined. So far as position and composition are concerned, the flow may reasonably be assigned to the necks now standing in Todilto Park or to those at the foot of Red Lake, or it may consist of coalescing flows from both these sources. On the other hand, the surface relief of the lava, its diversity in texture, and the presence of dikes cutting the platform on which it rests suggest that continued erosion might expose feeding dikes beneath the lava floor.

In a few places the lava at Zilditloi is amygdaloidal; elsewhere the rock is dense except for innumerable glistening flakes of biotite large enough to be distinguished by the unaided eye. Segregations of augite and of biotite and clusters of olivine fragments attain sizes exceeding half an inch. Inclusions of biotite granite, granite gneiss, hornblende gneiss, quartzite, and chert, a quarter of an inch to 3 inches in diameter, rarely larger, are sparingly distributed through the mass.

Microscopic examination of the lava from Zilditloi by Prof. Pirsson gave the following result:

The rock is composed mainly of phenocrysts of pale-brown to colorless augite thickly crowded and varying widely in size. The largest have spongy centers with glass inclusions. A few of the large phenocrysts are made up of small augites in parallel position with colorless material between. The crystals are in places somewhat altered to green serpentine. Many former phenocrysts of biotite, partly or wholly changed to opacite by resorption, are also present. The augites grade in size from the largest phenocrysts into those of the groundmass. The groundmass consists of augite, biotite, iron ore, and a colorless cement which shows low polarization in large patches. This cement has about the same index as balsam and is inferred to be nephelite or a mixture of nephelite with orthoclase. It is everywhere poikilitically filled with minute roundish spots of a very pale brown isotropic substance with lower refractive index, which may be leucite or analcite, and contains also very minute needles of apatite. The rock is considered to be a nephelinite.

VOLCANIC ROCKS OF TODILTO PARK.

Along the trail leading over the south rim of Todilto Park, at the east base of Zilditloi Mountain, the cores of two volcanoes are exposed. The larger one, Beelzebub, possesses the topographic features of a volcanic plug or chimney; the other, called here dike B, has the form of a wide dike. Beelzebub is a roughly cylindrical mass that rises precipitously to a height of 200 feet above a carved pedestal of Mesozoic strata. (See Pl. XVII, *B*.) It consists chiefly of agglomerate made up of angular fragments of lava and baked sandstone, together with smaller amounts of metamorphosed shale and limestone conglomerate from the Chinle formation. The blocks are of various sizes, the largest 2 feet in diameter. The lava in the ancient conduit is exposed on the west side of the neck as a large area of much jointed and roughly columnar massive igneous rock. From this central mass narrow dikes extend outward, and at the west base of the neck a dike may be traced for a distance of 400 feet.

Dike B is a broken, serrate ridge consisting of seven pinnacles or needles rising 100 to 150 feet above the sandstone slopes at its base. It extends in an easterly direction for a distance of about three-quarters of a mile. Like Beelzebub, it is composed essentially of agglomerate traversed by dikes. About half of the mass consists of blocks and slabs of igneous and sedimentary rock 1 to 6 feet in diameter; the remainder is a finer-grained breccia of similar composition. Many of the sandstone fragments included in the agglomerate have been altered to quartzite, but those on its borders are little metamorphosed.

To the unaided eye the igneous rocks from Beelzebub and from dike B are identical in composition. They are very dark in color and are made porphyritic by the presence of innumerable flakes of biotite and rare fragmentary prisms of augite set in a microcrystalline groundmass.

Thin sections from dikes traversing the agglomerates of necks in Todilto Park were studied by Prof. Pirsson, who makes the following report:

The rock from Beelzebub consists of many small phenocrysts of pale biotite with resorption borders and pale-brown unaltered idiomorphic augites and olivines, the latter mostly changed to serpentine, in a dense base consisting of minute grains of iron ore and augite and colorless cementing substances which, so far as can be determined, consist mostly of alkalic feldspar mingled with nephelite and zeolitic material, in part analcite. The rock falls in the general division of monchiquites and is closely allied to the cascadite from the Highwood Mountains.

The rock from dike B is a leucite basalt. It is of fine grain and consists of rather abundant pale-brown augites and rarer olivines in a fine granular base. The augites are not especially well shaped; many of them are broken, and some indicate resorption. They are of a type commonly seen in basaltic rocks, are locally grouped, contain blebs of brown glass, and are quite unchanged. The olivine is nearly everywhere more or less and in some places entirely changed to a light-green fibrous serpentine with rather high birefringence. A few scattered flakes of much resorbed mica with opacite rims are seen; the mineral has the pale colors and weak pleochroism of the phlogopite in the rocks of the Leucite Hills, Wyo. These complete the list of phenocrysts. The base consists of a mass of minute leucites whose more or less rounded forms are defined by interstitial crowded masses of minute augite prisms, clots of iron ore, etc., as commonly seen in many leucite rocks. The leucites show only very rarely an approach to that arrangement of inclusions so characteristic of them in many places, as at Capo di Bove, Italy. They are more or less filled, however, by excessively minute granules whose single and double refraction suggests that they are augite. Owing to these and to an incipient alteration, probably to kaolin, the leucites appear brownish in transmitted light; they are, however, isotropic and their refractive index is lower than that of balsam. In places the inclusions tend to be crowded toward the center. Almost no other felsic mineral, except possibly a little nephelite, is seen in the base.

The pattern of the fabric, as seen with a medium power in the section, is highly characteristic of leucite rocks with the dotting of the small rounded leucites. Quantitatively the amount of this mineral present is very large, for the rock is dopatic and it forms the bulk of its mass.

The north wall of Black Creek canyon is cut by two dikes, 1 foot and 2 feet wide; they occupy joints in the La Plata sandstone, which at this place forms a cliff 150 feet high. These dikes are composed of a breccia consisting of fragments of monchiquite, white, gray, and red sandstone, limestone, and baked shale and include rare angular pebbles of granite. Dikes were noted by Mr. Heald at the north base of Zilditloi Mountain and also east of Beelzebub.

VOLCANIC ROCKS BORDERING RED LAKE.

OUTLET NECK.

At the foot of the dam impounding the waters of Red Lake, N. Mex., is a volcanic neck more than 100 feet in height. (See Pl. XVI, *B*, p. 88.) Its base is a square with rounded corners, outlined by planes corresponding in position with the directions of major jointing. Its top has been weathered into overlapping slabs and presents the appearance of a thatched beehive. A central dense portion of massive rock has plastered on its southeast face a tightly fitting coat of conglomerate 10 to 16 feet thick. This covering consists of a pudding composed of angular, rounded, and slablike fragments of the igneous core rock and angular and rounded pebbles of sandstone, limestone, and quartz, presumably obtained from Chinle and Shinarump strata concealed by the surrounding alluvial flats. The conglomerate is only slightly less resistant than the massive igneous rock, and on the north side of the neck detached needles of this material, 75 feet in height, may be seen. Traversing the neck are narrow dikes in vertical and horizontal position. Between them and in the angles which they form with the central core are giant blocks of sandstone 10 to 200 feet in long diameter. Many of these blocks are intricately faulted and twisted; they are all somewhat metamorphosed, and, where inclosed by closely spaced dikes, the sandstone, here altered to quartzite, has taken the form of columns 1 to 6 inches in diameter having three to nine sides, with axes perpendicular to the face of the dike. Except for their composition these sandstone columns are the exact duplicates of the columns commonly formed in igneous rock. On the north face of the neck undisturbed Chinle strata in contact with igneous rock attain a thickness of 80 feet.

The unmodified igneous rock forming the center of Outlet Neck and its radiating dikes is a porphyritic monchiquite, the phenocrysts consisting of biotite. Angular fragments of metamorphosed sandstone occur within it, and cracks in the conglomerate as well as in the less dense portions of the igneous rock are lined with well-developed crystals of calcite.

East of Outlet Neck, and separated from it by the width of the Black Creek flood plain, a dike 200 feet long and 2½ feet wide cuts the sandstone of the La Plata group. Its trend is east, in harmony with a prominent plane of jointing. The face of the dike is in direct contact with the bordering sandstone, which is whitened and baked along a selvage zone 2 to 3 inches wide. The dike rock is monchiquite (?) sprinkled over with biotite and grains of olivine. No inclusions were found. Parts of the rock are amygdaloidal, and its contact surface is irregularly scored as if plastered by hand.

Along the Fort Defiance road about a mile southwest of Outlet Neck is a mass of agglomerate, forming a narrow two-humped ridge 150 feet long. The material of which it is composed is closely similar to that found in the necks of this vicinity—a conglomerate of igneous fragments with lesser amounts of broken sedimentary rock.

THE BEAST.

One mile southeast of Outlet Neck is a volcanic plug of striking form. (See Pl. XVII, *C*, p. 89.) Its eastern half is a round-backed ridge, above which rises a columnar mass forming a precipitous cliff over 200 feet in height, near the top of which a large cavity has been excavated by weathering. When the shadows are favorable the likeness of the mass to a crouching lion is unmistakable. The pedestal of La Plata sandstone on which The Beast rests is in some places undisturbed; elsewhere it is a brecciated mass of sandstone blocks resembling consolidated talus. The material composing the neck is of two types. Dense monchiquite (?) constitutes about one-third of the mass, and is best exposed on the southeast flank, but also traverses the stringers and fingers and conglomerate extending from the center outward. A conglomerate of chunks and slabs of monchiquite (?) and sandstone as much as 6 feet in long diameter constitutes about two-thirds of the material. The sandstone fragments, both rounded and angular, are in some places metamorphosed, in others unaltered. The massive and conglomeratic types are about equally resistant to weathering, and both extend from the bottom to the top of the plug. The rock of the core and dikes has acquired a schistose structure which facilitates decomposition. In texture the rock is porphyritic; innumerable flakes of mica as individuals and as segregated masses, needles of augite, and tiny nests of olivine are readily distinguishable from the microcrystalline groundmass.

About 200 feet north of The Beast is a dike 300 feet long and 6 feet wide which consists wholly of a brecciated mass of igneous and sedimentary materials. In this dike fragments of monchiquite with prominent crystals of biotite, augite, and olivine are twisted and folded in a singular fashion, and slightly metamorphosed sandstone blocks, 1 inch to 5 feet in diameter, are likewise twisted and bent about other blocks. The whole dike resembles a pudding of viscous materials which has been stretched and squeezed. In common with all the intrusives about Red Lake this dike, broken by three offsets, trends east.

GREEN KNOBS.

About 1½ miles north of Red Lake on the road between Fort Defiance and Crystal is a group of low hills whose light-green color contrasts strongly with the red of the adjoining sandstone cliffs. At this locality the bedrock covering an area of more than an acre is a conglomerate composed of a variety of pebbles held together by an igneous paste. Mr. Emery found that 20 per cent of the mass was composed of angular fragments exceeding 1 inch in diameter and 30 per cent of pebbles one-fourth to three-fourths inch in diameter. A boulder of granite 1 foot long and one of quartzite 18 inches in diameter were noted. About 60 per cent of the pebbles are granite; the remainder are gray and black quartzite except for chunks of shale, slate, and sandstone and of very basic igneous rock. The Green Knobs are believed to occupy the position of a volcanic vent, whose failure to be represented by a neck is due to the nonresistant character of the rock filling the ancient conduit. The remarkable assemblage of materials found at this place is substantially duplicated in the Wheatfields volcanic field and at Garnet Ridge and other points in the Monument Valley region. (See pp. 97–98 and 102.)

East of the Green Knobs, on Split Mesa, two basic dikes with inclusions of quartzite and sandstone and a 40-foot dike composed largely of granite fragments were noted by Mr. Heald. On the west side of Red Lake Mr. Emery mapped a basic dike 20 feet long containing inclusions of quartz, quartzite, chert, and shale.

VOLCANIC ROCKS OF BUELL PARK.

Buell Park, 12 miles north of Fort Defiance (fig. 2), is in many respects the most interesting area within the Zilditloi volcanic field. Its scenic features are unusually attractive; the sediments and volcanic rocks are admirably displayed, and olivine or peridot and garnet are abundant and easily obtained. The floor of the park, at an altitude of 7,000 feet, is flat; above it rise precipitous bounding walls to heights of 7,600 to 8,000 feet, justifying the Navajo name, Nihaldzis (that is, a basin sunk in the ground). The wall is breached at only one point, where a tributary to Black Creek leads outward through a narrow, steep-walled canyon. Projecting into the park from the north are masses of lava and volcanic conglomerate. Elsewhere the rim is formed of Moenkopi shales and De Chelly sandstone unconformably overlain by a thin cap of Shinarump conglomerate. Where bedrock is exposed on the valley floor it is seen to consist of agglomerate here and there intersected by basic dikes. The attitude of the strata indicates that the park has been carved in the crest of the Defiance monocline, which at this point has been crossed by a low anticline with east-west axis. These structural features have controlled the development of drainage, and the streams flowing eastward down the initial slopes have had their work directed to the removal of volcanic materials much less resistant than the Permian (?) and Triassic sediments.

Buell Mountain is the stump of a volcanic neck resting on the rim of the park 1,000 feet above the floor. Its precipitous southern slope is nearly covered with talus composed of fragments of gray biotite porphyry, but exposures at several points noted by Mr. Emery indicate that the thickness of igneous rock exceeds 500 feet. Lava from the ancient conduit forms the cap of Sterrett Mesa. The rock from Buell Mountain is a gray porphyry with fine-grained groundmass. The phenocrysts are olivine and biotite, averaging about one-sixteenth of an inch in diameter. In places the olivine is collected in clusters, and in one specimen the

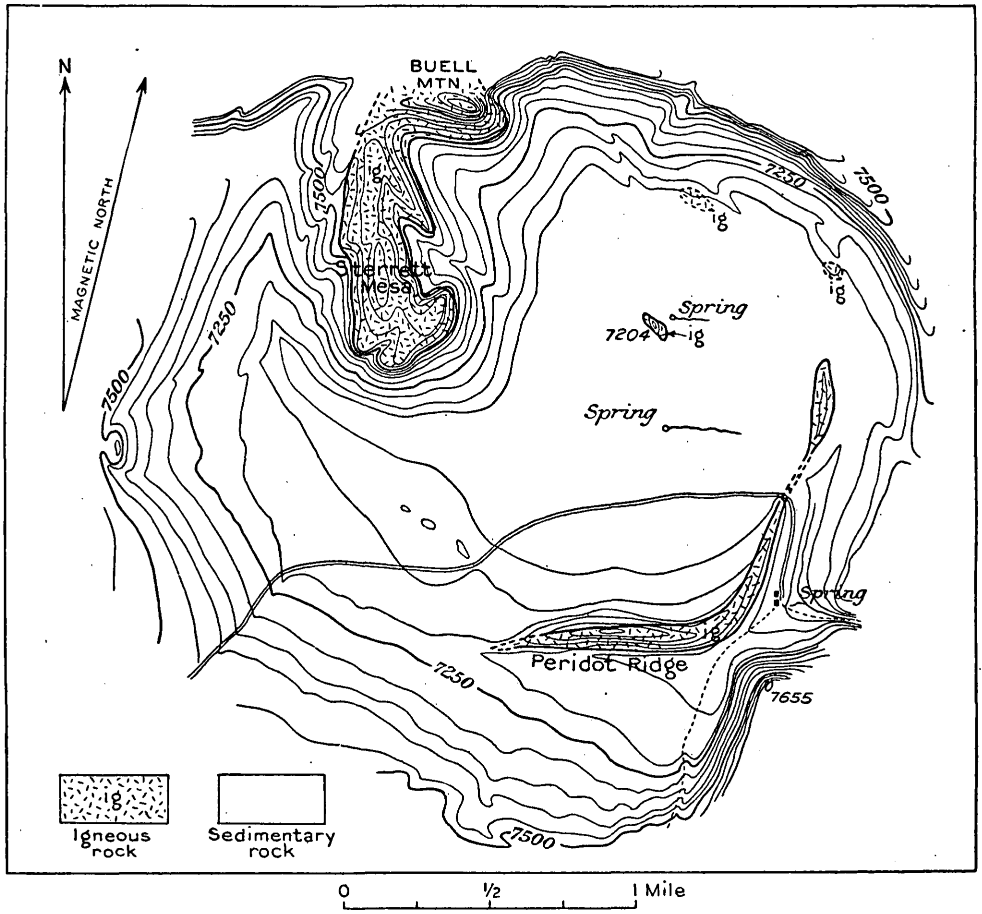


FIGURE 2.—Map of Buell Park, Apache County, Ariz. By W. B. Emery.

groundmass consists almost wholly of this mineral. With the massive igneous rock are large patches of greenish agglomerate, consisting of fragments of igneous rock, small pebbles of quartz, chert, and slate, and innumerable flakes of mica and fragments of olivine crystals.

Peridot Ridge, which forms the inner rim of Buell Park on the south side, continues with decreasing height and variable width and interruptions for nearly 2 miles. It consists essentially of a curved dike of basic granular to porphyritic igneous rock and is flanked on both sides by volcanic breccia. The core wall has a dip of about 30° and ranges in width from 50 feet to less than 5 feet; the bordering breccia attains thicknesses of 200 to 300 feet. A thin section from the rock at the center of this dike was examined by Prof. Pirsson, who reports as follows:

The rock is medium to fine grained and consists largely of a pale-brown augite, well crystallized in short, stout prisms of variable size, the smaller of which are longer on the vertical axis and some of them tipped with aegirite. With the augite is much biotite of a peculiar red-brown to orange-red color in formless flakes, many of which contain granules of iron ore. No olivine was seen. Iron ore occurs also in a few larger crystals. Between these minerals lies as a filling material a clear, colorless, untwinned feldspar with the habit of sanidine. It contains in many places globular to slightly ovoid masses of a very pale brown color and of a lower refractive index, which are isotropic. Similar masses are also found independent of the feldspar, crowded between the augites and biotites. They appear to have a very fine granular structure, which was not resolved by the use of high powers of magnification. They are thought to be leucite from certain considerations, though no direct proof of it was obtained, for they do not show the twinning or characteristic wreaths of inclusions. The brown color is believed to be an effect of light absorption. Considerable apatite is also present in acicular crystals. The texture of this rock, as shown by the gradation in the sizes of the augite crystals, is between that of a regular abyssal granular rock and that characteristic of a flow rock; and this tallies with its occurrence in a dike. It is in effect a coarser-grained, less porphyritic form of the lava from Zilditloi Mountain described above. It should be classified as a rather fine-grained shonkinite and, if the determination of the leucite is correct, a leucite shonkinite.

The rock forming the wall of this inner dike is a pudding of erratic fragments and local igneous material. The coarser ingredients, from one-eighth of an inch to 5 inches in diameter, include shonkonite, granite, hornblende-garnet gneiss, diorite, muscovite, schist, marble, chert, red and black slate, limestone, sandstone, and shale. Garnet and especially olivine are remarkably abundant in the rock and in the alluvium. (See p. 146.)

The knobs of igneous material rising from the floor of Buell Park and projecting from the slopes of Sterrett Mesa are, so far as observed, uniform in composition. They consist of brown conglomerate of rounded and angular pebbles, one-eighth of an inch to 6 inches in diameter, embedded in a groundmass of finely divided materials. Quartz, quartzite, chert, and slate are the most numerous pebbles, and augite and brilliant olivine are the most abundant minerals visible to the naked eye. The cleavage faces of the biotite and augite present are lusterless, and amorphous serpentine occurs as masses and as green zones surrounding pebbles.

The presence of shonkinite and the profusion of olivine distinguish the volcanic rocks of Buell Park from other occurrences in the Zilditloi field. With these exceptions the composition of the igneous masses and their field relations are essentially duplicated at Outlet Neck, at the Green Knobs, and in Todilto Park, and it seems reasonable to assume that the materials have a common source and that volcanic activity at these several localities was contemporaneous.

WHEATFIELDS VOLCANIC FIELD.

SALIENT FEATURES.

At the west base of the Chuska Mountains, on the headwaters of Canyon de Chelly, records of ancient volcanism are displayed in the form of necks, dikes, flows, and strata of volcanic ash. On the northern tributaries of Wheatfields Creek and at Palisade Creek the volcanic materials form part of the western wall of the Chuska and Tunitcha mountains; south of Whisky Creek the lofty mesas of the Sonsela Buttes are preserved by protecting caps of lava; and from the plateau west of the mountains Black Pinnacle and Sezhini [1] rise abruptly from the sandstone floor. The strata represented in the Wheatfields area are of Mesozoic and Tertiary age. Black Pinnacle and the dike at Whisky Creek rise through Chinle shales; the lava cap of the Sonsela Buttes rests on eroded surfaces of sandstone of La Plata and Tertiary age. Strata of the Chinle

[1] This butte was not visited. Its topographic form and the descriptions given by the Navajos indicate a dike or neck.

formation underlie the ash at Tubby Butte, and the tuff at the Palisades is separated from the Wingate (?) sandstone by a few feet of strata assigned to the Tertiary.

Throughout this area the Triassic and Jurassic strata form part of the east limb of the elongated De Chelly upwarp. The strata dip eastward at angles of 1° to 2°, which increase to 5° in the La Plata cliffs east of the Sonsela Buttes. Over the truncated edges of these tilted strata the Tertiary shales and sandstones lie practically horizontal.

The base of the volcanic ejecta at Tubby Butte is at an altitude of about 8,000 feet; at the Palisades it lies at 8,500 feet, and at the two Sonsela buttes, separated by less than 2 miles, the lava is at 8,900 and 8,600 feet. These figures indicate that the surface on which the volcanic material was deposited had considerable relief, a conclusion strengthened by the observation that approximately along the line of strike Jurassic and Tertiary sediments combine to form the floor. Although volcanism in this region is believed to have occurred in late Tertiary time, no conclusive evidence for such an interpretation was obtained in the field.

The various types of volcanic material found in the Wheatfields area present features sufficiently distinct to justify separate description.

SONSELA BUTTES.

The lava cap of West Sonsela has a thickness of about 100 feet and presents on the northwest face a sheer wall of well-developed columns. Beneath the lava are beds of cream-white ash interstratified with Tertiary sediments. La Plata and Chinle strata form the base of the mesa wall. The igneous cover of East Sonsela is more variable in thickness than that of its western twin, the measures at three localities giving 20, 66, and 90 feet. Tuff is present on East Sonsela as lenses and irregular sheets, but at a few localities visited the lava appears to rest directly on Tertiary sandstone. The position of the Sonsela Buttes, overlooking the deeply cut Canyon de Chelly, and the nonresistant Tertiary and Chinle sediments afford favorable conditions for vigorous erosion, and since the lavas were poured out over the Tertiary floor 1,400 to 1,500 feet of strata have been removed.

The lava of the Sonsela Buttes is a resistant dark-gray mass with a porphyritic aspect resulting from the presence of innumerable glistening specks too small to be determined with the unaided eye. Some of the specimens from West Sonsela are of microscopic fineness; at East Sonsela fine-grained, medium-grained, and scoriaceous textures were observed. Tiny pockets containing olivine were noted, and inclusions of granite and of quartzite are fairly abundant. In the talus bordering the pass between the two buttes are numerous boulders of coarse-grained biotite granite 3 to 14 inches in diameter and masses of quartzite cut by granite dikes. As determined by Prof. Pirsson the lavas present the following features:

The rock from East Sonsela Butte is found, in the section, to consist of a few rather large and many smaller, partly serpentinized olivines, light-brown augites that by decrease in size graduate into small columnar ones, which, with small biotites, a few well-formed crystals of iron ore (magnetite), and feldspathic material, compose the base. The felsic substance of the base is mostly clear, colorless sanidine, as shown by its biaxial nature, cleavage, and refractive index less than that of balsam; it occurs in large poikilitic plates inclosing all the mafic minerals and also very numerous small crystal grains of a feldspathoid. The latter exhibits roughly spheroidal forms, in places closely grouped together, and is now everywhere changed more or less to a very fine granular to fibrous material having feeble aggregate polarization; in plain light its color is a pale brown; probably it was originally either sodalite or nosean. That it is a soda mineral seems most probable, as sanidine and biotite contain the potash of the magma. Apatite occurs in slender needles. The rock is an alkalic basalt, one of Rosenbusch's trachydolerites,[1] and an effusive form of shonkinite. (See in this connection also the description of the lava of Tubby Butte, p. 98.)

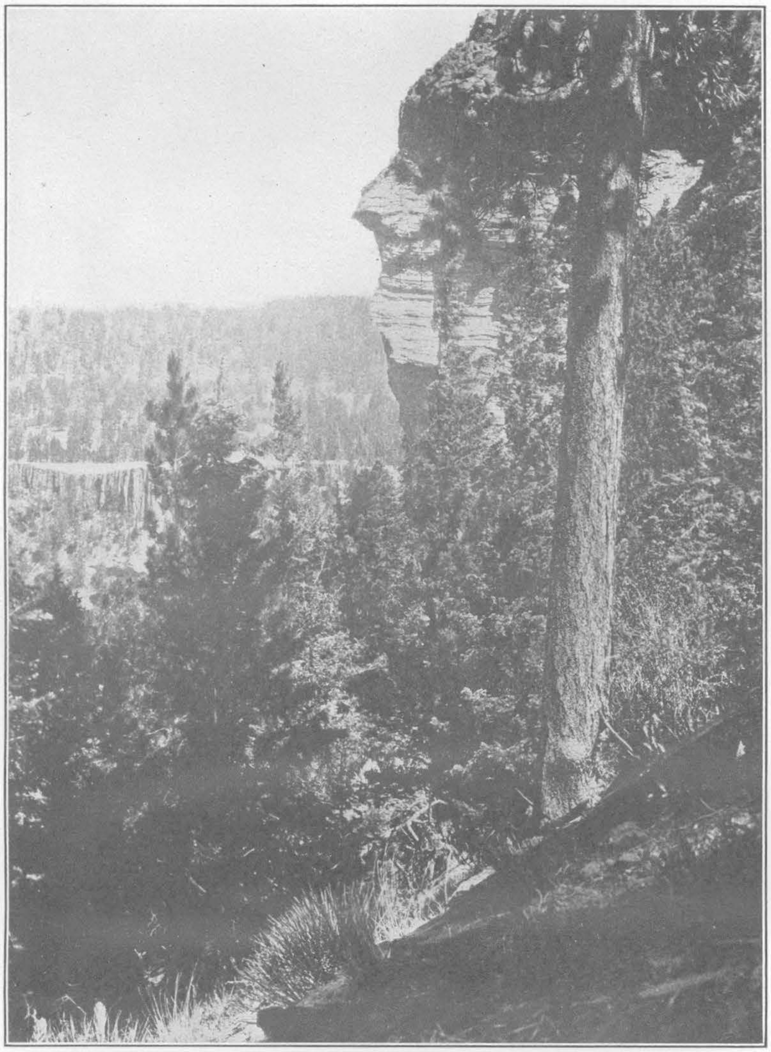
The rock of West Sonsela Butte is very similar except that there is a second crystallization of biotite in spongy flakes, poikilitic with the other minerals and locally extending beyond the opacite resorption rims of previously resorbed ones. Also there is some analcite among the feldspars which appears primary, as all the minerals in and about it are unaltered; it has cubic cleavage, its index is less than that of balsam, and it is isotropic.

DIKES ON WHISKY CREEK.

Rising from the flat east of the Sonsela Buttes and about a mile south of Whisky Creek is the dike described and figured by Simpson[2] in 1851. This intrusion forms a wall 3 to 5 feet wide and 400 feet long, which extends

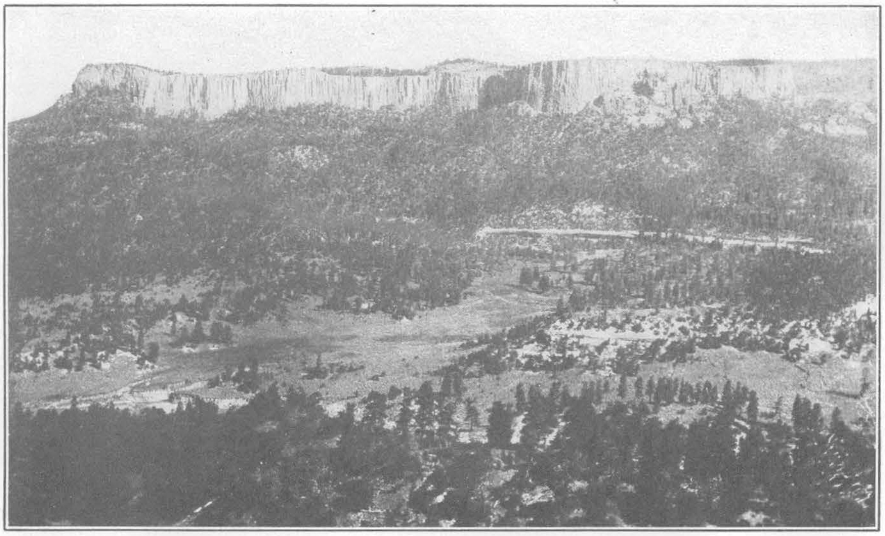
[1] Rosenbusch, H., Mikroskopische Physiographie der massigen Gesteine, 4th ed., p. 1348, 1907.

[2] Simpson, J. H., Journal of a military reconnaissance from Santa Fe, N. Mex., to the Navajo country, p. 97, pl. 47, 1850.



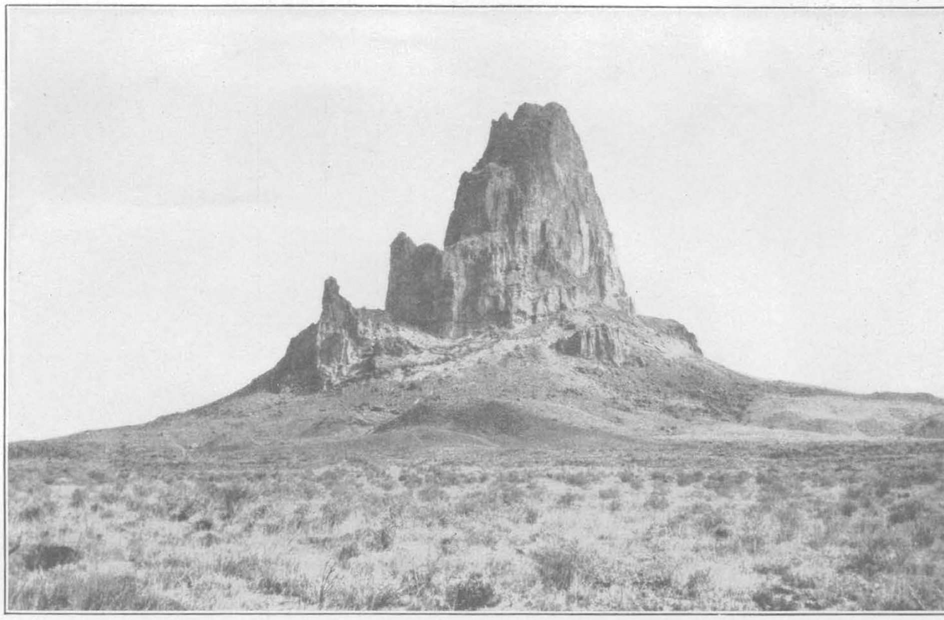
A. WASHINGTON PASS, CHUSKA MOUNTAIN, N. MEX.

Cliff in foreground composed of tuff; wall in background of shonkinite. Photograph by K. C. Heald.



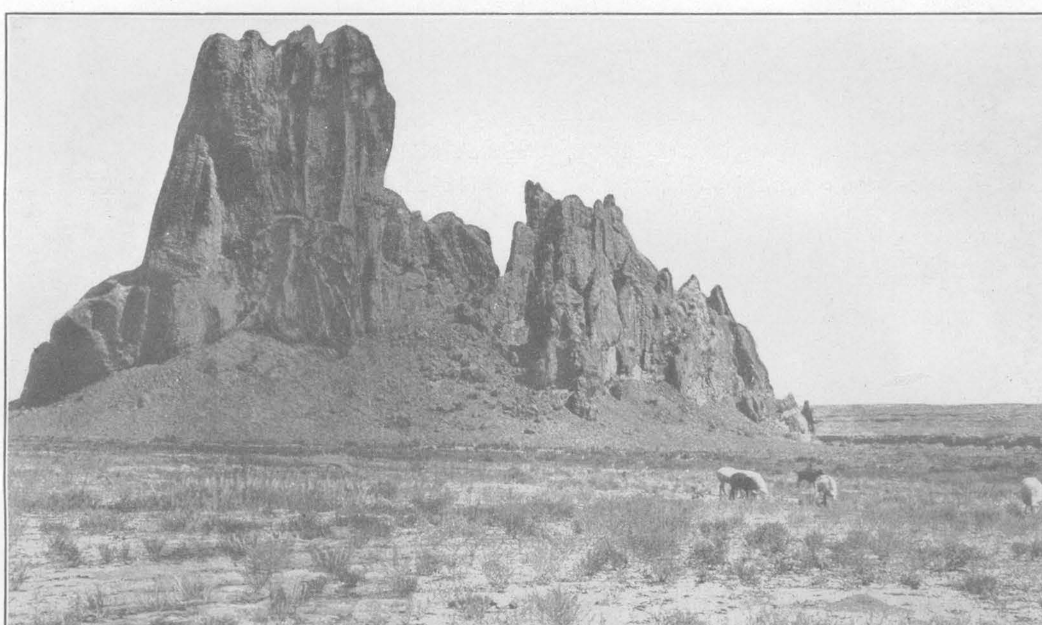
B. THE PALISADES, ARIZ.-N. MEX.

Columns of shonkinite and tuff.



A. AGATHLA, MONUMENT VALLEY, ARIZ.

A volcanic neck of trachydolerite and agglomerate, 1,225 feet high, rising through strata of Chinle formation.



B. CHURCH ROCK, TYENDE VALLEY, ARIZ.

Volcanic neck of agglomerate and monchiquite.

upward as a series of partly detached plates to a height exceeding 30 feet. Two miles farther east a butte of agglomerate and La Plata sandstone is cut by a dike 10 feet wide. Westward from the base of the butte this dike continues as a broken wall 2 to 3 feet in width for a distance of about 1,200 feet. The contact with the country rock is sharp, but the bordering walls of sandstone are little metamorphosed. The dike rock is exceedingly dense except for many small cavities filled with serpentinized olivine grains, and a much altered thin section was determined as alkalic diabase.

THE PALISADES.

The volcanic deposits forming the cliffs north of Palisade Creek are conspicuous for their remarkable development of columnar structure. With interruptions a stockade of nearly vertical columns of igneous rock and of tuff is exposed to view for a distance of over a mile. (See Pl. XVIII, *B*.) In some places lava forms the cap rock; in others the cliffs are composed wholly of tuff. A section of clastic materials forming the front of a partly detached mesa about 100 acres in area includes the following subdivisions:

Section in wall of Palisade Creek, on Arizona-New Mexico boundary.

	Feet.
1. Tuff; finer materials identical in appearance with consolidated ash of existing volcanoes; includes chunks of sandstone and of basic igneous rock, both scoriaceous and dense; coarse material is largely and in places entirely a cemented mass of blocks of shonkinite 2 to 10 feet in diameter; much secondary calcite	50±
2. Sandstone, white-yellow, containing fragments of black basic igneous rock 3 inches to 5 feet in diameter; sandstone altered to irregular band of pink quartzite at points along contact; round and subangular blocks of dense and amygdaloidal lava are partly embedded in arenaceous shale and fine tuff; appear to be bombs dropped into mud.	10–40
3. Sandstone, yellow-white, of uniform grain, cross-bedded (Tertiary)	6–12

The rounded pebbles and angular fragments embedded in the tuff include quartz of several colors, quartzite, flakes of biotite, aggregations and single crystals of olivine, and bombs and lapilli of various shapes.

The igneous blocks in places hold angular inclusions of granite, diorite gneiss, and sandstone and also rounded pebbles of hornstone 1 inch to 4 inches in diameter. A block of gneiss 14 inches long was noted. At one locality there were found angular masses of a coarsely crystalline rock, regarding which Prof. Pirsson writes:

> An inclusion in the lava of the Palisades is an interesting rock of a basaltic type. There are numerous olivines, usually more or less serpentinized, some of which show excluded secondary magnetite; brown augites of various sizes, the larger ones being stout crystals, the smaller columnar prisms; and ill-defined to patchy reddish orange-brown biotite, which is biaxial with considerable opening of the axial cross. In size and appearance these minerals resemble phenocrysts in a basaltic rock, but they lie poikilitically inclosed in large formless grains of sanidine which may be from 2 to 6 millimeters in diameter. That the sanidine is alkalic feldspar is shown by its biaxial nature, cleavage, and index of refraction, lower than balsam. There is some analcite with the sanidine, also in larger grains, which does not appear of a secondary origin. In addition to the mafic minerals the sanidine and analcite inclose poikilitically great numbers of globular masses of a pale-brown color; this material has a fine granular structure; some of it is isotropic and has a lower index of refraction than sanidine, and some of it is fibrous and spherulitic in structure with a feeble aggregate of fibrous polarization, has an index above that of the feldspar, and appears like chalcedony. The occurrence is very similar to that in the nephelinite from Zilditloi Mountain, previously described. The globular substances may be or may have been an isotropic mineral, but they are more suggestive of glass, now altered in places to chalcedony; their exact nature could not be definitely determined.
>
> This rock is practically a fine-grained shonkinite; if a distinction is made between intrusive and extrusive rocks, it must be classed as an orthoclase basalt on the assumption that it belongs among the effusives.

The lava associated with the tuff of the Palisades is too fine grained to permit the recognition of its component minerals in a hand specimen. In thin section it is seen to be porphyritic with phenocrysts of pleochroic biotite and of augite in two generations. Iron ore concentrated in the biotite is present, and also a considerable amount of chlorite. The twinned feldspar forming the groundmass is closely allied to orthoclase.

About a mile north of Palisade Creek, near the east base of White Top, is a mass of the agglomerate of somewhat unusual character. It includes slabs of red sandstone and of shale one-sixteenth of an inch to 1 foot in length, blocks of pure-white crystalline marble half an inch to 2 feet in diameter, blocks of fine-grained, coarse-grained, and porphyritic shonkinite half an inch to 6 feet in diameter, and boulders of coarse-grained biotite granite of three varieties, characterized by white, pink, and deep-red orthoclase. Within an area of 100 square feet 36 smooth, rounded granite boulders with diameters between 3 inches and 2 feet were counted.

TUBBY BUTTE.

The nature and arrangement of the volcanic deposits forming the cliffs of Tunitcha Mountain between Wheatfields Creek and Spruce Brook are shown in the following section, in which the thicknesses given are approximate:

Section of volcanic deposits at Tubby Butte, 2 miles east of Sehili, Ariz.

	Feet.
1. Lava, massive, in rudely shaped columns forming vertical walls; no regular system of division planes	200
2. Igneous breccia; slabs 10 to 15 feet long of amygdaloidal and dense lava intricately intermingled; resembles the broken edge of a flow; boulders of white granite and granite gneiss and scoriaceous bombs lined with calcite and zeolites occur as inclusions	30
3. Tuff, brown and black; groundmass essentially of biotite and augite with lesser amounts of olivine; resembles a comminuted recemented minette; abundant cavities filled with zeolites; the larger fragments are olivine basalt, half an inch to 6 inches in diameter, and well-rounded boulders of granite and granite gneiss half an inch to 16 inches in diameter.	60
4. Ash, yellow-gray, cross-bedded, containing fragments of lava of various textures, diorite gneiss, aggregates of mica, hornstone, marble, and baked, red sandy shales	200

The light-gray color of the lava at Tubby Butte contrasts strongly with the very dark colors of the rocks common to the volcanic areas of the reservation. The massive rock is little altered. Its vesicular cavities are thinly lined with zeolitic growths but not filled. Well-developed crystals of augite one thirty-second of an inch and less in length occur as phenocrysts. In other respects the rock is microcrystalline. Inclusions of granite and of porphyritic shonkinite were noted. A preliminary microscopic study by Prof. Pirsson of the main lava mass gave the following results:

The rock from Tubby Butte is an alkalic basalt. It contains phenocrysts of a pale olive-colored augite, poorly crystallized and agglomerated, with resorption masses of magnetite grains after former biotite, of which little now remains, seated in a groundmass of iron ore, augite grains, and closely packed, short, ill-formed laths of alkalic feldspar in which albite twinning is very rare but the Carlsbad twinning is very common. The rock is unaltered. It may be classed as a trachydolerite.

BLACK PINNACLE.

The intrusive mass known as Black Pinnacle consists of two parts. The eastern half is composed of a dense light-gray micaceous rock with inclusions of granite and shonkinite (?). The igneous rock of the western half is displayed as a series of columns and is partly covered with a thin cap of quartzite, probably the metamorphosed equivalent of the arenaceous beds in the lower part of the Chinle formation. The rocks from Black Pinnacle are described by Prof. Pirsson as follows:

Two rock types are present—a dark and a light one. The dark rock consists of colorless augite, present both as larger, well-formed phenocrysts and small prismatic crystals, and of biotite phenocrysts in a glass base of a rich reddish-brown color. The base is also specked with magnetite octahedrons. The arrangement of the augite prisms in the groundmass shows strong fluidal movements in the mass, so that it strongly resembles an effusive lava. The rock may be classed as an augitite.

The light type is an alkalic mafic rock or trachydolerite consisting of ill-formed colorless augites and strongly resorbed biotite in a groundmass of pyroxene granules, ore grains, and laths of sanidine.

The whole appearance of these associated rocks is much more suggestive of flows than of an intrusive dike; if they are dike rocks one would be led to infer that the original upper limit of the dike was near or at the surface and that it had been little eroded.

VOLCANIC ROCKS OF THE CHUSKA MOUNTAINS.

Except for the lavas and tuffs of the Wheatfields area, the western rim of the Chuska Mountains is free from volcanic deposits for a distance of 50 miles. On the eastern rim lavas occur at Beautiful Mountain and on the cliffs of Lukachukai overlooking Redrock Valley. On the mountain top, near the headwaters of Standing Redrock Creek, the highest points are igneous; and 30 miles to the south the lava and ash at Washington Pass rest on the crest of Chuska Mountain at an elevation of 9,000 feet.

WASHINGTON PASS.

The narrow defile of Washington Pass[1] was described by Simpson,[2] whose army encountered formidable obstacles in traversing the mountains by this route. The summit of the pass is the divide between Simpson Creek and a tiny stream of very steep gradient which, during the rainy season, finds its way to the Chaco. The gateway is barely 50 feet in width and is inclosed between walls of volcanic rocks 300 to 400 feet high. (See Pl. XVIII, *A*, p. 96.) Lava caps the mountain both north and south of the pass, covering an area, as determined by Mr. Emery, of about 2 square miles.[3] The deposits of tuff to the west of the pass somewhat increase the area occupied by volcanic material.

In some places the lavas lie on the unevenly eroded surface of sandstone; elsewhere they overlie beds of tuff which appear also to have been scored by stream channels. The underlying sandstone is the clean medium-grained quartzose rock typical of the Chuska sandstone (Tertiary), and although the lava occupies depressions in this rock and has in places the appearance of being interbedded with it, the field observations indicate that the lava is younger. The series of events appears to be as follows: Mature and postmature erosion of uplifted Tertiary beds; explosive volcanic eruptions resulting in extensive ash fields; erosion and redistribution of the ash; quiet eruption of viscous lava. Since the cessation of volcanic activity streams have cut their channels entirely through the volcanic materials. The source of the lava was not determined, but the coarsely porphyritic rock and coarse agglomerate of the necklike mass north of the pass suggest this point as the location of the vent.

The coarse variety of tuff is essentially a mixture of dense and scoriaceous fragments of basic rock rarely exceeding 2 inches in diameter. The finer tuffs consist of angular fragments of lava and lapilli with grains of quartz and bits of shales and of sandstones. Near the west entrance to the pass tuff forms cross-bedded and banded strata, beds of fine, even-grained material alternating with medium and coarse-grained layers. In addition to the foreign materials these clastic volcanic deposits consist chiefly of orthoclase and augite. In Pirsson's classification[4] they are intermediate between the crystal and lithic tuffs and are derived from a trachydoleritic magma.

The lava flow where measured was 75 feet thick and includes scoriaceous, vesicular, dense, and coarsely porphyritic varieties. In the hand specimen crystals of olivine and of augite are readily detected by their glistening cleavage faces, and the microscope reveals a composition almost identical with that of the shonkinite inclusions in the tuff at the Palisades. (See p. 97).

LUKACHUKAI MOUNTAIN.

At the head of Spruce Brook are two buttes of igneous rock which rest on the unevenly eroded surface of much-disturbed sandstone of Tertiary age. At the base of the buttes is 5 to 30 feet of coarse tuff, consisting of fragments 1 to 2 inches in diameter of dense igneous rock, scoriaceous lava, and baked sandstone. Above the tuff lies about 120 feet of scoriaceous lava of highly irregular form. Bread-crust pillows, solid, dense blocks, and stretched slabs are intermingled in a disorderly fashion. The flow from a local volcano appears to have advanced intermittently, breaking up, overriding, and incorporating partly cooled portions of previous extrusions. The texture of the rock composing the extrusion is too fine to allow the recognition of the component minerals, and thin sections have not been studied.

The projecting headland of Lukachukai, overlooking Redrock Valley, is rimmed about with igneous rock. On the west side a sheet is terminated by a palisaded wall formed of columns about 40 feet in length. Accompanying the sheet are numerous dikes ranging in width from a few inches to a few feet, which expand, contract, or pinch out entirely and bend in accordance with joints and bedding planes. The red sandstone adjoining the igneous rocks is greatly metamorphosed. In some places it is converted into massive quartzite; in others five or six sided columns of quartzite, 1 to 4 inches

[1] Named by Simpson in honor of Col. J. M. Washington. This difficult piece of mountain road is locally known as Cottonwood Pass.

[2] Simpson, J. H., Journal of a military reconnaissance from Santa Fe, N. Mex., to the Navajo country, pp. 64-65, 1850.

[3] As mapped by Shaler (U. S. Geol. Survey Bull. 316, pl. 22, 1906) and by Darton (U. S. Geol. Survey Bull. 435, pl. 1, 1910), the lavas at Washington Pass cover about 20 square miles.

[4] Pirsson, L. V., The microscopical characters of volcanic tuffs: Am. Jour. Sci., 4th ser., vol. 40, pp. 191-211, 1915.

in diameter and 4 to 6 feet in length, form a fluted wall. The rock forming the dikes and sheet is dense, black, and highly micaceous, closely resembling the minettes of Monument Valley. (See p. 103).

The northeastern part of Lukachukai Mountain was found by Mr. Emery to be capped with a vesicular lava flow, which is believed to have its source in an adjacent butte having an igneous core. To judge from the hand specimen the rock composing the flow is identical in composition with that forming the dikes and sheet. Opportunity was not afforded for more than a superficial examination of this interesting locality.

The lava cap of Beautiful Mountain, where examined by Mr. Emery, is about 440 feet thick and lies in a horizontal position upon the truncated beds of the McElmo formation and the Dakota sandstone.

VOLCANIC ROCKS OF THE CHUSKA VALLEY.

The dikes and necks of the Chuska Valley, including Ford Butte, Bennett Peak, and the magnificent Ship Rock, have been mapped by Shaler,[1] who found them to consist chiefly of monchiquite.

CARRIZO LACCOLITH.

Carrizo Mountain owes its form and preservation to intrusions of a laccolithic character. On the flanks and tops of the mountain igneous rock is widely exposed, and the entire northeast shoulder is a mass of diorite porphyry. At the southeast base of the mountain dikes of minette or biotite monchiquite accompany the larger intrusions, and in Redrock Valley there are six volcanic necks or plugs of minette-like material.[2]

MONUMENT VALLEY VOLCANIC FIELD.

GENERAL CHARACTER.

Along the Arizona border and extending northward into Utah is a region of profound canyons and lofty mesas and buttes. In the midst of columns carved from sandstone are volcanic necks, conspicuous alike for their towering heights and for their subdued colors, which contrast sharply with the brilliant tones of the adjacent sedimentary rocks. Chaistla Butte and the Tyende dikes mark the Navajo trail to the Piute country, and Alhambra Rock, overlooking the San Juan Canyon, is the white man's guide to the Goodridge oil fields. Dikes also traverse the Comb monocline, the sharply down-flexed border of the Monument upwarp, and immediately outside of the hogback rim in Tyende Valley and at Garnet Ridge there are a number of intrusive masses. The dominating feature of the landscape is Agathla, an isolated neck clearly visible for distances of 50 miles. No extrusive volcanic rocks were found in the region.

The structural relations of the Monument Valley volcanic field are simple. The Permian (?) and Mesozoic strata through which the intrusives rise are broadly arched to form the Monument upwarp. (See p. 113.) The necks rise higher than the dissected mesas of sedimentary rock, and the lavas and ash that were doubtless deposited on an ancient floor at still higher altitudes have long since been removed. The date of volcanic activity therefore can not be fixed. There is no reason, however, for assuming that the volcanism in this area was not contemporaneous with that in the Hopi Buttes and Zilditloi fields, for the dome of the Monument upwarp is favorably placed for rapid dissection, and it is probable that the lavas were poured out on a maturely eroded surface from which early Tertiary and Cretaceous sediments had been already removed. If this hypothesis is accepted, the thickness of the strata disintegrated and carried to the San Juan since the Tertiary volcanoes became inactive is 2,000 to 2,500 feet.

AGATHLA AREA.

Within a radius of 10 miles from Agathla are six necks exceeding 300 feet in height and seven dikes ranging in length between 300 and 8,000 feet, besides numerous exposures of smaller dimensions.

AGATHLA.

With the possible exception of the Monuments and Shiprock, Agathla is the most conspicuous landmark in the Navajo country. It rests on a symmetrical pedestal 200 feet in height, with terraced slopes carved from sandstone and shales of the lower part of the Chinle formation. The main shaft rises as a jagged

[1] Shaler, M. K., op. cit., pl. 22.

[2] The igneous rocks of Carrizo Mountain and vicinity are fully described by W. B. Emery in Geology of Carrizo Mountain, Ariz.: U. S. Geol. Survey Bull. — (in preparation).

peak 1,025 feet above the pedestal, or 1,225 feet above the surrounding plain, and has a basal diameter of about 3,000 feet. (See Pl. XIX, *A*.) It consists in the main of breccia or agglomerate traversed by branching dikes and sheets which intersect and coalesce, expand and contract in width in a capricious manner.

The agglomerate neck consists of angular and subangular fragments of basic igneous rock, sandstone, and shale 1 inch to 20 feet in diameter, together with scattered pebbles of granite and limestone. The sedimentary blocks observed are all more or less metamorphosed and where closely in contact with dikes are altered to quartzite and marble.

The unmodified igneous rock of the ramifying dikes exposed on the sides and at the tops of Agathla has in places a schistose structure; elsewhere it is dense and massive. Visible crystals of biotite and of augite in an otherwise fine-grained mass give to the rock a porphyritic appearance. A thin section of the rock is described by Prof. Pirsson as follows:

The section shows a rock composed of small phenocrysts of partly resorbed biotite and pale-brown augite rather thickly crowded in a compact groundmass of fine grains of iron ore, granules of augite, and flakes of biotite with a colorless cement consisting of laths of alkalic feldspar mixed with a nonpolarizing substance that may be glass or analcite. The section contains in addition some fragments of a dioritic rock consisting of grains of andesine and quartz which are partly digested, being embayed and rounded with glass skins. As a rock type it is basaltic, though without olivine, and may be classed as a trachydolerite; but if emphasis is laid upon its intrusive nature it is clearly lamprophyric in character and must fall into the camptonite-monchiquite series, and it resembles the rock from Black Pinnacle.

Two miles northeast of Agathla are two low, rounded buttes of igneous rock composed of similar material.

CHAISTLA.

The volcanic neck known as Chaistla Butte occupies a prominent position on the plain 4 miles south of Agathla. Its basal area is about 700 by 1,000 feet, and its height exceeds 400 feet. The material composing the neck is about 90 per cent agglomerate or breccia of igneous fragments, sandstone, shales, and rare limestone and 10 per cent monchiquite displayed as stringers and dikes. The breccia is more resistant to weathering than the massive igneous rock, and areas of decomposed minette are found in the midst of unweathered masses of agglomerate. As observed in the ledge the rock has a microcrystalline groundmass, in which are embedded innumerable flakes of biotite, rare augite and olivine, and irregularly shaped inclusions composed of aggregations of quartz grains.

TYENDE DIKES.

The volcanic neck about 3 miles east of Tyende consists of two dikelike masses 300 feet in height, which trend N. 14° W. and include between them a great mass of agglomerate or breccia. The total amount of massive igneous rock is relatively small; the breccia of sandstone and minette constitutes fully three-fourths of the exposure. The porphyritic appearance of specimens collected from one of the intrusive bodies is due to the presence of abundant bronze-colored biotite arranged in more or less definite lines. Grains of olivine are also visible. The microscope reveals biotite largely resorbed, augite of two generations, olivine, and iron ore of a second generation, in a groundmass of alkalic feldspar. The rock may be classified as augite minette.

CHURCH ROCK.

A volcanic neck that rises abruptly from the floor of Tyende Valley to a height of about 300 feet has a rectangular ground plan and a pointed tower that have suggested the name Church Rock. (See Pl. XIX, *B*, p. 97). The mass consists of groups of more or less parallel dikes with many cross connections. Included between the dikes and surrounding them is a giant breccia or agglomerate of sandstone and igneous fragments of various sizes, in quantity greatly exceeding the amount of unmodified igneous rock found in the dikes. The igneous rock is light gray to greenish in tone, and its only minerals visible to the unaided eye are glistening specks of biotite, needles of pyroxene, and rare grains of olivine. Fragments of granite occur as inclusions. With the aid of the microscope augite of two generations, partly resorbed biotite, and tiny inclusions of quartz were observed, set in a groundmass of augite, biotite, and iron ore cemented by alkalic feldspar. In appearance and composition the rock closely resembles that from Agathla, and it may be classed with the monchiquites.

A low dike extends eastward from Church Rock for about 1,000 feet, and in that distance its width gradually decreases from 20 to 5 feet. Along its narrower portions the central wall is plastered with a conglomerate of igneous and sedimentary fragments. With increase in thickness the plane of demarcation between the dike rock and agglomerate disappears and the mass becomes a pudding of blocks and pebbles attaining diameters of 1 foot. The core rock is light gray in color, sprinkled over with tiny flakes of mica, and includes fragments of quartz and much calcite. In a few specimens aggregates of biotite, olivine, and chlorite an inch or so in length in variable quantities were observed.

A dike 300 feet long and 50 feet wide, lying about 7 miles northeast of Church Rock, consists of blocks of sandstone as much as 20 feet in length, boulders of granite and of dense black igneous rock, and fragments of slate and limestone occupying compartments formed by intersecting dikes of monchiquite (?).

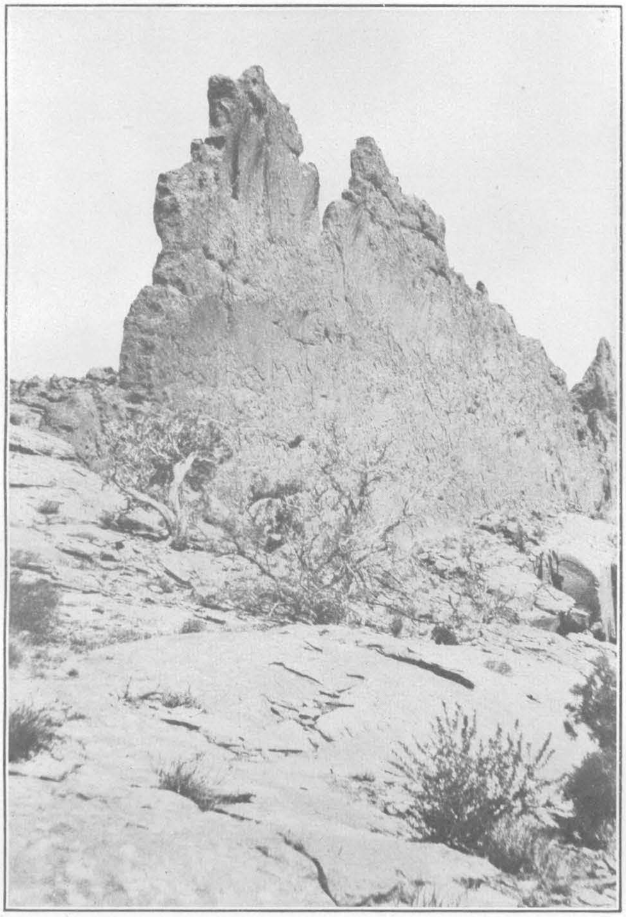
PORRAS DIKES.

The group of igneous needles and plates that form the culminating points of Comb Ridge in the Agathla region are collectively known as Porras dikes. The five lofty spires seen from a distance proved on examination to be pinnacles carved from two volcanic necks rising 300 feet above their base, or about 700 feet above the floor of the adjoining valley. (See Pl. XX, *B*.) The necks stand at the north end of a line of igneous dikes that extend southward for more than a mile. The material composing the towers is in large part an agglomerate which is more resistant than the igneous rock. The structure as a whole should be described as breccia or agglomerate irregularly intersected by dikes and sheets, rather than intrusive igneous rock surrounded or accompanied by volcanic breccia. The agglomerate consists of angular, subangular, and rounded boulders of basic igneous rock, granite, and sandstone, ranging in size from pebbles to blocks 20 feet in diameter. In places they are intricately fractured or crushed. The dikes that traverse the conglomerate exhibit both dense and amygdaloidal facies and include rounded pebbles of granite and segregations of biotite and olivine in varying proportions. In the hand specimen the rock closely resembles that from Chaistla and may be classed as a monchiquite. A dike of monchiquite (?) extending southward from the group of agglomerate needles averages 6 feet in width and is broken by a number of offsets arranged in accordance with the plan of major jointing in massive La Plata sandstone. Erosion of the bordering sediments permits the dike to stand 6 to 8 feet above the surface. At one point it rises as a giant fin 60 feet high. (See Pl. XX, *A*.) The walls of the dike are plastered with an agglomerate of igneous and sedimentary fragments, and within the dike rock are incorporated segregations of olivine, of biotite, and of a mixture of these two minerals.

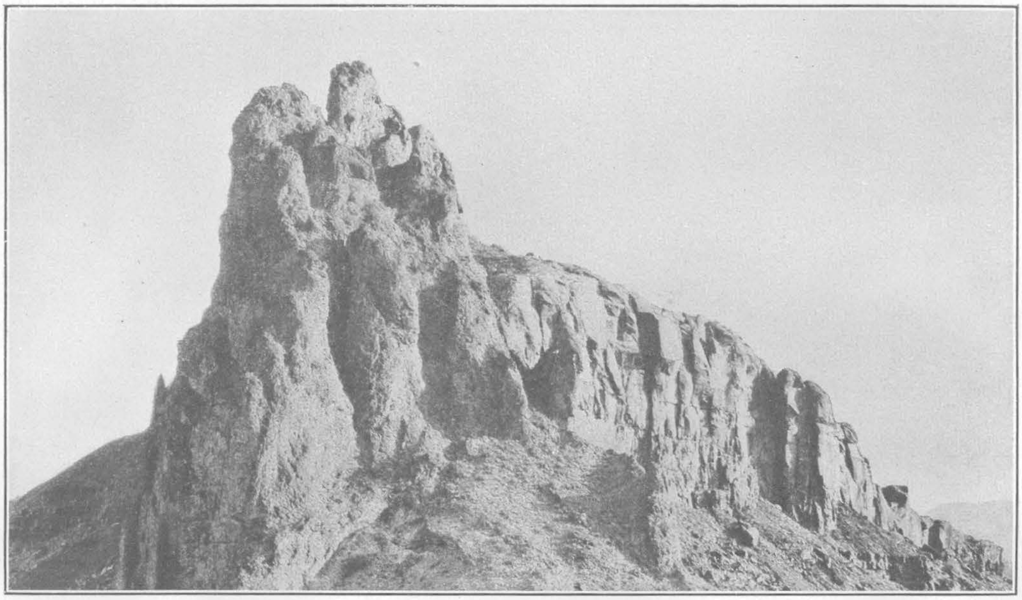
GARNET FIELDS.

The Arizona and Utah garnets of commerce have their source in igneous agglomerate and in a garnetiferous gneiss that occurs as inclusions in a group of intrusives at Garnet Ridge, Moses Rock, and Mule Ear. (See p. 146.) These three localities present practically the same igneous phenomena—a small neck or pipe with accompanying dikes protruding from strata of sandstone. An unusual feature, however, is the composition of the igneous rock, which consists essentially of a remarkable assemblage of inclusions held together by a minette-like paste. At Garnet Ridge were collected specimens of sandstone, shale, fossiliferous Carboniferous limestone, biotite granite, garnetiferous diorite, gabbro, minette, granite gneiss, porphyritic granite gneiss, garnetiferous diorite gneiss, muscovite schist, chlorite schist, slate, hornstone, quartzite, garnet, olivine or peridot, lustrous feldspar, quartz, chalcedony, augite, diopside, epidote, soapstone, tremolite, and asbestos. None of the igneous and metamorphic rocks included in this list are found in place within 100 miles of this area, and the nearest outcrop of Pennsylvanian limestone occurs in the bed of San Juan River, 20 miles to the north. The igneous rock readily decomposes, and the adjoining slopes are strewn with boulders closely resembling glacial erratics, for which they have been mistaken.[1] (See Pl. XXI, *B*.)

[1] Gregory, H. E., The igneous origin of the "glacial deposits" on the Navajo Reservation: Am. Jour. Sci., 4th ser., vol. 40, pp. 97-115, 1915.

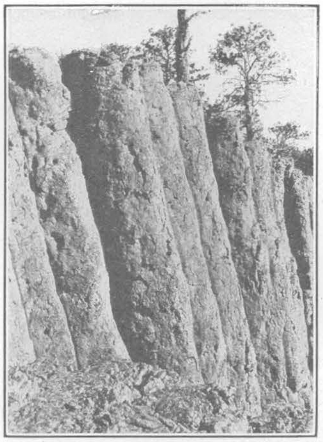


A. DIKE EXTENDING FROM A VOLCANIC NECK AT PORRAS DIKES, ARIZ.



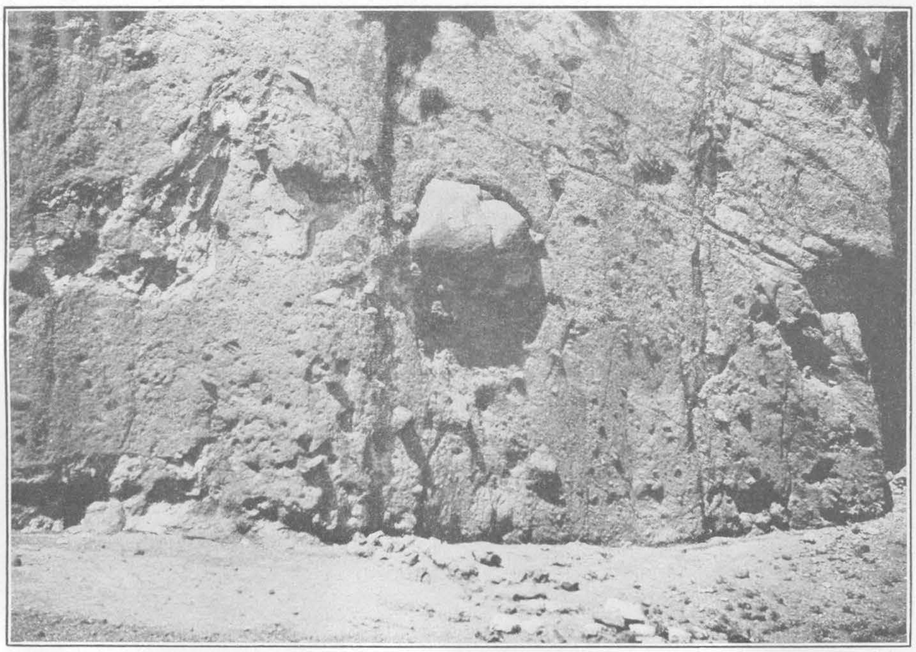
B. VOLCANIC NECK, NORTH END OF PORRAS DIKES, ARIZ.

Composed of monchiquite and agglomerate; rock at right is sandstone of La Plata group.



A. COLUMNAR WALL OF FLUTED ROCK, ARIZ.
Composed of minette and agglomerate.

B. ERRATICS, GARNET RIDGE, ARIZ.
The boulders, chiefly granite gneiss, have been weathered from volcanic agglomerate.



C. FACE OF BLACK ROCK, NEAR FORT DEFIANCE, ARIZ.
Agglomerate of orthoclase basalt and sedimentary fragments, forming part of volcanic neck.

OTHER INTRUSIVE ROCKS.

About 2 miles south of Oljeto a small dike that trends N. 5° W. cuts the De Chelly sandstone. It is composed essentially of a conglomerate of dark micaceous igneous rock (minette?) and fragments of sandstone.

A low greenish butte about 4 miles south of Douglas Camp was found to have a core of basic igneous rock sufficiently coarse in texture to permit the recognition of crystals of biotite and of pyroxene.

Alhambra Rock, 3 miles southwest of Goodridge, is a mass of volcanic conglomerate consisting of angular and rounded fragments of granite gneiss, quartzite, sandstone, and limestone, which range from a fraction of an inch to a foot in diameter. Cutting the central mass and extending for a mile and a half southward is a low dike 2 to 20 feet thick. The material composing it has been described by E. S. Larsen as an augite minette.[1]

VOLCANIC ROCKS OF THE TUBA REGION.

In the northwestern part of the Navajo Reservation, between Black Mesa and Colorado River, there has been little volcanic disturbance. The only igneous exposures mapped are in the vicinity of Tuba. They include two prominent points, Wildcat Peak and Tuba Butte, provisionally classed as necks, and three dikes in Moenkopi Wash, at Moa Ave, and in Echo Cliffs, 6 miles north of Willow Springs. Tuba Butte was observed only from a distance. According to Mr. S. S. Preston it is an igneous mass traversed by a long, narrow dike. The "cinder cone" 15 miles north of Moenkopi and the two "to the westward" mentioned by Howell[2] are believed not to exist.

WILDCAT PEAK.

Wildcat Peak is a prominent landmark rising above the desert floor of Kaibito Plateau to a height of about 500 feet. The sharp, serrate crest of the peak is cut from a dike 15 to 20 feet wide composed of basic igneous material, accompanied by large amounts of conglomerate of igneous and sedimentary fragments. Springing directly from the central mass are three dikes; two of them, 700 and 1,000 feet in length and 3 to 4 feet wide, extend northward; the third extends southward as a narrow wall for a distance of 900 feet. A fourth dike, three-fourths of a mile long, also with a northerly trend, is separated from the southern base of the peak by a mass of agglomerate. The rock from the central peak is coarse grained and porphyritic; crystals of olivine and innumerable prisms of augite with lengths 10 or 12 times their width are readily distinguished. The specimens collected from the radiating dikes are fine-grained, some of them glassy. Thin sections from two of the dikes were examined by Prof. Pirsson, who furnishes the following description:

> The rock is of considerable interest, for it contains the rare mineral melilite, and it has therefore been studied in detail. The chief minerals are augite and olivine. The olivine is fairly abundant as phenocrysts, and is mostly unaltered. The crystals range from those which are of good size down into those of the groundmass. The augite is of a yellowish-brown color; as phenocrysts it occurs in rather slender prisms, and these graduate into grains of groundmass size. Augite is by far the main constituent of the groundmass in slender prisms and elongate grains thickly packed and crowded together. Associated with it is a much smaller amount of melilite. This mineral has the characteristic tabular form parallel to the base and is fairly well crystallized; some crystals show a zonal arrangement of parts. It ranges from a colorless to a honey-yellow mineral, like the melilite in leucitite from Capo di Bove, Italy, but it differs in that the crystals are not poikilitic with other intergrown minerals. The index of refraction is high, giving a relief almost like that of the pyroxenes; the double refraction is very low, only occasionally showing the ultra blue. The sensitive tint shows that while, in general, the crystals are negative, interior portions in some are positive. The peg structure is well developed, and in addition the crystals are undergoing to a varying extent a process of alteration which may be similar to that described by Soellner[3] as occuring in the rock from the Kaiserstuhl in Baden, termed by him bergalite; but the small size of the crystals, the largest one observed being 0.15 millimeter broad by 0.02 millimeter thick, makes any detailed observations concerning it impossible.
>
> In the interstices between the augite and melilite are numerous grains of iron ore and flakes of biotite. Here and there are minute grains of a perofskite, and it is possible that some of the black opaque particles which appear like ore may be this mineral in altered condition. A colorless or brownish material serves as a cement, but on account of its more or less altered condition and its occurrence in minute masses it can not be very satisfactorily determined. Much of it is isotropic and lower in index than balsam and is thought to be analcite or glass. Other portions show low double refraction and are held to be sanidine and nephelite. Fibrous zeolitic material is also present in it. To this list of minerals apatite in

[1] Woodruff, E. G., Geology of the San Juan oil field, Utah: U. S. Geol. Survey Bull. 471, pp. 86–87, 1912.

[2] Howell, E. E., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 299, 1875.

[3] Soellner, J., Über Bergalith, ein neues melilithreiches Ganggestein aus dem Kaiserstuhl: Grossh.-bad. geol. Landesanstalt Mitt., Band 7, p. 415, 1913.

slender columns should be added. The rock is a melilite basalt, though the great predominance of the augite and olivine and the small amount of felsic material render it by no means typical. One might place it equally well in the limburgite-augitite group of Rosenbusch, but this assignment is not founded on a quantitative basis, the proportion of augite (and olivine) to glass base varying within wide bounds. On the other hand, if geologic mode of occurrence is considered, inasmuch as the rock occurs as a dike and not as a flow, it would have to be placed among the lamprophyres, and on account of the melilite it would be classed as alonite, of which it would form a fine-grained, dense example without the large biotite phenocrysts usually characteristic of that rock. As the rock is quite fresh, except for the small amount of felsic cement, a chemical analysis of it would be desirable to determine its magmatic characters.

MOENKOPI DIKE.

A wall of igneous rock about 4 miles south of the Hopi village of Moenkopi cuts the Jurassic (?) cliffs of Moenkopi Wash and traverses the floor of Ward Terrace for a distance of over 2 miles. For about half its length it stands as a serrate ridge 4 to 8 feet wide, bordered by dunes reaching nearly to the crest. The sedimentary rocks in contact with the dike are hard baked and more resistant than the igneous core, and in places rise high above the center of the dike, forming a groove along the crest. The dike rock is too fine grained to permit the determination of its constituent minerals in the hand specimen. In thin section augite and olivine, the latter represented by carbonates and serpentine, appear as phenocrysts. Interlocking crystals of augite and grains of iron ore, of a second generation, form part of an otherwise indeterminable groundmass. All the specimens obtained are much altered, but they closely resemble those from Wildcat Peak.

DIKES AT MOA AVE AND ECHO CLIFFS.

About a mile west of Moa Ave is an inconspicuous dike of augite minette (?) 300 feet long and 6 inches to 2 feet in width. The rock is very dense in texture and includes well-worn pebbles of hard-baked sandstone, some of which are crushed and faulted.

North of Willow Springs a dike extends from the top to the bottom of Echo Cliffs as a dark vertical band 3 feet in width. Phenocrysts of augite, olivine, and biotite mark the surface of the rock, and smaller crystals of augite and grains of iron ore may be distinguished with a hand lens.

VOLCANIC ROCKS OF THE LITTLE COLORADO VALLEY.

Little Colorado River is the boundary line between the ancient volcanic rocks of the Navajo country and the recent cones and flows of the San Francisco volcanic field. A journey of less than 10 miles to the west from the river will bring the observer to extensive fields of lava at almost any point between Canyon Diablo and the Moenkopi. At Tolchico a flow comes within 2 miles of the Little Colorado. At Grand Falls a narrow band of lava from the San Francisco field filled the immediate valley of the river and forced the stream to find a new course around the end of the flow. Black Falls also owes its position to a recent extrusion of basalt that probably came from a fissure concealed beneath the lava. At Black Point lava from an early eruption in the San Francisco field caps a beveled monocline that rises steeply above the river bed.

About 8 miles below the Government bridge the Little Colorado flows between inner valley terraces that are capped with olivine basalt resting on the beveled edges of faulted Moenkopi strata. The lava, which came from an undetermined source, appears to have followed the bed of an ancient canyon. Since the period of volcanic activity the river has sunk its channel 150 feet through lava and Carboniferous strata.[1] (See Pl. XXV, A, p. 126.)

BLACK KNOB.

The only recent lava mapped within the borders of the Navajo Reservation is at Black Knob, near the mouth of Moenkopi Wash. At this locality a flow over a mile in length flanks a butte of Triassic shales. As reported by J. E. Pogue, the surface of the lava is scoriaceous, and the vesicles are filled with aggregates of olivine. A microscopic study of a thin section from Black Knob by Prof. Pirsson gave the following result:

> The rock belongs to the class of the ordinary plagioclase basalts but is interesting and uncommon in its nature. It is rather fine grained and consists of labradorite, augite, olivine, and iron ore. Only the olivine appears in crystals that are large enough to be termed phenocrysts, and these are relatively so small and rare as to produce the general impression of only one generation of minerals as present; the rock is perpatic. Labradorite is the most

[1] For a general sketch of this area see Gregory, H. E., A reconnaissance of a portion of the Little Colorado Valley, Ariz.: Am. Jour. Sci., 4th ser., vol. 38, pp. 491-501, 1914.

abundant mineral, in thin, tabular twinned crystals, the face 010 of flattening being well developed, while other faces are lacking. As the crystals are cut they appear as slender laths which vary into broad, irregularly outlined plates. Olivine, the next most prominent mineral, occurs in small, irregular grains dispersed among the feldspars. The augite and iron ore are about equal in amount; the ore, many grains of which show the well-defined octahedrons of magnetite, is mainly scattered, but locally grouped. The augite is in the form of small, slender rods or prismoids of a rather dark chocolate-brown color and nonpleochroic; the rods are commonly aggregated into bunches or sheaves.

To the chemist and mineralogist the interesting feature of this rock is the dominance of the feldspar over the mafic minerals and of olivine over augite. The rock is to be classed as a troctolitic basalt, bearing somewhat the relation to ordinary basalt that troctolite does to common gabbro. It is of interest in this connection to note that a similar rock from this general region has been described by Noble,[1] who mentions a sill of diabase intrusive in the strata of the Shinumo area of the Grand Canyon. It is composed predominantly of olivine and labradorite and is classed as an olivine-diabase of troctolitic aspect.

MISCELLANEOUS INTRUSIVE MASSES.

During the course of field work a number of igneous masses, not included within the volcanic areas described above, were noted, and their locations are indicated on the map. Opportunity was afforded for an examination of those described below.

BLACK ROCK.

Because of its proximity to Fort Defiance, the oldest settlement in northern Arizona, Black Rock is the best known of all the igneous masses within the Navajo country. It was described by Simpson [2] and is included in a generalized section constructed by Newberry.[3] Topographically Black Rock is a massive neck of irregular shape about 800 feet long and 150 feet in average width. It is completely isolated and rises abruptly above the alluvial floor of Black Creek to a height exceeding 200 feet. The mass consists of material of two types described below:

1. Orthoclase basalt, microcrystalline in texture except for the innumerable tiny flakes of bronze-colored biotite and rare fragmentary crystals of augite. Hand specimens of this rock are indistinguishable from the augite minettes of Alhambra Rock (p. 103) and Boundary Butte (p. 106). Rock of this type is most abundant in the upper part of the mass, where it is characterized by a roughly columnar structure, with columns practically horizontal.

2. A coarse agglomerate or volcanic breccia. This type consists chiefly of fragments of igneous rocks of all sizes up to 15 inches in diameter and irregular pieces of shale and sandstone from the Chinle formation, which here forms the country rock. (See Pl. XXI, *C*, p. 103.) Some of the fragments of included shale have been metamorphosed into hornstone. The agglomerate forms about two-thirds of the entire neck and in general surrounds the more homogeneous igneous rock. The absence of clean contact between the country rock and the neck is very noticeable, and the mingling of sedimentary and igneous fragments, all of them angular, would seem to indicate that fragments from the dike wall had become rather thoroughly incorporated in the igneous mass at the time of its intrusion.

As determined by Prof. Pirsson:

> The igneous part of Black Rock is composed of large phenocrysts of pale-brown augite, with the centers of many of the large ones filled with glass inclusions, and partly resorbed rather pale brown biotite, resting in a fine groundmass of augite, iron ore, and biotite whose granules are cemented by a colorless material consisting mostly of small orthoclase laths and partly of indeterminable material. The rock is lamprophyric and is closely related to fourchite, to bermudite,[4] and to cascadite.[5] It might, perhaps, be most simply described as orthoclase basalt.

About 2 miles west of Black Rock is a dike 25 feet wide and 200 feet long, trending N. 60° W., which rises 100 feet above the general surface, and near at hand is another dike, perhaps a portion of the same general mass, 300 feet long and 10 to 30 feet wide. Unlike Black Rock, these dikes show a sharp contact with the border sediments and the pudding of breccia is absent. Columnar structure is well developed. The rock composing the dikes is porphyritic minette, in which the phenocrysts consist of augite, biotite, and rare olivine. The mica is arranged parallel with the surface of cooling, and along its planes the rock breaks readily into slabs. Cavities as much as 1 inch in long diameter are filled with calcite, and quartzite pebbles, probably from the Shinarump conglomerate, appear as inclusions.

[1] Noble, L. F., Contributions to the geology of the Grand Canyon, Ariz.: Am. Jour. Sci., 4th ser., vol. 29, p. 578, 1910.
[2] Simpson, J. H., op. cit., pp. 110-111.
[3] Newberry, J. S., op. cit. (Ives expedition), p. 93.
[4] Pirsson, L. V., Geology of Bermuda Island—Petrology of the lavas: Am. Jour. Sci., 4th ser., vol. 38, p. 340, 1914.
[5] Pirsson, L. V., Petrography and geology of the igneous rocks of the Highwood Mountains, Mont.: U. S. Geol. Survey Bull. 237, p. 142, 1905.

FLUTED ROCK.

The culminating point on the central part of Defiance Plateau is the igneous mass called Fluted Rock (Zildasaani of the Navajos). It is the remnant of a sheet or laccolith which rises above the surface to a height of about 400 feet, separated from the surrounding sedimentary strata by an almost continuous moat. Its sides are formed of columns, some vertical, others inclined at high angles. (See Pl. XXI, *A*, p. 103.) Over parts of the mass the original cover of vitrified sandstone remains in place, and fragments of white quartzite and baked sandstone are strewn over the surface. Blocks of quartzite are included also within the igneous rock. Abundant flakes of glistening bronze-colored biotite and prisms of augite give to the rock a porphyritic texture. The following petrographic description was furnished by Prof. Pirsson:

The rock is found in thin section to be made up of pale olive-tinted augite and of much resorbed biotite, more or less changed to opacite, in a groundmass of augite grains, iron ore, and a second biotite formation, with a colorless cement consisting of formless grains of very low birefringence whose refractive index is equal to that of balsam or distinctly lower. It is inferred that the orthoclase, which is the chief colorless constituent, is probably accompanied by some nephelite. The rock closely resembles the cascadites or "minettes" of the Highwood Mountains in Montana, and especially the rock from Williams Creek,[1] and may therefore be referred to them. Rosenbusch[2] classified these rocks as orthoclase camptonites. A section of a rock from the outer edge of this igneous mass is similar but lacks the second generation of biotite.

CHILCHINBITO DIKES.

Along the base of Black Mesa, north of Chilchinbito, two ridges having igneous cores, with a general trend N. 30° W., rise from a floor of McElmo strata and were examined by Mr. Pogue. One of these black ridges, which extends with slight interruptions for nearly a mile and has an average width of 15 feet, proved on examination to consist of about equal parts of micaceous diabase or minette and an agglomerate composed of fragments of igneous and sedimentary rock. The other ridge is also about a mile long, but as a rule it does not exceed 10 feet in width. Throughout most of its extent it forms a wall standing only a few feet above the surface, but at one point elongated vertical plates rise to a height of 200 feet.

The field relations and the uniformity in type of rock suggest that these two dikes are closely related and that they occupy fissures through which lava reached the surface.

BOUNDARY BUTTE.

Boundary Butte, so named from its position near the Arizona-Utah line, is the most conspicuous landmark between Carrizo Mountain and San Juan River. It consists of a central neck or volcanic plug, accompanied by seven circular dikes. Mr. Emery reports that the igneous rock is a porphyritic minette containing phenocrysts of biotite and augite.

GENERAL RELATIONS OF THE IGNEOUS ROCKS.

FIELD RELATIONS.

The position of volcanic vents and of dikes in the Navajo country has no evident genetic relation to crustal movements in the Colorado Plateau province. No intrusives or flows so far as observed are located on lines of fracture. The volcanic rocks of the Zilditloi and Monument Valley fields are associated with folds, and Black Rock and the dikes and necks of the lower Chuska Valley are near the Defiance monocline. Dikes also cut the Comb monocline and Echo monocline. On the other hand, the igneous rocks of Boundary Butte and Wildcat Peak and the lavas of the Hopi Buttes region have found their way to the surface through essentially horizontal strata. At Carrizo Mountain the laccolithic core is accompanied by intrusives at the mountain base, but in the neighborhood of the Navajo Mountain laccolith no igneous rock is exposed at the surface.

Well-defined masses of intrusive igneous rock sharply separated from the adjoining sediments are exceedingly rare. Dikes of all dimensions are commonly bordered by zones of agglomerates and include fragments of country rock. Several of the intrusive masses contain 10 to 30 per cent of foreign material, and a dike near Moses Rock is essentially an agglomerate of sedimentary fragments cemented with minette. It is therefore difficult to determine which of the igneous masses gave rise to surface flows, and it is not improbable that several of the igneous outcrops treated in this paper as dikes

[1] Pirsson, L. V., op. cit. (Highwood Mountains), p. 142.

[2] Rosenbusch, H., Mikroskopische Physiographie der massigen Gesteine, 4th ed., p. 698, 1907.

mark the position of vents. In my opinion, most of the masses mapped as intrusives are relatively near the top of their ancient conduits—a belief supported by the fact that the igneous material at Black Pinnacle and Fluted Rock, where the cover of sedimentary rocks remains, is essentially like that at other intrusive outcrops. The petrography of the rocks studied by Prof. Pirsson is in harmony with this conclusion. (See below.)

All the lavas and intrusive rocks of the Navajo country are basic; their igneous inclusions are prevailingly acidic. No representatives of the granite or syenite families were seen as flows, rocks, or dikes, but granite boulders are strewn over the surface at several localities. On the other hand, typical basalt is not represented by specimens collected in the field. Augite, biotite, and olivine are the minerals present in sizes sufficiently large to premit recognition by the unaided eye. Augite was noted in all ledges examined. Biotite phenocrysts are particularly abundant in the rocks in the northern part of the region but are much less common in the Hopi Buttes field. Olivine or peridot is unevenly distributed. At a few places it was not found in the rocks, but in Buell Park the weathered tuffs are thickly peppered with peridots of gem quality (p. 95).

The number of periods of volcanic activity in the Navajo country and their dates have not been determined. The strata of all formations are cut by intrusives. The volcanic ash of White Cone is interbedded with Tertiary sediments, and the lavas at Washington Pass rest on the Chuska sandstone, of Eocene or later Tertiary age. The basaltic flow at Grand Falls is probably as young as any other flow in northern Arizona and New Mexico that has been described. Since the last period of volcanism at least 800 feet of sediments have been removed at the Hopi Buttes, 1,200 to 1,500 feet in the Wheatfields area, and over 2,000 feet in the Monument Valley volcanic field.

GENERAL PETROLOGY OF THE REGION.

By L. V. Pirsson.

The study of the thin sections of the igneous rocks from the Navajo country which the writer has undertaken at the request of Prof. Gregory has brought out a number of features of general interest and importance which may be summarized here.

In the first place, all the types seen are of basaltic character and for popular field designation might well be termed basalts or rocks of basaltic habit; not a single felsic rock, such as rhyolite and trachyte has been observed in the whole collection. They are not, however, common plagioclase basalts but interesting rocks of uncommon types, closely related to lamprophyres; and this without regarding the nature of the occurrence, whether intrusive or extrusive. Rosenbusch[1] recognized that a considerable number of effusive rocks have strong affinities with the lamprophyric dike rocks and included them in a spearate division. Many of the outflows in the Navajo country would find appropriate position among these types. The porphyries composing the laccoliths of Carrizo Mountain, described by Emery,[2] are not here included.

In these rocks augite is practically everywhere the dominant mineral, and in many places it constitutes more than half of the rock. The most prominent associates with the augite are the potassic minerals, biotite, sanidine, and leucite. These in their various modifications and combinations with other minerals have afforded types recognized as trachydolerite, leucite basalt, melilite basalt, monchiquite, limburgite, augitite, etc., and it will be seen that these are rocks of high differentiation toward the mafic end of a strongly alkalic series. Moreover, they are of decidedly lamprophyric nature, not only the intrusives, but the flows as well. It would be practically impossible on any basis of mineral development and texture to separate the two from evidence afforded by the sections.

From a consideration of these facts it would appear, first, that the intrusive bodies as a whole have been only slightly eroded and are very near, in geologic position, to the flows—that is, to the original surface; and, second, that these rocks represent the lamprophyric stage of irruption from larger underlying masses of alkalic magmas which have not yet been uncovered by erosive dissection. Study of intrusive complexes of igneous rocks, especially alkalic rocks, has shown that the lamprophyric products of a high degree of differentiation are likely to be among the latest materi-

[1] Rosenbusch, H., Mikroskopische Physiographie der massigen Gesteine, 4th ed., p. 1476, 1908.

[2] Emery, W. B., Geology of Carrizo Mountain, Ariz.: U. S. Geol. Survey Bull. — (in preparation).

als intruded and that they extend, usually as dikes or sheets, to distances much greater than any other of the minor fringing intrusions that accompany the major parent and central masses.[1] As this conclusion has been repeatedly verified in a horizontal sense it seems logical to apply it in a vertical sense also; we could then understand how it might be possible that at a certain stage of erosive down-cutting the lamprophyric intrusives, or their surface equivalents, might be the only igneous rocks to be seen at the surface.

No analyses are available to furnish data with respect to the chemical nature of the underlying magma and its derivatives. Nevertheless, certain analogies with eruptive rocks of other regions may be observed by considering the mineral composition of the rocks. Thus the common occurrence of orthoclase, here and there accompanied by leucite, as the felsic component of these mafic rocks allies them very markedly with the eruptive rocks of central Montana, especially in the Bearpaw and Highwood mountains, and of the Leucite Hills in Wyoming. As in those areas, we have here a magma that appears to be dominantly potassic. Likewise as in those areas, the rocks commonly contain biotite (or phlogopite), which is abundant in good-sized phenocrysts, as well as in the groundmass; and this again speaks for the potassic nature of the magma. As in many other places where igneous rocks have been studied, it was noticed that the biotite and olivine bear a reciprocal relation. It is of interest to point out another region of potassic magmas in North America, for these are relatively rare compared with the sodic magmas.

The most noticeable feature of consanguinity in this group of rocks is the common distribution in them of yellowish-brown augite, which is by far the most abundant constituent and in many places composes the bulk of the rock. In many mafic rocks similar to these the augites are tinted green, a color which points to soda in the magma and the formation of the aegirite molecule in them; in other rocks the augite has a purplish color, which indicates titanic oxide in the magma. In the rocks of both kinds the augite tends to be more or less pleochroic. The rocks with green augite are illustrated by the shonkinitic rocks and their derivatives from Montana; the rocks with purplish augite by the nephelite, leucite, and melilite basalts from central Europe. The color of the augites in the igneous rocks of the Navajo country, then, tends to show that both soda and titanic oxide are low in these magmas. With respect to the soda this inference is confirmed by what has been said above; with respect to the titanic oxide attention may be called to the rarity or complete absence of perofskite ($CaTiO_3$) in the melilite basalts and other related rocks of the area, in which we should naturally expect it, and to the very common occurrence of the octahedral form of the iron ore, indicative of magnetite rather than of ilmenite ($FeTiO_3$). Another noticeable feature indicating the consanguinity of these rocks is their total lack of hornblende, which was not observed in a single specimen. The very common presence of hornblende in mafic sodic rocks, such as the camptonites, and its absence from potassic rocks are facts that demand explanation. As there are soda-iron and soda-alumina amphiboles while the corresponding potassic amphiboles have not been found, it may be that where the magmas are dominantly potassic they exert a certain control over the smaller amount of soda that they contain, preventing it from passing into hornblende.

In summation it may be said that this preliminary study of the petrology of the igneous rocks of the Navajo country shows them to be unusual types of great interest. It is clear that here is a field whose study, especially on the chemical side, will yield rich results to detailed petrographic investigation.

[1] Pirsson, L. V., Complementary rocks and radial dikes: Am. Jour. Sci., 3d ser., vol. 50, p. 116, 1895.

CHAPTER V.—STRUCTURE.

REGIONAL RELATIONS.

In the Grand Canyon district the dominating structural features are represented topographically by flat-topped plateaus, bordered by lines of displacement trending roughly north. West of the Kaibab Plateau these giant earth blocks are sharply bounded by faults; east of the Kaibab Plateau the descent from plateau top to valley flat is accomplished by monoclinal folds. In the Navajo country the type of structure represented by the eastern edge of the Kaibab Plateau and by Coconino Point and Black Point in the Little Colorado Valley becomes dominant, and for the long stretch between Marble Canyon and Mount Taylor, a distance of 250 miles, faults play an insignificant part. The simplicity of folded structures in the Grand Canyon district is not, however, duplicated in the region east of Colorado River. Synclines and anticlines, both broad and narrow, sharply delineated monoclines, and domical upwarps follow one another in succession or abut against one another like waves in a choppy sea. In one feature only—their general trend—do the flexures displayed in the Navajo country simulate those of the region farther west. Ten major folds and eight minor folds, in addition to local flexures of small dimensions, were noted in the region between the San Juan and the Puerco and Little Colorado. These structural features are described on the following pages, and their relations are shown in the sections on Plate XXII.

ZUNI UPWARP.

The Zuni Mountains are essentially an elongated domical upwarp 60 miles in length, trending northwest. The strata composing the southwest limb dip sharply downward in the Nutria monocline; those in the northeast limb have gentle dips; the top is nearly flat. North of the Santa Fe Railway the influence of the upwarp is shown in the strata of Dutton Plateau, which dip northwest, north, and northeast along an elliptical outcrop at angles of 1° to 3°. The date of the crustal movement that resulted in the Zuni upwarp is unknown beyond the fact that it involves late Upper Cretaceous sediments.

NUTRIA MONOCLINE.

The Nutria monocline, which borders the Zuni upwarp on the southwest has been fully described and figured by Gilbert[1] and by Dutton.[2] Newberry's vivid description of this fold[3] is the first account of this type of displacement recorded in American geologic literature.[4] Newberry was in error, however, in ascribing the uplift to fracture, for, as shown by Gilbert, the steeply inclined strata are connected with the horizontal beds immediately adjoining by short curved portions of Cretaceous sandstones. The abruptness of change of dip, of topography, and of geologic age on two sides of a narrow gap is impressive. Within the distance of less than a mile along Puerco River one passes from upper Mesaverde (Upper Cretaceous) to Chinle (Triassic) strata, a stratigraphic drop of about 2,500 feet, and near Nutria Mesaverde and Carboniferous strata occupy the same horizon. The crest of the Nutria monocline is sinuous, trending northwest, north, and northeast. Along the 50 or 60 miles of its course the westward dip varies between 10° and 70°. Where measured by Gilbert, at Nutria, the strata slope westward at a maximum angle of 80°; where crossed by the Santa Fe Railway the dip is 70°. About 6 miles north of Mineral Spring the monocline loses its identity as a hogback, swings eastward, and disappears among the northward-dipping strata of the Dutton Plateau. The Nutria monocline includes beds from the Pennsylvanian to the Upper Cretaceous (Mesaverde formation), inclusive, and its age is the same as that of the Zuni upwarp, of which it forms the outer rim.

[1] Gilbert, G. K., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, pp. 560-563, 1875.

[2] Dutton, C. E., Mount Taylor and the Zuñi Plateau: U. S. Geol. Survey Sixth Ann. Rept., pp. 142-145, 1885.

[3] Newberry, J. S., op. cit. (Ives expedition), p. 95.

[4] Strictly, the monoclines of the Plateau province are open unsymmetrical anticlines. The dips on one side of the axis of flexure rarely exceed 2°; on the opposite side they range from 10° to 80°.

GALLUP SYNCLINE.

Marcou[1] noted, in 1856, a synclinal valley east of Zuni and described the Valley of Zuni as a "longitudinal écaillement parallel with the Sierra de Zuni." Newberry[2] noted the northern continuation of this syncline on a traverse from Fort Defiance to the Continental Divide at Campbell Pass. Howell[3] illustrated the structure in an east-west section 8 miles north of Gallup, and Shaler[4] gave a section across the basin from Manuelito to Mineral Spring, along the line of the Santa Fe Railway, and included the syncline in the "Zuni Basin." To this structural basin the appropriate term Gallup syncline has been applied.[5]

The Gallup syncline has a maximum breadth of 18 miles. Its axis trends south from a point about 6 miles north of Gallup to Zuni and an unknown distance beyond. The western rim of the syncline is sharply upturned to form the Defiance monocline; on the east the even more prominent Nutria monocline forms the border. Between these monoclinal walls the strata are depressed more than 3,000 feet. As all the Cretaceous strata are involved in this displacement, its age is obviously post-Cretaceous, and it is believed to be contemporaneous in origin with the Defiance monocline. North of Puerco River the Gallup syncline is coterminous with the Manuelito Plateau, the surface of which is marked by mesas and ridges that rise 100 to 800 feet above the bordering flat-floored valleys.

The Gallup syncline is in general a flat-bottomed depression. At Torrivio Ridge, however, its even floor is interrupted by a northwestward-trending fold whose axis is about 15 miles long. Where crossed by Puerco River this fold, for which the name Torrivio anticline is proposed, is a low, flat swell having a breadth of about 2 miles. Northeast of the anticlinal axis the Cretaceous strata form a long dip slope with an angle of 4°. The western limb is short; it has a dip of 10° at one point and dies out a few miles beyond Defiance station.

CHACO DOWNWARP.

The northern rim of the Gallup syncline is upturned in the vicinity of the Gibson coal mines. North of this point the dips of the Cretaceous strata between the Defiance and Nutria monoclines converge toward the head of Chuska Valley. The dips are 4° N. 70° E. at the Clarke mine and 8° N. 25° W. at the Heaton mine. The divide between the Gallup syncline and the Chaco downwarp may thus be placed in the latitude of Gibson, a few miles south of the drainage divide that separates the waters of the Chuska Valley from those which enter the Puerco. From Gibson the axis of the downwarp has a general north-northeast trend to the great bend of Chaco River; it follows the Chaco Valley for about 10 miles, and then resumes a northeasterly direction to San Juan River near the mouth of Canyon Largo. Beyond the San Juan it extends for an undetermined distance. The western margin of the Chaco downwarp is the Defiance monocline; the strata forming the opposite limb slope upward along the eastern margin of the Chaco Plateau beyond the borders of the area mapped. For a distance of 80 miles south of the San Juan the dips of the strata involved in the downwarp are usually less than 4°, except along the extreme western edge of the basin, where slopes of 30° to 70° are not uncommon. A minor fold follows the Chuska Valley on the east and at a point near Tohasged assumes a monoclinal aspect with a westward dip of 10°.

DEFIANCE MONOCLINE.

The prominent fold whose dissection has given to Fort Defiance its picturesque setting may be termed the Defiance monocline. This feature was first described by Newberry,[6] who crossed it in a traverse from Oraibi to Fort Wingate. The section illustrating Newberry's description gives erroneous impressions in two respects—the monocline is represented as dipping westward, and its capping rock is indicated as Cretaceous instead of Permian (?) and Triassic. Howell's section[7] shows the monocline at Fort Defiance in its true relations. Gilbert[8] speaks of a monoclinal fold 45 miles south of Fort Defiance as the continuation of the Defiance monocline, and Dutton[9] states that a fold at Zuni trends northwest, crossing the railway west of Manuelito station and

[1] Marcou, Jules, U. S. Pacific R. R. Expl., vol. 3, pt. 4, pp. 149-150, 1856.

[2] Newberry, J. S., op. cit. (Ives expedition), p. 94.

[3] Howell, E. E., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 288, fig. 121, 1875.

[4] Shaler, M. K., U. S. Geol. Survey Bull. 316, p. 383 and pl. 22, 1906.

[5] U. S. Geol. Survey Bull. 435, p. 67, 1910.

[6] Newberry, J. S., op. cit. (Ives expedition), pp. 92-94.

[7] Howell, E. E., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 288, 1875.

[8] Gilbert, G. K., idem, p. 560.

[9] Dutton, C. E., op. cit. (Mount Taylor, etc.), p. 148.

APPROXIMATE SCALES

HORIZONTAL

10 0 10 20 30 Miles

VERTICAL

10000 0 10000 20000 Feet

TERTIARY — Eocene ?	Chuska sandstone and Tohachi shale	T
CRETACEOUS — Upper Cretaceous	Mesaverde and later formations	Kmv
CRETACEOUS — Upper Cretaceous	Mancos shale	Km
CRETACEOUS — Upper Cretaceous	Dakota sandstone	Kd
JURASSIC ?	McElmo formation	Jme
JURASSIC — La Plata group	Navajo sandstone, Todilto formation, and Wingate sandstone	Jlp
TRIASSIC	Chinle formation	Tc
TRIASSIC	Shinarump conglomerate	Ts
CARBONIFEROUS — Permian ?	DeChelly sandstone and Moenkopi formation	Cdcm
CARBONIFEROUS — Pennsylvanian	Kaibab limestone and Goodridge formation (relations unknown)	Ckg
TERTIARY	Extrusive volcanic rocks	Te
TERTIARY	Intrusive volcanic rocks	Ti

GEOLOGIC SECTIONS ACROSS THE NAVAJO COUNTRY

By Herbert E. Gregory.

extending northward beyond Fort Defiance. Its length as given by Dutton is 85 or 90 miles—50 miles south of the Puerco and about 40 miles north. Dutton uses the term Zuñi monocline for the southeastern portion of the Defiance monocline.

The Defiance monocline extends entirely across the Navajo country from Puerco River to San Juan River, a distance of over 100 miles. North of the San Juan this fold in modified form reaches to the latitude of Durango.[1] The monocline therefore has a total length of nearly 200 miles and takes rank as a major line of displacement for this portion of the Plateau province.

The axis of the monocline is sinuous; between Zuni and Manuelito its course is north-northwest; from lower Black Creek canyon to Durango the general trend is north-northeast. South of the Puerco the dips of the strata forming the monocline are usually less than 10°, in many places dropping to 3°. At Oak Springs and Hunter Point (Pl. XXIII, *B*) the strata turn downward with slopes between 40° and 70°, only to regain a horizontal position within a distance of a few hundred feet. Along this portion of Black Creek Valley the monocline forms the abrupt eastern wall of the Defiance Plateau, and the eroded remnants of Triassic and Jurassic strata[2] involved in the fold form "haystacks" and pinnacles in great variety. Between St. Michaels and the southwest base of Chuska Mountain the eastward dips range between 10° and 40° and the structure is represented by a series of cuestas, here and there eroded into pinnacles. At Zilditloi Mountain the normal expression of the monocline is greatly modified by an irregular quaquaversal uplift from which Todilto Park has been carved. In its course through the Chuska Mountains the monocline is concealed from view by the flat-lying Tertiary sediments that unconformably overlie it. At its point of emergence from the Chuska Mountains, near Toadlena, the eastward dip of the strata is 60°. From Toadlena to Jewett, on San Juan River, the monocline is represented by low peaks, serrated ridges, and deeply eroded cuestas composed of Cretaceous strata with eastward dips of 30° to 55°. The Great Hogback, or Hogback Mountain, on the San Juan, an unusually prominent portion of the Defiance monocline, was described by Newberry[3] as "the Creston."

The crustal movement which resulted in the formation of the Defiance monocline involved strata of Permian (?), Triassic, Jurassic, and Cretaceous age. The Mesaverde formation constitutes the crest of the anticline from the Puerco to the San Juan, beyond which, as shown by Shaler,[4] the "Laramie" beds also are disturbed. The date of the displacement is thus established as post-"Laramie" and pre-Tohachi (Eocene ?). That a long period of erosion intervened between the uplift and the deposition of the earliest Tertiary sediments represented in this region is amply demonstrated by the erosional truncation of the Defiance monocline at points where Tohachi shales immediately overlie it.

DE CHELLY UPWARP.

In passing from Oraibi to Fort Defiance Newberry[5] noted that strata with "strong westerly dip" in the "Navajo Valley" (near Ganado ?) extend eastward to a point about 5 miles west of Canyon Bonito, beyond which, at an altitude of 7,000 feet, the strata "pitch to the east at an angle of 10° to 15°, which brings in review within a few miles all the strata above the Carboniferous limestone." Gilbert[6] speaks of a broad arch "extending from Fort Defiance nearly or quite to the Moquis towns," with a width not greater than 30 miles.[7] Howell,[8] on whose field traverse the statement of Gilbert is based, shows this anticlinal uplift in section extending from Pueblo Colorado (Ganado ?) to Fort Defiance, 35 miles, and bounded on both its east and west edges by monoclinal folds. This structure, correctly interpreted by Howell, may be traced southward from Ganado nearly to Puerco River and northward beyond Round Rock, a north-south distance of about 100 miles; it is practically coextensive with the Defiance Plateau. The upwarp is trenched by Canyon de Chelly, which reveals the lowest strata involved in the displacement, and the name De Chelly upwarp therefore appears appropriate for this structural feature.

[1] Shaler, M. K., op. cit., p. 381.

[2] Dutton (op. cit., p. 148) is mistaken in his opinion that the strata forming the west limb of the Defiance monocline are Carboniferous.

[3] Newberry, J. S., op. cit. (Macomb expedition), pp. 107-108.

[4] Shaler, M. K., op. cit., p. 381.

[5] Newberry, J. S., op. cit. (Ives expedition), pp. 90-91.

[6] Gilbert, G. K., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 559, 1875.

[7] The distance from Fort Defiance to Walpi, the easternmost Hopi village, is about 72 miles.

[8] Howell, E. E., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, fig. 120, p. 288, 1875.

The strata forming the western limb of the De Chelly uplift disappear beneath the floor of the Chinle and Pueblo Colorado valley. The dips along this margin rarely exceed 3°, but at a point 3 miles northwest of Ganado the strata are sharply downfolded at an angle of 10° in a cliff of Chinle strata overlain unconformably by Tertiary sediments; this fold may be called the Ganado monocline.

The eastern edge of the De Chelly uplift is well defined by the Defiance monocline from Houck to the north end of the Chuska Mountains, but along its northeast border the limits of the uplift have not been determined. The Mesozoic beds continue to dip eastward and northeastward beneath the Tertiary cap of Tunitcha and Lukachukai mountains and emerge in a monoclinal fold at their bases. The axis of a fold at the Lukachukai Mountains, however, trends northwestward at nearly right angles to that of the Defiance monocline. This portion of the border is further complicated by abrupt downwarps and domical uplifts at the north end of the Lukachukai Mountains, in Redrock Valley, and in Alcove Canyon, as indicated by the structure symbols on the geologic map.

The formations involved in the De Chelly upwarp include the Permian (?), Triassic, and Jurassic, and it is highly probable that all the Cretaceous formations formerly extended over the arch uniting the strata of that age in the Chuska Mountains and the Manuelito Plateau with those which form Black Mesa. The base of the Moenkopi formation is exposed near Fort Defiance, and it is possible that Pennsylvanian strata will be found in the unexplored portions of Canyon de Chelly.

In a broad view the De Chelly upwarp may be considered as including all the area between the Defiance monocline on the east and the Ganado monocline continued to San Juan River on the west. As thus interpreted, this great upwarp extends from southeastern Utah to Zuni River, and the structural features north and northwest of the Lukachukai Mountains are considered as subordinate parts of it.

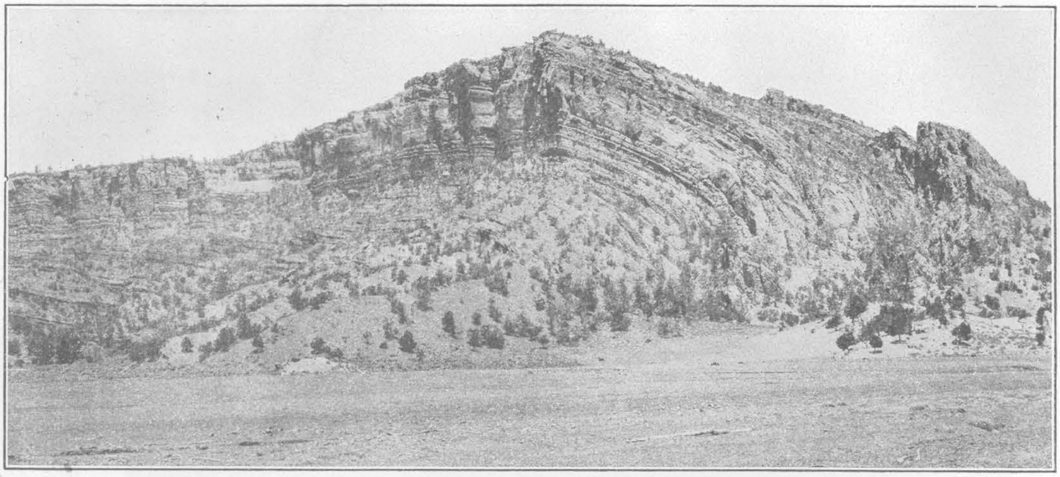
TUSAYAN DOWNWARP.

The southern margin of Black Mesa is the center of a broad and shallow structural basin for which the name Tusayan downwarp is proposed.[1] The western border of the Tusayan downwarp is formed by the Echo monocline and by the eastern limb of the upwarp on which rest the volcanic rocks of the San Francisco Mountain region. Its southern boundary is roughly coincident with Little Colorado River from Winslow to Holbrook. On the east it is limited by the De Chelly upwarp; at the north the rim of the structural basin is sharply upturned in Comb Ridge. As thus defined the north-south axis of the Tusayan downwarp extends from Marsh Pass to Holbrook, a distance of 120 miles, and the east-west axis, 90 miles long, passes through Jadito Springs, trending westward toward Black Falls, on the Little Colorado.

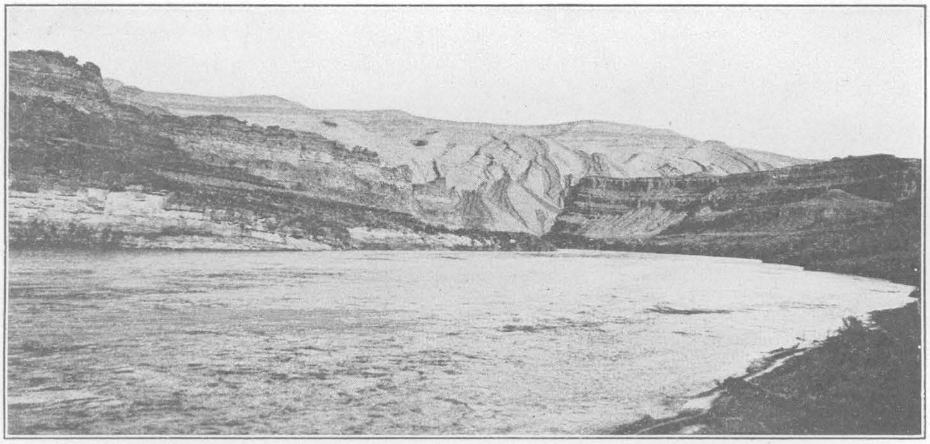
The dip of the strata descending into the Tusayan downwarp is 2° to 10° along its eastern margin and 1° to 9° along the Puerco and Little Colorado; its northern rim is abruptly downflexed with dips exceeding 30°. Within a few miles of its border the strata involved in the downwarp assume low dips; the beds of Black Mesa are in most places inclined at angles of less than 3°.

Within the basin are several minor folds. At Lohali, on the eastern border of Black Mesa, a monocline with northwest trend is crossed by a flat-topped anticline—structural features to which is due the branching bay that has here been cut into the island of Mesozoic rocks. On the west front of Black Mesa the Blue Canyon monocline is well exposed in the canyon of the Moenkopi. At this point the La Plata and McElmo beds abandon their gentle inclination and plunge eastward beneath Cretaceous sediments at an angle of 20°, only to regain their former attitude within a distance of a mile. North of Moenkopi Wash the Blue Canyon monocline may be traced along the border of Black Mesa to the latitude of Red Lake, where it is thought to be replaced by a broad arch in which the lowlands of Klethla Valley between White Mesa and Black Mesa have been carved. The structural relations of this part of the Navajo country, including the Shato and Rainbow plateaus and the northern half of the Kaibito Plateau, are imperfectly known.

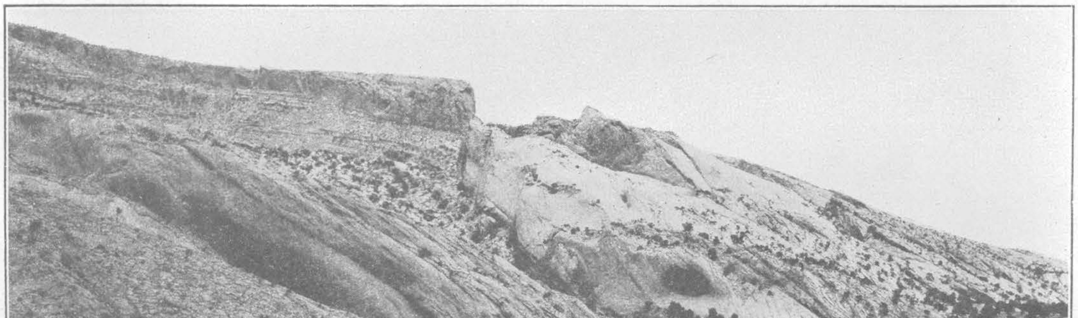
[1] The term Hopi syncline has been applied by Darton (U. S. Geol. Survey Bull. 435, p. 66, 1910) to the south end of the Tusayan downwarp.



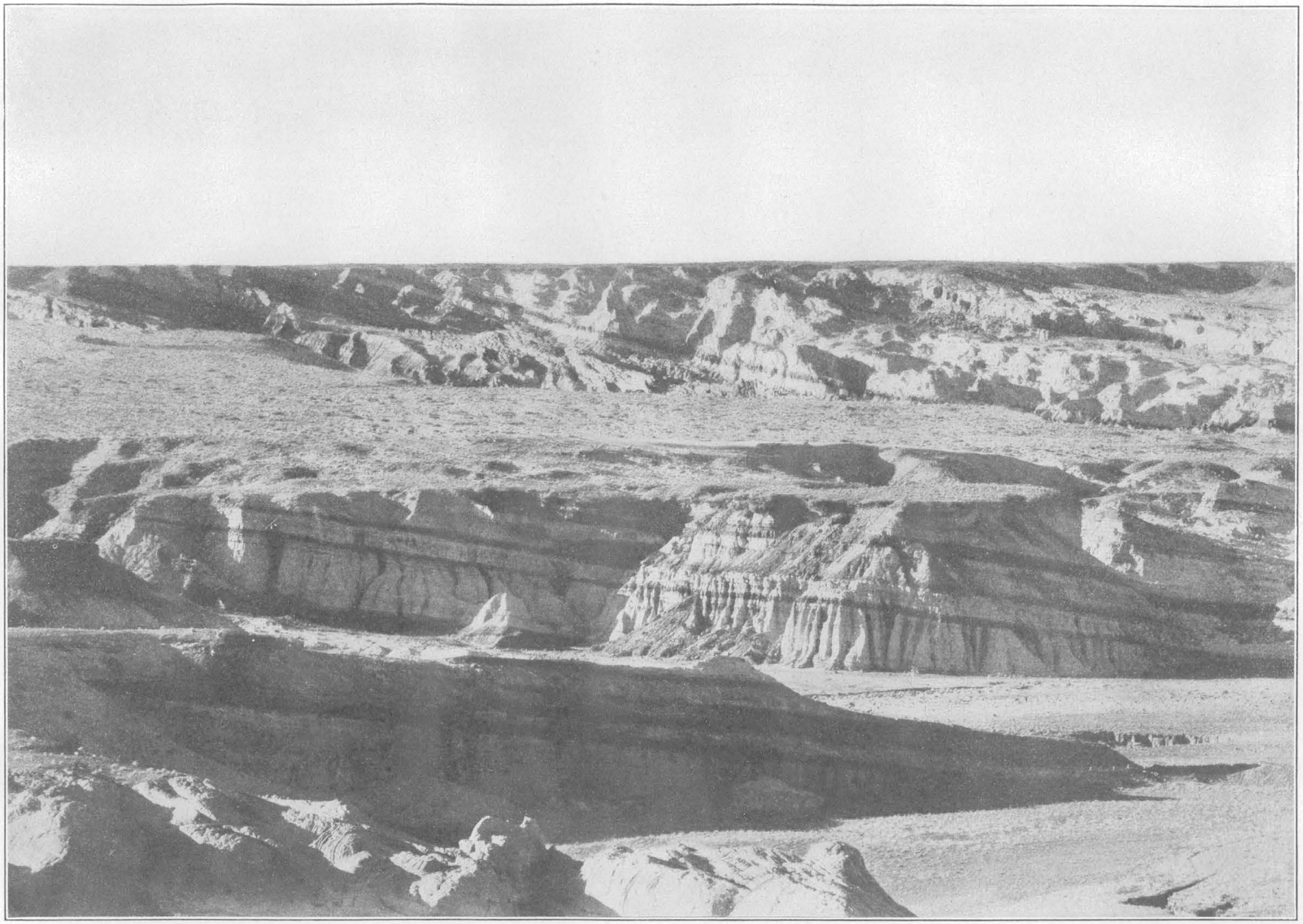
A. RAPLEE ANTICLINE AT MEXICAN HAT, ON SAN JUAN RIVER, UTAH.
Strata of Goodridge formation in background; of Moenkopi formation in foreground.



B. DEFIANCE MONOCLINE AT HUNTER POINT, ARIZ., LOOKING NORTH.
Strata involved belong to Moenkopi formation, De Chelly sandstone, and Shinarump conglomerate.



C. COMB MONOCLINE NEAR MARSH PASS, ARIZ.
Sandstone of La Plata group forms mesa cap and sloping wall; Chinle formation beneath.



BLUE CANYON, ARIZ.

Local peneplain developed at two levels on beveled edges of McElmo formation. Photograph by W. C. Mendenhall.

COMB MONOCLINE.

The north-central part of the Navajo Reservation is structurally distinct from regions farther south, and erosion controlled by structure has given to this area a topographic expression unlike that of any other part of the Plateau province. One of its most conspicuous features is the "Comb," a cuesta-like ridge that extends north-northeastward from Marsh Pass to the east base of Elk Ridge, beyond San Juan River. Throughout a distance of over 100 miles Comb Ridge presents a steep, usually precipitous westward-facing wall set with jagged teeth, forming a barrier impracticable for wagons except at two widely separated points. Structurally the ridge is a monocline, the border of a great upwarp that lies to the west and north. From San Juan River to Marsh Pass the Chinle and La Plata strata involved in the monoclinal ridge have average dips between 20° and 25°. Near Marsh Pass (see Pl. XXIII, *C*) the dip is 35° to 40°, and north of Moses Rock a measurement of 60° was obtained. At Tyende (Kayenta) the inclination of the Navajo sandstone included in the Comb monocline changes from 25° to 1° in a horizontal distance of 2,000 feet, bringing the McElmo strata to the level of the Chinle beds. West of Marsh Pass the downward flexure of the strata is increasingly less abrupt, and the monocline loses its prominent topographic form and probably dies out along the southern border of the Shato Plateau.

At Marsh Pass the axis of the Comb monocline bends southward in a sharp curve and abuts against the canoe end of the Tusayan downwarp. The complex structural features resulting from this contact have produced a somewhat unusual assemblage of topographic forms in the upper Tyende Valley.

MONUMENT UPWARP.

PRINCIPAL FEATURES.

The Comb monocline outlines one of the major upwarps of the Plateau province—a flat corrugated dome bisected by San Juan River. (See Pl. XXVI, *A*, p. 127.) The structure of the upwarp presents its simplest expression in the Monument Valley geographic province, and the name Monument upwarp is proposed for the flexure throughout its extent in northeastern Arizona and southeastern Utah. The upwarp is high and broad. The youngest formation involved, the Navajo sandstone, lies on Skeleton Mesa 2,000 feet higher than the top of this sandstone at Tyende, and the Goodridge formation, upturned in the fold, is the only Carboniferous rock exposed in the 260-mile stretch between the Little Colorado and the upper Dolores Valley. The Cretaceous strata that formerly covered the dome have been stripped back to Black Mesa on the south and to points beyond Colorado River on the west; Tertiary sediments also may have been present. On the east and south the Monument upwarp is definitely outlined by the Comb monocline; its western border is poorly defined across an area of westward-dipping strata on the Shato and Rainbow plateaus. Along the lower course of San Juan River the structural features have not been differentiated and the relation of the Monument upwarp to the Kaiparowits, Escalante, and Water Pocket flexures has not been determined. It is thought probable, however, that the Water Pocket fold is prolonged southeastward into the flexed strata at the great bend of the San Juan below the mouth of Nokai Canyon.

The dip of strata along the rim of the upwarp ranges from 1° or 2° to the steep inclinations in the Comb monocline. Inside the border dips exceeding 3° are rare except at local folds, and large areas of practically horizontal rocks underlie the Segi Mesas.

Within the Monument upwarp are several secondary flexures—wrinkles on the limbs and crest of the larger dome. Though relatively small these folds have exerted a profound influence in the molding of the topography. They include domes, anticlines, and synclines with axes 10 to 20 miles long and bear on their backs flexures of still smaller dimensions. In fact, it is not unreasonable to interpret the structures north of Marsh Pass as a series of coalescent flexures instead of one large domical uplift with subordinate folds. The largest of the folds within the borders of the Monument upwarp are briefly described in the following paragraphs.

RAPLEE ANTICLINE.

At the mouth of Chinle Creek the limestone of the Goodridge formation emerges from beneath the Comb monocline with an eastward dip of 40°. Ascending westward with decreasing dip the limestone forms the cap of an anticline or elliptical dome through which the San Juan has trenched its canyon. This fold is here called the Raplee anticline. Its axis trends N. 25° E. and is 15 miles long. The maximum width of the anticline is 6 miles. Like its eastern border, the western margin of the anticline is monoclinal; the dip near Raplee Camp changes from 48° to 4° within a distance of less than half a mile. (See Pl. XXIII, *A*, p. 112.)

MITTEN BUTTE ANTICLINE.

The flat synclinal trough of Gypsum Valley is the eastern border of an anticline whose western limb descends into Moonlight Valley. The axis of uplift, trending N. 20°–30° E., passes through Mitten Butte, from which the name of the fold is derived. Over the 20-mile expanse between its bordering synclines the Mitten Butte anticline is floored with Pennsylvanian and Permian (?) rocks, above which rise the buttes of Monument Valley (p. 133), cut in Moenkopi, De Chelly, and Shinarump strata. The loftiest buttes are on the very crest of the uplift. (See Pl. VI, *A*, p. 30.) The dips of the strata involved in the anticline measure 3° to 5° along the eastern and western margins and around the south end and 1° to 3° in the higher parts of the fold.

MOONLIGHT SYNCLINE.

The western dip of the strata involved in the Mitten Butte anticline is arrested on the floor of Moonlight Valley, beyond which the Moenkopi beds with their overlying erosion remnants dip upward at an angle which gradually increases to 7°. This structural trough, the Moonlight syncline, may be traced southward from San Juan River to Segihatsosi Canyon. Its features are well displayed in the gorges cut into the flanks of Azansosi and Hoskinnini mesas and in the picturesque erosion remnants adjoining the Oljeto ranch.

HOSKINNINI MONOCLINE.

The strata forming the western limb of the Moonlight syncline assume nearly horizontal positions at a distance of 2 to 4 miles from the synclinal axis. The surface thus formed is represented by Azansosi and Tyende mesas, which form a bench at 6,400 feet above sea level bordering the flat-topped Skeleton Mesa, 1,300 feet higher. The strata constituting Tyende and Skeleton mesas are identical; the difference in altitude is due to a fold, the Hoskinnini monocline, which has lifted the Navajo sandstone 1,300 feet along a narrow zone without interrupting its continuity. Consequent streams, scoring the dip slopes of the monocline, reveal Chinle and Shinarump beds, duplicating the sections exposed on the east face of Tyende Mesa.

ECHO MONOCLINE.

The western end of Glen Canyon is marked by the brilliantly colored Echo Cliffs which rise high above the bed of Colorado River. They extend as an escarpment 30 miles north and 60 miles south of the river, and throughout this stretch of 90 miles they are breached only at one point, where they have been attacked by the powerful Colorado. From Lees Ferry to McClellan Tank the line of cliffs rises 800 to 1,200 feet above the dissected platform at its western base, culminating in Echo Peaks, 1,800 feet above the rim of Marble Canyon. At Cedar Mesas, the drainage divide between Moenkopi Wash and the Colorado, the height of Echo Cliffs above the surrounding lands decreases to 400 feet. South of this point the cliffs again assume their ridgelike character and reach heights of 600 to 700 feet. Throughout their course the Echo Cliffs are gashed by short, deep canyons and show a serrated crest of sandstone. The teeth and crags of this crest, which are visible for distances of 50 miles, are features of normal erosion facilitated by jointing and cross-bedding, and do not appear to be the result of local increase in dip, as suggested by Dutton,[1] or of strike faults as suggested by Davis.[2] The Echo Cliffs owe their existence to a line of flexure extending from the base of the Kaiparowits Plateau as a sinuous line trending south-southeast to Lees Ferry, thence south to Limestone Tank, thence again south-southeast to Cedar Mesas. Throughout this distance of 60 or 70 miles the fold is monoclinal and may be termed the Echo monocline.[3] South of Cedar Mesas the monoclinal character is less pronounced, and in the vicinity of Willow Springs the axis of the flattened fold appears

[1] Dutton, C. E., Tertiary history of the Grand Canyon district: U. S. Geol. Survey Mon. 2, p. 205, 1882.

[2] Davis, W. M., An excursion to the Grand Canyon of the Colorado: Harvard Coll. Mus. Comp. Zool. Bull., vol. 38, pp. 141-142, 1901.

[3] The terms Paria fold, Echo Cliffs flexure, and Echo Cliffs monocline are used indiscriminately by Powell, Dutton, Gilbert, and Howell.

to turn south-southwestward and to die out on the floor of the Little Colorado Valley. It is improbable that the Wolf anticline, the gentle flexure near Tolchico, first described by Newberry,[1] has the genetic relation to the Echo monocline suggested by the geologists of the Wheeler Survey. A low anticline was noted by Ward on the bed of the Little Colorado below Tanner Crossing, and local gentle upwarps of slight extent are not uncommon in the region east of that river.

Along the line of sharpest flexure the dips of the strata in the Echo monocline range between 10° and 18°; south of Cottonwood Tank they are only 3° to 8°; and in a traverse from Willow Springs to the mouth of the Little Colorado Mr. Pogue found prevalent dips of 1° to 2°. East of the Echo Cliffs the strata assume a nearly horizontal position on the northern part of the Kaibito Plateau; near Tuba the eastward dip is 1° to 2°, and the same dips were measured on Ward Terrace and at points farther south in the Painted Desert. According to Dutton[2] the total downthrow of the monocline ranges from 3,500 to 4,000 feet. South of the Colorado, however, the amount of displacement rarely exceeds 3,000 feet.

The geologic date of the crustal movements that produced the Echo monocline deserves attention, especially as the place in the time scale of erosion cycles for the Grand Canyon district is based in large part on the supposed age of the flexures crossed by Colorado River. Regarding the Echo monocline Dutton[3] says:

> Its age is Tertiary and probably very nearly coeval with the East Kaibab monocline—in other words, rather late Tertiary. The proof of Tertiary age is conclusive, since the flexure bends the Cretaceous beds wherever it approaches them and its northward continuation involves the Eocene.

On physiographic evidence Davis[4] concluded that the flexures "seem to deserve an earlier date than has been assigned to them in Dutton's reports," and Robinson[5] has expressed the opinion that the Echo monocline dates from the Eocene-Miocene interval.

The only Tertiary sediments that could be included in the Echo monocline are those on the south edge of the Aquarius Plateau at Table Cliffs. Dutton[6] states that "the Echo Cliffs flexure * * * dies out near Paria settlement, at the base of the Vermilion Cliffs" (La Plata group, Jurassic), and in the atlas accompanying the Grand Canyon monograph he represents the monocline as extending northward into the Cretaceous beds but ending 15 miles south of the southernmost outcrop of Tertiary sediments. In another connection[7] he states that

> a great monoclinical flexure runs under the Aquarius from the south. * * * The monocline involves the whole Cretaceous system, but not the overlying Tertiary, and fixes the age of the disturbance between the close of the Laramie and the beginning of the Tertiary. * * * There appears to have been at this epoch a series of displacements having a north and south trend, breaking up the Mesozoic system into long blocks by well-defined monoclinal flexures, and the uplifted portions everywhere suffered denudation prior to the deposition of the Tertiary beds.

In Dutton's description of Table Cliff Plateau[8] he says that the Tertiary beds are "nearly horizontal" and the underlying Cretaceous strata are "turned upward."

In view of these apparently contradictory statements the Tertiary age of the Echo monocline is at least open to doubt, especially because if this flexure dates only from Miocene time it constitutes the one exception among a number of similar structures which are demonstrably of pre-Tertiary age. The Escalante monocline and the Water Pocket fold, involving Cretaceous strata, were truncated before the deposition of Eocene beds; the upturned Mesaverde strata in the Defiance monocline were maturely eroded before the horizontally bedded Tohachi shales and Chuska sandstones were laid down; and the Tertiary beds in the southern part of the Navajo country overlie with angular unconformity not only Cretaceous but also Jurassic and Triassic sediments. East of the Navajo Reservation, in the Nacimiento uplift, there has been "a slight folding of the Cretaceous rocks and subsequent erosion previous to the deposition of the Puerco (basal Eocene) formation."[9]

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[1] Newberry, J. S., op. cit. (Ives expedition), p. 77.

[2] Dutton, C. E., op. cit., p. 205.

[3] Idem, p. 205.

[4] Davis, W. M., An excursion to the Grand Canyon of the Colorado: Harvard Coll. Mus. Comp. Zool. Bull., vol. 38, Geol. ser., vol. 5, No. 4, p. 139, 1901.

[5] Robinson, H. H., The San Franciscan volcanic field, Ariz.: U. S. Geol. Survey Prof. Paper 76, p. 36, 1913.

[6] Dutton, C. E., Report on the geology of the High Plateaus of Utah, p. 44, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1880.

[7] Idem, pp. 156-157.

[8] Idem, p. 297.

[9] Gardner, J. H., Formations of the Nacimiento group: Jour. Geology, vol. 18, p. 722, 1910.

MINOR SYNCLINAL VALLEYS.

Copper, Nokai, and Desha creeks, tributary to the San Juan, occupy synclinal troughs that have not been examined in detail.

FAULTS.

Faults with displacements sufficient to exert structural control have not been observed in the Navajo country. Strike faults and dip faults with throws of 1 foot to 10 feet are found at a few places along the Nutria, Defiance, and Comb monoclines. On the east limb of the Monument uplift Woodruff[1] has mapped a fault 1¾ miles long that has an average throw of 20 to 30 feet and a maximum of about 200 feet. The mouth of Nazlini Canyon appears to be located on a fault, the trend and dimensions of which were not determined. At the lower crossing of Piute Canyon a fault trending N. 50° E. has a throw of 80 feet, and in the sandstone about Navajo Mountain faults having displacements of less than 6 feet are not rare. In the lower Little Colorado Valley several faults of a few inches to a few feet displacement were noted, and 3 miles below Tanner Crossing a fault trending N. 70° E. and having a throw of 75 feet was measured by Mr. Heald. At this place the downthrown and upthrown sides have been brought to a common level by erosion and the ancient surface is now protected by Tertiary lava flows.

[1] Woodruff, E. G., Geology of the San Juan oil field, Utah: U. S. Geol. Survey Bull. 471, p. 88, 1910.

CHAPTER VI.—PHYSIOGRAPHY.

INTRODUCTION.

The physiographic history of the Navajo country is included in that of the Colorado Plateau. The stratigraphic series of the area is essentially that of the Grand Canyon district; the crustal movements of the two areas, though different in kind, were probably contemporaneous, and it is reasonable to suppose also that the periods of igneous activity for the whole Plateau province are closely related in time. Moreover, the development of drainage in areas tributary to the Colorado is involved with the history of the master stream, and ancient peneplains north and west of the river should be represented south and east of that division line.

Inasmuch as physiographic studies of the whole Plateau province are now in progress, it has seemed wise to postpone the interpretative discussion of comprehensive physiographic problems. The treatment of material in the present chapter is therefore largely descriptive.

GENERAL RELATIONS.

The Tertiary and Recent geologic history of the Navajo country is written in terms of erosion, volcanism, and crustal movement—not as a record of successive faunal and floral populations. The history will become legible only after the work of streams conditioned by uplift and aridity has been analyzed and the results stated in quantitative terms. In the present state of our knowledge only sketches may be made; the completed picture must await a fuller knowledge of materials and processes. It is probable that all the sedimentary formations from Carboniferous to Tertiary, inclusive, formerly extended with relatively unimportant variations in thickness and composition over the larger part of the Navajo country, and the erosion of these beds represents the chief geologic work of late Tertiary, Pleistocene, and Recent time. Since the beginning of the Tertiary period continental conditions have prevailed in the Navajo country, and the regional uplift which removed the Cretaceous sea was accompanied by downwarping, domical upwarping, and monoclinal folding; faulting of significant amounts is absent. The tectonic history of the Navajo country is thus sharply contrasted with that of the region north and west of Colorado River. The warped and ridged surface produced by crustal movements is reflected in the position of many streams. Both sides of the De Chelly upwarp are traversed by important drainage channels; the Monument upwarp is encircled on the east by Tyende and Chinle creeks; the Chuska Valley follows the east side of the Defiance monocline; and the Little Colorado below Winslow traverses the east base of the flat dome of the San Francisco Plateau.

When compared with the surrounding country the region drained by the middle Colorado may be properly classed as a plateau. Long stretches of level sky line may be seen from almost any viewpoint, and an observer standing on the top of a mountain or the edge of a high plateau gains the impression of a nearly level surface deeply carved by streams and surmounted by volcanoes. From Lookout Ridge of Navajo Mountain, the center of the Plateau province, the general flatness of the area within the range of vision is its most salient feature. The igneous masses of Carrizo, Abajo, Henry, Trumbull, and San Francisco mountains seem strangely out of place, like rounded heads of tacks projecting from a floor, and the profound gorge of the Colorado appears but an insignificant feature. When the effect of distance is taken into account, however, the impression of levelness is lost entirely, and the region is seen to possess a ruggedness probably surpassed by few other parts of the world. The relief is produced by downward departures from a general surface rather than by hills and mountains rising above plains and valleys. Canyons are so deep and so thickly interlaced that the region appears to be made up of gorges and cliffs intimately associated with mesas and buttes and towers bounded by vertical walls. It is a region of cliffs and canyons. The streams appear to be impatient; not content with removing the products of weathering, they dig deep, closely spaced trenches directly into the rock and remove the intervening material by a process of lateral mining. Plateau blocks are first outlined by a series of master trenches; secondary trenches cut each block into mesas; ramifying ditches of the third and fourth order cut along planes of fracture, reducing the size of the unit of work and increasing the area exposed to attack. The quarrying streams, substantially aided by disintegration, have long been in operation. In a few places their work is complete, the surrounding land having been reduced to the level of the bottom of the trench; elsewhere various stages of the process may be observed. Probably at no time has the work been more vigorously prosecuted than at present. Graded streams are lacking in the Navajo country, waterfalls and rapids abound, and it is difficult to conceive of an intricacy of canyon labyrinth and a variety of erosion remnants surpassing those exhibited by the Rainbow Plateau.

FACTORS INFLUENCING EROSION.

GRADIENT OF STREAMS.

About half of the Navajo country lies more than 6,000 feet above the sea; its surface waters reach Colorado River at altitudes between 2,800 and 3,400 feet. The drainageway formed by the Puerco and Little Colorado descends from 7,000 feet at Campbell Pass to 2,800 feet at its mouth, a gradient of over 17 feet to the mile for 252 miles. The San Juan, between Farmington and its junction with the Colorado, 220 miles below, falls at the rate of 9 feet to the mile. Of streams entering the San Juan, Chinle Creek, including its headwater branch in the Canyon de Chelly, has a gradient of 45 feet to the mile; Moonlight, Copper, Nokai, and Piute creeks, between 30 and 40 miles long, fall 60 feet to the mile. Streams 10 to 20 miles long, leading directly to the Colorado, drop at an average rate of about 160 feet to the mile, and the short creeks from Navajo Mountain flow to the Colorado and the San Juan on slopes of nearly 800 feet to the mile. Navajo Creek, the longest direct tributary to the Colorado, drops 2,600 feet in 54 miles, or about 50 feet to the mile. In the Little Colorado drainage system there are seven streams exceeding 50 miles in length. Their lower portions are washes of moderate slope, but their upper parts are precipitous, and for their entire length these streams have an average fall of about 40 feet a mile. With gradients so steep conditions are favorable for erosion, and all the streams observed are not only carrying the waste supplied by their tributaries but are cutting their beds and removing materials deposited during a previous period of aggradation.

CLIMATE.

The region as a whole is arid, the average of the mean annual rainfull in nine stations being only 8.29 inches. The least rain recorded, 5.30 inches a year, falls on the Kaibito Plateau at Tuba, and the most, 12.80 inches, at Fort Defiance, in Black Creek Valley. The Painted Desert is believed to receive less than 3 inches of rain annually, and stations established on Navajo and Chuska mountains would probably record 18 or 20 inches. The precipitation is subject to wide variations in time as well as in amount. The months of July, August, and September and to a less extent January and February constitute the rainy seasons, but precipitation sufficient to enable the short-lived streams to partly clear their channels of débris is normal for all months except April, May, and June. The most significant feature of the rainfall as regards erosion is the violence of showers and the consequent flooding of the surface and piling of water into canyons. It is no infrequent experience to observe a rise of 5 to 10 feet in the water of a creek in response to a single shower or to see the floor of a gravel-filled wash deeply trenched in the course of a few hours. During the rainy months and occasionally at other times the many streams in dry canyons and washes become through-flowing and contribute their mud-laden waters to the Colorado and the San Juan.

Frost is an extremely active agent in the plateau country. Its quarrying action is noticeable not only at the beginning and end of the cold season but at other times, owing to the wide variation between day and night temperatures. On Navajo and Carrizo mountains the slopes above 8,500 feet are heavily coated with blocks of rock resulting from the mechanical work of ice. Insolation is likewise highly effective in the preparation of rock waste; in places it appears to play the predominant part in rock disintegration.

The prevailing southwest wind is a factor in erosion, deserving more attention than it has received. Its potency as an abrasive agent in grinding solid rock has doubtless been overestimated by some, but its importance as an agent which brings sand within the reach of streams has been to a large extent overlooked. Dust carried from the higher lands and lowlands alike is poured into stream channels between flood seasons, only to be removed at the coming of rains. (See pp. 136–137.)

VEGETATION.

The effect of vegetation in retarding the collection of water in drainage channels is much less conspicuous in the Navajo country than in regions where the climate is more humid. Forest litter is practically absent except on flat portions of the summits of Chuska, Navajo, and Carrizo mountains and to a less extent on Dutton Plateau and Black Mesa. Matted grass is also confined to a few localities. Sagebrush retards surface flow to some extent, and the wide-spaced pines associated with groves of oak interfere with the development of channels, On the whole, however, grass stalks, weeds, shrubs, and forest trees rise as individuals from a floor of rock or alluvium and leave spaces between them for drainage channels.

BEDROCK.

The stratigraphic series is favorable for erosion. Shale and sandstone alternate. The quartzitic Chuska sandstone is underlain by the Tohachi shale; the shaly Mancos formation lies between the Mesaverde and Dakota sandstones, both of which are resistant formations; below the Dakota the McElmo shales are readily worn away wherever they are exposed, and the massive sandstones of the La Plata group underlying the McElmo are in turn underlain by the easily eroded Chinle beds; the Shinarump conglomerate, below the Chinle, rests on friable Permian (?) shales, and these in turn are underlain by firm strata of the Kaibab and Goodridge limestones. A glance at the geologic map will show that the broad valleys of the area are carved in shales of the Chinle and Moenkopi formations, and that the Mesaverde, the Dakota, the Navajo, the Wingate, the Shinarump conglomerate, and the Chuska sandstone constitute the cliffs and the mesa caps.

GROUND WATER.

The Navajo country is a region of springs and seeps. The predominance of isolated high-lying areas bordered by lofty cliffs favors the emergence of subsurface water; surfaces otherwise dry are kept moist, and weathering is greatly facilitated. Caves and alcoves and pits sunk deep into canyon walls indicate effective erosional work by ground water. (See p. 133.)

RATE OF DENUDATION.

The relative efficiency and the net result of the work of these factors concerned with erosion can not be stated in quantitative terms, and comparison with other regions involves an equation in which some factors are unequal or unknown. It is believed, however, that denudation of the land in the Navajo country is proceeding as fast as in any other part of the continent, if not faster.

RELATION OF TOPOGRAPHY TO STRUCTURE.

One of the most impressive features of the geology of northern Arizona and southern Utah is the control exerted by the attitude, structure, and composition of the rock strata. The drainage and sculpture may be almost completely stated in terms of dome and fold, of hard and soft rock. The great Tusayan downwarp in its protected position stands like an island in the midst of upturned and eroded beds. Its counterpart, the overset canoe of the De Chelly upwarp, has been stripped on all sides down to the resistant Shinarump conglomerate. The Monument upwarp has been denuded in like manner but to a lower level because of its proximity to a master drainage line. Nokai, Copper, and Moonlight creeks flow in synclinal troughs, and monoclinal structure guides the courses of Black Creek, the upper Puerco, and the lower Little Colorado. Mesas cut from massive beds are straight sided; where thin-bedded strata form the base they rest on pedestals. The Dakota, the Shinarump, the basalt, and other resistant formations preserve friable rocks beneath. Where streams flow through hard rocks, their channels are narrow; where soft rocks intercept the stream, wide valleys appear. The lower San Juan can be approached where the Moenkopi and Chinle shales crop out, and the two crossings of the Colorado, Dandy and Lees Ferry, are made possible by folds that have brought Moenkopi shales within reach of the river. Within the canyons themselves the effect of joints is plainly evident; the streams progress by a series of sharp turns outlined by planes of weakness in the canyon walls.

PENEPLAINS.

OCCURRENCE.

One of the most fertile of Dutton's bold generalizations is the suggestion[1] that immediately before the erosion of the Grand Canyon

> region near the [Colorado] river was flat and destitute of deep canyons and valleys such as now exist there, and therefore destitute of great hills, buttes, or mesas. The meaning of this is a base-level of erosion. The rivers could not corrade, because they had reached for the time being their limiting depth in the strata. The work of erosion would then be confined to leveling the sculptural inequalities without the power to produce new ones or to augment the relief of old ones.

The peneplain thus described was believed by Dutton to have been developed on Permian beds and its remnants preserved by Tertiary basalt on the Uinkaret and Sheavwits plateaus, at the San Francisco Mountains, at Red Butte, and in the Little Colorado Valley. Dutton's observation that eroded surfaces of a former cycle are preserved beneath lavas has been verified by Huntington and Goldthwait[2] in southern Utah and by Robinson[3] in the region adjoining San Francisco Mountain.

The features described by Dutton are duplicated in the Navajo country. Peneplain remnants have been preserved also in places where erosion has been retarded by a protective cover of consolidated gravel or in consequence of a topographic position inconsistent with vigorous stream work. Selected examples will be briefly described.

BLACK POINT PENEPLAIN.

On the Little Colorado about 10 miles above Tanner Crossing is the east end of a monocline locally known as Black Point. Included in this fold are strata of the Kaibab, Moenkopi, Shinarump, and Chinle formations, sloping eastward with a dip of 25° that abruptly flattens to 3°. As shown by Robinson,[4] the upturned strata are beveled and preserved from erosion by a cap of basalt assigned to the Pliocene.[5] The lava not only covers the steeply inclined beds but reaches back beyond the crest of the monocline and lies on strata in nearly horizontal position. Where not protected by lava the shales of the Chinle formation in this vicinity have been removed, and buttes of the Moenkopi, here and there capped by Shinarump conglomerate, rise above the floor of Kaibab limestone. The base-leveled surface covers about 3 square miles at an altitude of about 4,400 feet. Robinson[6] has described similar occurrences at Anderson Mesa, 8 miles southeast of Flagstaff, and at other localities on the San Francisco Plateau.

BOX SPRING PENEPLAIN.

East of Box Spring, on the Little Colorado, the cliffs overlooking the floor of the Painted Desert are formed of the Shinarump conglomerate and Chinle shales and limestones, dipping 2° NE. These cliffs, which rise to heights of 200 to 500 feet, are the mural faces of buttresses, westward projections of the Moenkopi Plateau. Viewed from favorable points the tops of these cliff-faced buttresses are seen to form a practically flat surface at an altitude of approximately 4,700 feet, sloping gently in a direction opposite to the dip of the strata—that is, the even surface is produced by beveling the edges of the strata comprising the Chinle formation. (See fig. 3.) The topographic position of this peneplain remnant and the distribution of existing drainage indicate a period of development antedating the formation of the present Little Colorado Valley.

CEDAR MESAS PENEPLAIN.

The Cedar Mesas, at an altitude of 6,000 feet, form the divide between Hamblin Creek, which flows southward to join Moenkopi Wash, and Roundy Creek, which enters the Colorado at Marble Canyon. At their heads the drainage channels of these two ephemeral streams are not clearly differentiated; the divide is a soil-coated grassy flat about 6 square miles in area,

[1] Dutton, C. E., op. cit. (Grand Canyon district), p. 224.

[2] Huntington, Ellsworth, and Goldthwait, J. W., The Hurricane fault in southwestern Utah: Jour. Geology, vol. 11, pp. 46–63, 1903.

[3] Robinson, H. H., The Tertiary history of the Plateau district: Am. Jour. Sci., 4th ser., vol. 24, pp. 109–129, 1907.

[4] Robinson, H. H., The Tertiary peneplain of the Plateau district and adjacent country in Arizona and New Mexico: Am. Jour. Sci., 4th ser., vol. 24, pp. 109–129, 1907.

[5] Robinson, H. H., The San Franciscan volcanic field, Ariz.: U. S. Geol. Survey Prof. Paper 76, pl. 3, 1913.

[6] Idem, p. 39.

sharply bounded on the east by the cliffed face of the Echo monocline. Roundy Creek, on the northward-sloping surface of the dividing mesa, is relatively inactive, but Hamblin Creek is vigorously cutting headward and has exposed the soft Chinle shales, revealing the relation between the flat divide and the underlying structure. The divide is seen to be a peneplain remnant—a base-leveled surface cut across the upturned edges of Triassic strata. It owes its preservation to its topographic position. A former greater extent of the peneplain is indicated by terraces along the course of Hamblin Creek.

BLUE CANYON PENEPLAIN.

About 18 miles east of Tuba Moenkopi Wash leaves the Cretaceous rocks of Black Mesa and makes its way westward through McElmo and La Plata beds, forming the picturesque Blue Canyon. At this point the La Plata, McElmo, and overlying formations, involved in an eastward-dipping monocline, are truncated in a remarkable manner. (See Pl. XXIV, p. 113.) The peneplained surface is developed at two levels, each of which is essentially flat and heavily coated with cemented gravels. The upper surface, standing at about 5,400 feet, presents an unusually even sky line; when viewed from the south wall of Blue Canyon it appears to stretch indefinitely to the north and west. Its eastern boundary is the cliffed face of Black Mesa, its northern boundary swings to the northwest, and the gravel floor was traced by Mr. Heald to a point 5 miles south of Red Lake and thence westward nearly to Tuba. The peneplain is poorly developed on the steeply rising slopes south of the Moenkopi Canyon, but patches of gravel 2 miles south of Moenkopi village, at an altitude of 5,100 feet, are believed to represent the same surface. The lower surface of denudation is also best developed on the north side of Blue Canyon, where it forms a terrace 1 to 2 miles in width, bounded by a strikingly banded wall of McElmo sandstone. This lower peneplain may be traced downstream to Reservoir Canyon.

The conglomerate floor of the upper peneplain, 3 to 15 feet in thickness, forms a continuous stratum in the vicinity of Blue Canyon; elsewhere it is represented by caps of low-lying mesas and disconnected patches of gravel. The pebbles composing the bed are both rounded and angular in form and vary in size from small marbles to boulders and slabs 1 foot to 4 feet in long diameter. About 40 per cent of the conglomerate consists of fragments of brown and gray sandstones; pebbles of quartz and quartzite, white, black, red, yellow, mottled, and banded, are next in abundance; limonite concretions, blue limestone, gray shale, red chert, and rare igneous fragments also occur. The pebbles are firmly cemented by lime and form a resistant stratum. The conglomerate cap of the lower peneplain is finer grained and contains a larger percentage of sandstone pebbles and limonite concretions; it is also less firmly cemented. The materials composing the conglomerate have been derived largely from the Mesaverde, Mancos, Dakota, and La Plata formations in the immediate vicinity; the nearest outcrop from which igneous pebbles could have been derived is Wildcat Peak, 16 miles to the north. The area over which the Blue Canyon peneplain can be traced with confidence is about 80 square miles; it doubtless has a still greater extent and may be found to include large areas in the southern part of the Kaibito Plateau and the northwestern part of the Moenkopi Plateau. Its chief significance is the evidence it affords of two erosion cycles preceding the period of uplift that enabled the Moenkopi to carve its rock canyon 600 feet below the ancient surface.

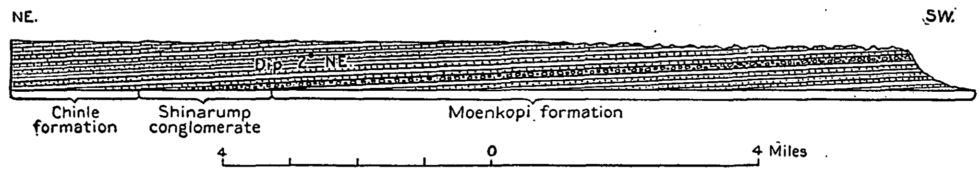


FIGURE 3.—Diagram showing structure of the Box Spring peneplain, Ariz. Dip is exaggerated.

HOPI BUTTES PENEPLAIN.

The lavas of the Hopi Buttes volcanic field were poured out over eroded surfaces of Mesozoic strata. Dissection has broken the flows into detached masses displayed as caps of mesas. At the northwest edge of the volcanic field the strata underlying the lava belong to the Mancos formation; farther south the

Mancos strata are replaced in turn by Dakota, McElmo, La Plata, and Chinle beds. Restoration of the ancient surface protected by lava reveals a plateau having an average surface slope to the south of 12 to 15 feet to the mile and standing at an elevation of 5,900 to 6,400 feet above the sea. The hills rising above this ancient floor and the valleys intrenched below it were relatively inconspicuous; the region had reached a stage of late maturity. Remnants of this ancient surface preserved by lavas are included within an area of about 90 square miles. On the north the peneplain is limited by the sandstone walls of Black Mesa; south and west of Hopi Buttes it may have extended to points beyond the Little Colorado.

EROSION SURFACES AT OTHER LOCALITIES.

The valley of Black Creek in the latitude of Fort Defiance is formed by the beveled edges of Chinle strata. The western wall of the valley below Hunter Point stands at 7,000 feet and presents a surface produced by the truncation of beds involved in the Defiance monocline. The divide between Chinle Creek and Pueblo Colorado Wash is an ancient erosion surface heavily coated with gravel and standing at 6,500 feet. At Black Lake, altitude 7,300 feet, where Black Creek and De Chelly Creek are competing for the surface drainage, similar conditions prevail, and at Sunrise Springs volcanic ash and sands are deposited on an eroded surface of McElmo beds. Several peneplain remnants of small extent were noted within the San Juan drainage basin. Southeast of the area under discussion a local peneplain was mapped near Fort Wingate, within the Zuni uplift, at an altitude of 7,000 feet, and Dutton [1] has described an ancient surface of erosion developed on upturned strata of Jurassic (?) and Cretaceous age northeast of Grant station.

CYCLES OF EROSION.

The existence of numerous peneplain remnants within the Colorado Plateau province demonstrates the fact that this region, including the Navajo country, has experienced one and probably two cycles of widespread erosion between the Cretaceous-Tertiary interval and the Canyon cycle. The history of San Juan River and Puerco River furnishes additional evidence of the former reduction of at least part of the region to a stage of late maturity. (See pp. 125–127) The number of cycles, their geologic date, and the area involved remain to be determined.

Because of the desirability of stating the physiographic history of the Plateau province in the simplest possible terms, I feel inclined to accept the conclusion of Robinson [2] that the several widely separated peneplains between the California-Nevada line and the Rio Grande "are all the eroded remnants of a single peneplain with the possible exception of the Little Colorado area." Robinson's suggestion that two peneplains may be present is borne out by observations in the Moenkopi Valley and in the Chinle Valley. Three ancient erosion levels, one of them perhaps of local significance, are recorded in the Little Colorado Valley. Furthermore, the peneplain remnants in the Navajo country are at widely separated altitudes (4,400 to 7,000 feet). Their correlation involves more knowledge than is now possessed of the physiographic history of northern Arizona.

As regards the position of the erosion cycles in geologic time field studies have so far yielded no reliable evidence. According to Dutton's analysis,[3] "The great erosion of the Plateau was most probably accomplished in Miocene time but continued with diminished rapidity throughout the Pliocene." The erosional work of the Pliocene was believed by Dutton to be represented by the outer gorge of the Grand Canyon; the cutting of the inner gorge was assigned to the Quaternary. These dates were based on the assumption that Miocene time was humid and therefore favorable for rapid erosion, whereas during the Pliocene epoch the climate probably was similar to that of to-day. No corroborative evidence of Tertiary climates as assumed by Dutton has been presented; on the other hand, the geographic position of Miocene and Pliocene lands with reference to mountains on the windward side suggests continuous aridity. Robinson [4] places the "peneplain cycle of erosion," the "Great Denudation" of

[1] Dutton, C. E., op. cit. (Mount Taylor, etc.), p. 151.

[2] Robinson, H. H., The Tertiary peneplain of the Plateau district and adjacent country in Arizona and New Mexico: Am. Jour. Sci., 4th ser., vol. 24, pp. 123-124, 1907.

[3] Dutton, C. E., op. cit. (High Plateaus), p. 21.

[4] Robinson, H. H., A new erosion cycle in the Grand Canyon district, Ariz.: Jour. Geology, vol. 18, p. 763, 1910.

Dutton, in Pliocene time on the basis of correlation with little-known strata and topographic forms in southern Nevada and assigns the making of the Grand Canyon to late Quaternary time.

The dates assigned to the several epochs of faulting, folding, and peneplanation during the history of the Plateau province rest on assumptions that the upwarps trenched by the middle Colorado date from Pliocene, Miocene, or late Eocene time. There is reason to believe, however, that the first profound folding and flexing, which built the horizontal strata into a series of domes and monoclines, occurred at the end of the Cretaceous period. (See p. 115.) Detailed study of the Eocene has not proceeded far, and the terms Miocene, Pliocene, and Pleistocene have little significance in this region.

Though no dates can be set with confidence for the events that have taken place between the post-Cretaceous uplift and the present period of canyon cutting, the occurrence of many episodes of far-reaching importance during the vast stretch of time embraced in the Miocene, Pliocene, and Pleistocene epochs is abundantly attested by local peneplains and the nature of the drainage, but the character and significance of the physiographic changes are so little understood that even an outline history is subject to radical revision.

Among the probable events in the Tertiary and Quaternary history of the Navajo country, the following are recorded:

1. A period of widespread folding associated with regional uplift from the Cretaceous sea. The major structural features developed during this period—the Monument upwarp, the De Chelly upwarp, the Defiance, Comb, and Echo monoclines, the Tusayan downwarp, the Gallup syncline, and the Zuni upwarp—together with certain flexures of smaller dimensions, are believed to date from the Cretaceous-Tertiary interval.

2. A period of erosion, during which the domes and ridges of Cretaceous rock were much reduced in height and a system of subsequent streams was developed. Earliest Tertiary.

3. A second period of differential warping, perhaps associated with regional depression. On the long slopes and on the floors of basins thus formed the Eocene beds of continental origin were laid down. Unconformities within the Eocene (?) formations of the Chuska Mountains indicate that at various times aggradation was halted and erosion became dominant. Volcanism active.

4. Post-Eocene uplift.

5. A period of extensive and long-continued erosion, interrupted by intervals of quiescence and uplifts. During this period most of the Tertiary beds were removed, the present plateau blocks were outlined, and erosion surfaces of low relief were developed along the San Juan, the Puerco, the Little Colorado, the Colorado, and many of the larger tributaries to these streams. Sequence of events and their place in the time scale undetermined.

6. A regional uplift that revived the streams of the region and provided favorable conditions for the cutting of Glen Canyon and its many companions.

7. A period of aggradation—the filling of rock canyons with alluvium in consequence of regional downwarp or climatic change.

8. A period of degradation—the trenching of gravel floors, of canyons, and of alluvial slopes on mountains. (See p. 130.)

The filling and trenching of the rock-walled canyons are not events of great antiquity and may have been accomplished within the period of human occupation. The cutting of Glen Canyon, San Juan Canyon, Canyon de Chelly, Little Colorado Canyon, and other profound gorges—gigantic pieces of river sculpture—does not demand a long period of geologic time. The conditions for river erosion in this region are so favorable that even a part of Quaternary time is sufficient.

MAJOR PHYSIOGRAPHIC FEATURES.

VALLEYS.

REGIONAL FEATURES.

With few exceptions the streams of the Navajo country flow between canyon walls. Where they traverse rocks of the Mesaverde, La Plata, De Chelly, Goodridge, and Kaibab formations, and to a less degree the Moenkopi, the canyons are narrow and in many places deep. In the McElmo, the Mancos, and parts of the Chinle beds the immediate stream channels are wider, but they usually retain their vertical walls. Even streams that flow between banks of alluvium maintain the canyon form. The lower half of the Chinle formation offers the least resistance to stream erosion of all the strata within the Plateau province, and where these beds are exposed flaring valleys and rounded buttes with badland topography prevail.

All the canyons are sinuous to a degree very much greater than indicated on topographic maps. Close-set meanders with horseshoe curves and goosenecks are common, and the traverse of many a canyon involves passing to right and left about towering buttresses with turns approaching 180°.

The floors of the canyons are in general flat in cross profile; V-shaped bottoms are rare. In longitudinal profile the beds of the canyons are very uneven; no valley in the region is graded throughout its course. The stream progresses by rapids and waterfalls separated by stretches of steep or flat gradient. By a series of steps that increase in number and in height downstream the floors of the tributary canyons are lowered until they meet the master canyons at grade. So perfect is this adjustment that along Colorado and San Juan rivers hanging valleys are exceedingly rare, and at high-water stages in those rivers the lower ends of side canyons are drowned. In some respects these side canyons, dry or occupied by trickling rills and in places barely wide enough to permit the passage of a pack train, are more remarkable than the broad canyons cut to an equal depth by the powerful Colorado. Hanging valleys, however, enter many of the shorter canyons, particularly those cut in the Navajo and Wingate sandstones.

The heads of most of the canyons are boxed by steeply inclining or vertical walls, many of them deeply undercut. In places drainage channels on the rims of canyons are not well marked and the water from thunder showers descends as a sheet.

Rapid migration of divides is a characteristic feature of the Navajo country. The streams that enter the San Juan and the Colorado are shorter and steeper than those that join the Puerco and Little Colorado and are forcing the divide to retreat southward. Likewise the valleys tributary to the Colorado are lengthening at the expense of those tributary to the San Juan. The process of stream capture is in active operation in the Sonsela Buttes region, where branches of Canyon de Chelly are undercutting flats tributary to Black Creek. At Marsh Pass Tyende Creek is working its way into Klethla Valley, and on the Shato Plateau the vigorous Navajo Creek is capturing territory from Tyende and Piute creeks, of the San Juan River system, as well as from streams tributary to Moenkopi Wash. At the north end of the Lukachukai Mountains, Alcove and Hasbidito creeks are in vigorous competition with the equally powerful streams of Redrock Valley, the contest producing a maze of canyon, butte, and terrace of bewildering complexity. Farther south the canyons entering the San Juan in New Mexico have eaten their way into the Chuska Mountains at the expense of the Chinle system. Along the north rim of Black Mesa the valleys trending southward to the Little Colorado end abruptly; their heads have been severed by the steep, short streams of the Tyende and Chinle systems.

Nearly all the canyons are bordered by terraces developed in bedrock. In some places a single bench is cut in the wall, forming an outer and an inner gorge; elsewhere the ascent from the canyon floor is accomplished by a flight of two to five steps. Many of the rock terraces, like the "esplanades" on the San Juan and the Colorado, result from the stripping of weaker rock from more resistant beds during the present cycle; others are cut across hard and soft beds alike or across the basset edges of upturned strata, affording mute evidence of previous erosion cycles. Terraces cut in alluvium, rarely more than one in addition to the present flood plain, are common along the valleys.

Valley form in the Navajo country is so largely expressive of attitude and structure of rock that the terms "youth" and "maturity" have little significance. If the prevalent nomenclature is used, it may be said that valleys of youthful form predominate. The valleys on Black Mesa, Skeleton Mesa, Dutton Plateau, and the Chuska Mountains have reached very late maturity; their floors are nearly flat, and their soil-covered sides slope gently upward and are mantled with grass and brush. Some of these valleys have advanced to old age, and their drainage systems, in response to solution and alluvial damming, have become disintegrated. Except on these flat-topped highlands, valleys such as are usually classed as mature are rare.

PUERCO AND LITTLE COLORADO VALLEY.

From Marble Canyon to the Continental Divide at Campbell Pass the Little Colorado and its principal tributary, the Puerco, occupy the longest, widest, and probably one of the oldest valleys of the Navajo country. In a large view the valley constitutes a lowland between the mountains of central Arizona and the high table-lands farther north. From its source to Mineral Springs the Puerco occupies a flat-floored monoclinal valley developed on upturned Triassic shales along the northern flank of the Zuni upwarp. West of Mineral Springs it crosses in succession the Nutria monocline, the Gallup syncline, the Torrivio anticline, and the Defiance monocline in a course nearly at right angles to the axes of folding. There is reason to believe that the Puerco through this part of its course is a superposed stream. From Houck to Winslow the valley skirts the southern edge of the De Chelly upwarp and occupies a flat structural trough included between the Tusayan downwarp on the north and the rising limb of the uplift south of the Santa Fe Railway. Within this stretch the Puerco and Colorado have a gentle gradient, and the low bordering Triassic and Permian cliffs have retreated for a distance of half a mile to 3 miles. From Winslow to Black Point the Little Colorado occupies a valley near the junction of the eastward-dipping Kaibab limestone and the overlying Moenkopi shales. From a point near Winslow to Tolchico the valley is flat and broad and the flood plain attains a width exceeding a mile. The form of the valley in this meandering stretch is doubtless due to the anticline bisected by the river at Wolf Crossing. From Grand Falls (see Pl. XXV, *B*) to Black Falls the river threads a canyon cut in Pennsylvanian rock; below Tanner Crossing the canyon reappears and increases in depth until the Colorado is reached (see Pl. XXV, *A*).

Leveled erosion surfaces a short distance above high-water level of the stream were noted north of Tolchico and near the Government Bridge, and disconnected rock terraces coated with gravel are not uncommon along the river below Black Falls. These features, in connection with the peneplain remnants at Box Spring and at Black Point, suggest a consequent origin and indicate that the present course of the Little Colorado is the result of a series of adjustments during the process of destruction of former higher surfaces. In any case the valley is developed in monoclinal strata and largely controlled by structure.

At Black Falls and Grand Falls the normal course of the stream's development has been interrupted by outflows of lava. The lava flow at Grand Falls came from the west at right angles to the axis of the stream. Entering by a tributary wash, it filled the Little Colorado Canyon and passed to a point a quarter of a mile beyond. The stream thus driven from its bed expanded as a lake and eventually found its way around the end of the lava flow into its former channel. (See Pl. XXV, *B*.) The width of the fall is about 400 feet and its height, including a short rapid, is 130 feet, a figure which represents approximately the depth of the original canyon.[1]

The channel of the Little Colorado at Black Falls is blocked by a small basalt flow. The stream was ponded for about 2 miles and reestablished its course partly by corrading the lava and partly by cutting a channel along the edge of the flow. When water is running in the river it forms a picturesque cascade 10 feet high; at other times the falls are practically obliterated by drifting sands. (See p. 137.)

Throughout most of its lower course the Puerco and Little Colorado is on or near bedrock. At Leupp and at Holbrook the depth to rock exceeds 60 feet, and the railroad well at Manila passes through 130 feet of alluvium. At Gallup 165 feet of unconsolidated materials were penetrated, and at other points along the Puerco the valley fill of a former canyon ranges from 30 to 60 feet.

In consequence of the relatively rapid deepening of the channel of the Colorado the profile of the Little Colorado, like those of many other streams in this region, is a reversed curve showing steep downward grades at the head and mouth with a long intermediate stretch of lower gradient.

Tributaries to the Puerco and Little Colorado, so far as observed, are consequent or obsequent with the exception of Black Creek, which is probably superposed in its course

[1] For a sketch map of Grand Falls see Robinson, H. H., The San Franciscan volcanic field, Ariz.: U. S. Geol. Survey Prof. Paper 76, p. 17, 1913; or Cleland, H. F., Geology, physical and historical, fig. 70, p. 93, 1916.

through the Defiance monocline at Oak Spring. Bonito Creek, a tributary to Black Creek at Fort Defiance, is superposed through its meandering course in quartzite and shales.

COLORADO VALLEY.

The course of Colorado River through the Navajo country is interrupted by the Echo monocline, which crosses the river at Lees Ferry and divides the gorge into two sections—Glen Canyon and Marble Canyon. Glen Canyon is cut in Jurassic and Triassic strata; sandstone of the La Plata group forms the rim and in most places the entire wall, but the underlying Chinle shales are exposed by small monoclinal uplifts near the mouth of Navajo Creek and in the vicinity of Bridge Canyon. In Marble Canyon the stream flows between walls of Carboniferous rock capped by Kaibab limestone. Except for local folds, the strata cut in Glen Canyon are practically horizontal; those in Marble Canyon dip persistently to the northeast—that is, upstream. Notwithstanding this difference in rock composition and structure, the two canyons have about the same average width. Glen Canyon in many places is a flat-bottomed, straight-sided trench with sheer walls rising vertically from the water to heights exceeding 1,500 feet; the walls of Marble Canyon rise in terraces developed on evenly bedded strata. The two canyons are probably of equal age, as they form a continuous channel across the Echo monocline, which is much older than either. However, the amount of erosion performed by the stream in Marble Canyon and its tributaries is much greater than that accomplished by the Glen Canyon system. South and west of the Echo Cliffs the country has been stripped down to the Pennsylvanian by the removal of Permian (?), Triassic, Jurassic, Cretaceous, and probably also Tertiary beds; east of the Echo Cliffs, Permian (?), Triassic, and lower Jurassic strata are in place and upper Jurassic and Cretaceous beds lie near the canyon rim. The lands north and west of both Glen and Marble canyons have been much less eroded than those on the opposite side of the river. South of Glen Canyon areas of land stratigraphically higher than those at the canyon rim are few and small and distant; north of the river high mesas of Cretaceous strata lie near at hand. The Paria Plateau lies close to the north rim of Marble Canyon; south of the canyon strata in similar position have been entirely removed.

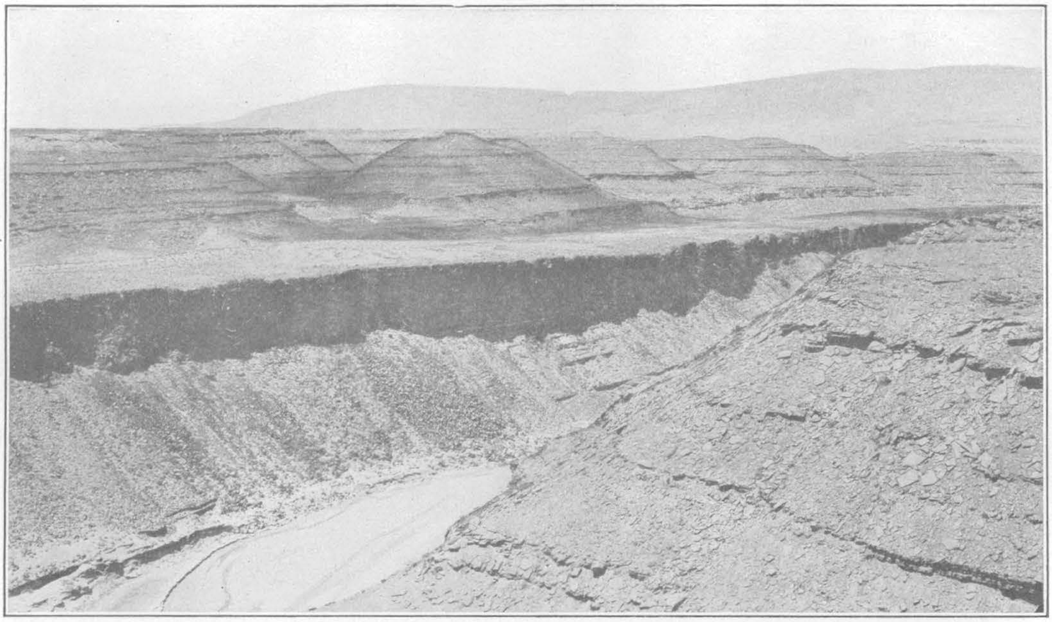
The Echo monocline is a considerable obstacle in the path of the Colorado and is being vigorously eroded at the present time. The necessity of cutting this bar has delayed corrasion through Glen Canyon and allowed this portion of the Colorado to be reduced practically to grade—indeed, in places it appears to be aggrading. The fall from the mouth of the San Juan to Lees Ferry, a distance of about 75 miles, is about 2 feet to the mile. Boating in Glen Canyon presents few difficulties; loaded barges may be towed safely for at least 40 miles above the mouth of the Paria. The larger streams tributary to Glen Canyon meet the Colorado at grade; some of them maintain that level for 2 to 3 miles from their mouths; others reach the master stream by a series of rapids. At their mouths most of the tributary gorges are very narrow—mere gashes that interrupt the continuity of towering red walls. On the other hand, the gradient of the Colorado through Marble Canyon is more than 10 feet to the mile; swift rapids occur, and the traverse by boat is accompanied by serious difficulties.

Structure has determined the location of the Colorado in the Navajo Mountain region and probably also in the upper and lower parts of Glen Canyon.

SAN JUAN VALLEY.

From Farmington to Bluff the San Juan flows between broken walls of rock rarely exceeding 100 feet in height and set on the average half a mile back from the stream. Within these boundaries the river has built a flood plain that is utilized by Indians and whites for agriculture. At Bluff the walls become higher, and from the mouth of Chinle Creek to Colorado River the San Juan occupies a canyon that has an average depth of about 1,000 feet. Where Chinle and Moenkopi strata are encountered the banks recede and flatten. In the bedded Carboniferous strata rock terraces develop; in sandstones of the La Plata group the stream is narrow and the walls are nearly vertical, and rise directly from the water's edge.

Throughout its canyoned course the San Juan appears to be indifferent to structure. It crosses the Comb monocline and the Raplee

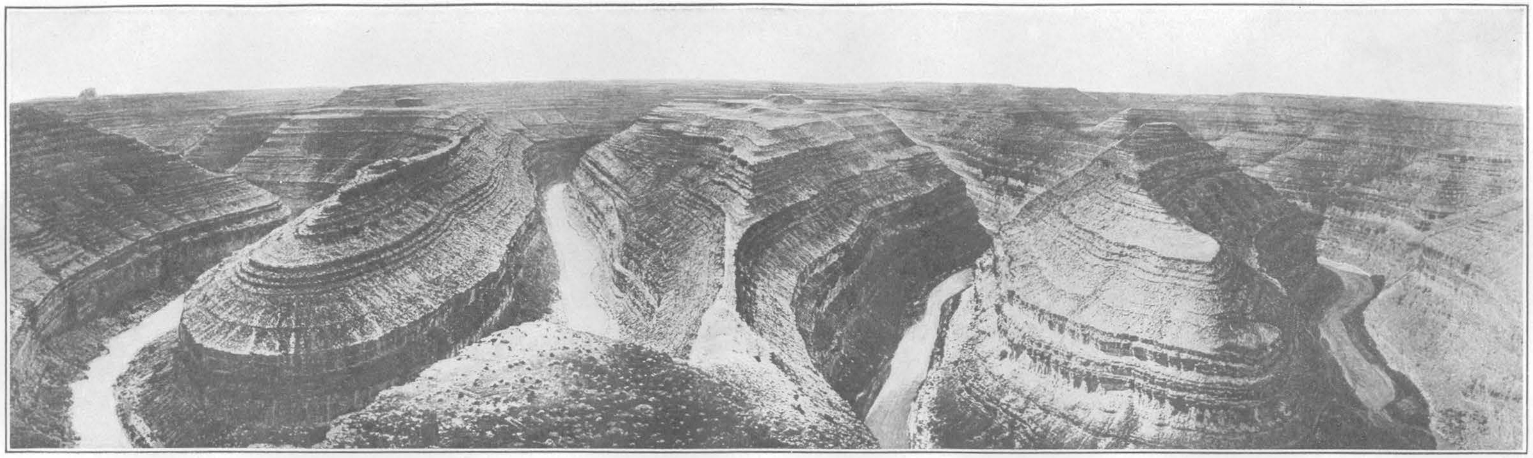


A. CANYON OF LITTLE COLORADO RIVER 1 MILE BELOW MOUTH OF MOENKOPI WASH, ARIZ.

Canyon cut in Moenkopi strata and top of Kaibab limestone; Shinarump conglomerate caps mesas in middle distance; basalt flow forms terrace adjoining the stream. Coconino Point in background.

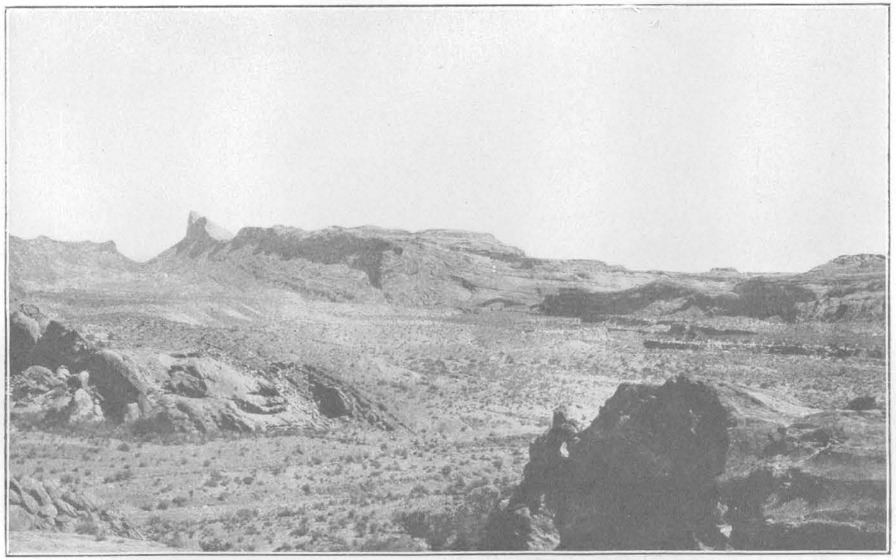
B. GRAND FALLS, LITTLE COLORADO RIVER, ARIZ.

Portion of lava flow filling the ancient canyon seen in foreground.



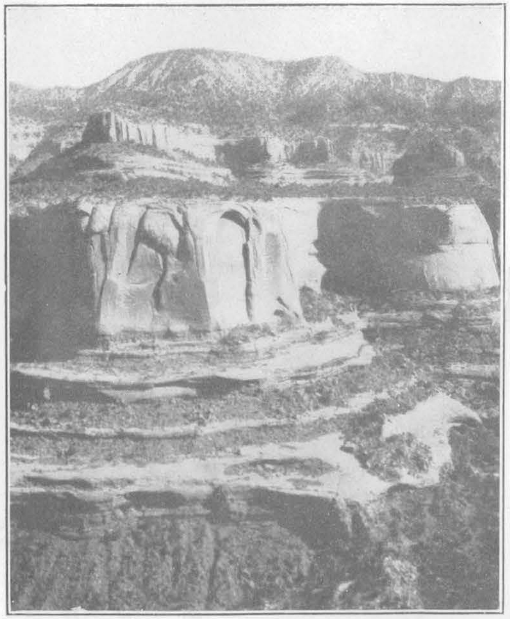
A. INTRENCHED MEANDERS IN SAN JUAN CANYON, UTAH.

Cut in Goodridge formation, involved in Mitten Butte anticline. Photograph copyrighted by H. H. Vinson.



B. VALLEY OF CHINLE CREEK NEAR MOSES ROCK, UTAH.

The stream at this point, leaving its subsequent course, turns eastward through the Comb monocline. Mule Ear in left background.



C. WEST FACE OF CHUSKA MOUNTAINS NEAR LUKACHUKAI, ARIZ.

Rincons and blind windows developed in massive sandstone; Chinle formation in foreground, Tertiary sediments in background. The view includes a vertical distance of 1,800 feet.

and Mitten Butte anticlines and continues on its way through four synclines, crossing the axes of flexure nearly at right angles. Within its canyon walls the stream swings back and forth in a series of close-pressed turns, exhibiting a remarkable series of intrenched meanders. (See Pl. XXVI, *A*.) It is reasonable to suppose that the course of the stream and its meandering habit were established during a time when the region was near base-level. During the process of trenching at least one period of halting has intervened. Terraces cut in rock and heavily coated with coarse gravel well above the reach of the highest floods border the river at Aneth, Goodridge, and a number of other points. In the "goosenecks" below Goodridge intrenched meanders are found at two levels. At its junction with the San Juan the water in Comb Wash flows in a shallow inner canyon sunk below a local peneplain developed on folded sandstones and shales. Similar evidences of erosion cycles may be observed in other tributaries. Near the mouth of the San Juan an outer canyon or "esplanade" has been developed by the stripping away of the Navajo sandstone, but this is a normal feature of erosion and does not demand the assumption of former planation.

As bearing on the superposed origin of the San Juan certain features of its longest southern tributaries are suggestive. The Chaco from its source on Chaco Plateau trends westward in accord with the gentle dip slope of the Mesaverde strata and then turns abruptly northward along the strike. Before reaching the San Juan the river leaves its broad, flat valley and, turning again sharply westward, passes through a narrow ridge, Hogback Mountain. The bed of the stream at this water gap is 600 feet below the crest of the hogback. Hogback Mountain is a cuesta remnant of the Defiance monocline that dates from pre-Tertiary time, and the normal process of stream adjustment during a single cycle should have resulted in a subsequent course for streams along the fold. The present course of the lower Chaco therefore appears to have been inherited.

Tyende and Chinle creeks are likewise out of accord with structure and with the present topography. In the Segi Mesa geographic province the many-branched canyon of Tyende Creek is consequent. From March Pass to the San Juan a continuous valley is developed in the less resistant strata of the Comb monocline. For part of its course Tyende Creek utilizes this subsequent valley, but for a distance of about 13 miles in the vicinity of Tyende Indian School the stream leaves the valley and meanders through the resistant beds of the Comb monocline with slight regard to structure. Below the mouth of the Tyende, in the vicinity of Moses Rock, the Chinle leaves its structural valley and directs its course westward across the strike and against the dip of the steeply inclined strata of Comb Ridge. (See Pl. XXVI, *B*.) After flowing across the floor of a subsequent valley developed on soft Chinle shales the stream turns eastward through a narrow, deep canyon cut in the Navajo sandstone, and before reaching the San Juan again crosses the monocline through a water gap. The seeming vagaries of the Tyende and Chinle require for their interpretation the assumption of a previous stage in which the relief was much less pronounced than it is at present, and in which the drainage channels were free from inequalities incident to differences in structure and relative rock hardness.

Chinle Creek from Ganado to the mouth of Tyende Creek occupies a subsequent valley and receives obsequent tributaries from the west. From the east the Chinle is joined by a number of valleys whose features were but briefly examined. The streams from Carrizo Mountain are in general accord with the rock structure and composition. Lukachukai Creek has adjusted itself to the eastward-descending limb of the De Chelly upwarp and collects the waters from obsequent valleys on the rim of the Chuska Mountains. Stretches of abandoned intrenched meanders between Round Rock and Sehili point to a former cycle of erosion. Canyon de Chelly and its upper branches, Wheatfields and Whisky creeks, rise in old valleys on the Chuska Mountains, cut through monoclines, meander across a wide inner lowland, and traverse the De Chelly uplift at nearly right angles to its axis. This drainage system presents problems too complex for solution with the available data.

MOUNTAINS.

CHUSKA MOUNTAINS.

The list of major topographic features in the Navajo country includes three mountain groups—the Chuska, Carrizo, and Navajo; the lofty plateaus, Black Mesa and Skeleton Mesa, might well be put in the same category. The Chuska Mountains owe their position to uplift associated with the development of the Defiance monocline, the De Chelly upwarp, and the folds of the Lukachukai Mountains. Their present height is due to erosion, which has stripped the surrounding country of its cover of Tertiary sediments and lavas. The top of the Chuska Mountains is relatively flat, and its valleys have reached a stage of very late maturity. Its western border is cliffed and gashed by short, steeply inclined obsequent valleys and scalloped by a sinuous line of rincons and buttresses. (See Pl. XXVI, *C*.) The northern third of its eastern border is likewise precipitous and recessed by deep box-headed canyons; but from Pena Blanca Creek to Tohachi the eastern flank of the mountains is a slope of moderate gradient developed on Tohachi shale and eastward-dipping beds of the Mesaverde formation. The slope, which terminates upward in a structural terrace at the base of the Chuska sandstones, is heavily coated with débris, including material furnished by landslides. At the top and bottom of this slope—horizons marked by lines of springs—rock cutting is active; over the slope itself erosion is much less vigorous than on other parts of the mountain border.

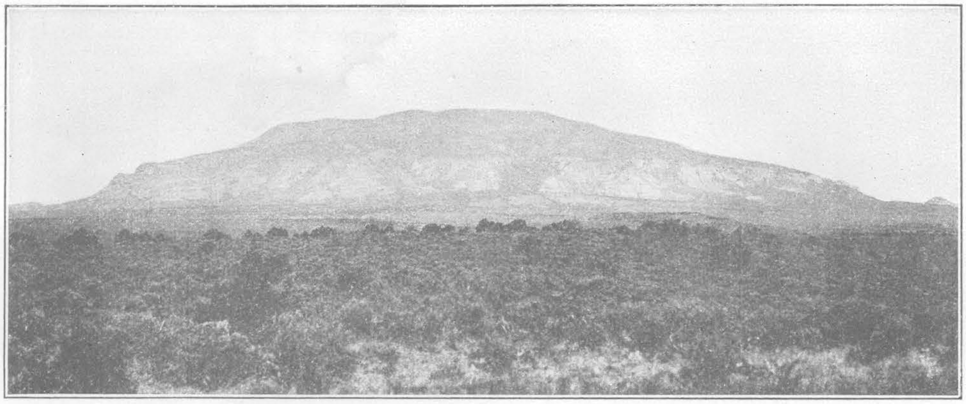
CARRIZO MOUNTAINS.

The Carrizo Mountain group is a much dissected laccolith of irregular form. At an altitude of 8,800 to 9,000 feet a fragmentary plain is developed on igneous and sedimentary rocks alike. Above this plain valleys in late maturity and old age extend toward isolated, flattened summits culminating in Zilbetod and Pastora peaks; below the plain canyons extend to the mountain base. The physiographic features of the Carrizo Mountains are such as result from normal erosion controlled by structure. Whether or not the mountains attained their present altitude by one or more than one uplift is not known. The evidence is conclusive, however, that the present period of active degradation was preceded by a period during which large amounts of stream-borne débris were accumulated along the drainage channels as well as on interstream spaces.[1]

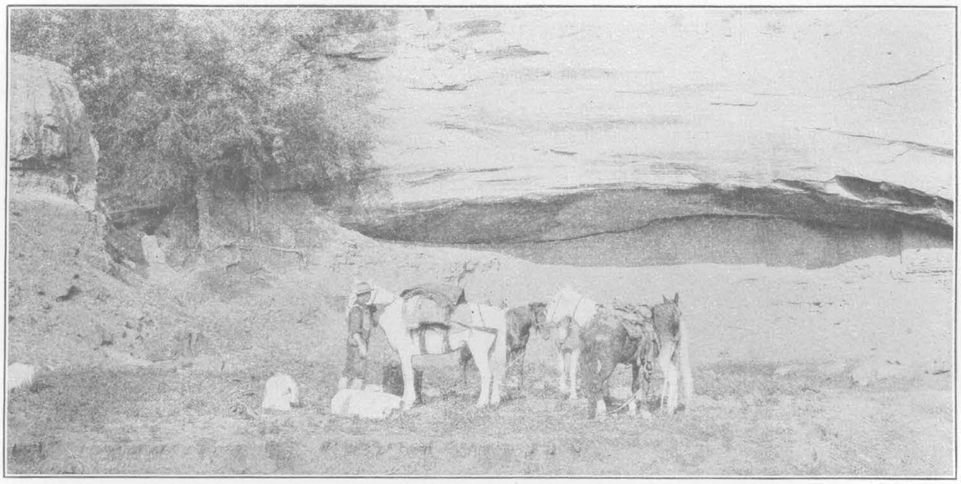
NAVAJO MOUNTAIN.

Navajo Mountain is a laccolith of fairly regular outline, but it differs from the other laccolithic uplifts of the Plateau province—La Sal, Abajo, El Late, and the larger units of the Henry Mountain group—in the absence of igneous rock exposed at the surface. Cretaceous sandstones cover the top, and Jurassic (?) sediments constitute the flanks. Viewed from a distance Navajo Mountain appears as a symmetrical mound rising 4,000 feet above the flat floor of Rainbow Plateau, an island in the midst of a sea of waterworn and wind-worn, brilliantly colored sandstone. Nearer at hand the profile consists of a steeply rising curve terminated upward by a bench above which lies a forest-covered dome. (See Pl. XXVII, *A*.) On ascending the difficult trail the bench observed from a distance is found to be confined to the south side of the mountain, and its surface at 8,500 feet is traversed by valleys of a structurally controlled drainage system. Above 8,000 feet the flat valleys are in late maturity or old age, and the miniature cliffs that border them are in many places concealed by talus. The mountain top also was found to be nearly flat over an area of about 200 acres underlain by slightly inclined beds of Mancos sandstone. There are no crags or pinnacles. Frost work predominates at these altitudes, and areas acres in extent are thickly strewn with large angular blocks extending downward as rock streams. Streams in steep-walled canyons reaching up from the Rainbow Plateau are actively eroding the mountain slopes. On the north and northwest sides headward gnawing is particularly vigorous. So deep and so close-spaced are the canyons leading to the Colorado and the San Juan that the interstream ridges stand out like buttresses supporting the mountain from the north. The intricacy and grandeur of the stream-carved sculpture are unexcelled in any other part of the Plateau province. Talus and alluvial fans have been largely stripped from the northern slopes of the mountain, but on

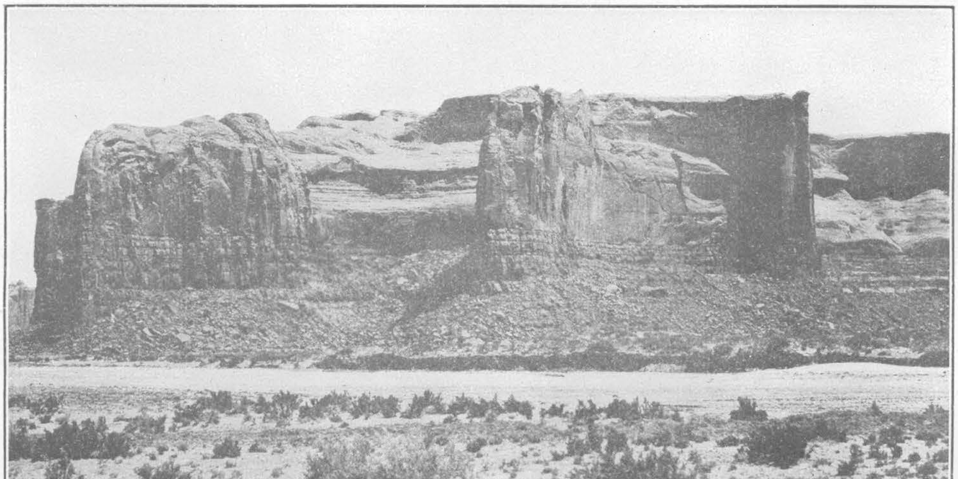
[1] The physiographic features of Carrizo Mountain are treated in detail by W. B. Emery in a Survey bulletin now in preparation.



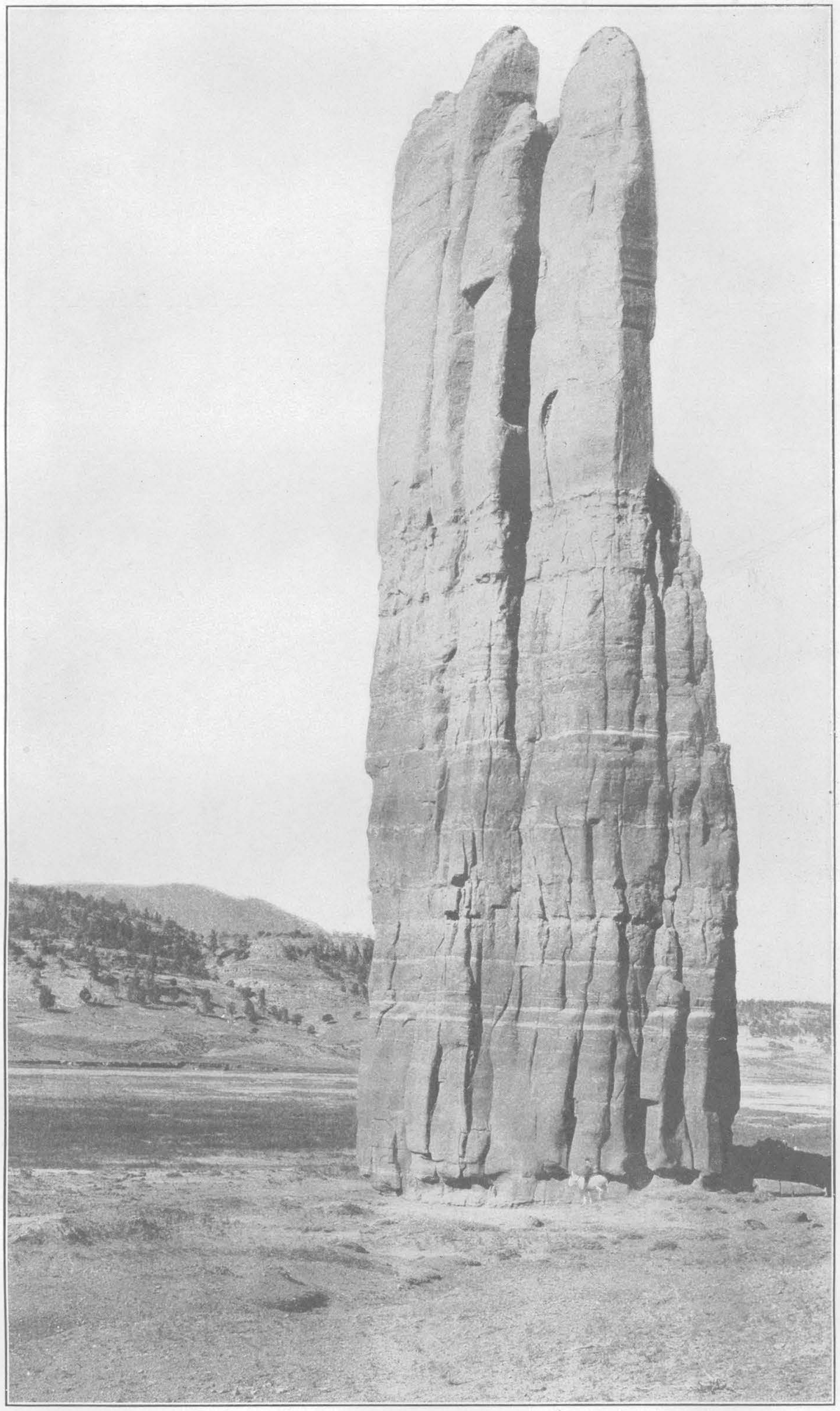
A. NAVAJO MOUNTAIN, ARIZ.
Looking north from a point 3 miles away.



B. NICHE AT HEAD OF BOX CANYON, CHINLE VALLEY, ARIZ.
Developed in massive cross-bedded sandstone at a dry waterfall.



C. RINCONS NEAR MOUTH OF LUKACHUKAI CREEK, ARIZ.
Sandstone of La Plata group.



VENUS NEEDLE, TODILTO PARK, N. MEX.

Column of sandstone of La Plata group. Height may be judged by comparison with horse at the base.

the southeast side gravel and boulders are banked against the base in enormous quantities. The period of aggradation thus indicated has been replaced in the present cycle by effective degradation; the alluvial slopes are deeply trenched.

PREDOMINANCE OF CLIFFS.

That the surface of the Navajo country has reached its present attitude by a series of uplifts interrupted by pauses of sufficient length to permit the development of mature or old topography is a hypothesis supported by deductive reasoning and field evidence. Intermittent uplift should, however, be recorded in the quality of adjoining slopes. For instance, in a series of three cycles the undestroyed remnants of the oldest peneplain should be beveled by mature slopes of the second cycle, and these in turn should be truncated by slopes of the latest cycle. This arrangement is illustrated by so many examples in widely separated localities that it may be considered normal. In fact, the relation and nature of slopes in many parts of the world constitute the most convincing proof of successive stages of regional uplift.

Evidence of this sort is not available for the discussion of the physiography of the Navajo country. Valleys with late mature profile are found on the summits of the Chuska Mountains, Black Mesa, and many smaller highlands where the cap rock is a continuous stratum in essentially horizontal position, but mature cliff slopes and mature valley profiles are conspicuous for their absence. Mural escarpments bordered by slightly inclined surfaces prevail; the predominance of cliffs is impressive. Nearly every stratum is a cliff maker, and traverse of the Navajo country consists in large part of ascending and descending steps of various heights. This characteristic feature in the topography of the Navajo country is due to the interaction of several causes, chief among which are character of the rock, stage of physiographic development, and climate.

The composition, structure, and attitude of the rock in the Navajo country favor the development of cliffs. Sandstones constitute perhaps 80 per cent of the strata exposed; even the thinly foliated beds are prevailingly arenaceous; typical clay shales are rare, and large parts of the small amount of limestone present are siliceous. The Mesaverde sandstones, the thin strata of the Dakota sandstone and Shinarump conglomerate, and the even thinner beds of limestone in the Chinle formation are resistant to erosion, but the great cliff makers of the region, the De Chelly sandstone and the members of the La Plata group, consist of rock of uniform grain weakly bound together. In these strata the retreat of cliffs is usually more regular and more rapid than in the underlying shales, undermining is a relatively unimportant process, and the shale slope extends with steep inclination as a glacis from the base of a towering wall. In places where the Dakota sandstone is underlain by the soft members of the McElmo formation, and where the Shinarump conglomerate caps Moenkopi shales the shales are commonly cut back until they combine with the resistant cap rock in producing a nearly vertical cliff. Walls of shale 100 feet or more in height with slopes exceeding 60° are conspicuous features. Moreover, with the exception of the beds involved in monoclines, the strata throughout this region are flat or slightly inclined and the joints are commonly vertical, thus facilitating the retention of cliff profile.

The region is physiographically young. Canyons are trenched along the lines of major drainage, and the making of innumerable lateral canyons lags but little behind. The revival of erosion processes involves the retreat of cliffs and widening of channels, as well as the cutting of gorges. The new local base-level defined by the major trenching means added power to the tributary streams on the slopes developed in a previous cycle. If these slopes are on weak strata they are rapidly dissected, the materials previously collected are removed, and the cliff in the overlying strata is rejuvenated. If the slopes are on hard strata the wall of the newly made canyon is carried backward as an escarpment.

The influence of climate is expressed chiefly in the quality of surface drainage and the behavior of ground water. The ephemeral streams are nearly always at flood stage, and their potency in removing the products of disintegration is truly enormous. Their efficiency in stripping the slopes of waste and preventing the formation of talus is augmented by the texture of the rock. Much of the material supplied to the base of the cliff is fine, the product of disintegration of poorly compacted sandstone. In the areas of the Wingate, Navajo, and De Chelly sandstones large blocks pried off from the tops of the cliffs are so lacking in firmness that they crumble to sand on striking the lower slopes; the conditions for the formation of talus are absent. Cliffs in these strata are steep not because the rocks are hard but because they are friable.

Ground water plays an important part in the production of cliffs in this region. Only the surface of a shale slope at the base of a cliff maker is moistened by the short-lived showers; no appreciable amount of water is abstracted by downward percolation. All the power of the swollen stream is suddenly applied to the task of pushing rock waste from slopes and benches into the adjoining flooded canyons. On the other hand, water falling on the surface of horizontal sandstone at the top of the cliff is imbibed in appreciable quantities and reappears on the face of the cliff as a film that is quickly evaporated or as seeps that serve to disintegrate the rock and to increase the amount of fine waste available for transportation.

Wind also assists to a minor degree in the removal of débris whose accumulation would tend to produce soft outlines.

As in general talus is the regulator of cliff profiles, the action of the erosive forces which prevent its persistent accumulation is in large part the controlling cause of the mural aspect of the scenery of the Navajo country.

ALLUVIAL TERRACES.

DISTRIBUTION.

With unimportant exceptions the streams of the Plateau province are deepening their channels. In the Navajo country many of them are corrading rock; others are at work removing previously deposited gravel. The stream in Canyon de Chelly, Walker Creek, the lower Chinle, Moenkopi Wash, and Tyende Creek are examples of streams flowing between alluvial banks included within canyons whose walls are built of rock. The gravel fans at Navajo Mountain are dissected by arroyos 100 to 200 feet deep, and the alluvial fill of wide, flat washes—Cottonwood, Oraibi, Dinnebito, and many others—is also trenched. In some canyons only small patches of stream-laid gravels cling to the rock walls; in others the work is complete and the top of the former gravel fill is indicated by a band drawn on the canyon wall separating zones on unequally weathered rock. In a few places two or even three terrace levels are indicated by remnants, but in general each valley is bordered by a single set of terraces which is increasing in length by headward erosion and in height by downward cutting. Not uncommonly the bedrock of the former canyon floor has been reached.

DATE OF THE TERRACE EPICYCLE.

That the streams of the region were formerly aggrading their canyon floors and that they are now trenching the valley fill are facts abundantly supported by field evidence. If the period of rock canyon cutting is termed the "canyon cycle," the periods of aggradation and degradation may be considered, respectively, the epicycle of alluviation and the terrace epicycle. The recency of both periods is indicated by the presence of corn cobs and pottery buried beneath terrace gravels and exposed in the banks of present streams and by the old cottonwood trees of the upper Moenkopi Valley, whose trunks, buried to depths of 10 to 30 feet, have recently been excavated.

The date of the beginning of the terrace epicycle through which this region is now passing may be fixed with a fair degree of approximation. The lake in Bonito Canyon described by Simpson [1] in 1850 has disappeared, and the present arroyo is sunk 20 to 30 feet in sands and clays including layers of peat. In Laguna Canyon the lakes shown on the Marsh Pass topographic map, published in 1882, are drained, and their floors are deeply trenched. According to the Navajo legend the Segi region was bewitched in 1884; the farm lands were cut out and the lakes vanished. Certain events are well authenticated. In 1880 a perennial water body existed in Tyende Valley 15 miles east of Porras Dikes, and in 1893 a road traversed this valley from its mouth to Tyende, crossing and recrossing the stream at points now marked by arroyos 20 feet deep. In 1894 the flat-bottomed alluvial floor of Walker Creek was occupied by Indian farmers, and the

[1] Simpson, J. H., op. cit., p. 110.

bed of the Chinle was cultivated; in 1913 the terraces on Walker Creek were 80 feet above the stream and the Chinle flowed between alluvial banks 100 feet in height. Since the Mormon occupation of Tuba in 1878 the Moenkopi has intrenched itself in alluvium to depths of 15 to 40 feet. The terraces on Pueblo Colorado Wash at Ganado date from about 1890. At Keams Canyon the deep alluvial fill is being removed so rapidly that location of roads and preservation of buildings has become a serious problem. Accounts of prospectors, pottery hunters, Government officials, Navajos, and Hopis agree in placing the formation of terraces within the last 25 to 35 years. During the course of my field work in this region, in 1900 and 1909–1913, significant changes have been effected in the width and length of alluvial terraces. The floods that follow showers in July and August perform an incredible amount of erosion; it is unsafe to stand near the bank of a stream while torrents of liquid mud carrying trees and blocks of alluvium are passing.

At Kanab the beginning of the work is definitely dated by the flood of July 29, 1883, followed by high waters of 1884 and 1885, resulting from an unusually heavy precipitation of snow.[1] During these years the alluvial floor of Kanab Creek was cut down about 60 feet for a distance of 15 miles and widened nearly 70 feet.

That alluvial terraces were not to be seen in the Grand Canyon district during the surveys of Powell and Dutton, in 1878–1880 is attested by the following statement:[2]

> Most of those lateral canyons * * * are slowly filling up with alluvium at the present time, but very plainly they were much deeper at no remote epoch in the past. The lower talus in some of them is completely buried, and the alluvium mounts up on the breasts of perpendicular scarps. In some cases a smooth floor of alluvium extends from side to side of what was originally a canyon valley. The recurrence of a climate sufficiently moist to sustain a vigorous perennial stream would probably sweep out all this unconsolidated alluvium and return the valley to its former condition of an ordinary canyon.

No such conditions prevail at present and the photograph entitled "A canyon refilled by alluvium," used in illustration of Dutton's description, could not be duplicated at any locality in the Plateau province with which I am familiar.

CAUSE OF TERRACING.

The nature of the change in physiographic environment that called a halt in the work of rock canyon cutting and introduced the epicycle of alluviation is not clearly understood. As I have shown in another connection,[3] a pause in regional uplift or a change to a more humid climate would permit wider distribution of gravel and better grading of streams. That the crust of the earth in northern Arizona is unstable is indicated by the recurrence of earthquakes, but no direct evidence of movement within the past few centuries has been recorded. The stream profiles are now greatly oversteepened—a condition which doubtless existed during the epicycle of alluviation. The contrary view involves the improbable assumption that the present valley gradients have resulted from differential uplift of large amount since the cliff dwellers occupied the country. A climatic rather than a tectonic cause for the epicycle of alluviation is thus suggested.

Change in stream habit from aggradation to degradation, introducing the terrace epicycle, is best explained also on the hypothesis of climatic fluctuation. Terracing appears to be universal over the Colorado Plateaus and adjoining regions at the present time, and an uplift sufficient to produce the results accomplished in the last 30 or 35 years would need to have been almost continental in extent and to have been abnormally rapid. The rainfall records at Fort Wingate and at Fort Defiance show no significant cycle, either wet or dry, for the years 1880 to 1885, the period during which the vigorous down cutting became dominant, but the rainfall in southern California for 1883–84 was the heaviest ever recorded. Measures of fluctuation in mean annual rainfall have, however, little significance in this region. Erosion results from sudden violent showers followed by unobstructed run-off, and, if suitably distributed, in time an annual rainfall of half the normal amount may be more effective in denuding the land than a precipitation of twice the normal. Under present

[1] Riggs, H. E., of Kanab, Utah, quoted by Davis, W. M., An excursion to the Plateau province of Utah and Arizona: Harvard Coll. Mus. Comp. Zool. Bull., vol. 42, p. 11, 1903.

[2] Dutton, C. E., Tertiary history of the Grand Canyon district: U. S. Geol. Survey Mon. 2, pp. 228-229, 1882.

[3] Gregory, H. E., The formation and distribution of fluviatile and marine gravels: Am. Jour. Sci., 4th ser., vol. 39, pp. 487-508, 1915.

conditions terraces are produced by floods; the streams are aggrading during periods of low water and degrading when their volume is increased—a statement, however, which implies nothing as regards cyclical conditions of aridity or humidity. It is important to note in this connection that the balance between aggradation and degradation is nicely adjusted in an arid region where the stream gradients are steep, and that accordingly small changes in the amount of rain, its distribution, or the character of storms and changes in the amount and nature of the flora result in significant modification of stream habit. Even the effect of sheep grazing is recorded in the run-off, and this influence combined with deforestation has been considered by many investigators as the sole cause of recent terracing in the Plateau province. For the Navajo country these human factors exert a strong influence but are not entirely responsible for the disastrous erosion of recent years. The region has not been deforested; the present cover of vegetation affects the run-off but slightly (p. 119), and parts of the region not utilized for grazing present the same detailed topographic features as the areas annually overrun by Indian herds.

MINOR PHYSIOGRAPHIC FEATURES.

The surface of the Navajo country has been carved rather than built; features resulting from deposition are relatively unimportant. Talus slopes and alluvial fans are replaced by cliffs; hills and knolls give way to buttes and towers; and graded slopes are represented by walls sculptured into rincons, recesses, alcoves, niches, windows, and arches, of large variety. Most of these minor features are common to the Plateau province and to arid lands in general. Some of them are so characteristic of Navajo topography as to merit brief description.

RINCONS.

The Spanish term "rincón" (the inside corner of a house or box as distinguished from "esquina," the outside corner) is applied by the Mexicans of Arizona and New Mexico to the square-cut recesses between buttresses of cliffs and canyon walls. (See Pl. XXVII, *C*, p. 128.) They are distinguished from the semicircular recesses that resemble parts of an amphitheater and are differentiated from box canyons by the absence of defined drainage. These forms are well displayed in the Navajo country, particularly in cliffs carved from the massive beds of the La Plata group. In ground plan such cliffs are outlined by angles rather than curves; the line following their base is a simple Greek fret rather than a scroll formed of curves united by cusps. Rincons are features of dry climates; they are due to disintegration, aided by ground water and controlled by structure, rather than to stream corrasion. During showers the walls of rincons are wet directly by rain, but a more effective work of erosion is performed by the surface film of water that makes its way slowly down from the top of the cliff or oozes from the porous rock, clinging tightly to the wall by surface tension until it is removed by evaporation. All parts of the rincon walls are about equally well coated with drops, and accordingly all faces weather or disintegrate substantially alike. Once outlined the rincon may therefore retain its form for an indefinite period. The wind is not an effective agent in the development of rincons. Most of these recesses are protected from the wind; they show little evidence of abrasion, and their orderly arrangement is satisfactorily explained as the result of weathering.

BOX CANYONS AND WATERFALLS.

The typical canyon of the Navajo country is an elongated box terminating abruptly at both ends. Its mouth is entered by a portal; its head is walled in by steeply inclined, vertical, or even overhanging cliffs. Exploring parties find to their cost that the entrance and exit may be the same. The trail into a canyon enters at the mouth, drops over the wall on sand dunes, or makes its way down the ragged side of some tributary ravine; access from the head usually involves "building trail," and in many canyons this route is impossible. The stream at the canyon head enters as a waterfall, dry throughout most of the year. Where the walls consist of relatively thin bedded rock the water from infrequent showers bounds from ledge to ledge in a rapid; where the walls consist of thick-bedded massive strata the stream reaches the canyon floor by a single plunge. Some of the falls have no projecting lips, but most of them show the familiar arrangement of overhanging rim and recessed wall. Because of the intermittent activity of the streams favorable opportunity was afforded for studying the effect of waterfalls on the recession of cliffs, with a result somewhat at variance with prevailing views. It was found that corrasion on the top ledge is actively progressing; potholes are common on the crest of the falls but exceedingly rare on the canyon floor beneath. Most of the niches below the lip—the "caves of the wind"—are in positions where the return spray does not wet the wall of the cavity, back of the falling sheet of water. (See Pl. XXVII, *B*, p. 128.) In fact, it is possible to remain in one of these "caves" without feeling the spray while the waterfall set in action by a thundershower runs its course. The descending mass of water therefore appears to take little if any part, either as a mechanical or a chemical agent, in the carving of the recessed cliff. Two other agents, however, are actively at work. A film of water may be seen creeping down the wall behind the cascade and spreading until all the rock face is coated. It clings by surface tension and remains long after the stream has ceased to flow. Ground water also makes its presence felt. After the lapse of an hour or so, sometimes of several hours, following a storm, water may be seen to ooze from the porous rock or to trickle from bedding planes. These tiny flows may continue for hours or even days; not infrequently a permanent spring of small flow is found in this position. Efflorescence of lime or alkali or salt coating the recessed wall indicates that the supply of water is intermittently renewed. By these two weathering processes the wall of a canyon is horizontally notched, cavities are formed, the rim is undermined, and the cliff recedes regardless of the plunging cataract. It is probable that this explanation applies, in part at least, to the headward erosion of waterfalls in humid regions.

BUTTES AND TOWERS.

In the process of destruction of plateaus and mesas portions of walls outlined by planes of structural weakness become detached and stand as isolated buttes, taking the form of monuments, towers, pinnacles, and spires, not uncommonly of striking aspect. In the Monument Valley and Segi Mesas provinces these forms are unusually well displayed. The Monuments include 15 to 20 shafts of De Chelly sandstone resting on symmetrically carved and banded pedestals of Moenkopi shale. They have been famous since the days of the earliest explorers. As seen by Newberry[1] from a distance of 30 miles:

> The features presented by this remarkable gateway [Monument Pass] are among the most striking and impressive of any included in the scenery of the Colorado country. The distance between the mesa walls on the north and south is perhaps 10 miles, and scattered over the interval are many castle-like buttes and slender towers, none of which can be less than 1,000 feet in height, their sides absolutely perpendicular, their forms wonderful imitations of the structures of human art. Illuminated by the setting sun, the outlines of these singular objects came out sharp and distinct, with such exact similitude of art and contrast with nature as usually displayed that we could hardly resist the conviction that we beheld the walls and towers of some cyclopean city hitherto undiscovered in this far-off region.

The lofty buttes of the Rainbow Plateau, and the igneous spires of the Tyende region, dominated by the peerless Agathla, are equally impressive illustrations of the work of erosion. Groups of towers resting on narrow bases rise to heights of 100 to 600 feet from the floors of Glen Canyon, Alcove Canyon, Redrock Valley, Todilto Park, and Canyon de Chelly. Isolated examples are widely distributed. (See Pls. VI, p. 30; XXVIII, p. 129.)

ROCK SHELTERS.

The sandstone cliffs in this region are beautifully sculptured; buttresses and recesses are common, overhanging walls are characteristic, and the wide, open mouths of niches and caves perched high on the canyon walls are conspicuous. These cavities, protected from rain, from the glaring heat of the sun, and from the suffocating sandstorms, were widely utilized by the ancient inhabitants as building sites—"rock shelters" or "cavate dwellings," as the terms are used by archeologists. Rock shelters of two types were selected for homes by the cliff dwellers of the Navajo country. Some houses are built in recesses eroded from shale beneath a resistant cap of sandstone, conglomerate, or lava. The famous cliff houses of Canyon de Chelly and Canyon del Muerto, the little-known villages of Segi Mesas and Navajo Canyon, and some of the unexplored ruins of the Rainbow Plateau are in caves within single massive beds of De Chelly, Wingate, or Navajo sandstone. (See Pl. XXIX, *B*.) The structure of these beds is favorable for the

[1] Newberry, J. S., op. cit. (Macomb expedition), pp. 103-104.

production of rock shelters. The rock composing them is porous, elaborately cross-bedded, and traversed by joint planes set far apart. The curved laminae of the cross-bedded strata, 1 inch to several feet thick, are held together by weak cement that is easily removed by percolating water. Slight undermining along zones of the more impervious rock permits the overlying laminae to fall in response to gravity. They drop to the floor as a unit or in separate slabs; the crushed fragments, with cement already largely removed from the spherical grains, rapidly disintegrate and make their way to the mouth of the cave. As the process continues shell after shell is removed and the arched-roof cave is sunk farther and farther into the face of the cliff, until building sites 200 to 3,000 square feet in area are prepared for the cliff dweller. All stages of the work are represented. In some caves shells of partly detached rock bridge the entrance; in others blocks on the point of falling extend downward from the roof, and the floor is piled high with fragments that crumble under the blow of a hammer; still others are free of débris, and the rock of the roof and sides is firm. (See Pl. XXIX, *B*.) The work of ground water in forming these rock shelters is evident. Some of the caves are dry or streaked with moist alkali "bloom"; in others water oozes continuously from the wall over a wide area marked by moss and ferns; many caves contain perennial springs whose outlet is definitely localized. The explorer in this desert region soon learns to search these cavities for water.

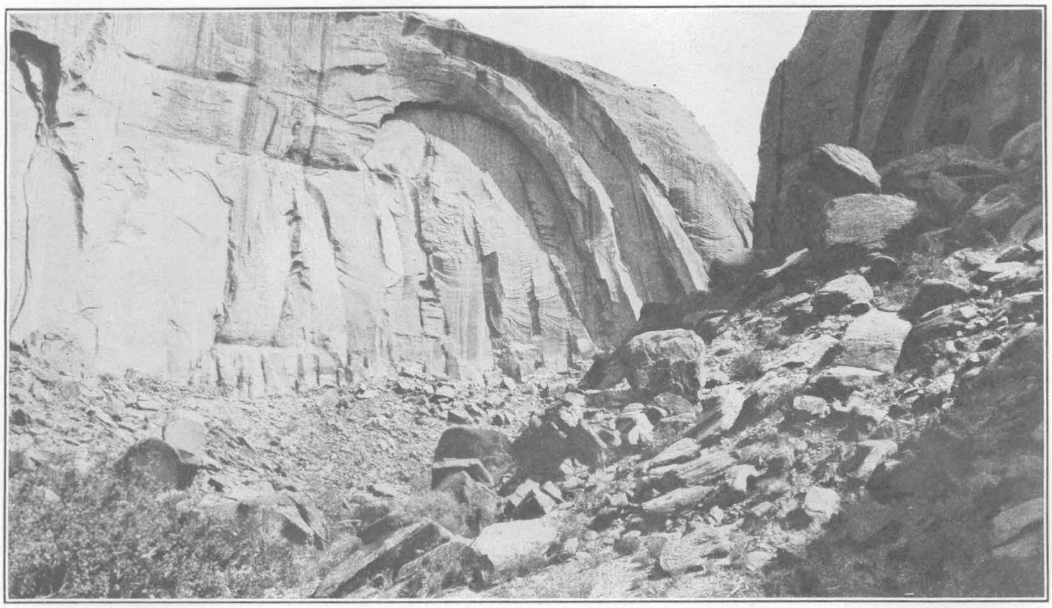
WINDOWS AND ARCHES.

Natural arches resulting from the solution of limestone were not observed in the Navajo country. Bridges formed by the undercutting of jointed strata of resistant rock were noted at several places. A typical example is Black Rock Bridge, 2½ miles south of Fort Defiance, in a small canyon leading down the dip slope of the Defiance monocline. At this place a consequent stream has sunk its bed through the resistant Shinarump conglomerate into the softer De Chelly sandstone. Before the removal of the conglomerate ground water doubtless circulated freely along the unconformity between the Shinarump and De Chelly—an important water-bearing zone in this area. As the subsurface drainage channels were enlarged the water entering joints in the Shinarump fed the underground channels to an increasing degree and enlarged the open space beneath the cap rock. In many places the roof has failed, and broken blocks of Shinarump lie upon the canyon floor; at the bridge, however, the stratum is continuous and spans the shallow canyon as a roadway 70 feet long, 15 feet wide at its narrowest point, and about 10 feet above the canyon floor.[1]

The conditions that permit the formation of rock shelters in massive beds of sandstone—namely, tangential cross-bedding and porosity in rock of uniform composition—also favor the production of windows and natural bridges. It is therefore not surprising to find these features best displayed in the thick-bedded homogeneous sandstones of the La Plata group. The curved cross-bedding in these strata is reflected in all their erosion features. The arch is the dominating architectural form. Blind arches and curved panels are recessed in the cliff faces, and the roofs of niches and rock shelters are vaulted. Detached arches of sandstone rest against cliffs (Pl. XXIX, *A*); here and there they swing free and rise above rock slopes in a fantastic manner (Pl. XXX, *A*).

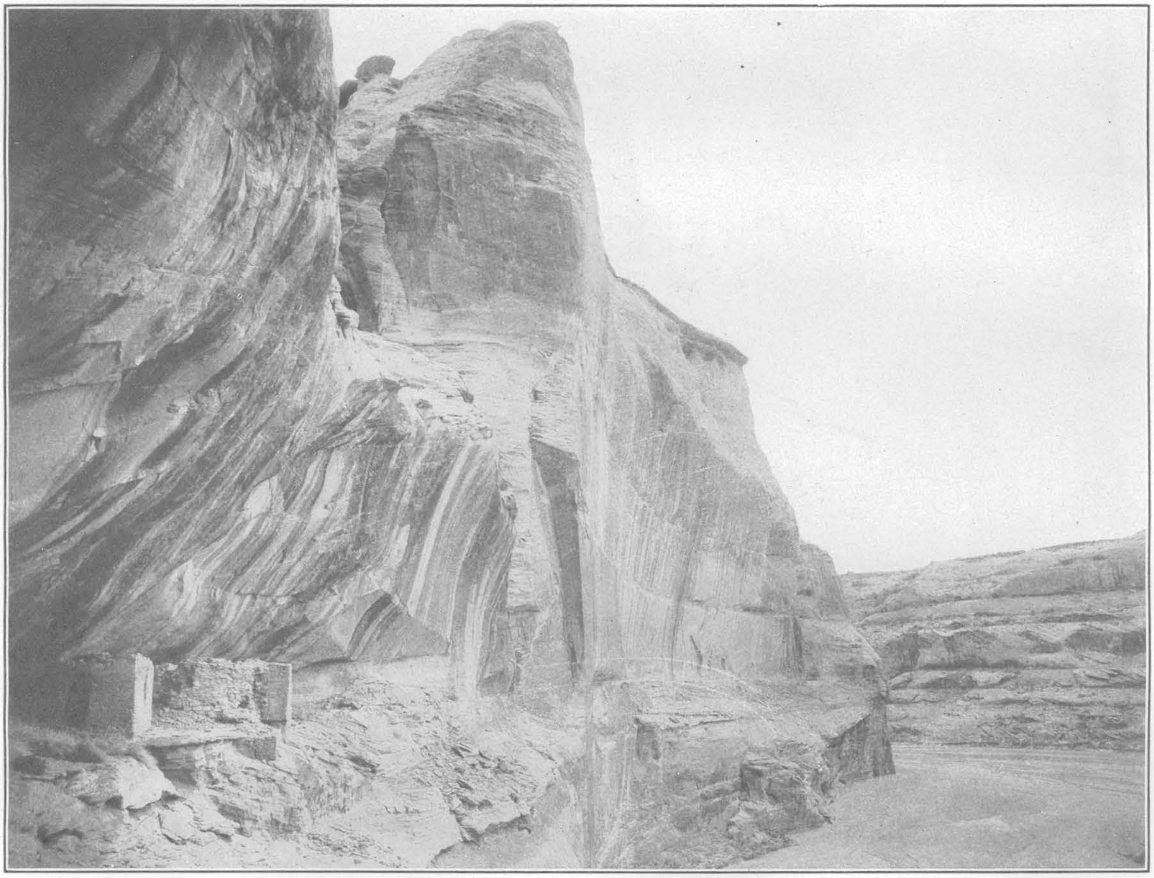
Erosion of these massive cross-bedded sandstones involves not only disintegration and decomposition but also the removal of disks of rock of varying thickness and width. All cliff faces are subject to attack and are forced to retreat at varying rates. If the wall is thin—a cusp of an intrenched meander or a dike-like buttress—the removal of successive shells from opposite sides may result in a perforation, or window. Windows thus formed may be seen at a number of points in the Navajo country. Some, like the Defiance Window, are set high on the wall; others are near the surface of the ground; a few are cluttered with débris, but most of them are swept clean by rain and wind. (See Pl. XXX, *B*.) The windows vary in shape from narrow slits and irregularly shaped portholes to almost complete circles and attain diameters exceeding 100 feet. These perforated walls are not a distinct species of erosion form; they represent merely a stage in an erosion process—one term in a series that includes niches, rock shelters, blind fan windows, open windows, and the arches of natural bridges.

[1] This bridge is probably the one described by Frederick Gardiner (An Arizona natural bridge: Science, vol. 6, p. 67, 1885).



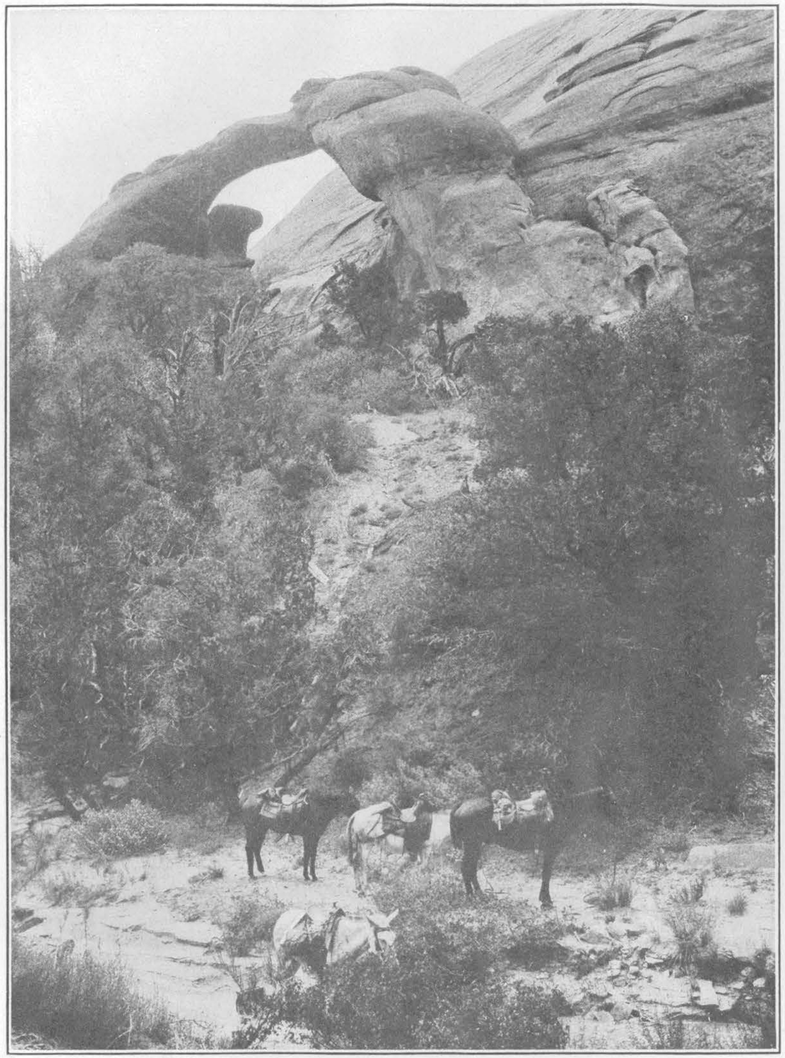
A. CLIFF OF SANDSTONE OF LA PLATA GROUP NEAR GLEN CANYON, UTAH.

Showing stage in process of forming bridges. The arch in the middle background is detached from the cliff.



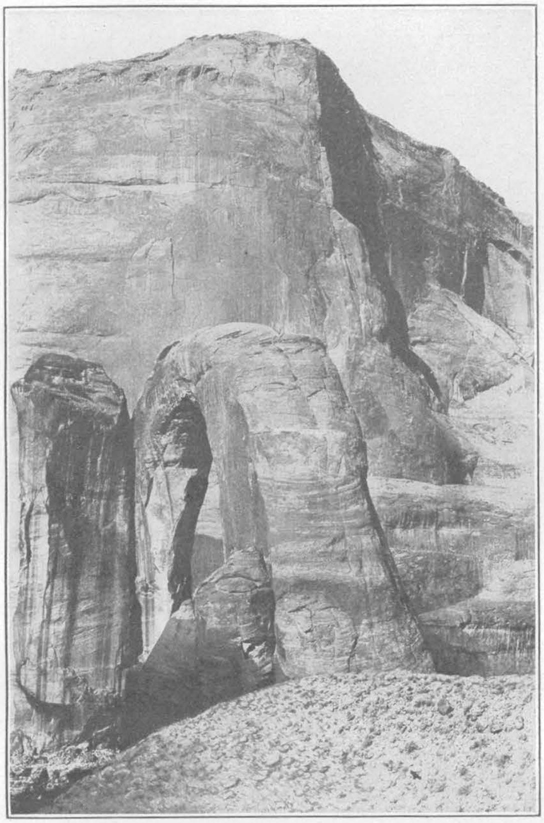
B. ROCK SHELTER, CANYON DE CHELLY, ARIZ.

Resulting from weathering of massive cross-bedded De Chelly sandstone. Photograph by W. C. Mendenhall.



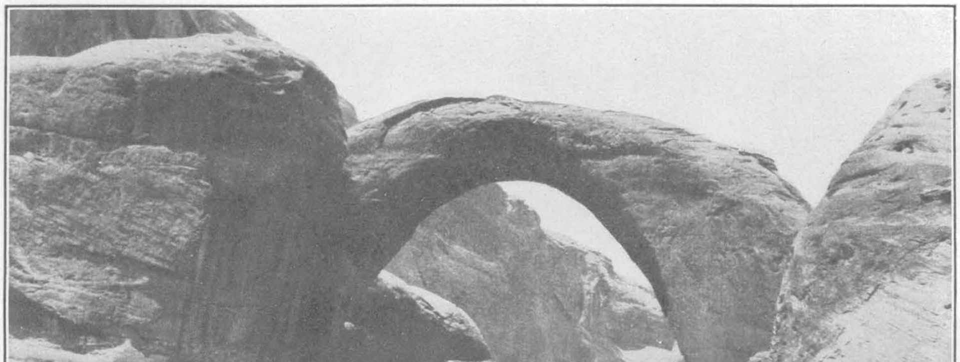
A. OWL BRIDGE, NASJA CANYON, UTAH.
Development of arch controlled by cross-bedding in massive sandstone.

B. HOPE WINDOW, CARSON MESA, ARIZ.
Perforated wall resulting from erosion controlled by cross-bedding in massive sandstone.

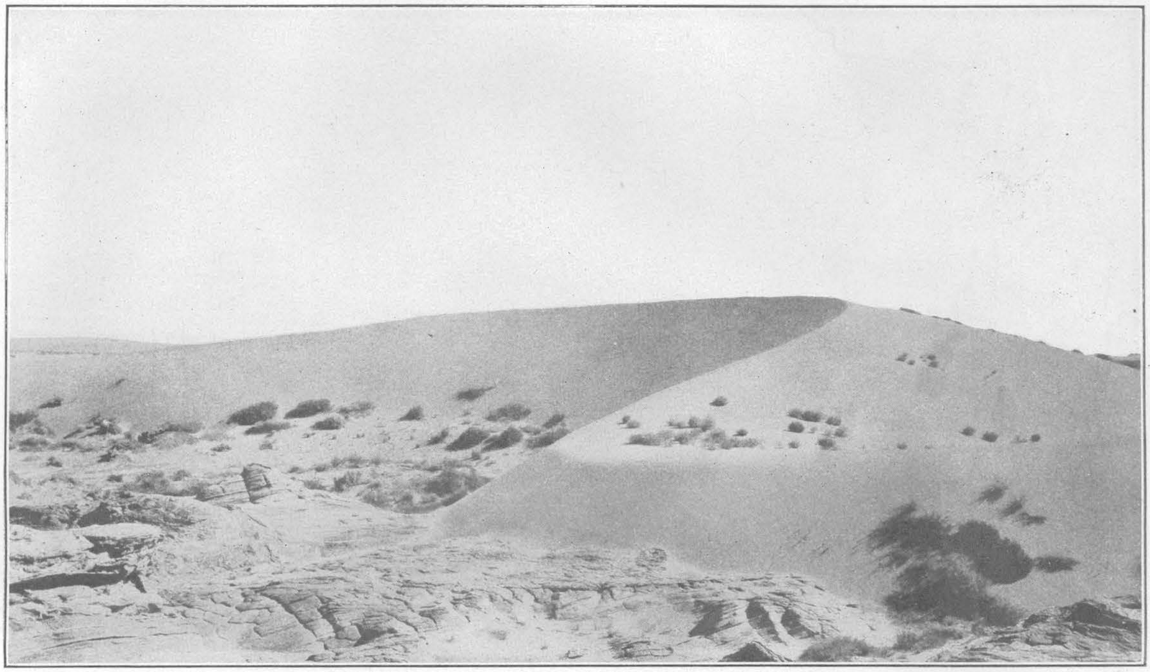


A. RAINBOW BRIDGE, UTAH, FROM CANYON WALL.

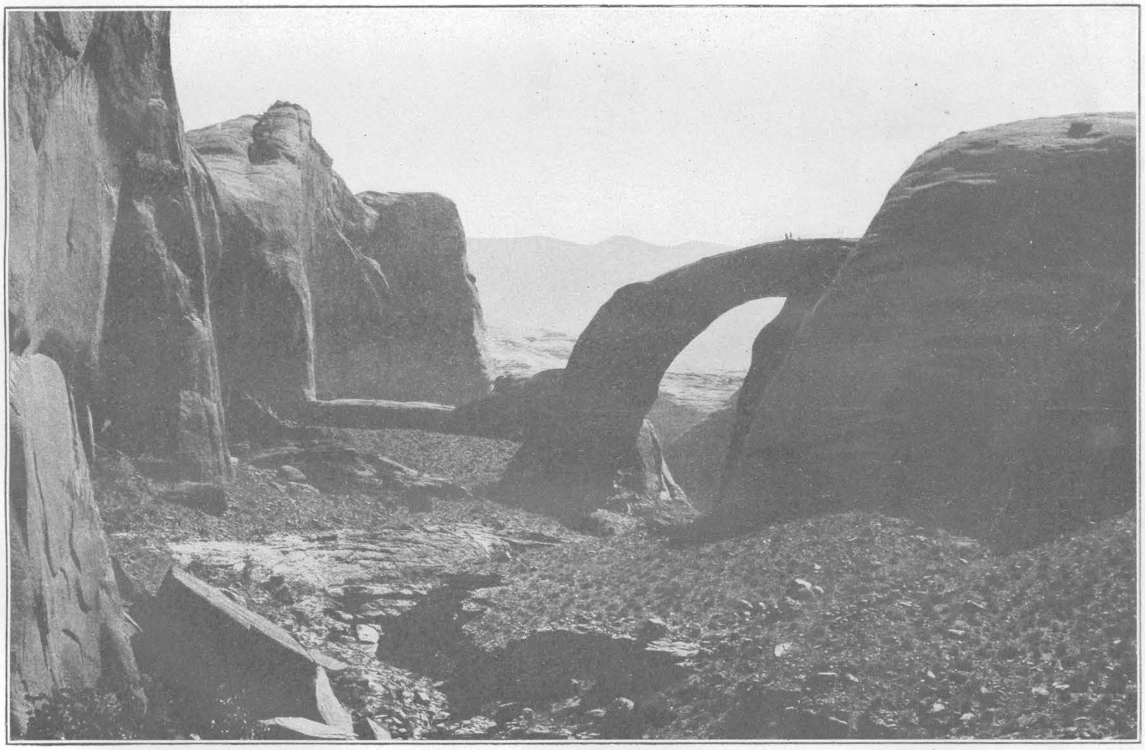
Showing development from massive cross-bedded Navajo sandstone.
Photograph by A. R. Townsend.



B. RAINBOW BRIDGE, UTAH, SPANNING BRIDGE CANYON.



A. BARCHAN, OR TRAVELING DUNE, KAIBITO PLATEAU, ARIZ.



B. RAINBOW BRIDGE, UTAH.

Showing process of formation. On the left is the abandoned meander of ancient Bridge Creek. Photograph by A. R. Townsend.

Perhaps the most striking erosion feature within the Navajo country is the recently discovered Rainbow Bridge, which spans Bridge Canyon, on the northwest slope of Navajo Mountain. (See Pl. XXXI, *B*.) Its symmetry and graceful proportions, as well as its size and beauty of color, give to this arch a commanding position among the natural bridges of the world. For the Navajos the bridge is Nonnezoshe, the great stone arch; to the Piutes its form and bright-red tones suggest Bárohóini, the rainbow, the mythical path of the sun. In the landscape of Rainbow Plateau the bridge is not a conspicuous feature, being lost in a labyrinth of profound canyons and lofty towers. From the rim of Bridge Canyon it appears as a hoop bent across an inner gorge. (See Pl. XXXI, *A*.) In near view its grandeur is realized and its structural plan revealed. The arch rests on a bench of bedded sandstone below which the inner gorge of Bridge Creek is sunk to a depth of 80 feet. Between the chord uniting the springers at the level of this supporting bench and the lower side of the keystone point the vertical distance is 187 feet, and the arch at its summit is 42 feet thick. The total height of the crown above water is therefore 309 feet—exceeding that of the second greatest bridge in the United States, Sipapu (the gate of heaven), in White Canyon, Utah, by 89 feet. The span of the bridge is 278 feet.[1]

The bridge can not be traversed; its curvature is too great and its smoothed rock sides offer no footholds. Access to the summit is obtained by the use of ropes let down from the cliffs above.

The Rainbow Bridge (see Pl. XXXII, *B*) is carved from a single massive cross-bedded stratum of Navajo sandstone; the ends of the arch rest on bedded rock of middle La Plata age. One limb of the arch rises free from a broad platform and is encircled by an abandoned meander curve; the other limb is firmly buttressed against the canyon wall. In the light of these facts, the steps in the formation of the bridge may be traced. In its first expression the block from which the arch is carved extended from the canyon wall as a narrow meander cusp. The attack of the erosive forces was twofold: disks and shells outlined by curved laminae of the porous Navajo sandstone were removed from both faces of the spur and at the same time ground water was making its way through joint cracks and along the surface of the underlying relatively impervious beds. The spur was thus continuously narrowed and undermined. Whether the scaling reached a stage when the spur wall was perforated is not known; but it is believed probable that the wall was pierced by a window that stood above the newly developed subterranean channel. As time went on Bridge Creek adopted the shorter, steeper course beneath the spur, abandoning the ancient meanders. Undermining and scaling could then proceed at an increasing rate; the bridge was narrowed and increased in height and in length of span until the present magnificent arch was formed. The bridge thus owes its position to stream adjustment; its form is due to erosion of homogeneous sandstone guided by tangential cross-bedding.

[1] These measurements are based on a survey of the Rainbow Bridge National Monument by W. B. Douglas, of the United States General Land Office.

LANDSLIDES.

At first sight the topography of the Navajo country appears to favor the development of landslides. The cliffs are steep and high; they face valleys in which erosion is active; and heavy-bedded sandstones are underlain by shales. In general, however, the steep slopes are bare or coated with only ribbons and scattered patches of débris; the products of disintegration are removed about as fast as they are formed. Landslides are rare. At a few widely separated localities slide materials cover the lower slopes and extend out to the valleys below; their presence is due to favorable combinations of surface water, ground water, and rock structure. The slides on the east face of Chuska Mountain are due to the fact that surface drainage from the mountain summit is retarded by the attitude and structure of the Chuska sandstone. An unusually large portion of the precipitation enters ground-water channels. From the base of the sandstone cap the ground water emerges in a line of springs and seeps and makes its way over the surface of the Tohachi shales. A sliding plane is thus provided for the talus furnished by the upper cliffs. At the south end of Chuska Mountain the strata are identical with those on the east.

face. Surface drainage, however, is well developed; springs are rare, and landslides are inconspicuous. On the southeast front of Black Mesa masses of the horizontally bedded Tertiary rock have been carried beyond the bases of the cliffs for a quarter of a mile and upturned at angles of 20° to 50°. The drainage conditions here are similar to those on Chuska Mountain. Landslides also occur at the sites of the Hopi villages, on long, narrow capes projecting from Black Mesa. The Cretaceous strata forming the mesa dip south, and the prominent saturated zone at the top of the Mancos shale favors the sliding of insecure blocks of the overlying Mesaverde sandstones. Sections of the cliffs at Shimopovi are found 1,000 feet from their original position. That the process has been long continued is indicated by gradations in the degree of decomposition of the fallen masses and by the traditions of the Hopis. In recent years slides have occurred at times when ground water was present in unusual amounts. On the north border of Black Mesa, where springs at the contact of the Mancos and Mesaverde formations are rare, landslides are poorly developed.

Landslides fringe the western border of the Echo monocline for a distance of 18 miles south of Lees Ferry. They attain perhaps their best development at Bitter Springs, where the rock slope is completely concealed by fragments from the Chinle and La Plata formations—a flood of débris that pours over the low cliff of Shinarump conglomerate, buries Moenkopi strata, and comes to a halt only after it reaches the flat surface of the Kaibab limestone. Within the zone of slides the unresistant Chinle shales and "marls" are upturned in the Echo monocline. The Echo Cliffs face westward, but the surface drainage flows eastward from their crest, thus reducing the collecting area of the obsequent streams to a minimum. The subsurface drainage, on the other hand, finds an easier channel westward and emerges as springs and seeps. For 30 miles south of the Bitter Springs region the Echo Cliffs do not include the Chinle shales; springs are absent and there are no landslides. The absence of slides on the Echo Cliffs south of Cedar Mesas and their presence north of Bitter Spring was cited by Davis[1] as evidence of revival of drainage in the Plateau province. It is not necessary, however, to assume a casual relation between these slides and the revived Colorado, for the nature of the strata and the distribution of ground water satisfactorily account for the difference of expression in the two otherwise similar portions of the Echo Cliffs. The value of landslides as evidence of youthful conditions consists in their wide and systematic distribution; they should occur more abundantly near the more deeply trenched channels of the new cycle. In this respect the evidence in the Navajo country is not as conclusive as might be desired. Landslides are absent in the cliffs of Chinle shales overlain by La Plata sandstones along the San Juan Canyon, in upper Moonlight Canyon, and on Ward Terrace, localities in which cliff recession is actively progressing, but they are well developed at places on the borders of Chuska Valley, Pueblo Colorado Valley, and the Tusayan Washes, where drainage from the cliffs is poorly developed. The distribution of ground water appears to be the controlling factor; erosion induced by rejuvenation is auxiliary.

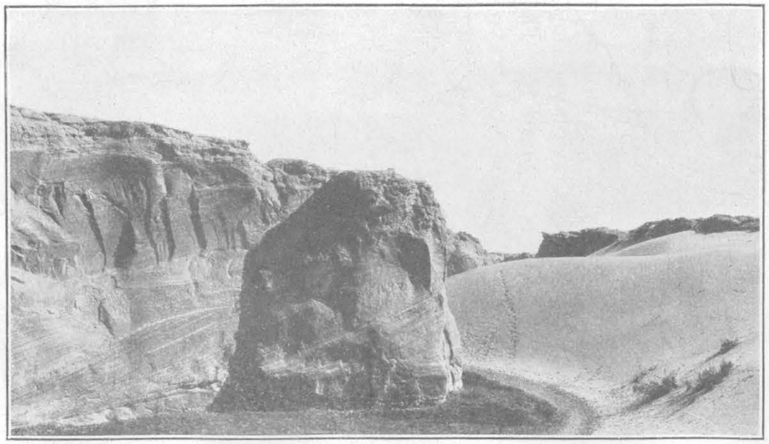
[1] Davis, W. M., An excursion to the Grand Canyon of the Colorado: Harvard Coll. Mus. Comp. Zool. Bull., vol. 38, pp. 121-126, 1901.

WORK OF THE WIND.

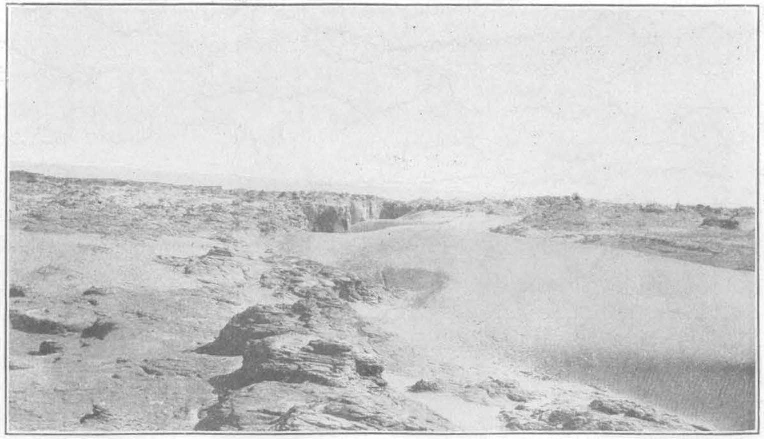
Southwest winds blow throughout the year across the Navajo country. Days on which the air is quiet are exceedingly rare. The effects of this continuous stream of air at work in a region of small rainfall and scant vegetation may be seen on all sides. Wind-swept surfaces of bare rock are widely displayed, and areas without dunes are uncommon. The country is coated with a broken and frayed mantle of wind-borne dust, composed of materials originating in and beyond the borders of the reservation. Topographic forms resulting from eolian deposition and from abrasion, including minor features of picturesque expression, may be studied at a number of places. They are the most numerous and varied in the Painted Desert, on the Kaibito and Rainbow plateaus, along the Tusayan Washes, and within the Chinle Valley.

EOLIAN DEPOSITS—LOESS AND DUNES.

Frequent dust storms and ever-present whirlwinds lift the finer soil particles into the upper air. These tiny bits of rock travel with the prevailing wind and come to rest on the slopes and summits of highland areas. By

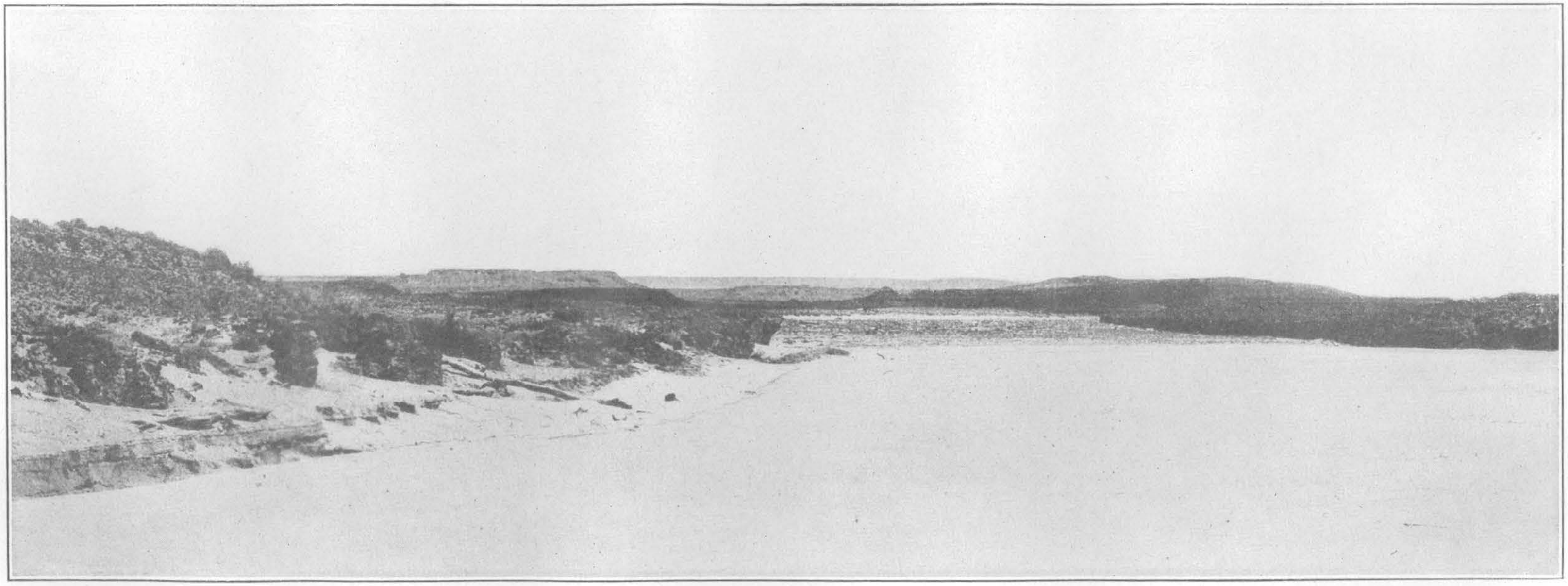


A. RESERVOIR CANYON, ARIZ., IN PROCESS OF FILLING BY DRIFTING SANDS.



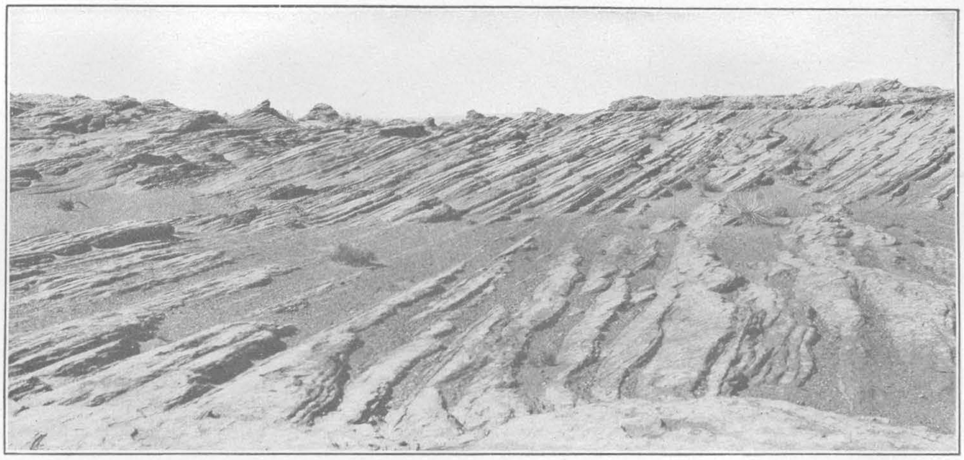
B. WIND-FILLED CANYON, KAIBITO PLATEAU, ARIZ.

Depth 150 feet.

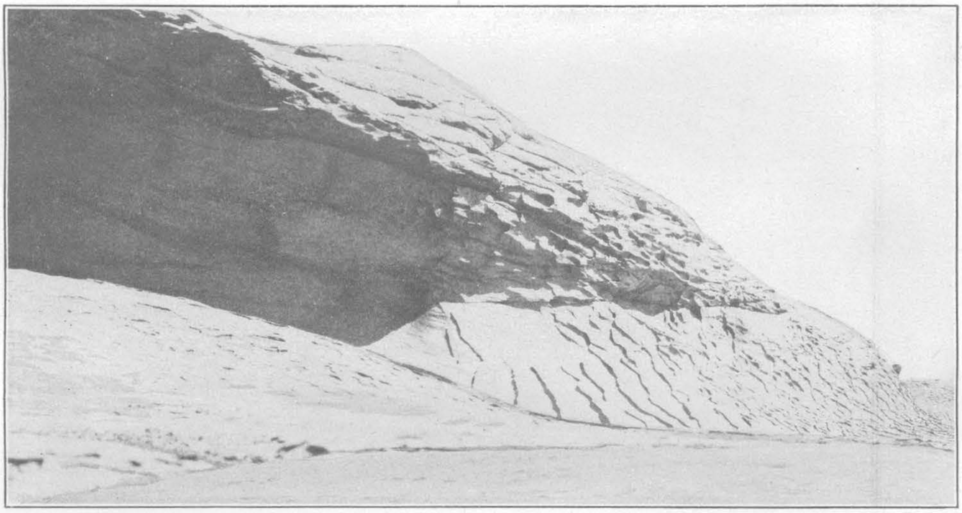


C. BLACK FALLS, LITTLE COLORADO RIVER, ARIZ., LOOKING UPSTREAM.

Falls obliterated by wind-blown sand that fills the canyon.



A. WIND-SWEPT SURFACE, KAIBITO PLATEAU, ARIZ.



B. ETCHED SANDSTONE, KAIBITO PLATEAU, ARIZ.

C. WIND-ABRADED DE CHELLY SANDSTONE, MONUMENT VALLEY, ARIZ.
Holes are solution cavities, simulating those made by wind.

these means trees and brush are coated with dust, and in protected places on Black Mesa, on the Chuska Mountains, and elsewhere the rock powder is widely distributed during the dry season. With the coming of rains most of the dust is carried into stream channels and becomes part of the alluvium, but a portion of it remains in position and, aided by the roots of grasses, accumulates from year to year as loess. No large areas of loess were observed, and the thickest deposit seen measured 3½ feet.

Sand dunes floor the Tusayan Washes almost without interruption and are piled high against the broken southern wall of Black Mesa. More than half of the surface of the Kaibito Plateau is occupied by dunes, and portions of the Chinle Valley are literally seas of sand roughened by waves and hollows of traveling dunes. Along cliff walls dunes enter rincons, hide behind dikes and ridges, and make their way into the larger alcoves. In a canyon the sand streaming over the rim is picked up by winds within the gorge and deposited as a narrow dune extending from the top to the bottom of the wall, concealing its rough face and forming a practicable roadway to points otherwise inaccessible. Many of the groups of dunes change their form and position but little from year to year; others assume new shapes and alignment each season without increasing their areal extent; still others are moving in a constant direction. Two dunes near Tuba which have been under observation since 1909 are moving across their bare rock floors at an average annual rate of 7 feet. These crescentic traveling dunes or barchans of the Kaibito Plateau, supplied with sand from the immediate locality, supplemented by dust from the Painted Desert and the volcanic field beyond, are carrying vast quantities of material to the leeward and completely remodeling the landscape. (See Pl. XXXII, *A*.)

An important modification in drainage has resulted from the passage of barchans across the dissected land surface of the Kaibito and Shato plateaus. Begashibito Canyon and to a less extent Shato Canyon have been broken into chains of short gorges by dunes that have poured over the canyon rims. The compartments thus formed are now occupied by swamps and lakes, singular features in a region of less than 6 inches of rainfall a year. The canyon that formerly drained the Red Lake region, to the southwest, is now replaced by a valley in which lakes, open flats, masses of dunes, bare rock floor, alluvium-walled ditches, and stretches of rock canyon are represented. The filling of depressions by dunes is actively in progress at Reservoir Canyon. (See Pl. XXXIII, *A*.) The floor of the upper part of this drainage channel is now level with its banks. (See Pl. XXXIII, *B*.) The springs in Reservoir Canyon constitute an almost indispensable water supply, and in anticipation of their complete destruction culverts have been constructed along the canyon floor. During the last five years sections of these artificial conduits have been deeply buried by dunes.

In varying degrees this process of filling is in operation throughout the Navajo country; in many places the wind is forcing sand over the canyon walls as well as building layers and mounds on their floors. For example, in 1913, between two periods of stream flow, Black Falls on the Little Colorado disappeared and horses could be ridden over its crest. (See Pl. XXXIII, *C*.) The amount of wind-borne sand required to establish this grade was estimated at 36,000 cubic yards. When water began to flow in response to July rains the dunes were quickly removed and the falls regained their form.

On the margins of temporary water bodies lacustrine, fluviatile, and eolian strata are all represented, and it is probable that part of the adobe has its origin in loess and the finer dune sands. The aggregate mass of wind-borne material supplied each year to the streams of the Plateau province must be large and constitutes a factor of significant proportions in the formula of subaerial denudation. In deposition it is mingled with débris from other sources, but it would appear that in most places the first stratum laid down by the current of ephemeral streams is sand of eolian origin, and that the matrix of stream boulders may be eolian sand deposited in place. As water and wind are alternately in control of the canyon floor, conditions are favorable for the preservation of wind ripples by alluvium or by eolian sand, and for the burial of stream and sun-made structures directly by eolian sand or indirectly by fluviatile deposition.

The results of detailed study of a group of 26 dunes 2 miles south of the Chinle Indian

School are condensed in the following statement. The dunes range in height from 8 to 40 feet. A composite profile is a compound curve 164 feet long. Beginning on the windward side with an upward slope of 10° for 80 feet, followed by a slope of 4° for 60 feet, the curve descends from the crest to the leeward with a gradient of 30° for 18 feet and 2° for 6 feet. As observed in groups of three, the crests of ripples were parallel for distances of only 3 inches to 1 foot, or in one place 3 feet. The texture of the sand was identical on both slopes; a body of fine grains, 0.16 to 0.20 millimeter in diameter, overlain by a sheet of scattered grains, 0.50 to 0.75 millimeter in diameter, or three times the size of the grains forming the body of the dune. The coarse grains were abundant on the crests, rare on the slopes, and mingled with fine grains in the trough. Gravity streams of sand were sliding down the lee slopes of all the dunes observed, building aprons of paper-thin strata in which grains of the two sizes were intermingled. Artificial and natural sections of dunes revealed curved and straight laminae of fine sand separated by sheets of coarse sand the thickness of a single grain. The included angles of cross-bedding laminae of 30 selected dunes ranged from 3° to 16°, with an average of about 6°. Angular cross-bedding is less common than the tangential variety.

WIND ABRASION—ETCHED ROCK.

In the Painted Desert, where the wind has almost uninterrupted sweep and where volcanic ash and alluvium are ready at hand, the conditions are favorable for eolian abrasion. Sand is dragged by the wind across bare rock, grinding and grooving its surface. The process is closely similar to corrasion by streams, and the resulting features are much alike. The work of the wind as a sand blast may be examined at a number of places, particularly on the Kaibito and Rainbow plateaus and in the Painted Desert. The most effective work is performed within 2 or 3 feet of the surface of the ground, and weakly cemented rock arranged in laminae dipping downward toward the wind appears to offer the most favorable conditions. (See Pl. XXXIV, *A* and *B*.)

Erosion features simulating forms produced by the natural sand blast include mushroom rocks and buttes with smoothed surfaces, rounded contours, and scalloped edges. With the production of some of the "mushrooms" or "rock babies," to use the Navajo term, the wind is chiefly concerned; in the making of others the wind has assisted; many of them have attained this shape without the aid of the sand blast. It was found that except in the rock babies less than 3 feet high the windward side was not eroded to a perceptibly greater degree than the leeward side and that the neck of the baby, which should be firm and hard if wind abrasion were dominant, was in reality surrounded by a collar of weathered rock.

Many smoothed buttes give the appearance of having been sandpapered by wind. That drifting sand has small value in their modeling is suggested by the facts that the smoothed surfaces are in many places high above the plane of effective wind work; that they are chiefly developed in a stratum of a particular type—one that assumes rounded contours under all conditions of weathering; and that the leeward and windward sides are about equally well carved and polished.

Cavities etched by wind are shallow basins rather than drill holes, and their interior surfaces are firm and hard. In the Navajo Reservation true wind-scoured pits may be seen, but most of the niches and small holes in the rock result from the action of ground water controlled by rock composition and structure. Their likeness to "wind-drilled holes" is striking (see Pl. XXXIV, *C*), but when closely examined they are found to expand and branch back of the orifice and to contain decomposed rock and leaves. Many of them serve as the homes of birds and bats.

In general it may be said that direct abrasive work of the wind in preparing land waste on a large scale is not a prominent feature of the geology of the Navajo country. As an agent that removes the products of decomposition and disintegration and therefore facilitates erosion the wind has high value.

CHAPTER VII.—ECONOMIC GEOLOGY.

AVAILABLE MINERAL RESOURCES.

The rocks of the Navajo country are mineralized only to a slight extent. Pegmatite veins and quartz reefs are unknown, and the basic igneous intrusions are unaccompanied by precious metals. Gold and copper are found in small amounts; peridot, garnet, and agatized wood are abundant in certain localities; and specimens of carnotite were collected. Sandstone and adobe for use in building are common, but limestone is relatively rare, and gypsum, though widely disseminated, does not occur in deposits suitable for mining. The accumulations of salt near the borders of the reservation are ample in amount for the Indian population but not for commercial exploitation. Petroleum issues from the strata in the San Juan Canyon, and oil wells have been drilled in the San Juan and Seven Lakes fields, with somewhat unsatisfactory results.

In addition to water the one deposit of large economic importance is coal, which occurs on Dutton, Chaco, and Manuelito plateaus, in Chuska Valley, and at Black Mesa.

GOLD.

DISCOVERIES.

Gold ornaments have not been found in the ruins of the cliff houses of northern Arizona, and the Hopis appear to have been introduced to this metal by the Spaniards. The Navajos likewise have no native term for gold, and the Spanish explorers, always on the lookout for gold and silver, vigorously expressed their disappointment at the absence of precious metals in the Navajo country. In spite of these significant facts, prospectors who have been able to circumvent the hostility of the native tribes have from time to time conducted explorations in the more accessible parts of the reservation, and the belief is still strong in certain quarters that gold in large quantities remains to be discovered in this section of the Plateau province. For this reason the following sketch of the history of the exploration for gold is given:

In 1869 a party of 22 prospectors, under the leadership of Calvin Jackson, reached San Juan River by way of Fort Wingate and Fort Defiance without finding gold or silver along the route.[1] One member of this party, Adnah French, is reported to have returned at a later date, and the worthless prospect holes in the shales underlying the lava at French Butte are credited to him. The unfavorable results obtained by the well-equipped Jackson expedition served to discourage prospectors for the next 20 years, but beginning with 1891 interest was again aroused by reports of discoveries on lower San Juan River and at Carrizo Mountain.

GOLD ON THE LOWER SAN JUAN.

Reports of rich deposits in the gravel bars and terraces of the San Juan, below the mouth of Montezuma Creek, caused the "Bluff excitement" of 1892. At this time it is said 1,200 people were working along the river in search of the precious metal, only to return empty-handed. In 1906 the Oregon Gold Mining Co. established near the mouth of Montezuma Creek a plant that cost approximately $12,000. Boilers, separators, and screens were installed, buildings were erected, and runways for the dredges were built. The plan was to treat large quantities of gravel taken from the bed of the river. Stock was sold, but according to the engineers in charge less than $100 worth of gold was recovered. At Zahn Camp, 3 miles below the mouth of Nokai Canyon and about 20 miles above the junction of the San Juan and the Colorado, a plant for washing the gravel bar has been installed. Work has been carried on here intermittently, and it is reported that a small amount of gold was obtained. The camp was abandoned during the summer of 1909.

At Spencer Camp, in the great bend of the San Juan, 6 miles below Zahn Camp, machinery has been erected for washing gravel in the terraces, bars, and talus and for crushing the partly disintegrated sand rock. Pierce riffles were used and gasoline power provided. The expense of installation was much increased by the necessity of procuring supplies and fuel from

[1] Hall, F., History of Colorado, vol. 2, p. 197, 1890.

Gallup, 160 miles distant. The plant was established on the supposition that gravel carrying 25 cents a ton could be treated for 10½ cents. Owing, however, to the unfavorable report of the consulting engineer, all work was "temporarily" abandoned in August, 1909.

In 1910 the Red Rock Mining & Exploring Co. was doing assessment work at the mouth of Copper Canyon. During the preceding year the San Juan Mining Co. installed a crusher and screens 4 miles below the mouth of Nokai Canyon and undertook the establishment of a line of boat transportation from Lees Ferry, on Colorado River. So far as known by the writer all gold-mining operations on the lower San Juan were discontinued in 1912.

That gold is widely distributed in small quantities in the San Juan Valley is indicated by reports that "nearly every pan from the bars shows a color." The metal, however, is in excessively fine flakes. The greatest obstacle to mining in this region is the cost of transportation, which is too great to justify commercial operations except on the basis of a yield much larger than any so far reported.

GOLD IN THE CARRIZO MOUNTAINS.

No minerals of value have been discovered in the Carrizo Mountains, but permits for prospecting there are frequently asked for, doubtless in ignorance of the fact that the mountains have been thoroughly explored. In 1891 two companies of prospectors, 15 men in all, entered this field without permission. Trouble between these men and the Navajos arose at once, and at the request of the Indian agent the Sixth Cavalry escorted the prospectors beyond the limits of the reservation. In the protest filed by the ejected men the claim was made that "very valuable deposits of gold and silver had been located." To test these claims and to consider the advisability of restoring this part of the Navajo Reservation to the public lands, a commission was appointed by the Secretary of the Interior. This commission, of which Gen. A. McD. McCook, U. S. Army, was chairman and J. G. Allyn secretary, visited the Carrizo area in May, 1892. They were accompanied by two geologists and one professional prospector. Two prospectors from Gallup, N. Mex.—William Smith and Olla Bishop—who had previously worked in the Carrizo Mountains and who claimed to know the location of rich veins, were later added to the party. During the two weeks devoted to an examination of this region small amounts of copper and iron pyrite were found but not in workable bodies, and the absence of gold and silver and lead ores was demonstrated. Eighteen of the most promising samples were assayed; three of them carried averages of 2.95 ounces of silver and 0.015 and 0.025 ounce of gold to the ton. The field and laboratory examination led the commission to report "that the region was barren of metallic wealth and worthless for mining purposes." [1] In spite of this well-considered report the belief remained that Carrizo Mountains were rich in mineral wealth, and in 1901 a party in charge of Tom Leaden, a prospector and miner of unusual ability, was outfitted by J. W. Worth. During this year a shaft was sunk at the most promising locality to a depth of 15 feet without discovering evidence of valuable mineral except some copper stains in joints near the surface. The work was continued during 1902 under the financial management of a Pennsylvania capitalist. The shaft was continued to a depth of 47 feet, and the whole mountain group was prospected with the greatest care for a period of four months, but no mineral deposits were found. Another party examined the mountains during 1907 without discovering anything of value.

COPPER.

OCCURRENCE.

Chrysocolla, malachite, and rarely azurite as disseminated grains, patches, or tiny bands of irregular orientation are found in the sandstones of the Navajo country, especially in the region north and west of Marsh Pass. In the Kaibito Plateau and Segi Mesas provinces exposures of copper-impregnated rock 10 to 50 square feet in area are not uncommon. At most of the localities visited the copper is included within the Navajo sandstone and the lowermost strata of the McElmo formation, but the sandstones of the Chinle formation are also stained with copper at a few places, particularly at fossil localities; and some hollow logs of petrified wood in the Shinarump conglomerate are lined with dark-green malachite.

[1] Comm. Indian Affairs Rept., 1892, p. 75.

Copper deposits on the Kaibito Plateau and along tributaries to the San Juan have long been known to the Navajos, who are constantly in search of turquoise and who have, therefore, a keen interest in all minerals and rocks of greenish tones. Specimens exhibited by the Indians led to exploration in Copper and Nokai[1] canyons, where numerous small pits testify to a somewhat thorough search.

WHITE MESA COPPER DISTRICT.

DEVELOPMENT.

In 1882 the region south of Navajo Canyon was carefully prospected by Thomas V. Keams, who with his companions located about 40 claims in the area known as the White Mesa or Keams copper district,[2] 35 of which were eventually recorded. On nearly all the claims development work has been undertaken, and prospect holes may be seen in many places. The excavations are usually 4 by 6 feet in cross section, 2 to 12 feet in depth, and grouped about the most promising surface exposures of ore. Shallow trenches and open cuts on the flanks of low mesas are also to be seen. Four short tunnels were noted, and several shafts 20 to 40 feet deep have been sunk at the intersections of prominent joints. It is reported that one shaft reached a depth of 212 feet without encountering ore except within a few feet of the surface. Much of the ore obtained remains on the ground. Some was removed to Tuba, and a small amount was carried to mills for testing. For the last 20 years, so far as known, no mining has been done in this district beyond the amount of assessment work required to validate titles.

The White Mesa copper district is about 100 miles from the railway at Flagstaff, and supplies may be delivered at the mines at a cost of about $60 a ton. The region is without water except for two wells of very small yield about 5 miles from the claims and shallow rock pools supplied by infrequent rains.

ORE DEPOSITS.

The copper ore at White Mesa occurs in the Navajo sandstone, a fine-grained rock composed of white and red quartz grains held together by calcareous and ferruginous, rarely siliceous cement. Cross-bedding is almost universal, and joints are well developed. The color of the rock is normally light red, but changes to greenish white, light green, and dark blue-green, with increasing amounts of copper. Patches of copper-stained rock are seen in the ledge and on the sides of shafts and pits, but no veins of ore are traceable on the surface and none are exposed in excavations. Some of the shafts in the White Mesa district reveal no copper; some have the richest ore at depths below 20 feet, others within a few feet of the surface, and still others at intermediate depths. Types of accumulation were noted as follows: (*a*) Bands of copper-bearing sandstone lining joints, (*b*) bands of copper-bearing sandstone on bedding planes and along the leaves of cross-bedded strata; (*c*) spherical areas of impregnated sandstone a few inches to a foot or more in diameter with dark-green centers surrounded by zones of light green which gradually change to red as the circumference is reached; (*d*) cylindrical and lozenge-shaped masses of copper-bearing sandstone with horizontal, oblique, and vertical axes; (*e*) widely distributed grains of ore varying from 1 to 30 to the cubic inch.

The most abundant copper mineral is chrysocolla, which constitutes approximately 80 per cent of the ore. Malachite forms irregular masses within the chrysocolla and occurs as isolated grains; in places it is associated with hematite. Azurite is rare. Samples of light-green ore were found by Hill[3] to contain 0.5 to 3 per cent of copper; the dark-green ore assayed between 5 and 8 per cent of copper, and one specimen from the Pais-Lee-Chee claim was found to carry 14 per cent of copper.[3] Ore of so high a tenor is uncommon, however, and the sample tested by Lunt,[4] which yielded 32 per cent copper, must have been carefully selected. The low average value of the ore, its extremely irregular distribution, its inaccessibility, the scarcity of water for leaching, and the absence of flux for smelting are conditions which make mining under present conditions unprofitable.

ORIGIN OF THE COPPER.

The distribution of copper ores in irregular patches, lining joint cracks, and separating

[1] Nokai is the Navajo term applied to Mexicans, who were among the earliest prospectors.

[2] Personal communication from E. S. Clark, of Phoenix, Ariz.

[3] Hill, J. M., Copper deposits of the White Mesa district, Ariz.: U. S. Geol. Survey Bull. 540, p. 163, 1913.

[4] Lunt, H. F., Copper deposits of the Kaibab Plateau: Am. Inst. Min. Eng. Trans., vol. 34, p. 989, 1904.

layers of irregularly bedded or cross-bedded sandstones has been noted in a number of localities in Arizona and adjoining States. It has given rise also to considerable discussion, but no generally accepted theory for the genesis of such ores has yet been advanced. The copper deposits of the Kaibab Plateau, described by Jennings,[1] and similar deposits on the Coconino Plateau, described by Emmons,[2] seem to be uninfluenced by igneous intrusions, and the idea is favored "that the ore has been leached down from above and is of secondary origin rather than that it is an original deposit from uprising solutions." Kohler[3] considers the process of disposition as "adsorption"—that is, the copper has been separated from solution by the action of clayey substances present in the rock. The tests made of this process by E. C. Sullivan in the Survey laboratory seem to indicate that it is an important factor in the explanation of such deposits. Kohler, indeed, goes so far as to suggest that even where copper is found associated with organic remains the deposition was induced by the film of clay surrounding the wood fragments.

A study of the deposits of copper in the "Red Beds" of Fremont County, Colo.,[4] showed that the primary ore is chalcocite and that the deposits are associated with carbonaceous beds. In fact, at Red Gulch coal is replaced by chalcocite. The presence of gypsum and barite at this locality indicate abundant sulphate solutions, permitting a reaction in which chalcocite and carbon replace each other. On this hypothesis only ordinary temperature of circulating water would be required, but oxygen would need to be brought in from the surface in large quantities. The improbability that surface water percolating through hundreds of feet of strata would retain large amounts of oxygen requires a revision of this hypothesis. In a discussion of copper deposits in sandstone Lindgren[5] calls attention to the fact that the characteristic water of the "Red Beds" is rich in chlorides and sulphates, chiefly of sodium and calcium, and at great depths would attain high temperatures and take up hydrogen sulphide from organic matter distributed sparingly through the rock. Under these conditions the cupric sulphate would probably become a sulphide, which though somewhat soluble in water of this type "might be precipitated by suitable minerals under favorable conditions." Lindgren concludes that the copper of the "Red Beds" finds its source in pre-Cambrian deposits and that its localization is the result of concentration by circulating atmospheric waters charged with chloride and sulphate.

In the Navajo country the copper ores, for the most part, replace the calcareous and ferruginous cement in the sandstones. The deposits are not associated with igneous intrusions nor with lines of fracture. They lie about 8,000 feet stratigraphically above pre-Cambrian sediments and from 1,000 to 1,200 feet above the "Red Beds" of New Mexico and Arizona. The Navajo sandstone, in which they occur, consists in part of consolidated dune sands; calcium carbonate is present; barium sulphate was not noted; sodium chloride and calcium sulphate, if present, are in quantities so minute as to be imperceptible in the waters issuing from these strata. Fragments of wood and of vertebrate bones are sparingly distributed. The fact that the copper is confined to one group of strata throughout which it is widely distributed would appear to indicate a sedimentary origin, but the source and the original nature of the ore and the details of the chemical process whereby the copper salts were concentrated are unknown. The minute quantities of carbonaceous matter and vertebrate fossils in the Navajo sandstone and the arid climate of Jurassic time are factors probably involved in the mode of origin.

COAL.

The distribution of coal in the Navajo country is practically coextensive with that of the strata of Upper Cretaceous age. As shown on the geologic map there are two large areas of Cretaceous rock between San Juan River and the line of the Santa Fe Railway—Black Mesa and the broad strip of diversified topography extending northeastward from Gallup to Shiprock. Two coal fields may therefore be dis-

[1] Jennings, E. P., Copper deposits of the Kaibab Plateau: Am. Inst. Min. Eng. Trans., vol. 34, p. 840, 1904.

[2] Emmons, S. F., Copper in the Red Beds of the Colorado Plateau region: U. S. Geol. Survey Bull. 260, p. 222, 1904.

[3] Kohler, Ernst, Adsorptionsprozesse als Faktoren der Lagerstättenbildung und Lithogenesis: Zeitschr. prakt. Geologie, vol. 11, pp. 49-59, 1903.

[4] Lindgren, Waldemar, Notes on copper deposits in Chaffee, Fremont, and Jefferson counties, Colo.: U. S. Geol. Survey Bull. 340, pp. 173, 174, 1908.

[5] Lindgren, Waldemar, Graton, L. C., and Gordon, C. H., The ore deposits of New Mexico: U. S. Geol. Survey Prof. Paper 68, pp. 76, 79, 1910.

tinguished—the Black Mesa coal field of Arizona and the Gallup-Durango coal field of New Mexico and Colorado.

BLACK MESA COAL FIELD.

Coal in quantities sufficient to justify mining was found in measured sections on the west, south, east, and northeast faces of Black Mesa. In the canyons dissecting the top of the mesa coal is also exposed, and it is probable that strata of coal extend with interruptions beneath the sandstone cap of the entire mesa. Coal is included in the strata of Howell Mesa and in the beds at its base; at Padilla Mesa thin beds of coal were noted by Mr. Pogue. The fragmentary Cretaceous beds underlying the lava caps of the Hopi Buttes region contain irregular layers of coal a few inches thick.

Coal is found in all three formations of the Cretaceous system represented in the Black Mesa field. In the Dakota sandstone the carbonaceous strata are impure and widely variable in extent, rarely attaining a foot in thickness. The coal is in lenses rather than in beds and, so far as observed, is without commercial value. The Mancos shale and the Mesaverde formation include beds of coal suitable for mining.

COAL IN THE MANCOS SHALE.

The Indian school at Tuba is supplied with fuel from a mine about 14 miles southeast of the agency. A section at the mine is as follows:

Section including coal beds at Tuba mine, Ariz.

	Ft.	in.
1. Shale, yellow, arenaceous	4	0
2. Shale, dark, with *Ostrea patina* and *Serpula* tubes	6	0
3. Coal	1	4
4. Shale	2	0
5. Coal, mined		8
6. Bone		1
7. Coal, mined	1	2
8. Bone		½
9. Coal, mined	3	6½
10. Shale, brown and gray	6	0
11. Coal in beds 6 inches to 2 feet thick, interstratified with shale	15	0
12. Sandstone, buff	4	0
13. Shale, arenaceous, with lenses of coal	10	0
	53	10

The coal beds in the Mancos formation of Black Mesa show wide variation in number and thickness. The greatest number of beds noted in the 11 sections measured is 12, and the thickest bed observed is a little over 6 feet thick. At some points no coal was found. Part of a section measured at the northeast edge of Black Mesa may be taken as typical.

Section of Mancos shale on Black Mesa 5 miles south of Bitsihuitsos Butte, Ariz.

[Measured by J. E. Pogue.]

	Ft.	in.
1. Shale, dark gray, with sandstone band	2	0
2. Coal		5
3. Shale, blue-gray	1	5
4. Coal	1	1
5. Shale, drab	1	7
6. Coal		6
7. Shale, gray		9
8. Coal	2	0
9. Shale and sandstone, drab and gray, thin bedded	1	6
10. Coal	1	0
11. Shale, gray, sandy	4	8
12. Coal		9
13. Shale and sandstone, gray, thin bedded	7	6
14. Coal, with bone and thin shale partings	6	2
15. Shale, dark gray, alternating with thin beds of sandstone	7	7
	38	11

At all localities noted the topography and the position of the sandstone roof are favorable for mining. The scarcity of water and the expense of constructing roads are, however, obstacles to be overcome.

COAL IN THE MESAVERDE FORMATION.

The Mesaverde formation contains much more coal than the Mancos in the Black Mesa field. The coal beds are in general thicker and more persistent. A mine producing about 1,600 tons a year supplies the Government school at Keams Canyon, two mines each yielding 100 to 200 tons a year are operated at the Hopi villages, and at many other points coal may be obtained from Mesaverde strata at slight expense. The arrangement of the coal-bearing strata on the south edge of Black Mesa may be illustrated by a section measured at the Keams Canyon mine.

Section of Mesaverde formation, including coal beds, at Keams Canyon, Ariz.

	Ft.	in.
1. Sandstone, gray, fine, with thin shale partings	30	0
2. Shale	1	4
3. Coal		8
4. Shale		7
5. Coal	1	3

	Ft.	in.
6. Sandstone, shaly, and shale	3	0
7. Coal	2	3
8. Shale, carbonaceous		5
9. Coal, "excellent blacksmith coal"		11
10. Shale, black		7
11. Coal	1	3
12. Clay		5
13. Sandstone, thin bedded, friable	60	0
	102	8

In the wall of the Moenkopi Canyon, 6 miles east of Blue Canyon store, the Mesaverde strata include the following coal beds:

Section in Moenkopi Canyon, Ariz.

	Ft.	in.
1. Sandstone, buff, thin bedded, fine grained	30	0
2. Coal	2	0
3. Sandstone, buff, massive	12	0
4. Coal	1	6
5. Shale, gray		5
6. Coal		4
7. Shale, black, carbonaceous		3
8. Coal	1	3
9. Shale and sandstone	12	0
	59	9

At three places examined on the north and east faces of Black Mesa the coal beds were partly concealed by talus; at other points the coal has been burned and the inclosing shale baked and crumbled, so that it was found impracticable to obtain satisfactory measurements. At Marsh Pass no coal was found in place, but in a section 6 miles southeast of the pass five coal beds, the thinnest 4 inches and the thickest 4 feet, were noted.

At Chilchinbito the coal-bearing strata underlying 440 feet of thick-bedded sandstone show the following arrangement:

Section of Mesaverde formation, including coal beds, at Chilchinbito, Ariz.

	Ft.	in.
1. Coal		6
2. Shale, carbonaceous	3	0
3. Sandstones, thin bedded, and gray-brown shales	15	0
4. Coal	1	4
5. Sandstone, shaly	3	6
6. Coal	1	1
7. Shale, gray, with plant fragments	1	1
8. Coal	2	2
9. Sandstone, thin bedded, and shale	10	0
	37	8

At a number of points along the rim of Black Mesa coal beds exceeding 2 feet in thickness were noted, and groups of strata 10 to 20 feet in thickness, including shale and coal, from which 3 to 5 feet of coal might be obtained, are not uncommon.

QUALITY OF THE COAL.

The coal from Black Mesa varies greatly in quality. Near Blue Canyon specimens were obtained which were firm and broke with a fracture similar to that of high-grade bituminous coal. On the other hand, coal beds 6 to 8 inches thick at two localities between Chilchinbito and Marsh Pass consist essentially of carbonized plant fragments embedded in sand and clay. So far as observed the coal in the southern part of the field is of somewhat better quality than that farther north. In general the coal from the upper beds of Black Mesa may be classed as subbituminous. Samples of coal from the mines at Tuba and at Oraibi were considered by Campbell [1] as "on or about the dividing line between bituminous and subbituminous coal."

Dry samples from the Tuba mine analyzed in the Survey laboratory contained 15.1 per cent of ash and showed a heat value of 6,415 calories or 11,550 British thermal units. The corresponding figures for the Oraibi coal are 11.78, 6,660, and 11,980. As compared with the coal from the Gallup area [2] the Black Mesa coals, so far as indicated by two analyses, have much more ash and a slightly lower calorific value but a higher percentage of fixed carbon.

DURANGO-GALLUP COAL FIELD.

Owing to its commercial exploitation coal in the New Mexico portion of the Navajo Reservation has received considerable attention. Mines producing 400 to 1,500 tons a year have been opened for Government use at St. Michaels, Fort Defiance, Tohachi, and Crown Point. Along the railway in the vicinity of Gallup coal mining is the principal industry; Allison, Navajo, Gibson, and Heaton are busy coal-mining camps.

In the Gallup district coal occurs in three formations of the Upper Cretaceous.[3] The Dakota

[1] Campbell, M. R., and Gregory, H. E., The Black Mesa coal field, Ariz.: U. S. Geol. Survey Bull. 431, pp. 229-238, 1911.

[2] Shaler, M. K., A reconnaissance survey of the western part of the Durango-Gallup coal field of Colorado and New Mexico: U. S. Geol. Survey Bull. 316, p. 423, 1907.

[3] It is of interest to note that fossil resin (wheelerite) was first described from the coal beds of the Gallup region. Loew, Oscar, On wheelerite, a new fossil resin: Am. Jour. Sci., 3d ser., vol. 7, pp. 571-572, 1874.

coal at Pyramid Butte and other localities near by is in thin lenses and traversed by numerous shale partings. The Zuni Indian School obtains its coal from two beds about 40 inches thick in the Mancos formation. At Satan Pass this formation includes a 10-foot bed of subbituminous coal of good quality. At the present time the coal mined in the southern part of the Durango-Gallup field is obtained from the Mesaverde formation. The beds are of wide extent and range in thickness from a few inches to 3 or 4 feet. The "third bed" in the Clark mine (abandoned), 4 miles west of Gallup, attains a maximum thickness of 8½ feet. Mining of coal in the Gallup area began in 1882. The production during the last four years was: 1912, 735,544 tons; 1913, 824,762 tons; 1914, 706,731 tons; 1915, 785,490 tons.

To those interested in the coals of the eastern portion of the Navajo country the following Survey publications will be found of value:

Schrader, F. C., The Durango-Gallup coal field of Colorado and New Mexico: U. S. Geol. Survey Bull. 285, pp. 241–258, 1906.

Shaler, M. K., A reconnaissance survey of the western part of the Durango-Gallup coal field of Colorado and New Mexico: U. S. Geol. Survey Bull. 316, pp. 376–426, 1907.

Gardner, J. H., The coal field between Gallup and San Mateo, N. Mex.: U. S. Geol. Survey Bull. 341, pp. 364–378, 1909.

OIL.

Oil has been found at two places in the Navajo country—at Goodridge, in the San Juan Valley, and at Seven Lakes, on the Chaco Plateau.

SAN JUAN OIL FIELD.

The significance of oil seeps in the San Juan Canyon about 30 miles below Bluff was first recognized by E. L. Goodridge, who in 1882 staked a claim at the town site named in his honor. Drilling was begun in 1907, and the next year high-grade oil under artesian pressure was struck at a depth of 225 feet in Crossing well No. 1, on the banks of the San Juan at Goodridge. Twenty-seven wells, nine of which are productive, had been drilled by the end of 1911. Since that date little work has been done in the field. The results so far obtained indicate that the oil is of good quality but that no great yield is to be expected.

The oil occurs in five beds of sandstone of the Goodridge formation, of Pennsylvanian age and the productive wells are in a synclinal trough between the Raplee and Mitten Butte anticlines. Development has been limited to the north side of the San Juan, though south of the river the geologic conditions are equally favorable for the production of oil.

The geography, stratigraphy, structure, and economic aspects of the San Juan oil field are discussed in the following reports:

Gregory, H. E., The San Juan oil field, San Juan County, Utah: U. S. Geol. Survey Bull. 431, pp. 11–25, 1911.

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

SEVEN LAKES OIL FIELD.

The presence of petroleum in surface sand near Baker's trading post and the finding of gas in wells at Gallup led to exploration for oil in this vicinity. Several unsuccessful wells, the deepest 1,500 feet deep, were sunk along the west base of Dutton Plateau in 1910.

Oil was discovered on the Chaco Plateau in 1911.

In sinking a well for water in sec. 18, T. 18 N., R. 10 W. New Mexico principal meridian, Henry F. Brock unexpectedly found a considerable amount of gas and some oil. As a result 3,000 claims were located in 20 townships near by, and drilling on a moderate scale was begun. By the end of 1912 oil with gas had been found in six wells, in quantity not sufficient to justify exploitation on a commercial scale, and in 1913 the field was practically abandoned. The petroleum was encountered between 350 and 600 feet below the surface and, so far as known, in strata of the Mesaverde formation, which in this locality dip to the north and northwest at an average angle of about 2°.

SALT.

No deposits of salt of commercial value are known within the limits of the Navajo Reservation. Small amounts of salt are commonly found in this region, however, particularly in strata of Permian (?) age, and the water from wells at Adamana and other points along the railway and also from certain springs in the Moenkopi formation is so highly charged with saline matter as to be unfit for use. Before the establishment of trading posts the Hopis obtained salt from the "salt spring" near Winslow (Sunset Crossing), on the Little Colorado, and from the Zuni Salt Lake. A chemical analysis of the evaporation residue of the brine at Winslow gave the following result:

Analysis of residue from brine from Winslow, Ariz.[1]

	Per cent.
Chloride of sodium	78.79
Chloride of calcium	5.48
Chloride of magnesium	12.16
Sulphate of lime	3.07
Traces of alumina, oxide of iron, and loss	.50
	100.00

PRECIOUS STONES.

PERIDOT.

Olivine suitable for gem purposes (peridot) occurs at a number of localities in the Navajo country. In the basic rocks of volcanic necks and dikes it occurs as phenocrysts; in lavas it not uncommonly appears as a group of grains occupying vesicles. In localities where peridots are abundant the matrix is a breccia or agglomerate of volcanic origin. The most accessible collecting ground for peridots and the one so far yielding the largest amount of gem material is Buell Park, in the Red Lake volcanic field, but the necks and dikes at the foot of Red Lake also yield peridot, and gems have been obtained at Black Rock, near Fort Defiance. At Peridot Ridge, in Buell Park, the gems are found in place in a large mass of agglomerate, a rock composed of rounded and angular fragments of shonkinite (?), sandstone, shale, granite, quartz, and various other ingredients, set in a dark-greenish paste. Minerals associated with the peridot include pyrope garnets, emerald-green diopside, calcite, titanic iron ore, limonite, enstatite, augite, biotite, and a large amount of serpentine. The peridots are freed by the disintegration of the agglomerate and are thickly spread over the slopes and flats at the southeast base of Peridot Ridge. The gravel strewn over the surface and built into mounds by ants contains from 20 to 60 per cent of peridot in sizes of 4 millimeters and less. Although this ground has been searched by the Indians for many years, gems of 1 to 2 carats' weight, particularly those of yellow-green tones, are abundant, and a few clear golden-green stones weighing over 3 carats were found. It is believed by Sterrett,[2] who described these deposits, that a large supply of gems might be obtained by working over favorable areas of the valley floor.

GARNET.

In curio and jewelry stores of many western cities "Arizona rubies" are offered for sale, both as uncut stones and as jewelry. At the trading posts within the Navajo Reservation quantities of these stones may be seen. They have been collected by the Navajos, who find a ready market for them. The "Arizona ruby" is a pyrope garnet with the characteristic color of Burgundy wine; lighter shades are frequently found, however, and dark-red stones are not uncommon. Selected specimens possess great beauty and are much in demand, but most of the stones have little value as gem material because of their small size or imperfections.[3]

Garnets were seen in association with basic intrusive rock at more than 20 localities in this region. They are sufficiently abundant to be of commercial importance at four localities—Buell Park, in the Red Lake volcanic field, and Garnet Ridge, Mule Ear, and Moses Rock, near the Arizona-Utah boundary. In addition to their commercial value the garnets possess considerable interest as regards their origin and mode of occurrence. Blake[4] assigns the garnets in the alluvium at Fort Defiance to "granitic and metamorphic rocks of the [Chuska] Mountains." Newberry[5] believed that the garnets were derived from the decomposition of the [Shinarump] conglomerate. Sterrett[6] and Woodruff[7] consider the deposits in which the garnets are found as probably of glacial origin.

It is my belief that the garnets are derived from none of the sources mentioned. No granitic nor metamorphic rock was observed

[1] Loew, Oscar, U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 628, 1875.

[2] Sterrett, D. B., U. S. Geol. Survey Mineral Resources, 1908, pt. 2, pp. 832-835, 1909.

[3] For a mineralogic and economic discussion of the Arizona garnets see Sterrett, D. B., U. S. Geol. Survey Mineral Resources, 1908, pt. 2, pp. 823-827, 1909; Gregory, H. E., Garnet deposits on the Navajo Reservation, Arizona and Utah: Econ. Geology, vol. 11, pp. 223-230, 1916.

[4] Blake, W. P., U. S. Pacific R. R. Expl., vol. 3, pt. 4, p. 38, 1856.

[5] Newberry, J. S., op. cit. (Ives expedition), p. 93.

[6] Sterrett, D. B., U. S. Geol. Survey Mineral Resources, 1908, pt. 2, pp. 823-827, 1909.

[7] Woodruff, E. G., Geology of the San Juan oil field, Utah: U. S. Geol. Survey Bull. 471, pp. 85-86, 1912.

in the Chuska Mountains; the Shinarump conglomerate is without garnets, and a study of the "garnet-bearing drift" in the northern part of the reservation proved it to be of igneous rather than of glacial origin.[1] Wherever observed the garnets are genetically related to igneous intrusions and occur most abundantly in agglomerate of volcanic origin. In the Red Lake and Wheatfields volcanic areas and at various localities in the Agathla area garnets are found embedded in agglomerate. At Garnet Ridge, Moses Rock, and Mule Ear the material associated with the garnets is unique. In these areas the surface is strewn with unassorted heterogeneous accumulations of boulders and gravel grouped as hillocks and bands and presenting the appearance of glacial drift. The similarity to glacial deposits is strengthened by the fact that the most abundant boulders are those of granite and gneiss, which are not found in place within a hundred miles of this locality. The presence of snubbed and soled and polished fragments is also suggestive of ice work. However, on closer examination it was found that dikes and irregular intrusive masses in each of the garnet fields contained this unusual material, and there was no reason to assume that the "drift" and its included garnets were of other than volcanic origin. The ultimate source of the garnets appears to be a richly garnetiferous diorite gneiss, boulders of which are fairly abundant as inclusions in igneous rock.

JASPER, OR PETRIFIED WOOD.

Silicified wood is of common occurrence on the Navajo Reservation. It is universally present in the Shinarump conglomerate, is widely distributed in the Chinle formation, and is also found in the McElmo formation, the Dakota sandstone, and Tertiary sediments. Of the wood in these formations only that of the Chinle beds is of such color as to be of commercial importance. The petrified forests at Adamana, Lithodendron Creek, Beautiful Valley, Round Rock, and Willow Springs are probably the largest deposits of jasper in the world. With the jaspers are varying amounts of chalcedony, amethyst, and quartz crystals. Much of the jasper is highly colored; various shades of red are perhaps most common and range from lusterless brown to brilliant scarlet; the scale of yellow tones is particularly complete; patches of black and dark-blue jasper form a striking contrast to the more brightly colored portion of the broken logs. (See p. 49.)

BUILDING MATERIALS.

Like the cliff dwellers, the traders, missionaries, and Government officials in the Navajo country have constructed their buildings from the materials at hand—adobe and stone from various geologic formations. At Leupp, Tolchico, and Chinle the buildings are constructed in part of Moenkopi sandstone; at Fort Defiance, wood, adobe, brick, and Chinle sandstone have been utilized. The Red Lake store is built of McElmo sandstone. The rock for the Indian school at Tyende and for the recently constructed buildings at Tuba was obtained from the La Plata group. At Crown Point, Keams Canyon, and the Hopi villages quarries have been opened in Mesaverde strata. With the exception of the Todilto limestone none of the rock used can be classed as high-grade building material, and the Navajo sandstone in particular is very susceptible to changes of weather.

Clay suitable for brick is very rare in the region between the Puerco and the San Juan. The strata are prevailingly arenaceous, and the alluvial deposits are almost wholly sand and gravel, in many places charged with lime or gypsum. The Mancos shale affords the best brickmaking material in this region, and a plant 2 miles east of Gallup utilizing it was operated for a time. Quarry sites in the Mancos should be selected with care, however, for these shales in many places carry much lime, gypsum, and carbonaceous material. Semirefractory clay obtained from Cretaceous beds at Clarksville and Gallup is used for lining copper converters at Jerome and other points in southern Arizona.

[1] Gregory, H. E., The igneous origin of the glacial deposits on the Navajo Reservation: Am. Jour. Sci., 4th ser., vol. 40, pp. 97-115, 1915.

Strata meriting investigation as producers of lime are the Kaibab and Todilto limestones. Calcareous bands in the Moenkopi appear to be too impure and too variable to justify quarrying, and the limestone conglomerates of the Chinle are also sporadic and of small extent. From the Kaibab limestone at Flagstaff a kiln produces a small amount of lime for local use. Chemical analyses showed this rock to be suitable for cement, but local conditions prevented profitable commercial development.[1] The Todilto limestone capping the Wingate sandstone at Frederick's trading post was quarried and burnt for lime at various periods between 1889 and 1908. Lime from this bed used at Fort Wingate and Fort Defiance gave satisfactory results.

[1] Personal communication from John D. Guthrie, forest supervisor.

At Woodruff, on the Little Colorado, and to a less extent at Holbrook, St. Joseph, and Winslow the thin bands of gypsum found in the Moenkopi formation are used on a small scale as a source of plaster.

CARNOTITE.

In Monument Valley a uranium-vanadium mineral, probably carnotite, was found among the pebbles of the Shinarump conglomerate and in association with petrified wood of the Chinle formation.

APPENDIX.—GEOGRAPHIC TERMS.

The Navajo language possesses a number of sounds unfamiliar to the English ear, and for this reason the spelling of Navajo place names varies with different authors. Heretofore there has been no escape from this confusion, for no comprehensive study of this difficult language had been made. Recently, however, two scholarly works have been published by the Franciscan fathers—"An ethnologic dictionary of the Navajo language" (1910) and "A vocabulary of the Navajo language" (1912)—and the worker in this field is provided with a better standard than his untrained ear. In the following table these volumes are treated as authoritative for all terms concerning which doubt has arisen. The Hopi language is better known, and the publications of the Bureau of American Ethnology furnish a reliable guide for the spelling and meaning of place names.

Spanish and English terms offer few difficulties, although names in these languages have suffered mutilation to some extent. Some terms, for example, Canyon de Chelly, the product of erroneous translation, are too firmly fixed in the literature to justify reconstruction.

In the subjoined table all names appearing on the geographic map have been listed except such as are well established both in spelling and in application and a few about which no satisfactory information could be obtained.

Geographic names in the Navajo country.

Name.	Geographic feature.	Province.	Authority.	Significance or origin.	Other names in use.
Agathla	Volcanic peak	Monument Valley	Topographic map.	Obscure; Navajo, agha=wool; la=much; much wool.	
Alcove	Canyon	Gothic Mesas	This paper	Alcoves in canyon walls.	
Alhambra Rock.	Dike	Monument Valley	Usage	Topographic form	
Awatobi [1]	Historic ruined pueblo; spring.	Black Mesa	J. W. Fewkes	Hopi, high place of the Bow people.	Talahogan, Awatubi.
Azansosi	Mesa	Segi Mesas	This paper	Navajo, slim woman	
Beast, The	Volcanic neck	Black Creek Valley.	do	Topographic form	
Begashibito	Canyon	Shato Plateau	do	Navajo, begashi=cow; bito=water.	Bako - shi-bito; Beki-shibito.
Bekihatso	Lake	Chinle Valley	do	Navajo, beek'id=lake; hatso'o=large in area.	Pragaatzo.
Bennett	Peak	Chaco Valley	United States Army, 1892.		Mount Bennett.
Betatakin [2]	Prehistoric cliff dwelling.	Segi Mesas	United States Land Office, 1910.	Navajo, side hill house	
Bidahochi	Butte and spring.	Hopi Buttes	Usage; this paper.	Navajo, red rock slide	Biddehoche.
Biltabito	Settlement; spring.	Chaco Valley	do	Navajo, spring under a rock.	Beclabato.
Bitsihuitsos	Butte	Chinle Valley	This paper	Navajo, at the base of a cliff.	Pitsebytso.
Black	Mesa	Black Mesa	Usage; this paper.	Navajo, Dzilijini=black streak mountain (coal beds).	Zilh-le-jini; Black Mountains.
Black Mesa	Province		This paper	Includes Black Mesa	
Black Creek Valley.	do		do	Includes Black Creek Valley.	
Blackhorse	Creek	Chaco Valley	Usage	Name of a Navajo chief.	
Black Knob	Butte	Painted Desert	This paper	Isolated butte of lava	Pogue Butte; Lava Butte; Black Peak.
Black Pinnacle	do	Defiance Plateau.	Topographic map.	Navajo, Tsezhini=black rock.	Sajini; Sezhini.

[1] Visited by Tovar and Cárdenas in 1540. Destroyed in war, 1700. Now in ruins.

[2] One of the Navajo national monuments.

Geographic names in the Navajo country—Continued.

Name.	Geographic feature.	Province.	Authority.	Significance or origin.	Other names in use.
Blue Canyon	Canyon; store	Black Mesa	Usage; this paper.	Navajo, Bokogo dotklish=blue canyon.	Boo-koo-dot-klish.
Boiling	Spring	Segi Mesas	This paper	Navajo, Tohalushi=boiling water.	To-haul-hace.
Bonito	Canyon	Defiance Plateau.	Simpson, 1850, and earlier.	Spanish, beautiful	Canoncito Bonito.
Bridge	do	Rainbow Plateau.	This paper	Spanned by Rainbow Natural Bridge.	Sebige-hotsou.
Buell Park	Valley	Defiance Plateau.	Usage	Named for Maj. Buell, U. S. Army.	Yule Park; Jewell Park; Bule's Park.
Burro	Spring	Tusayan Washes	do		
Canyon de Chelly.[1]	Canyon	Defiance Plateau.	Simpson, 1850; topographic map.	Navajo, tseye=in the rocks.	Challe; Dè Chelley.
Canyon del Muerto.	do	do	Topographic sheet.	Spanish, canyon of the dead; canyon is lined with ruins.	
Carrizo	Province; mountain.	Carrizo Mountain.	Usage	Spanish, reed grass	Carriso.
Carson	Mesa	Chinle Valley	This paper	Named for Kit Carson	
Cha	Stream and canyon.	Rainbow Plateau.	do	Navajo, Cha=beaver	Chalth.
Chaco [2]	Plateau and river.	Chaco Plateau; Chuska Valley.	This paper; Simpson, 1850, and previously.	Coal (?)	
Chaco Plateau	Province		This paper	Embraces Chaco Plateau.	
Chaistla	Butte	Monument Valley.	Topographic map.	Navajo, beaver rincon.	Cha-ez-kla.
Chaol	Stream and canyon.	Kaibito Plateau.	This paper	Navajo, piñon	
Chezhindeza	Canyon; mesa.	Carrizo Mountain.	W. B. Emery	Navajo, lava	Malpais Point.
Chilchinbito	Creek; canyon; settlement.	Black Mesa	This paper	Navajo, sumac springs.	Chilchi-vito; Chilchin-vito.
Chinle	Settlement; school; geologic formation; valley.	Chinle Valley	This paper; United States Indian Office; usage.	Navajo, at the mouth of the canyon.	Chinlee; Chinli.
Chinle and Pueblo Colorado valleys.	Province		This paper	Includes the valleys of Chinle and Pueblo Colorado creeks.	
Chinlini	Canyon	Carrizo Mountain.	do	Navajo, at the mouth of the canyon.	To chinlini.
Chuska	Mountain; mountain range; valley.	Chuska Mountains; Chuska Valley.	Simpson, 1850, and previously; this paper.	Navajo, Choshgai=white spruce.	Choiskai; Chusca.
Chuska Valley	Province		This paper	Includes Chuska Valley.	
Comar	Spring	Hopi Buttes	Topographic map.		Kaibito.
Comb	Ridge	Monument Valley.	This paper	Topographic expression.	
Copper	Stream and canyon.	Segi Mesas	Usage	Copper prospects	
Crozier [3]	Settlement	Chuska Valley	do		Two Gray Hills; Davies; Williams.
Dadasoa	Spring	Chuska Mountain	This paper	Navajo, corn spring(?)	
Debebekid	Lake	Black Mesa	Topographic map; this paper.	Navajo, sheep lake	Te-ye-ba-a-kit.
Defiance	Plateau	Defiance Plateau.	This paper	Named for Fort Defiance.	
Delnazini	Spring; store	Chaco Plateau	United States Army.	Navajo, standing crane.	Tiz-nat-zin.
Desha	Canyon	Rainbow Plateau.	This paper	Navajo, curved	
Deza	Headland	Chuska Mountain.	Topographic map.	Navajo, a point or promontory.	Tezah.
Dinne	Mesa	Gothic Mesas	W. B. Emery	Navajo, the Navajo people.	
Dinnebito	Spring; wash	Tusayan Washes; Painted Desert.	Usage	Navajo, Dinne=Navajo; bito=his spring.	Denebito; Denabito; Tinebito.

[1] Pronounced deshay. [2] Navajo name for river is Tsegilini, stream in white rocks. [3] United States post office.

Geographic names in the Navajo country—Continued.

Name.	Geographic feature.	Province.	Authority.	Significance or origin.	Other names in use.
Dot Klish	Canyon	Black Mesa	This paper	Navajo, blue	Boo-Koo-dot-Klish.
Dutton	Plateau	Dutton Plateau	do	Named for Capt. C. E. Dutton.	
Dutton Plateau	Province		do	Includes Dutton Plateau.	
Egloffstein	Butte	Hopi Buttes	do	Named for Frederick F. W. von Egloffstein of the Ives Expedition.	
Espejo	Spring	Moenkopi Plateau.	do	Named for Antonio de Espejo, Spanish explorer, 1583.	
Figueredo	Creek	Chuska Mountain; Chuska Valley.	do	Named for Roque de Figueredo, missionary to the Zunis, 1629.	
Fluted Rock	Butte	Defiance Plateau.	Usage	Bordered by columns	Black Rock; Zilh-Tusayan.
Ford	do	Chuska Valley	do		Wilson's.
Garces	Mesas	Tusayan Washes	This paper	Named for Francisco Garcés.	
Garnet	Ridge	Chinle Valley	do	Sources of the Arizona garnets.	
Goodridge	Geologic formation; bridge; store.	San Juan Valley	E. G. Woodruff; this paper.	Named for E. L. Goodridge.	
Gothic	Wash	Gothic Mesas	Macomb, 1859	Type of dissection	
Gothic Mesas	Province		This paper	Includes Gothic Wash	
Greasewood[1]	Spring	Defiance Plateau; Pueblo Colorado Valley.	do	Navajo, Duwuz, hibito=spring among the greasewood.	Dewogibito.
Hamblin	Creek	Painted Desert	do	Named for Jacob Hamblin.[2]	
Hano[3]	Settlement	Black Mesa	Usage	Hopi, eastern people	
Hasbidito	Valley; stream; spring.	Chuska Mountains; Chinle Valley.	Topographic map; T. M. Prudden.	Navajo, turtle dove	Hospitito.
Hogansaani	Spring	Gothic Mesas	This paper	Navajo, lone house in the desert.	Ojo de Casa; Hogan Sayani.
Hope	Window	Chinle Valley	do	Named for Edna Earl Hope.	
Hopi	Buttes	Hopi Buttes	do	Group of igneous buttes on Hopi Reservation.	Blue peaks; Rabbit Ear Mountain; Moqui Buttes; Moki Buttes.
Hopi Buttes	Province		do	Includes the Hopi Buttes	
Hoskinnini	Mesa	Segi Mesas	do	Name of a Navajo headman.	
Hotevila[4]	Spring; settlement.	Black Mesa	Usage		
Howell	Mesa	Moenkopi Plateau	This paper	Named for E. E. Howell, geologist of the Wheeler Survey.	Cedar Mesa.
Ives	do	Hopi Buttes	do	Named for Lieut. Joseph C. Ives.[5]	
Jadito	Spring; canyon; wash.	Black Mesa; Tusayan Washes.	Usage	Navajo, antelope spring	Jetty-to.
Junction	Canyon	Rainbow Plateau	United States Land Office, 1910.	Enters near junction of Colorado and San Juan rivers.	
Kaibito	Spring; plateau	Kaibito Plateau	Topographic map; this paper.	Navajo, willows at a spring.	Kaipeto.
Kaibito Plateau	Province		This paper	Includes Kaibito Spring.	
Keams	Canyon and settlement.	Black Mesa	Topographic map.	Named for Tom Keams[6].	

[1] Two springs of this name mapped; there are several others.
[2] Jacob Hamblin served as guide for Maj. Powell.
[3] Hano was colonized by Tegua peoples early in the eighteenth century.
[4] Hopi pueblo built within recent years by secession from Oraibi.
[5] The party in charge of Lieut. Ives traversed this mesa in May, 1858.
[6] Thomas U. Keams made the first permanent settlement in the Hopi country.

Geographic names in the Navajo country—Continued.

Name.	Geographic feature.	Province.	Authority.	Significance or origin.	Other names in use.
Keet Seel[1]	Cliff dwellings	Segi Mesas	United States Land Office, 1910.	Navajo, broken pottery	Kit sil; Kit siel.
Klethla	Valley	Shato Plateau	Topographic map		
Laguna	Canyon	Segi Mesas	Usage	Lakes in canyon	Tsegi; Sagy.
Leroux	Stream and valley.	Pueblo Colorado Valley.	Whipple, 1856	Named for Antoine Leroux, guide for Whipple and for Sitgreaves's expedition.	Le Roux.
Lime Mountain	Peak	Defiance Plateau	United States Land Office, 1909.	Prominent landmark	
Lithodendron	Creek	do	Whipple, 1856	Petrified forest	Carrizo.
Lizard	Spring	Chinle Valley	This paper	Navajo, nashbito=lizard water.	
Lohali	Point on mountain.	Black Mesa	Topographic map; this paper.	Navajo, fish spring	Hlohahle.
Lokasakad[2]	Spring	Black Mesa; Hopi Buttes.	Topographic map	Navajo, place where reeds grow.	Lokasakal; Lukasakad; Lucasaka; Lucacsaca.
Lolomai	Headland	Black Mesa	This paper	Hopi, good, name of a prominent Oraibi chief.	
Lookout Ridge	do	Navajo Mountain	do	Point of view on Navajo Mountain.	
Lukachukai	Stream; mountain.	Chuska Mountains; Defiance Plateau.	Usage; this paper.	Navajo, luka chugai= patches of white reeds.	Carrizo (for the stream).
Maito	Spring	Chinle Valley	Topographic map	Navajo, coyote spring	Mayeto.
Manuelito	do	Chuska Valley	Usage	Name of Navajo chief	
Manuelito Plateau.	Province		This paper	do	
Marcou	Mesa	Hopi Buttes	do	Named for Jules Marcou, geologist of Whipple expedition.	
Matthews	Peak	Chuska Mountains.	do	Named for Washington Matthews, ethnologist.	
Meridian	Butte	Monument Valley.	do	Butte near 110th meridian.	
Mishongnovi[3]	Settlement	Black Mesa	Usage	Hopi, the other (of two sandstone columns) remains standing.	Mishonginivi; Mashongnivi.
Mitten	Butte	Monument Valley.	Usage; this paper.	Form of butte	
Mitten Rock	do	Chuska Valley	United States Army, 1892.	do	Little Shiprock.
Moa Ave	Settlement and spring.	Kaibito Plateau	Usage		Moenave; Moenave.
Moenkopi Plateau.	Province		This paper	Bordered by Moenkopi Wash.	
Moenkopi[4]	Settlement and wash.	Kaibito Plateau	Usage; this paper.	Hopi, running water	Moenkapi; Moencopie; Concaba.
Monument	Canyon; valley; pass.	Defiance Plateau; Monument Valley.	This paper and topographic maps.	Columns of sandstone	
Monument Valley.	Province		This paper	Includes Monument Pass and Monument Valley.	
Moonlight	Valley	Monument Valley.	Usage; this paper.	Navajo, Oljeto=moonlight water.	Oljato.
Mormon	Ridge	Kaibito Plateau	This paper	The Mormons were the first white settlers on Kaibito Plateau.	
Nasja	Creek; natural bridge.	Rainbow Plateau	United States Land Office, 1910.	Navajo, Noeshja=the owls.	

[1] One of the Navajo national monuments.
[2] Several springs with this name.
[3] Built about 1680 near site of ancient pueblo. Navajo term is Tseitsokit, great rocky dune.
[4] Called by Oñate, 1604, Ranchería de los Gandules.

Geographic names in the Navajo country—Continued.

Name.	Geographic feature.	Province.	Authority.	Significance or origin.	Other names in use.
Navajo	Mountain; canyon; spring; geologic formation.	Rainbow Plateau; Kaibito Plateau.	Usage; this paper.	The Navajo Tribe	
Navajo Mountain.	Province		This paper	Includes Navajo Mountain.	
Nazlini	Stream and canyon.	Defiance Plateau; Chinle Valley.	Topographic map.	Navajo, running crooked	Nashlini.
Nikehoshi	Spring	Chuska Mountains	This paper	Navajo, one eye; named for an Indian.	Negausi; Nicausi.
Nokai [1]	Stream; canyon.	Segi Mesas	Usage	Navajo term for a Mexican.	Noki.
Nottahndelit	Spring	Black Mesa	Topographic map.		Not-tahn-de-lit.
Oak	Stream and canyon.	Rainbow Plateau.	This paper	Navajo, chechil=oak	Se chil.
Oljeto [2]	Ranch	Monument Valley	Usage	Navajo, moonlight water	Oljato; Moonlight.
Oraibi [3]	Settlement; butte.	Black Mesa	do	Hopi, place of the rock.	Orayhe; Orabi, etc.
Padilla	Mesa	Tusayan Washes	This paper	Named for Fray Juan de Padilla, of Coronado's expedition, 1540.	
Padres	do	Defiance Plateau.	do	Named for Spanish padres.	
Painted Desert	Province		Ives, 1861; this paper.	Variegated color of rocks exposed.	
Pilot Rock	Peak	Defiance Plateau.	This paper	Prominent landmark	Mitten Peak.
Piute	Canyon	Segi Mesas	Usage	Tribe of Indians	Pahute; Paiute.
Porras	Dikes	Monument Valley	This paper	Name for Francisco de Porras, Spanish missionary, 1629.	
Pueblo Colorado [4]	Valley	Defiance Plateau; Pueblo Colorado Valley.	Ives and Newberry, 1858.	Spanish, red house, an ancient ruins.	
Quartzite	Canyon	Defiance Plateau.	This paper	Kind of rock	Blue canyon.
Rainbow	Plateau; natural bridge.	Rainbow Plateau.	This paper; presidential proclamation, 1910.	Piute, Barohoini=rainbow. Navajo, Nonnezoshi (na'nanzozh)=great arch.	Barohoini; Nonnezoshie.
Rainbow Plateau.	Province		This paper	Includes Rainbow Plateau.	
Redrock	Valley	Chaco Valley	do	Color of rock	
Round Rock [5]	Butte; store	Defiance Plateau.	Usage	Navajo, Tsenakani=round butte.	
Roundy	Creek	Painted Desert	This paper	Named for Bishop Roundy, Mormon pioneer.	
Sahotsoidbeazhe	Canyon	Chinle Valley	Topographic map.	Navajo, small meadow in a rock canyon.	Tsehetsoibiyazhe.
Salahkai	Mesa	Black Mesa	do		
Saneneheck	Butte	Shato Plateau	do	Navajo, thief rock	
Segeke	do	Segi Mesas	Usage	Navajo, square rock	
Segetoa	Spring	Defiance Plateau.	This paper	Navajo, water in the canyon.	Tsegitoe.
Segihatsosi	Canyon	Segi Mesas	Usage	Navajo, slim rock canyon.	Tsegihatsosi; Sagyatsosi.
Segi Mesas	Province		This paper	Navajo, mesas trenched by tseye=canyons.	
Seklagaidesa	Canyon	Gothic Mesas	W. B. Emery	Navajo, prominent white cliffs.	
Sehili	Settlement	Defiance Plateau.	Usage	Navajo, place where water disappears into a canyon.	Tsalee;Tse-a-lee; Salee.
Selukai	Sheep dip; spring.	Chaco Plateau	do	Navajo, reeds among the rocks.	Tse lukai; Tseloke.
Senatoa	Spring	Black Mesa	do		Tsenato.

[1] Nokai (Mexican) and Nokaito (Mexican water) are applied by the Navajos to a number of places.
[2] Formerly a post office and store; now unoccupied.
[3] Largest of the Hopi pueblos. Antedates the Spanish conquest.
[4] The name of Pueblo Colorado was originally applied to that portion of the valley above Ganado.
[5] Navajo term for Round Rock store is Bisdotl's desaki—blue clay point.

Geographic names in the Navajo country—Continued.

Name.	Geographic feature.	Province.	Authority.	Significance or origin.	Other names in use.
Setsiltso	Spring; store	Chinle Valley; Chaco Plateau.	United States Army, 1892; topographic map; this paper.	Navajo, water dripping from rocks.	Tsetsiltso; Tsatsil-too; Salltso; Saletso.
Sezhini	Butte	Defiance Plateau.	Topographic map.	Navajo, black rock(lava)	Tsezhini; Sajini; Black Rock; Malpais.
Shato	Stream; plateau; springs.	Shato Plateau	Topographic map; this paper.	Navajo, sha = sunny side to water—that is, water on south side of a rock wall.	Shonto.
Shato Plateau	Province		This paper	Includes Shato Springs	
Shinarump conglomerate.	Geologic formation.		do	Piute, Shinarav, the Wolf God whose weapons were logs of petrified wood.	
Shipolovi	Settlement	Black Mesa	Usage	Hopi, mosquitoes	Shipauiluvi, Shipowlawe, etc.
Shiprock	Peak	San Juan Valley; Chaco Valley.	do	Navajo, tsebidai= winged rock.	The Needle, Wilson Peak.
Ship Rock	Settlement				
Shongopovi [1]	Settlement and spring.	Black Mesa	Usage	Hopi, place of Chumoa grass.	Shimopovi, Shumuthpa, Shungopovi, etc.
Sichomovi [2]	Settlement	do	do	Hopi, place of wild currant bush mound.	Sichomivi, Siviuni, etc.
Simpson	Creek	Chuska Mountains.	This paper	Named for Lieut. J. H. Simpson.	Cottonwood.
Sonsela	Volcanic buttes	Defiance Plateau.	Topographic map.	Navajo, twin stars	Sonsola.
Spruce	Brook	Chuska Mountains.	This paper	Spruce trees	Tsehili, mountain brook.
Standing Redrock.	Stream	Chuska Mountains; Chaco Valley.	United States Army, 1892.	Sandstone columns	
Steamboat	Canyon	Black Mesa	Usage	Erosion remnant shaped like a boat.	
Stephen	Butte	Hopi Buttes	This paper	Named for A. M. Stephen, ethnologist.	
Tahchito	Stream	Black Mesa	Topographic map.		Tachito.
Talahogan	Spring	do	This paper; usage.	Navajo, house at the water.	Tallyhogan.
Tatezaka	Tank	Defiance Plateau.	Topographic map.	Navajo, tata, rock ledge; saka, cold.	
Teadepahto	Spring	Black Mesa	do		
Tegua [3]	Spring; settlement.	do	Usage	Hopi, moccasins	Tewa.
The Beast	Volcanic neck	Black Creek Valley.	This paper	Topographic form	
Tisnasbas	Stream; settlement.	Carrizo Mountain; Chaco Valley.	This paper	Navajo, circle of cottonwoods.	Tees-nos-pos.
Toadindaaska	Mesa	Black Mesa	Topographic map.	Navajo, to, water; adin, none; daaska, pool; dry lake bed.	Toatindahaska.
Toadlena	Settlement	Chuska Mountains	United States Army, 1892.		Toadalena.
Todilto Park	Valley	do	This paper	Navajo, sounding water.	
Todokozh [4]	Spring	Defiance Plateau; Chinle Valley; Gothic Mesas.	do	Navajo, sour water; that is, alkaline, salty, or sulphurous.	Totocong.
Togoholtsoe	do	Black Mesa	Topographic map.		Togoholtase.
Tohachi	Spring; settlement; geologic formation.	Chuska Mountains.	Usage; this paper.	Navajo, water is scratched for.	Tohatchie; Tohatchi; Little Water.
Tohadistoa	Spring	Black Mesa	This paper	Navajo, bubbling water is heard.	To-hah-le-tis-ta.

[1] Built about 1680 near site of ancient pueblo.
[2] Navajo term is Itt'hagi=halfway house. Present pueblo built about 1750.
[3] A colony of the Tegua Tribe settled Hano on first mesa.
[4] Local name for springs at several localities.

Geographic names in the Navajo country—Continued.

Name.	Geographic feature.	Province.	Authority.	Significance or origin.	Other names in use.
Tohasged	Spring	Chuska Valley	Topographic map.	Navajo, water is dug out.	Tohoscade.
Tohonadla	do	Gothic Mesas	United States Army, 1892.		
Tolani	Lakes	Tusayan Washes	This paper	Navajo, to lani=many water bodies together.	
Tolchico	Settlement	Painted Desert	Usage	Navajo, Red Canyon stream, name of Little Colorado River.	Tolchaco.
Torrivio Ridge	Mesa	Manuelito Plateau.	This paper	Named for Torrivio, Mexican assistant to Whipple, 1853.	
Tovar	do	Tusayan Washes	do	Named for Pedro de Tovar, of Coronado's expedition, 1540.	
Tseanazti	Stream	Chuska Mountains.	United States Army, 1892.	Navajo, rock fence	Tsa-a-no-sti.
Tuba	Settlement	Kaibito Plateau	Usage	Name of a Hopi man	Tuba City.
Tunitcha	Mountain	Chuska Mountains.	Simpson, 1850, and previously.	Navajo, tuntsa=much water.	Tunicha; Tumecha.
Tuntsa	Stream	Chuska Valley	This paper	Navajo, to=water; ntsa=large, referring to lakes.	Captain Tom's Wash.
Tusayan Washes[1]	Province		do	Zuni (?) name for Rocky Mountains (?); people of Usaya.	
Tuye[2]	Spring	Black Mesa; Chuska Valley.	Usage	Navajo, tuye=echo of thunder.	Togay; Togai; Tuyey.
Twin	Mesas	Hopi Buttes	This paper	Connected lava-capped mesas.	Zuni Mountain.
Tyende	Creek; mesa; school.	Chinle Valley; Segi Mesas.	do	Navajo, where they fell into a pit; that is, where animals mire.	Ta enta; Te en ta; Laguna; Kayenta.
Ventana	Mesa	Chinle Valley	Topographic map.	Several natural windows are found here.	
Venus Needle	Butte	Chuska Mountains.	This paper; K. C. Heald.	Tall, slim erosion remnant.	
View Point	Peak	do	do	Prominent headland at north edge of Lukachukai Mountain.	
Walker	Creek	Gothic Mesas	do	Named for Capt. Walker, of Macomb's expedition.	
Walpi[3]	Settlement	Black Mesa	Usage	Notch in the cliff	Hualpi; Wolpi; Gualpi, etc.
Ward Terrace	Mesa	Moenkopi Plateau.	This paper	Named for Lester F. Ward, geologist.	
Washington	Pass	Chuska Mountains.	Simpson, 1850	Named for Col. Washington, a governor of New Mexico.	Cottonwood.
Wepo	Spring, valley, or wash.	Black Mesa	Usage		Wipo; Weepo.
White top	Butte	Defiance Plateau.	This paper	White sandstone cap over red.	
Wide Ruin	Stream and valley; store.	do	Usage; this paper.	Ruins of ancient village.	
Wildcat	Volcanic peak	Kaibito Plateau	This paper	Navajo, nishduitso=mountain lion.	Nic-doit-soe.
Yale Point	Headland	Black Mesa	do	Named for Yale University.	
Zilbetod	Peak	Carrizo Mountains.	do	Navajo, dzil=mountain; betod=bare or bald.	
Zilditloi	Mountain	Chuska Mountain.	do	Navajo, dzil=mountain; ditloi=hairy or wooded.	Baigaichi.
Zillesa	Mesa	Black Mesa	do	Navajo, mountain surrounded by bare soil.	
Zilnez	do	Segi Mesas	do	Navajo, long mountain	Zihl Nez; Dzil nez.

[1] The name Tusayan or Province of Tusayan is commonly used for the region including the Hopi villages.
[2] A common name for springs at heads of box canyons.
[3] Built after 1680 near site of an ancient pueblo.

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