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GEOLOGY OF THE MONUMENT VALLEY-NAVAJO MOUNTAIN REGION, SAN JUAN COUNTY UTAH

BY

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GEOLOGY OF THE MONUMENT VALLEY-NAVAJO MOUNTAIN REGION, SAN JUAN COUNTY, UTAH

By ARTHUR A. BAKER

ABSTRACT

The Monument Valley-Navajo Mountain region is part of the Colorado Plateau and includes about 1,100 square miles in San Juan County, southeastern Utah, lying between the San Juan and Colorado Rivers on the north and the Utah-Arizona State line on the south. Included in the region are Navajo Mountain, the Rainbow Natural Bridge, and a part of the picturesque Monument Valley. The surface of the region is an upland, consisting of an alternating series of high eastward-facing escarpments and broad westward-sloping plateaus, dissected by the deep canyons of the San Juan and Colorado Rivers and their tributaries. The altitude above sea level of most of the surface is 4,500 to 6,000 feet. This region has unusual scenic beauty, with its varicolored rocks practically unobscured by soil and with its deep canyons, high cliffs, and a variety of fantastic rock forms carved by erosion.

The region is about 175 miles by road from Thompson, Utah, on the Denver & Rio Grande Western Railroad, and nearly 200 miles by road from Flagstaff, Ariz., on the Atchison, Topeka & Santa Fe Railway. A road from Flagstaff to Thompson crosses Monument Valley. Practically none of the area is tillable and under cultivation. The only inhabitants are about 20 white persons, who live at 4 trading posts, and about 100 Indians. The meager vegetation consists of shrubs and other small plants of desert types and a few trees; cottonwood trees grow sparsely along the stream courses, cedar and piñon grow on the uplands in scattered patches, and pine and spruce grow on the upper slopes of Navajo Mountain.

The exposed sedimentary formations range in age from Pennsylvanian to Quaternary. The oldest formation crops out in the deep, narrow canyon of the San Juan River in the eastern part of the area, and progressively younger formations are exposed toward the west in a succession of steep slopes, cliffs, and broad benches. The Upper Cretaceous Dakota (?) sandstone, Tropic shale, and Straight Cliffs sandstone crop out at the west boundary of the area. Cemented gravel that may be of Tertiary age floors several remnants of old erosion surfaces. An old surface stands about 1,350 feet above the river level near the junction of the San Juan and Colorado Rivers, and a small remnant northeast of Monument Pass stands about 1,250 feet above the San Juan River. The aggregate of the average thickness of the formations is about 8,200 feet. Most of the formations are of continental origin, but the Pennsylvanian Hermosa formation, the Upper Jurassic Carmel formation, and the Upper Cretaceous Tropic shale are marine, the Permian Rico formation is in part

marine, and the Lower Triassic Moenkopi formation may be marine. Among the beds of continental origin are several massive sandstones—the Cedar Mesa and De Chelly sandstone members of the Cutler formations, and the Wingate, Navajo, and Entrada sandstones—which were deposited either entirely or in part under eolian conditions. The Permian Cutler formation consists of 3 tongues of red beds and 2 massive sandstone members; the upper sandstone (De Chelly) wedges out toward the north near Clay Hill Crossing of the San Juan River, and the lower sandstone (Cedar Mesa) changes laterally into red beds a few miles east of the region.

Volcanic necks and dikes of basic igneous rock of Tertiary (?) age crop out at three localities. Alhambra Rock, a jagged spire of igneous rock, is a prominent surface feature, and because of its black color contrasts strikingly with the red rocks of the surrounding country.

The principal feature of the regional geologic structure is a westward or northwestward dipping monocline interrupted by several small transverse folds and the large dome of Navajo Mountain. The folds have a northerly trend, and the anticlines are characterized by steeply dipping east flanks and gently dipping west flanks. The Navajo Mountain dome is a huge, nearly circular dome which is probably underlain by a laccolithic intrusion of igneous rock. Only a few faults, all of them with small displacement, cut the rocks of the region.

The shaping of the land forms in the Monument Valley-Navajo Mountain region has been in progress since early Tertiary time, when the position of the main drainage courses was determined. As the ancient San Juan and Colorado Rivers cut through the nearly flat-lying Eocene rocks, their courses were superimposed upon folded older rocks and consequently are not controlled by the attitude of the rocks in which they are now entrenched. Meanders that were formed when the rivers were flowing high above their present channels have been entrenched at places where the channels have been cut down through hard rocks. The positions of streams tributary to the San Juan and Colorado Rivers, however, are closely adjusted to the structure of the underlying rocks.

Oil seeps from the Rico and Hermosa formations at several places in the Canyons of the San Juan River, and small amounts of oil have been produced from these formations by wells drilled in a syncline near Mexican Hat, a few miles east of the Monument Valley-Navajo Mountain region. The Rico and Hermosa formations contain the only petroliferous rocks that crop out in the region or that are known to underlie it. Several wells have been drilled on the Halgaito anticline, and one well has been drilled on the Organ Rock anticline, but none of the wells found large bodies of oil. Although none of these wells have been drilled deep enough to test the basal part of the Hermosa or underlying rocks, they have reached the principal zones that are oil-bearing near Mexican Hat. As oil has accumulated near the axis of a syncline at Mexican Hat, the oil-bearing strata at that locality apparently do not contain sufficient water to cause the accumulation of oil at the crests of anticlines. It is possible that a similar lack of water in these oil-bearing strata in the Monument Valley-Navajo Mountain region has permitted oil to accumulate in the synclines, but in the absence of extensive prospecting with the drill it is impossible to predict the degree to which water may have controlled accumulation of oil. The small production of oil thus far obtained and the difficulties and expense of exploration in this remote region are factors that would appear to discourage further drilling.

Various attempts have been made to mine placer gold from the gravel bars and terraces along the San Juan River, but the recovery of gold has been insufficient to repay the cost of operations. Copper minerals are present locally, impregnating the Shinarump conglomerate and sandstones in the Chinle formation, but prospecting has not revealed deposits of commercial value.

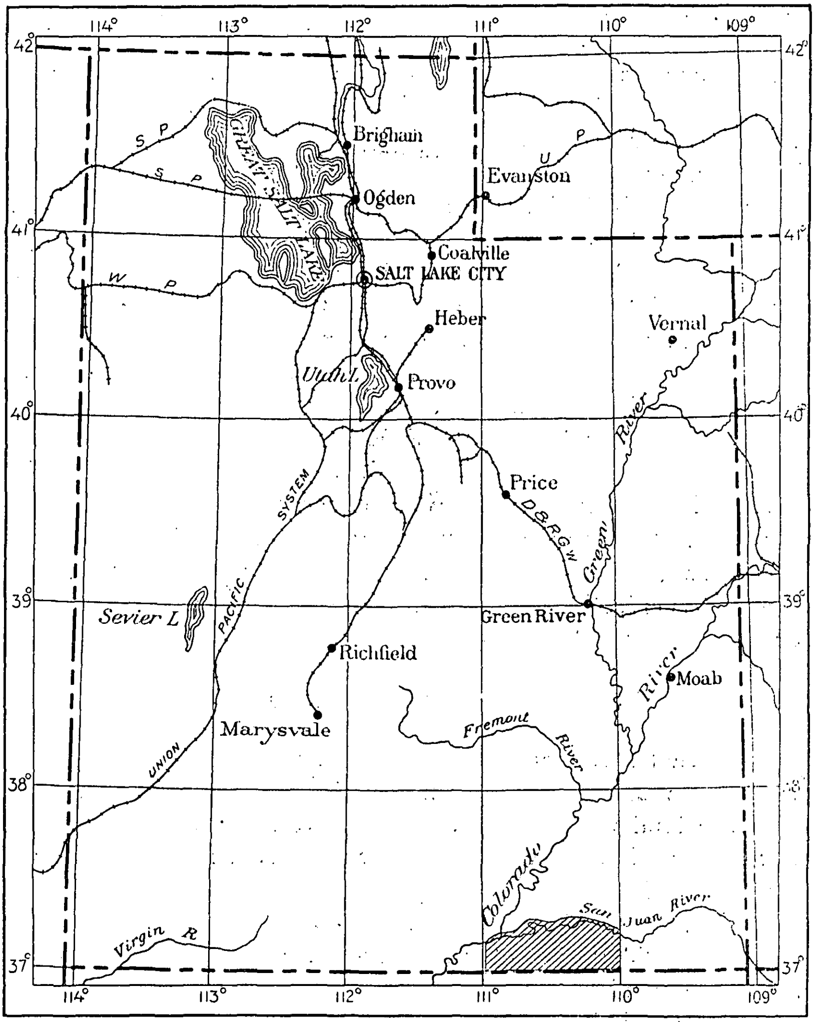


FIGURE 1.—Index map of Utah showing the location of the Monument Valley-Navajo Mountain region.

INTRODUCTION

LOCATION AND EXTENT OF AREA

The Monument Valley-Navajo Mountain region is a narrow belt of country in southern San Juan County, southeastern Utah, and is limited on the north by the San Juan and Colorado Rivers and on the south by the Arizona-Utah State line. (See fig. 1.) It extends westward from about the 110th to about the 111th meridian, a distance of 62 miles, and at its widest place is 26 miles across; its area is about 1,100 square miles. The region is part of the Colorado Plateau. It includes in its eastern portion much of the picturesque Monument Valley with its numerous buttes and spires, and in its western portion Navajo Mountain and the Rainbow Natural Bridge.

The Monument Valley-Navajo Mountain region and the adjacent country form an area of unusual scenic beauty, with its single lofty mountain peak, deep canyons, sheer cliffs, and varicolored rocks carved by erosion into a variety of fantastic forms. The varied scenic effects compacted into a relatively small area have attracted many visitors and will doubtless attract a greater number whenever the various parts of the region become more accessible.

A tract of 160 acres, including the Rainbow Natural Bridge, was set aside by Presidential proclamation May 30, 1910, as the Rainbow Bridge National Monument. White men first visited the bridge August 14, 1909, in a party under the joint leadership of W. B. Douglass and Byron Cummings.

All of the land in Utah south of the San Juan and Colorado Rivers is part of the Navajo Reservation. The part of the area west of the 110th meridian, which lies near the east range line of Tps. 41, 42, and 43 S., R. 17 E., was formerly a part of the Piute Indian Reservation but had been restored to the public domain in 1922. It was established as an addition to the Navajo Indian Reservation by act of Congress March 1, 1933.

PRESENT INVESTIGATION

The present investigation of the Monument Valley-Navajo Mountain region was undertaken primarily for the purpose of classifying the public land with respect to its oil possibilities. Reconnaissance examination of the area had previously revealed the presence of anticlinal folds.

The field work upon which this report is based was done in 1928, between May 20 and October 20. I was assisted in the mapping by L. W. Clark and L. A. Kelly during the entire field season and by L. G. Snow and R. M. Larsen during part of the season. The late J. W. Steele served the party as packer and Arthur Steele as assistant packer and cook.

The location and altitude of the different geologic boundaries and the location of geographic features were determined with the plane table and telescopic alidade. The triangulation method of mapping was used exclusively. Numerous triangulation points were established by expanding a triangulation network from a measured base line, and the features to be put on the map were then located by intersection or resection from these points. The accuracy of the triangulation, which was started in the eastern part of T. 42 S., R.

17 E., was checked occasionally during the work by measuring the distance between triangulation points with a steel tape and by checking the distance between land corners as located from triangulation in the part of the area where land surveys have been made. Altitudes with respect to mean sea level were determined by vertical-angle measurement and are based on the altitude of the water level of the San Juan River taken from the contour map of the river canyon,[1] which shows contours at intervals of 5 feet on the water surface. The altitude of the water surface varies with the discharge of the river, but as there was not unusually high water at the time of either the river survey or the present survey, it seems probable that the altitude taken from the river maps is less than 5 feet in error.

Individual members of the party carried on independent mapping under my supervision, but it is impracticable to indicate specifically the portions of the region for which each man is responsible. L. W. Clark and L. A. Kelly did the greater part of the mapping.

Automobiles and horses were used for transportation during the field work. The only use for automobiles was the transportation of supplies and members of the party to a few of the main camps. Part of the region was reached with saddle horses from a few such camps, but most of it was reached with saddle horses from a succession of short camps, to which supplies and light camping equipment were transported on pack animals. The last camp to be reached with automobiles was near the mouth of Nokai Creek. Pack and saddle animals working from this base camp were used to reach the valley of upper Nokai Creek and all the area that lies west of this creek.

Mapping in the vicinity of Navajo Mountain, particularly north and west of the mountain, was done with less detail than in the rest of the region. The difficulty of traversing this nearly impassable area, the distance to a base of supplies, the lack of feed for the horses, and the necessity of using the slower method of stadia-traverse mapping to prepare a detailed map made it inadvisable to attempt to make this part of the map commensurate in detail and accuracy with the rest.

ACKNOWLEDGMENTS

The industry and cooperation of L. W. Clark, L. A. Kelly, L. G. Snow, and R. M. Larsen, who served as assistants and who are responsible for the gerater part of the map, are here gratefully acknowledged. J. B. Reeside, Jr., was a member of the party during

[1] Plan and profile of Colorado River, Lees Ferry, Ariz., to mouth of Green River, Utah; San Juan River, mouth to Chinle Creek, Utah; and certain tributaries, U. S. Geol. Survey, 1922.

much of the field season and cooperated with me in a study of the stratigraphic problems of the area. F. P. Lowry was associated with the party for part of the season, and I desire to express appreciation for his willing cooperation and valuable assistance. Because of his skill in caring for the horses and his long experience in similar country, J. W. Steele contributed greatly to the progress of the work. I wish to acknowledge also the services performed by Arthur Steele as assistant packer and cook. H. D. Miser visited the field party and has offered valuable advice and criticism during the field and office work. Many of the inhabitants of the region rendered indispensable service to the party by caring for equipment, sharing limited water supplies, contributing information concerning little-known country, assisting in obtaining supplies and mail, and in numerous other ways. To J. H. Taylor, H. R. Goulding, John Wetherill, Ben Wetherill, W. W. Wilson, and many others I am especially indebted for their aid and cooperation.

GEOGRAPHY

SURFACE FEATURES

General features.—The surface of the Monument Valley-Navajo Mountain region, most of which is 4,500 to 6,000 feet above sea level, consists of several plateaus, each of which rises toward the east to the rim of a high eastward-facing escarpment. The San Juan and Colorado Rivers flow westward along the north boundary of the region through winding canyons. The canyons of numerous tributaries of the San Juan and the Colorado trench the plateau surfaces, particularly in the western part of the region, and divide them into many mesas and buttes. The solitary peak of Navajo Mountain rises high above the upland surface near the west boundary, and the small mesas, buttes, and spires of Monument Valley rise above a plateau surface in the southeastern part of the region.

The surface features of the region are shown on the topographic map, plate 2, and by the block diagram, plate 3. The map was constructed in the office from numerous altitudes determined in the field and therefore is not an accurate topographic map, but it portrays the surface features in a somewhat generalized form. For this map the topography of the lower walls of the canyons of the Colorado and San Juan Rivers was taken from the published map of the rivers.[2] The reconnaissance topographic maps of the Henry Mountains and Abajo quadrangles include the Monument Valley-Navajo Mountain region, but these exploratory maps prepared about 50 years ago are

[2] Plan and profile of Colorado River, Lees Ferry, Ariz., to mouth of Green River, Utah; San Juan River, mouth to Chinle Creek, Utah; and certain tributaries, U. S. Geol. Survey, 1922.

now of little practical value because of their small scale, large contour interval, and erroneous representation of land forms.

The maximum relief in the region is about 7,000 feet. The altitude of the summit of Navajo Mountain, the highest point, is shown as 10,416 feet on the Henry Mountains topographic map, but my observations indicate that it is about 10,250 feet. The lowest point is in the canyon of the Colorado River at the west boundary of the region, where the river surface is about 3,225 feet above sea level. Both points are in the western part of the region, and the distance between them is only 10 miles. The distance between the top of Navajo Mountain and the nearest point on the Colorado River is 8 miles. Local relief elsewhere in the region is 2,000 feet or more in short horizontal distances. The top of Douglas Mesa is slightly more than 2,100 feet above the water level of the San Juan River, which is only about 2⅓ miles distant. The south tip of No Man's Mesa is more than 2,000 feet above the bed of Copper Canyon, 3 miles to the east. The top of Piute Mesa, near the southeast corner of sec. 32, T. 41 S., R. 12 E., is 2,300 feet above the San Juan River, 2½ miles to the north.

Canyons of the San Juan and Colorado Rivers.—The San Juan River flows through a practically continuous canyon across the Monument Valley-Navajo Mountain region. From a point near the east boundary of the region the walls of the canyon become progressively lower toward the west, and their rims descend to river level near Clay Hill Crossing, where, for a short distance, the river flows through a wide valley, but at the Piute Farms (abandoned) it enters another canyon, which extends to the mouth of the river. The length of the meandering river canyon across the region is 104 miles; the air-line distance is only 55 miles. The altitude of the surface of the water drops from 3,980 feet at the east boundary of the region to 3,260 feet at the mouth of the river. East of Clay Hill Crossing the canyon has close precipitous walls with a maximum height of about 2,100 feet (pls. 7, *A*, *B*, and 8, *C*), but west of the crossing the river traverses belts of soft strata where the canyon is wide and other belts of resistant rock where the canyon is narrow and has practically vertical walls that rise several hundred feet above the river. The depth of the canyon ranges from 800 to 2,300 feet.

From the mouth of the San Juan River to the west edge of the region the Colorado River flows for 12 miles through a part of the winding Glen Canyon. This canyon is narrow and has steep walls surmounted by high rounded domes. Its maximum depth does not greatly exceed 1,000 feet except at the west boundary of the region, where the north end of Cummings Mesa rises about 2,300 feet above river level.

Upland surface of the region.—The surface features of the region vary in detail in different areas and can be assigned to four or more geographic areas or subdivisions. Gregory [3] divided the region into the Navajo Mountain, Rainbow Plateau, Segi Mesas, and Monument Valley subdivisions, and his classification is followed in this report (fig. 2).

The Navajo Mountain area includes only the isolated dome of Navajo Mountain (pls. 4, *A* and 12, *B*), which rises nearly 5,000 feet above the adjoining Rainbow Plateau. The lower flanks of the mountain are largely bare rock that has been carved into jagged promontories, spires, and pinnacles but presents many sheer walls 1,000 feet or more in height along the short, deep canyons that dissect the lower slopes. The upper slopes of the mountain are steep but are usually less rugged than the lower slopes. At its crest there is a nearly flat area perhaps half a square mile in extent.

The Rainbow Plateau area includes Cummings Mesa and the Rainbow Plateau and extends as far east as Piute Creek. It is trenched by numerous short, deep canyons of streams tributary to the San Juan and Colorado Rivers. In its eastern part a few domes of sandstone rise above a rolling surface broken by low ledges and shallow gulches. Toward the west the sandstone domes become more numerous, and north and west of Navajo Mountain there is an indescribable maze of high rounded knobs of sandstone separated by deep clefts and deep, narrow canyons; the height of many of the knobs is 1,000 feet or more. This part of the plateau presents a remarkable view when seen from the top of Navajo Mountain. The dissected area is bounded on the west by the sheer east wall of Cummings Mesa, which rises about 1,900 feet above the floor of Forbidding Canyon and extends north from the Arizona-Utah line nearly to the Colorado River. North of the river the dissected area is bounded by the south end of the Kaiparowits Plateau, which rises to an altitude of 7,500 feet above sea level, or about 4,300 feet above water level of the Colorado River.

The Rainbow Natural Bridge and several smaller ones, including the Owl and Hawkeye Natural Bridges, are in the Rainbow Plateau. The Rainbow Bridge is in the midst of the maze of sandstone knobs and canyons about 6 miles northwest of the summit of Navajo Mountain. It is a huge graceful sandstone arch spanning an inner gorge of Bridge Canyon (pl. 16, *B*). The northeast end of the arch rests upon the platform at the top of the inner canyon, but the southwest end coalesces with the wall of the main canyon. The height of the arch is 309 feet above the creek and 235 feet above the top of the inner canyon. It has a span of 278 feet. At its highest point the

[3] Gregory, H. E., The Navajo country: U. S. Geol. Survey Water-Supply Paper 380, pp. 44–49, pl. 1, 1916.

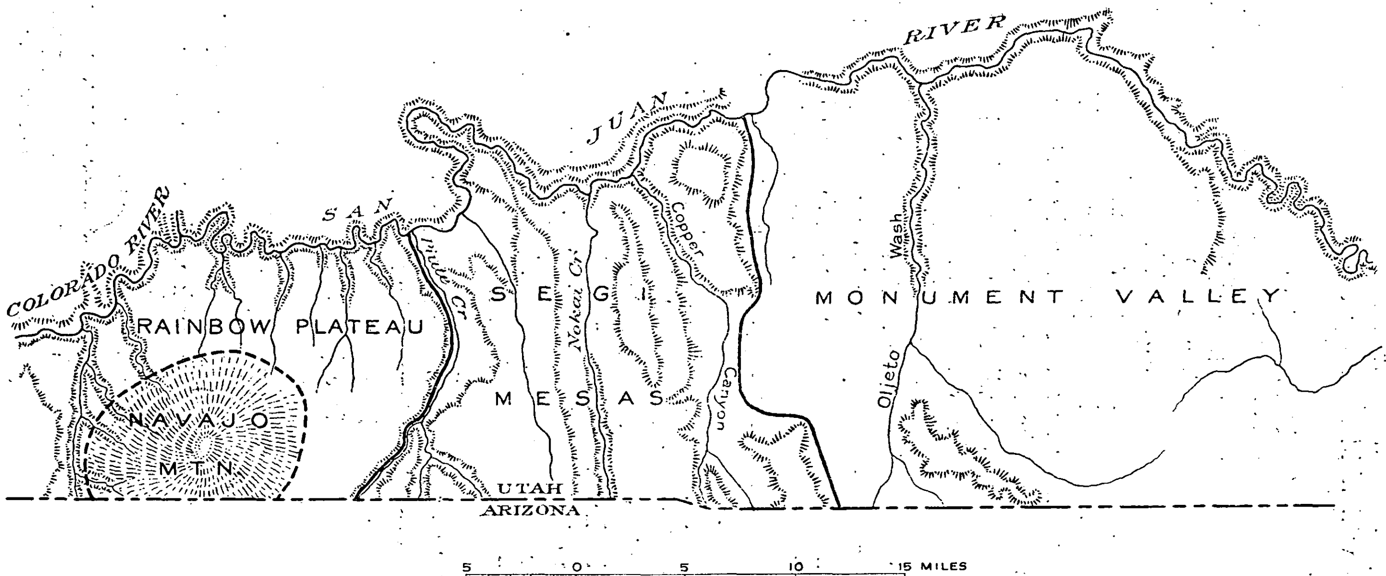


FIGURE 2.—Diagram showing the geographic subdivisions of the Monument Valley-Navajo Mountain region. The heavy lines mark the outlines of the named divisions.

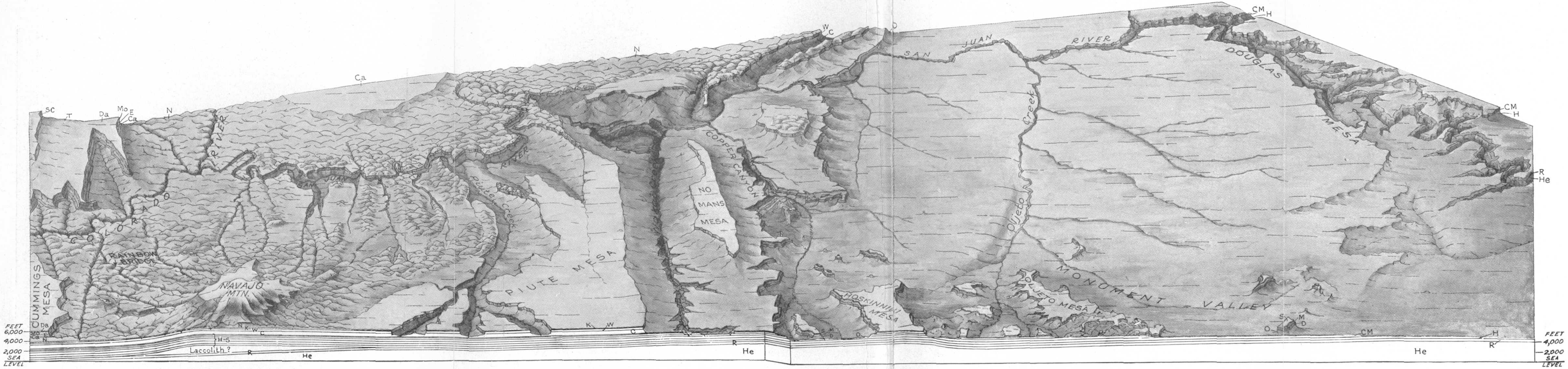
thickness of the arch is 42 feet and it is 33 feet wide; these dimensions are not greatly exceeded on the limbs. In spite of the great size of the arch it is well hidden among the sandstone domes that tower high above it.

The Segi Mesas area includes the portion of the region between Piute Creek and about the west line of Tps. 41, 42, and 43 S., R. 14 E. The upland surface in this area consists of two westward-sloping plateaus separated by cliffs about 1,200 feet high. Deep canyons of several tributaries of the San Juan River divide the plateaus into many mesas and buttes. Monitor Butte and No Man's and Piute Mesas are remnants of the higher plateau, and Hoskinnini Mesa and the flat intercanyon areas south of Monitor Butte and No Man's Mesa are remnants of the lower plateau. The tops of the plateau remnants are areas of low relief but are bounded by nearly vertical cliffs which are impassable to a man on foot for continuous stretches many miles in length. No Man's Mesa is about 9 miles long and 1¾ miles wide at its widest place. Its sides can be ascended on foot at only one locality—near the west quarter corner of sec. 12, T. 42 S., R. 12 E.—and even here the climb is a difficult one. The local relief between the floors of the larger tributaries, such as Piute and Nokai Creeks, and the top of the canyon walls is commonly 1,500 to 2,000 feet.

The Monument Valley area is east of the Segi Mesas area and occupies approximately the east half of the Monument Valley-Navajo Mountain region. The upland surface, trenched by small canyons and broken by innumerable ledges, rises toward the east from altitudes of about 3,620 feet at Clay Hill Crossing and 4,200 feet in Copper Canyon near Jacobs Monument to about 6,000 feet at the east edge of Douglas Mesa, in the southern part of T. 41 S., R. 17 E. The east edge of Douglas Mesa is an escarpment with a maximum height of about 800 feet that rises above a rolling surface extending to the east boundary of the region. Near the State line in Monument Valley many buttes, mesas, and spires rise hundreds of feet above the general surface (pls. 8, *A*, *B*, and 9, *B*).

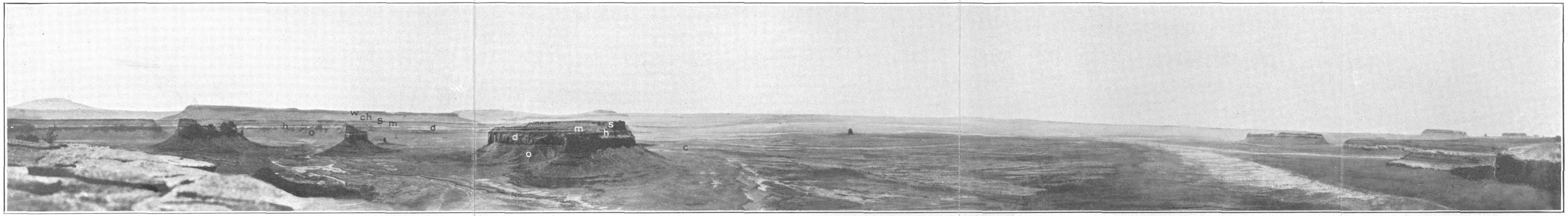
DRAINAGE AND WATER SUPPLY

The Colorado River crosses the northwest corner of the Monument Valley-Navajo Mountain region. The San Juan, one of its large tributaries, flows westward across the region near the north boundary and joins the Colorado River about 10 miles north of Navajo Mountain. It is a perennial stream which heads in the mountains of southwestern Colorado. The San Juan River is normally a shallow stream, but it is subject to floods, which rise rapidly.



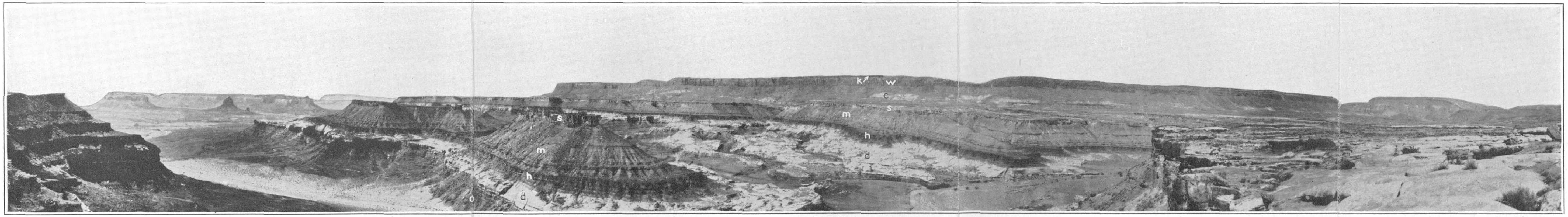
BLOCK DIAGRAM SHOWING THE SURFACE FEATURES OF THE MONUMENT VALLEY-NAVAJO MOUNTAIN REGION.

He, Hermosa formation; *R*, Rico formation; *H*, Halgaito tongue of Cutler formation; *CM*, Cedar Mesa sandstone member of Cutler formation; *O*, Organ Rock tongue of Cutler formation; *D*, De Chelly sandstone member of Cutler formation; *M*, Moenkopi formation; *S*, Shinarump conglomerate; *C*, Chinle formation; *W*, Wingate sandstone; *K*, Kayenta formation; *N*, Navajo sandstone; *Ca*, Carmel formation; *E*, Entrada sandstone; *Mo*, Morrison formation; *Da*, Dakota (?) sandstone: *T*, Tropic shale; *SC*, Straight Cliffs sandstone.



A. PANORAMIC VIEW OF THE EAST-CENTRAL PART OF THE MONUMENT VALLEY-NAVAJO MOUNTAIN REGION FROM THE NORTHEAST CORNER OF HOSKINNINI MESA.

Shows the wide expanse of Monument Valley with Train Rock, Oljeto Mesa, some of the monuments at the right, and Organ Rock near the center. The mesas, buttes, and spires at the left are in upper Copper Canyon, with No Man's Mesa rising in the background. Navajo Mountain, rising above the rim of Piute Mesa, shows at the left. *c*, Cedar Mesa sandstone member of the Cutler formation; *o*, Organ Rock tongue of the Cutler formation; *d*, De Chelly sandstone member of the Cutler formation; *h*, Hoskinnini tongue of the Cutler formation; *m*, Moenkopi formation; *s*, Shinarump conglomerate; *ch*, Chinle formation; *w*, Wingate sandstone. Photograph by J. B. Reeside, Jr.



B. PANORAMIC VIEW OF LOWER COPPER CANYON FROM THE EAST RIM.

Shows the Balanced Rock anticline at the right, the east rim of No Man's Mesa in the center, and some of the buttes and mesas in upper Copper Canyon at the left. Note the sparseness of vegetation. Symbols same as in *A* except *c*, Chinle formation, and *k*, Kayenta formation. Photograph by J. B. Reeside, Jr.

Miser [4] reports a flood in October 1911 that reached a height of 50 feet in the narrower parts of the canyon. The usual average depth of the water between the mouth of Moonlight Wash and the east limit of the region probably does not exceed 5 or 6 feet, but Miser [5] reports that for much of the distance between the mouth of Oljeto (Moonlight) Wash and the junction with the Colorado River the San Juan at low water is less than 6 or 8 inches deep. The average fall of the river between the east limit of the region and its mouth is about 7 feet to a mile, and the current is fairly swift.

The tributaries of the San Juan and Colorado in the region here described are all small. The northern tributaries of the San Juan were not observed except from the south side of the river, but they are briefly described by Miser.[6] Named from west to east they and the canyons that are occupied by streams are Wilson Creek, Alcove Canyon, Castle Wash, Clay, Grand, and Slickhorn Gulches, and Johns Canyon. Miser reports that all these streams except those in Clay Gulch and Johns Canyon, which are intermittent, had a small flow of potable water at their mouths in 1921, when he visited the region. In addition, he cites several small perennial or intermittent streams that enter the river from less prominent drainage channels than those mentioned. The principal southern tributaries of the San Juan River are Oljeto Wash, Nokai Creek, Piute Creek, and the stream in Copper Canyon. All these southern tributaries head in Arizona and flow northward across the area. They are all intermittent and flow perennially only in short stretches that are fed by springs, but all have large drainage basins, and for short periods during and after storms they are turbulent muddy streams that commonly have a depth of several feet. Ordinarily the dry sandy beds of upper Oljeto Wash and lower Copper Canyon are used as roads by wagons and automobiles. There is considerable subsurface flow in Oljeto Wash, and the supply of water at the Oljeto trading post is obtained from a well that penetrates this flow. About a mile downstream from Oljeto the subsurface drainage has been diverted to obtain water for use in irrigating a few acres of land. The water has a high mineral content. West of Piute Creek several intermittent streams or perennial streams of small flow drain the flanks of Navajo Mountain and the adjacent country. Most of the creeks between the Piute drainage basin and Cummings Mesa carry a small flow of clear pure water in some parts of their courses.

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[4] Miser, H. D., The San Juan Canyon, southeastern Utah: U. S. Geol. Survey Water-Supply Paper 538, p. 56, 1924.

[5] Idem, p. 49.

[6] Idem, pp. 72–73.

The water supply for human beings and stock in the Monument Valley-Navajo Mountain region as a whole is rather meager. The San Juan and Colorado Rivers offer a supply of potable water, but the streams flow in deep canyons and are accessible at few places. During the fieldwork for this report water from the San Juan River was used while the party was camped near the mouth of Nokai Creek, but it is so heavily charged with mud and silt that it is suitable for use only after it has been set aside in containers for several hours to permit the sediment to settle. The principal source of water for people and for stock consists of springs. The water from many of the springs contains so much mineral matter that it is not suited to human use, but it is an important source of water for stock. The location of most of the springs is shown on plate 1, except in the part of the region north and west of Navajo Mountain, where there is an adequate supply of water from numerous springs. In general springs issuing from red rocks are noticeably alkaline and are unfit for use; but springs issuing from the light-colored rocks are suitable for human use. In areas where there are no springs a supply of water is frequently obtained for a short time after rainstorms from accumulations of rain water in natural tanks (depressions in the rocks) or in artificial tanks formed by damming small drainage channels on rock surfaces. The supply of water from springs whose flow is too small to meet the demand made upon them is frequently supplemented by such accumulations of rain water.

CLIMATE AND VEGETATION

The climate of the greater part of the Monument Valley-Navajo Mountain region is arid. There are no climatologic stations within the region, but records obtained at a station in the valley of the San Juan River at Bluff, Utah (altitude 4,200 feet), about 25 miles east of the region, and at a station at Kayenta, Ariz. (altitude 5,800 feet), about 20 miles south of the region, are representative of the climate of the greater part of the region. A 12-year record at Bluff up to 1927 shows an average annual precipitation of 6.26 inches, and an 11-year record at Kayenta up to 1927 indicates an average annual precipitation of 8.86 inches. The minimum temperature at both stations during the same period was −18° F., and the maximum temperature was 104° at Kayenta and 106° at Bluff. These figures are observed maximum and minimum temperatures during the recording period and represent more than the average range. The average annual range in temperature at Kayenta is between −8° and 101° and at Bluff between −2° and 103°. No climatic records have been obtained at Navajo Mountain, but the vegetation shows that the climate is more humid on the mountain than elsewhere in the region, and storms occur more often on the high peak of the mountain than in the surrounding lower country. Much of the rainfall takes place as torrential downpours in small areas during short thunderstorms. It sometimes happens that one locality receives more than the average rainfall, owing to a succession of storms, while another locality not more than 5 or 10 miles distant is suffering from a drought. Owing to the torrential character of the rainfall and the abundance of bare rock surfaces, with the consequent rapid run-off, most storms anywhere in the drainage basin of a creek will produce floods capable of considerable damage to property.

The vegetation is that which is typical of a large area in southeastern Utah and parts of adjacent States. Scattered cottonwoods are present in the lowlands along the stream courses, but in general the lowlands are bare of trees. Sagebrush, blackbrush, greasewood, rabbitbrush, shadscale, yucca, and numerous varieties of cactus are common. Grass is not abundant, but with the browse it affords a moderate amount of grazing for horses, sheep, and cattle. Juniper and piñon are abundant on the uplands west of Nokai Creek, and a sparse growth is present on Douglas Mesa and other high land in the eastern part of the region. Yellow pine and some spruce grow on Navajo Mountain.

POPULATION

Most of the inhabitants of the Monument Valley-Navajo Mountain region are Indians. It was estimated that about 100 Indians were living in the area during the summer of 1928. There were a few families of Piute Indians, and the rest were Navajos. Most of the Indians own small bands of sheep and a few cattle and horses. The nomadic Navajos move their stock from place to place in search of the best grazing land. In the summer of 1928 most of the Indians were living in small groups in Monument Valley and two families were living in the canyon of Piute Creek. At other seasons of the year the distribution of Indians would probably be somewhat different. A great many Indian hogans, mostly for winter occupation, are scattered throughout the area, but they are particularly abundant between Piute Canyon and Navajo Mountain. The Indians living in the canyon of Piute Creek were cultivating a small plot of ground, on which the principal crops were melons and corn, and were also raising some corn on Piute Mesa.

About 20 white inhabitants of the region all live at four trading posts except one man, who cultivates a small plot of ground in sec. 13, T. 43 S., R. 14 E., where melons, tomatoes, corn, and other vegetables are grown. The Goulding and Oljeto trading posts are in Monument Valley. The Wetherill trading post is about 1 mile north of the Arizona-Utah line and about 4 miles east of Navajo Mountain. Rainbow Lodge is at the southwest base of the mountain and is in Arizona about half a mile south of the State line. Besides the trading post at Rainbow Lodge, there are a number of cabins for the accommodation of guests, and mules and horses are kept for horseback trips to the summit of Navajo Mountain, to the Rainbow Bridge, and to other points of interest in the region.

Prehistoric inhabitants lived in the region, as is shown by the ruined cliff dwellings, remnants of masonry walls, pictographs, and fragments of pottery that were seen at many localities.

ACCESSIBILITY AND ROUTES OF TRAVEL

The Monument Valley-Navajo Mountain region is remote from railroads and is difficult of access. The nearest standard-gage railroads are the main line of the Atchison, Topeka & Santa Fe Railway, which passes through Flagstaff, Ariz., 197 miles by road southwest of the Goulding trading post in Monument Valley, and the Denver & Rio Grande Western Railroad, which passes through Thompson, Utah, 174 miles by road northeast of Alhambra Rock. The Rio Grande Southern Railroad, a narrow-gage line, passes through Dolores, Colo., 100 miles by road northeast of Alhambra Rock. Kayenta, a small settlement and post office in northern Arizona, about 30 miles by road southwest of the Utah-Arizona line at the southeast corner of sec. 31, T. 43 S., R. 16 E., is connected by a semiweekly stage with Flagstaff. The stage route from Kayenta to Flagstaff is 165 miles long and follows a road through Red Lake, Tuba, and Cameron. The portion of the road between Kayenta and Tuba, a distance of 83 miles, was a dirt road and in poor condition at the time of the field work. Kayenta, which was the source of mail and supplies during the field work in 1928, is said to be the most distant post office from a railroad in the United States. A poor road branches from the Kayenta-Flagstaff road a short distance northeast of Red Lake and leads to Rainbow Lodge and the Wetherill trading post, in the southwest corner of the region. The distance from Red Lake to Rainbow Lodge is 66 miles; from Flagstaff to Rainbow Lodge, 177 miles. From Kayenta a rough sandy road passes north through Monument Valley and continues northeastward to Bluff, on the San Juan River. It crosses the river on the Goodridge Bridge, near the trading post at Mexican Hat (formerly known as Goodridge). Mexican Hat, which is about 4 miles east of the region, is about 53 miles by road from Kayenta. Bluff, a small settlement and post office, is 27 miles by road east-northeast of Mexican Hat. There is no stage operating between Kayenta and Bluff. Bluff is connected with the railroad at Thompson, Utah, by a succession of stages which follow a road through Blanding, Monticello, and Moab. The distance by road from Thompson to Bluff is 143 miles. A short distance north of Bluff a poor road branches to the east and passes through Montezuma, Utah, and McElmo and Cortez, Colo., before reaching Dolores, on the narrow-gage Rio Grande Southern Railroad.

There are few roads within the area. A road that branches from the Monument Valley road near the east line of T. 42 S., R. 17 E., leads to the Utah Petroleum Corporation's well in sec. 36, T. 41 S., R. 17 E., but has been little used since this well was abandoned in 1927. Another road leaves the Monument Valley road near the Goulding trading post and runs northwest and then south around Oljeto Mesa to the Oljeto trading post. Several roads radiate from this trading post. Two roads lead south from Oljeto; each follows the bed of a fork of Oljeto Wash, and they join the Monument Valley road about 15 miles north of Kayenta. The choice between these roads depends on the condition of the sand and the recency or imminence of floods in the creeks. One branch of a road leading west from Oljeto reaches the Wilson-Cranmer well, in sec. 35, T. 42 S., R. 14 E., but it is no longer used. Another branch of this road leads to the bed of Copper Canyon in sec. 15, T. 42 S., R. 13 E., and by following the canyon bed to sec. 32, T. 41 S., R. 13 E., and then following an old road around the north end of No Man's Mesa, it is possible to drive an automobile to the edge of a bench just above the mouth of Nokai Creek. Continuations of this road, built long ago to reach the Spencer and Zahns mining camps, west of Nokai Creek, are now impassable.

Saddle and pack animals must be relied upon for transportation in the greater part of the region. Most places are accessible by horseback, but it is often necessary to travel a circuitous route, for innumerable canyons and cliffs offer barriers to direct travel. The principal trails are shown on plate 1. The trail that circles Navajo Mountain is of particular interest, for it is the only means of access to the Rainbow Natural Bridge except by ascending Bridge Canyon on foot from the Colorado River. The trail is largely a built trail on the north and west sides of the mountain and offers practically the only route of travel through a rough and inaccessible part of the region. The inaccessibility of this area is shown by the fact that the Rainbow Bridge was not visited by white men until 1909. The Honaker Trail into the canyon of the San Juan River in sec. 29, T. 41 S., R 18 E., was built in 1904 by gold prospectors who were attempting to work the placer deposits in and near the river channel; although built with the intention of using pack animals on it, it proved to be too dangerous to use for that purpose.[7]

[7] Miser, H. D., The San Juan Canyon, southeastern Utah: U. S. Geol. Survey Water-Supply Paper 538, p. 28, 1924.

Rowboats and rafts have been used by prospectors on the San Juan River, but their use is accompanied by hazards and delays, as the river flows through a canyon in the greater part of its course, the water is normally shallow, the current is swift, bars and rapids are numerous, the stream is heavily laden with silt and thus subject to sand waves, and sudden floods cause wide fluctuations in the water level. Motor boats of shallow draft have been used on the Colorado River below the mouth of the San Juan, where normally the water is deeper and the current is less swift than in the San Juan.

FUEL

Wood is the only fuel in the region, and it is present only in meager quantities and in small areas. Coal deposits are either remote or inaccessible. A low-rank bituminous coal is mined for local use at several places on Black Mesa, in northern Arizona, but the mine nearest the Monument Valley-Navajo Mountain region is about 12 miles southwest of Kayenta, Ariz., and is thus about 44 miles from the Goulding trading post. Still more remote deposits are those of subbituminous coal near Gallup, N. Mex., on the Atchison, Topeka & Santa Fe Railway, and of bituminous coal along the Denver & Rio Grande Western Railroad in western Colorada and eastern Utah. Some bituminous coal underlies the Kaiparowits Plateau a few miles northwest of Navajo Mountain, but it is separated from the Monument Valley-Navajo Mountain region by a practically impassable rugged country and by the canyon of the Colorado River. Petroleum was formerly produced from shallow wells near Mexican Hat and refined at a local refinery, but in 1928 there was no production at that locality. There is commercial production of oil in northwestern New Mexico about 40 miles southeast of the region, but in 1928 the direct roads between Monument Valley and the oil field were practically impassable because of sand.

LAND SURVEYS

Surveys by the General Land Office have established the land subdivisions in the greater part of the Monument Valley-Navajo Mountain region. These surveys were made in 1924–26, and most of the metal stakes marking the land corners are in place. The western part of the region, including Navajo Mountain, Cummings Mesa, and the greater part of the Rainbow Plateau, is unsurveyed.

PREVIOUS PUBLICATIONS

The Monument Valley-Navajo Mountain region has been visited by many geologists, and descriptions of its geologic features have appeared in several publications. In connection with his examination of the Navajo country, lying principally in Arizona, Gregory made several reconnaissance trips into this region and described the broad features of the geology and geography.[8] The eastern part of the region was also described by Gregory[9] and by Woodruff[10] in discussing the occurrence of oil near Goodridge and Mexican Hat. In 1921 a party under the direction of K. W. Trimble descended the canyon of the San Juan River from Bluff to the mouth of the river and prepared a topographic map of the lower walls of the canyon.[11] H. D. Miser was a member of this party and has described the geology and geography of a narrow strip on each side of the river.[12] Many papers describing the stratigraphy of the formations exposed in the country adjacent to the Colorado River have discussed the formations exposed in this region.[13]

Excellent descriptions and photographs of the Rainbow Bridge and other geographic features of the region have been published by many people who have visited the region as members of exploring expeditions or who have been attracted by its picturesque scenery.[14]

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

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

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

[11] Plan and profile of Colorado River, Lees Ferry, Ariz., to mouth of Green River, Utah; San Juan River mouth to Chinle Creek, Utah; and certain tributaries, U. S. Geol. Survey, 1922.

[12] Miser, H. D., The San Juan Canyon, southeastern Utah, a geographic and hydrographic reconnaissance: U. S. Geol. Survey Water-Supply Paper 538, 1924; Geologic structure of San Juan Canyon and adjacent country, Utah: U. S. Geol. Survey Bull. 751, pp. 115–155, 1925; Erosion in San Juan Canyon, Utah: Geol. Soc. America Bull., vol. 36, pp. 365–377, 1925.

[13] Gregory, H. E., The Shinarump conglomerate: Am. Jour. Sci., 4th ser., vol. 35, pp. 424–438, 1913. Longwell, C. R., Miser, H. D., Moore, R. C., Bryan, Kirk, and Paige, Sidney, Rock formations in the Colorado Plateau of southeastern Utah and northern Arizona: U. S. Geol. Survey Prof. Paper 132, pp. 1–23, 1923. Hager, Dorsey, Stratigraphy, northeast Arizona-southeast Utah: Mining and Oil Bull., vol. 10, pp. 135–139, 167, 383–385, 423, 437–439, 1924. Darton, N. H., A résumé of Arizona geology: Arizona Univ. Bull 119, 1925. Baker, A. A., Dobbin, C. E., McKnight, E. T., and Reeside, J. B., Jr., Notes on the stratigraphy of the Moab region Utah: Am. Assoc. Petroleum Geologists Bull. vol. 11, pp. 785–808, 1927. Baker, A. A., and Reeside, J. B., Jr., Correlation of the Permian of southern Utah, northern Arizona, northwestern New Mexico, and southwestern Colorado: Am. Assoc. Petroleum Geologists Bull., vol. 13, pp. 1413–1448, 1929. Gregory, H. E., and Moore, R. C., The Kaiparowits region, a geographic and geologic reconnaissance of parts of Utah and Arizona: U. S. Geol. Survey Prof. Paper 164, 1931. Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., Correlation of the Jurassic formations of parts of Utah, Arizona, New Mexico, and Colorado: U. S. Geol. Survey Prof. Paper 183 (in press).

[14] Prudden, T. M., The prehistoric ruins of the San Juan watershed in Utah, Arizona, Colorado, and New Mexico: Am. Anthropologist, new ser., vol. 5, pp. 224–288, 1903. Cummings, Byron, The great natural bridges of Utah: Nat. Geog. Mag., vol. 21, pp. 156–167, 1910. Pogue, J. E., The great Rainbow Natural Bridge of southern Utah: Nat. Geog. Mag., vol. 22, pp. 1048–1056, 1911. Roosevelt, Theodore, Across the Navajo Desert: The Outlook, Oct. 11, 1913, pp. 309–317. Miser, H. D., Trimble, K. W., and Paige, Sidney, The Rainbow Bridge, Utah: Geog. Review, vol. 13, pp. 518–531, 1923. Morris, E. H., An unexplored area of the Southwest: Nat. History, vol. 22, pp. 499–515, 1922. Bernheimer, C. L., Encircling Navajo Mountain with a pack train; Nat. Geog. Mag., vol. 43, p. 198, 1923. Judd, N. M., Beyond the Clay Hills: Nat. Geog. Mag., vol. 45, pp. 275–302, 1924; Explorations in San Juan County, Utah: Smithsonian Misc. Coll., vol. 76, no. 10, pp. 77–82, 1924. Bernheimer, C. L., Rainbow Bridge, Doubleday, Page & Co., 1924. Kluckholm, Clyde, To the foot of the rainbow, The Century Co., 1927.

STRATIGRAPHY

GENERAL FEATURES

The sedimentary rocks exposed in the Monument Valley-Navajo Mountain region range in age from Pennsylvanian to Quaternary, and the aggregate of the average thickness of the formations is about 8,200 feet. The oldest rocks crop out in the canyon of the San Juan River in the eastern part of the region, and progressively younger rocks are exposed toward the west. Formations of Upper Cretaceous age crop out at the west boundary of the region. Remnants of old erosion surfaces near Monument Pass and Navajo Mountain are floored by cemented gravel that may be of Tertiary age. Most of the formations are of continental origin, but the Pennsylvanian Hermosa formation, the Upper Jurassic Carmel formation, and the Upper Cretaceous Tropic shale are of marine origin; the Permian Rico formation is in part marine, and the Lower Triassic Moenkopi formation may be marine. The Permian Cutler formation exhibits much lateral variation in the thickness and character of its beds, but the other formations are fairly constant in lithology, although the thickness changes. The dominant color of the formations is red, although gray and buff beds are common. Rock exposures abound everywhere because of the lack of soil and vegetation in this country of arid climate, and this region, like most other portions of the Colorado Plateau, is characterized by long escarpments, numerous deep canyons, and lofty mesas whose walls reveal rock exposures that are continuous for many miles. The geologist is thus afforded an unusual opportunity to trace the formations, study their changes, and make correlations on lithologic evidence that could reasonably be questioned if made in areas of less satisfactory exposures. It is necessary to rely largely on lithologic evidence in making correlations, as fossils are scarce in most of these formations. Diagnostic fossils are abundant in the Hermosa formation, the Rico formation, and the Tropic shale, but are rare or absent in the other formations.

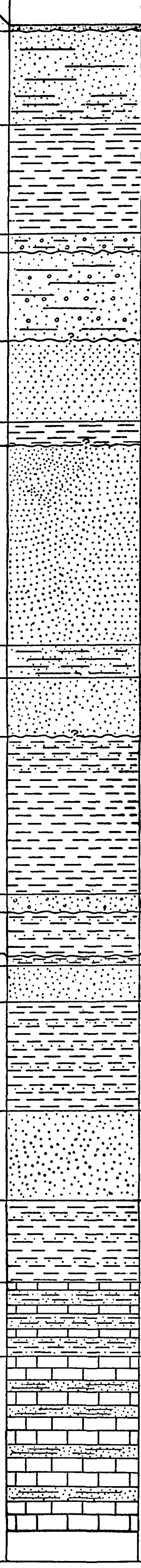
The areal distribution of the formations is shown on plate 1. A generalized columnar section showing their succession and lithologic character is given in plate 5, and variations in thickness of some of the formations are shown in plate 6.

CARBONIFEROUS SYSTEM

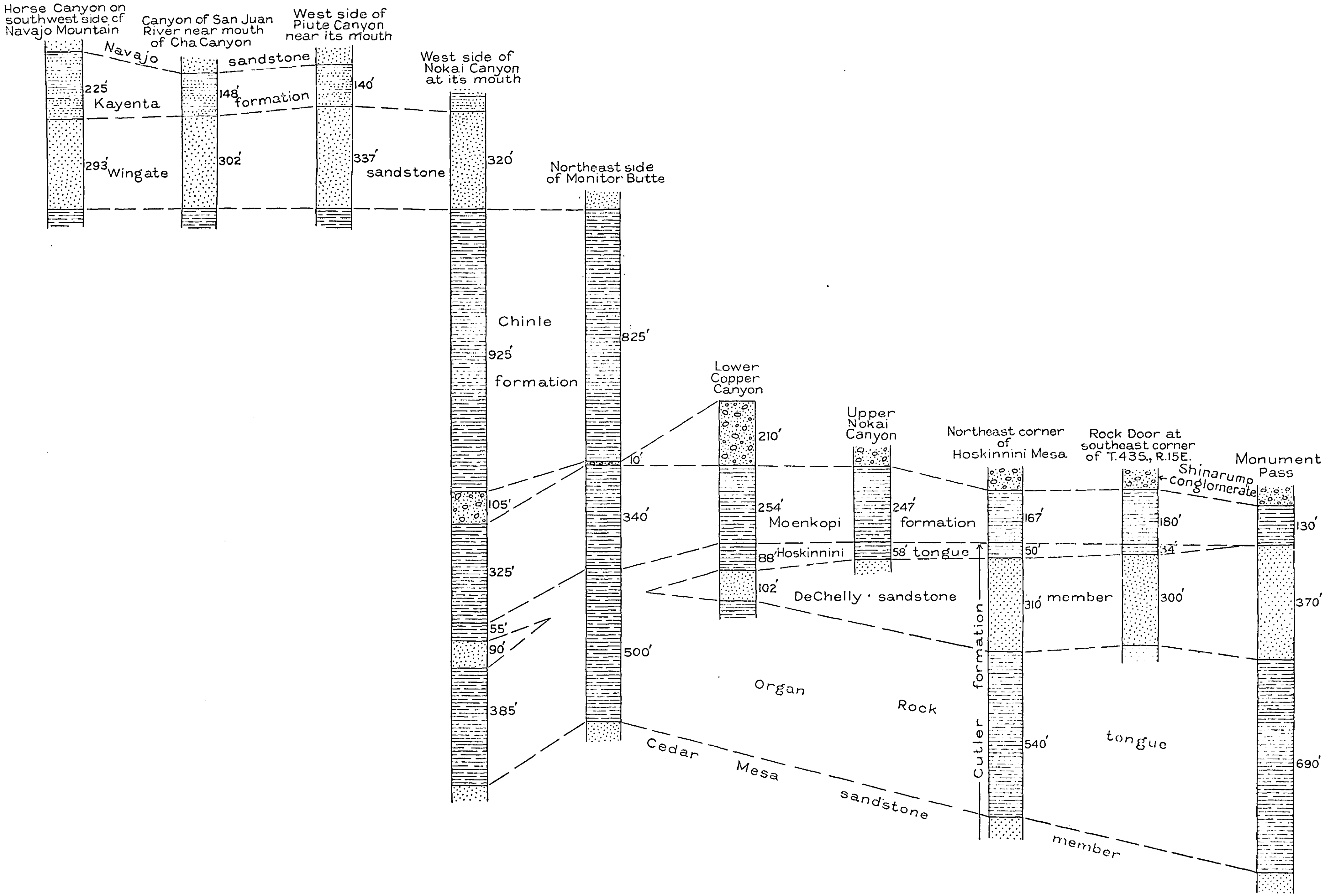
PENNSYLVANIAN SERIES

HERMOSA FORMATION

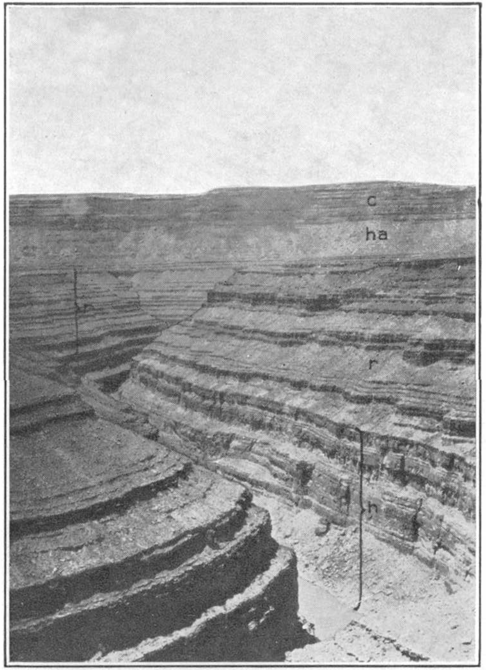
The Hermosa formation, of Pennsylvanian age, is the oldest formation exposed and crops out in the canyon of the San Juan River near the eastern margin of the region here described (pl. 7). Oil

Age			Formation	Section	Thickness (feet)	Character of rocks
Tertiary (?)						Gravel composed of boulders of sedimentary rock cemented in a sandy matrix and deposited as outwash aprons of local extent.
Upper Cretaceous			Straight Cliffs sandstone.		500+	Massive beds of fine- to medium-grained yellow, buff, or brown sandstone interbedded with drab shale near base; coal bearing.
Upper Cretaceous			Tropic shale.		600±	Dark-drab clay shale, more or less sandy in upper part, with a few thin beds of sandstone.
Upper Cretaceous			Dakota (?) sandstone.		100±	Irregularly bedded coarse-grained gray to brown sandstone, locally conglomeratic, and light-gray sandy shale; locally contains carbonaceous shale and impure coal.
Upper Jurassic			Morrison formation.		480	Irregularly bedded massive gray to brown, locally cross-bedded sandstone and conglomerate with thin beds or lenses of green or red shale; conglomerate pebbles consist of shale, variegated sandstone, chert, and quartz.
Upper Jurassic		San Rafael group	Entrada sandstone.		440	Massive orange-brown cross-bedded cliff-forming sandstone.
Upper Jurassic		San Rafael group	Carmel formation.		130	Interbedded red sandstone, shale, and mudstone with some ledges of gray sandstone.
Jurassic (?)		Glen Canyon group	Navajo sandstone.		1,100	Massive buff to gray cross-bedded sandstone with a few lenses of gray limestone.
Jurassic (?)		Glen Canyon group	Kayenta formation.		140–225	Buff to red irregularly bedded sandstone with some interbedded shale and lenses of conglomerate.
Jurassic (?)		Glen Canyon group	Wingate sandstone.		290–337	Massive cross-bedded buff sandstone, which weathers into vertical cliffs characterized by vertical joints and coating of desert varnish.
Upper Triassic			Chinle formation.		825–925	Variegated shale with thin beds of red sandstone near the top and a few thin beds of gray limestone.
Upper (?) Triassic			Shinarump conglomerate.		0–210	Massive gray cross-bedded conglomeratic sandstone with quartz pebbles 2 inches in maximum diameter and lenses of greenish-gray shale; silicified wood abundant.
Lower Triassic			Moenkopi formation.		130–340	Evenly bedded chocolate-brown shale interbedded with brownish-red ripple-marked platy to massive sandstone.
Carboniferous	Permian	Cutler formation	Hoskininni tongue.		0–88	Red-brown nodular-weathering sandy mudstone.
Carboniferous	Permian	Cutler formation	De Chelly sandstone member.		0–375	Massive cross-bedded buff to gray quartz sandstone.
Carboniferous	Permian	Cutler formation	Organ Rock tongue.		385–696	Nodular-weathering red-brown sandy mudstone with interbedded red to gray sandstone, red to lavender shale, and thin pellet conglomerate which locally contains vertebrate remains; sandstone more abundant near base; locally contains fossil plants.
Carboniferous	Permian	Cutler formation	Cedar Mesa sandstone member.		500±	Massive cross-bedded light-gray to brown sandstone with some thin beds of greenish-gray or red micaceous sandstone and shale and blue-gray unfossiliferous limestone.
Carboniferous	Permian	Cutler formation	Halgaito tongue.		380–465	Red to chocolate-brown fine-grained silty sandstone and shale with thin beds of gray unfossiliferous limestone and thin irregular beds of clay-pellet conglomerate that locally contain vertebrate remains.
Carboniferous	Permian		Rico formation.		458–473	Gray to white fossiliferous limestone interbedded with gray massive sandstone, thin-bedded red sandstone, some red shale, and mudstone.
Carboniferous	Pennsylvanian		Hermosa formation.		1,020+	Gray cherty limestone interbedded with gray, black, red, and lavender shale and some gray sandstone.

ROCKS EXPOSED IN MONUMENT VALLEY–NAVAJO MOUNTAIN REGION, UTAH.

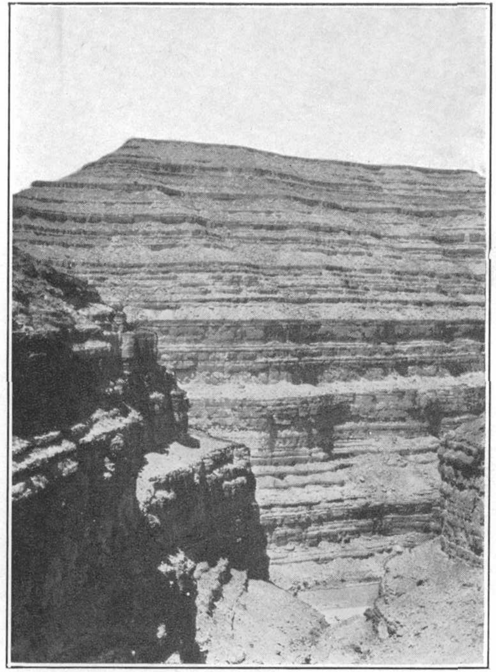


SECTIONS SHOWING LATERAL VARIATIONS OF SOME OF THE FORMATIONS EXPOSED IN THE MONUMENT VALLEY-NAVAJO MOUNTAIN REGION.



A. CANYON OF THE SAN JUAN RIVER LOOKING SOUTH FROM A POINT NEAR THE MOUTH OF JOHNS CANYON.

Shows the rim of Douglas Mesa and the narrow canyon cut in the Hermosa formation. *h*, Hermosa formation; *r*, Rico formation; *ha*, Halgaito tongue of the Cutler formation; *c*, Cedar Mesa sandstone member of the Cutler formation.



B. CANYON OF THE SAN JUAN RIVER LOOKING NORTH FROM A POINT NEAR THE WEST QUARTER CORNER OF SEC. 30, T. 41 S., R. 18 E.

Shows the steep walls formed by the massive beds in the Hermosa formation and the thin bedding in the overlying Rico formation. The skyline is the edge of a wide bench formed by the stripping of the upper part of the Rico formation.

seeps from the formation at several places, and some oil has been obtained at different horizons in it near Mexican Hat, a few miles east of the region. The Hermosa formation is not completely exposed in the Monument Valley-Navajo Mountain region, but the greatest thickness—about 1,020 feet—is revealed in the steep canyon walls on the crest of an anticline about 3 miles northwest of the Honaker Trail. The Hermosa and the overlying rocks dip westward from this locality, and the Hermosa formation disappears beneath the canyon floor near the mouth of Slickhorn Gulch.

The formation consists of massive beds of gray limestone with thin-bedded limestone and interbedded gray, black, and lavender shale and gray, brown, or yellow calcareous fine-grained sandstone. The limestone contains nodules of flint, jasper, and variegated chert. The shale interbedded with the limestone is usually gray, and the lavender shale is present only near the top, where it is an inconspicuous part of the formation.

I did not measure a complete section of the exposed part of the Hermosa formation, but Miser[15] and Woodruff[16] each measured a section of the undifferentiated Hermosa and Rico formations on the Honaker Trail. The part of the section measured by Miser, which is included in the Hermosa formation on the basis of lithology, follows:

Section of Hermosa formation at Honaker trail on San Juan River

[Measured by H. D. Miser]

	Feet
Rico formation.	
Hermosa formation:	
1. Limestone, compact, dove-colored, massive, with nodules of variegated chert	20
2. Shale, gray and black, with thin layers of limestone	10
3. Limestone, drab, knotty, with some gray shale	18
4. Limestone, drab, cherty, with some gray shale	25
5. Shale, gray and lavender, with some thin beds of knotty limestone	78
6. Limestone, massive, gray, coarse-grained, free from chert	15
7. Shale, limy, gray	10
8. Limestone, drab, cherty	6
9. Shale, gray, with thin layers of drab limestone near top	11
10. Limestone, massive, compact, dove-colored; breaks with conchoidal fracture	8
11. Shale, gray, interbedded with equal amount of gray fine-grained cross-bedded sandstone	11
12. Limestone, massive, compact, dove-colored; breaks with conchoidal fracture	8

[15] Miser, H. D., Geologic structure of the San Juan Canyon and adjacent country, Utah: U. S. Geol. Survey Bull. 751, pp. 127–129, 1925.

[16] Woodruff, E. G., Geology of the San Juan oil field, Utah: U. S. Geol. Survey Bull. 471, pp. 81–82, 1912.

Hermosa formation—Continued.	*Feet*
13. Shale, gray with beds of calcareous sandstone near top and base; cherty, knotty limestone in lower half	49
14. Limestone, massive, cherty, fine-grained, drab	3½
15. Shale, gray, and shaly limestone, with a bed of knotty black chert in lower half; chert weathers brown	33
16. Limestone, massive, drab, fine-grained, cherty; forms top of point known as "the Horn", which overlooks canyon	11
17. Sandstone, brownish	5
18. Limestone, massive, gray, medium-grained, with chert nodules	30
19. Limestone, knotty and cherty; grades upward into overlying bed and grades downward into gray shale	16
20. Limestone, drab, cherty	4½
21. Shale, gray, limy	4
22. Limestone, massive, drab	25
23. Concealed	5
24. Limestone, massive, drab, fine-grained, cherty	10
25. Limestone, massive, drab, sandy	30
26. Shale, drab, sandy; grades into overlying bed	25
27. Shale, gray, containing knotty black chert	15
28. Shale, papery, black	5
29. Shale, gray, interbedded with drab limestone; crops out on bench along which trail runs to north for about half a mile	6
30. Limestone, massive, fine-grained, dove-colored; 7 feet below top, a foot of limestone contains sulphur in cavities as much as 1 inch in their longest dimension	15
31. Shale, gray, limy, with a few nodules of black chert near base	20
32. Limestone, shaly and sandy, with nodules of black chert	34
33. Limestone, sandy, drab, fine-grained	5
34. Limestone, massive, compact, drab, with nodules of black chert in upper part	17
35. Shale, gray, sandy	10
36. Limestone, drab, with nodules of black chert; more massive in lower part	71
37. Sandstone, yellow, cross-bedded, fine-grained	5
38. Concealed	5
39. Limestone, massive, drab, fine-grained, grading into earthy sandy limestone below	16
40. Shale, gray, sandy and limy	8
41. Limestone, drab, thin-bedded	10
42. Shale, gray, sandy and limy	7
43. Limestone, drab, thin-bedded	6
44. Shale, gray, sandy and limy	10
45. Limestone, drab	3
46. Sandstone, gray, calcareous, fine-grained	6

Hermosa formation—Continued.	Feet
47. Limestone, drab, cherty	5
48. Sandstone, calcareous	1½
49. Limestone, massive, drab, cherty	3
50. Sandstone, limy, gray	3
51. Limestone, drab, sandy, cherty	5
52. Sandstone, gray, limy, fine-grained	7
53. Shale, gray, sandy	6
54. Limestone, massive, drab	40
55. Sandstone, gray, calcareous, fine-grained	5
Talus to river level	20
Total exposed thickness of Hermosa formation	840½

The Hermosa formation of this area contains abundant marine fossils, which are of Pennsylvanian age and establish the correlation with the Hermosa formation of the type locality in southwestern Colorado [17] and with the Hermosa formation as exposed near Moab, Utah.[18] The overlying Rico formation has previously been grouped with the Hermosa formation to form the †Goodridge formation,[19] but the unit to which that name was applied has been subdivided on the basis of lithology and, in a broad way, on the basis of invertebrate fossils.

There is a gradation between the Hermosa formation and the overlying Rico formation, and at many localities the boundary must be selected arbitrarily within a zone 15 to 25 feet thick. The massive cliff-making sandstone and limestone of the Hermosa formation, in which beds with a red color are inconspicuous or absent, contrast, however, with the rocks of the Rico formation, which are relatively thin-bedded, form a steep slope, and include many red beds.

The fossils in the Hermosa and Rico formations are of little assistance in determining the boundary between these formations, as the change from the Hermosa to the Rico fauna does not always coincide with the change in lithology. Where the upper part of the Hermosa and the Rico formations were measured in secs. 25 and 36, T. 41 S., R. 17 E., the faunal boundary as determined by G. H. Girty coincides with the lithologic boundary, but 1½ miles east of this locality, at the Honaker Trail, the faunal boundary as selected by Girty is about 117 feet above the lithologic boundary.

Concerning the value of the paleontologic evidence in separating the Hermosa and Rico formations, Mr. Girty says:

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[17] Cross, Whitman, and Spencer, A. C., Geology of the Rico Mountains, Colo.: U. S. Geol. Survey 21st Ann. Rept., pt. 2, pp. 40–49, 1909.

[18] Baker, A. A., Geology and oil possibilities of the Moab district, Utah: U. S. Geol. Survey Bull. 841, pp. 18–23, 1933.

[19] Woodruff, E. G., Geology of the San Juan oil field, Utah: U. S. Geol. Survey Bull. 471, pp. 80–85, 1912. A dagger (†) preceding a geologic name indicates that the name has been abandoned or rejected for use in classification in publications of the U. S. Geological Survey. Quotation marks, formerly used to indicate abandoned or rejected names, are now used only in the ordinary sense.

The paleontologic distinction between the Rico and Hermosa, as is well known, lies mainly in the fact that the Rico fauna consists largely of pelecypods and the Hermosa fauna consists largely of brachiopods. In some collections this distinction is sharply drawn; in others it is more indefinite and it is open to the interpretation of reflecting local conditions that were contemporaneous. That it has been found useful over an extensive area and in general accord with stratigraphic and lithological evidence indicates that the distinction has also a larger significance and that it represents widespread changes in the relation of land and sea. From the very nature of the case, however, the changes were probably not quite contemporaneous: Rico conditions may have set in earlier in areas where the sea was shallow, and Hermosa conditions persisted longer in areas where it was deep.

The fossils collected from the Hermosa formation have been determined by Mr. Girty. Those obtained at three horizons in the upper part of the formation in secs. 25 and 36, T. 41 S., R. 17 E., are as follows:

Lot 6593b, 129–161 feet below top of Hermosa formation:

Campophyllum torquium
Delocrinus sp.
Hydreionocrinus acanthophorus
Echinocrinus longispina
Fistulipora n. sp.
Stenopora sp.
Polypora sp.
Rhombopora sp.
Derbya? sp.
Chonetes mesolobus var. decipiens
Chonetes granulifer
Pustula sp.
Marginifera splendens
Spirifer triplicatus
Spiriferina kentuckyensis
Squamularia n. sp.?
Ambocoelia planiconvexa
Composita subtilita
Cleiothyridina pecosi

Lot 6593a, 315–321 feet below top of Hermosa formation:

Climacammina sp.
Tetrataxis sp.
Lophophyllum profundum
Fistulipora sp.
Stenopora sp.
Leiopora subnodosa
Rhombopora sp.
Rhipidomella carbonaria
Chonetes granulifer
Marginifera splendens
Dielasma bovidens
Spirifer cameratus
Spiriferina kentuckyensis
Composita subtilita
Cleiothyridina pecosi
Prismopora triangulata
Bairdia cf. B. beedei
Bairdia sp.
Gnathodus sp.

Lot 6593, 321–352 feet below top of Hermosa formation:

Productus semireticulatus
Productus nolani?
Avonia? sp.
Pustula aff. p. pustulosa Marcou (not Phillips)
Spirifer cameratus var.
Deltopecten aff. D. eurekensis

The fossils collected along the Honaker Trail in that part of the †Goodridge formation which is included in the Hermosa formation by me are listed below. The stratigraphic positions of the beds from which the fossils were collected are as reported by Woodruff,[20]

[20] Woodruff, E. G., Geology of the San Juan oil field, Utah: U. S. Geol. Survey Bull. 471, pp. 81–85, 1912.

but the positions may not be accurate, as Woodruff's section shows the thickness of the †Goodridge formation to be 232 feet more than is shown in a section measured at the same locality by Miser.[21] The height of the canyon wall as determined with a transit shows that Miser's measurement is approximately correct.

Lot 174, 33 to 43 feet below top of Hermosa formation:

Lophophyllum profundum	Productus cora
Fistulipora? sp.	Spiriferina kentuckyensis
Rhombopora lepidodendroides	Composita subtilita
Derbya? sp.	Hustedia mormoni

Lot 173, 60 to 74 feet below top of Hermosa formation:

Fusulina sp.	Productus cora
Crinoidal remains	

Lot 172, 102 to 105 feet below top of Hermosa formation:

Fusulina sp.

Lot 171, 164 to 177 feet below top of Hermosa formation:

Lophophyllum profundum	Productus sp.
Productus punctatus	Spirifer cameratus
Productus cora	Composita subtilita

Lot 170, 298 to 306 feet below top of Hermosa formation:

Fusulina sp.	Composita subtilita

Lot 169, 358 to 433 feet below top of Hermosa formation:

Polypora sp.	Marginfera splendens?
Rhombopora sp.	Pugnax rockmontanus?
Lingulidiscina missouriensis	Spirifer scobinus?
Derbya? sp.	Ambocoelia planiconvexa?
Chonetes mesolobus	Aviculipecten sp.
Productus semireticulatus	Fish remains
Productus sp.	

Lot 168, 628 to 662 feet below top of Hermosa formation:

Orthothetina, n. sp.	Productus semireticulatus
Productus cora	Spirifer rockymontanus
Productus punctatus	Schizostoma sp.

Lot 167, 735 to 829 feet below top of Hermosa formation:

Echinocrinus cratis	Spirifer cameratus
Rhombopora lepidodendroides	Squamularia perplexa
Rhipidomella pecosi	Composita subtilita
Productus semireticulatus	

Lot 166, 893½ to 899 feet below top of Hermosa formation:

Echinocrinus sp.	Spirifer cameratus
Chonetes sp.	Squamularia perplexa
Marginifera muricata	Composita subtilita
Marginifera wabashensis	

Lot 165, 990 to 1,022 feet below top of Hermosa formation:

Syringopora sp.	Echinocrinus sp.

[21] Miser, H. D., Geologic structure of San Juan Canyon and adjacent country, Utah: U. S. Geol. Survey Bull. 751, pp. 127–129, 1925.

PERMIAN SERIES

The eastern part of the Monument Valley-Navajo Mountain region is a critical area in the study of Permian sedimentation, as it marks a zone of transition between Permian sediments of southwestern Colorado type and those present in the Grand Canyon district. Various reports by Cross and his coworkers have described the Permian sediments in southwestern Colorado, and the stratigraphy of the Grand Canyon district is likewise well known, as the result of many reports by different geologists.

Information concerning the Permian rocks in the intervening area has been obtained by several geologists.[22] That Monument Valley and the Moab district were areas in which rapid lateral changes in the sediments occurred has been shown by detailed mapping in southeastern Utah [23] and regional reconnaissance work in connection with it. The regional correlation of the Permian formations as it is interpreted at present has been published [24] and will be discussed in the present report only to the extent necessary for an understanding of the geology of the Monument Valley-Navajo Mountain region.

RICO FORMATION

The Rico formation makes the upper wall of the canyon of the San Juan River near the Honaker Trail and the Gooseneck. The upper 100 feet of the formation weathers back from the canyon rim and underlies a large area just northeast of Halgaito (Hulkito) Spring. West of the Honaker Trail the Rico forms a bench at the top of the inner canyon, and it passes below the level of the river about 1½ miles below the mouth of Grand Gulch, in the eastern part of T. 40 S., R. 15 E.

The Rico formation is composed principally of sandstone with interbedded limestone, shale, and mudstone. The sandstone is massive to thin-bedded, limy, medium- to fine-grained, white to dark red. The massive sandstone is commonly light gray on fresh surfaces but weathers brown, and the thin sandstone is commonly salmon- to

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[22] Longwell, C. R., Miser, H. D., Moore, R. C., Bryan, Kirk, and Paige, Sidney, Rock formations in the Colorado Plateau of southeastern Utah and northern Arizona: U. S. Geol. Survey Prof. Paper 132, pp. 7–9, 1923. Gilluly, James, and Reeside, J. B., Jr., Sedimentary rocks of the San Rafael Swell and some adjacent areas in eastern Utah: U. S. Geol. Survey Prof. Paper 150, pp. 63–64, 1928. Gregory, H. E., and Moore, R. C., The Kaiparowits region, a geographic and geologic reconnaissance of parts of Utah and Arizona: U. S. Geol. Survey Prof. Paper 164, pp. 38–45, 1931.

[23] Dane, C. H., Geology of the Salt Valley anticline and the northwest flank of the Uncompahgre Plateau: U. S. Geol. Survey Bull. 863 (in press). McKnight, E. T., Geology of a portion of Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. (in preparation). Baker, A. A., Geology and oil possibilities of the Moab district, Utah: U. S. Geol. Survey Bull. 841, pp. 23–33, 1933.

[24] Baker, A. A., and Reeside, J. B., Jr., Correlation of the Permian of southern Utah, northern Arizona, northwestern New Mexico, and southwestern Colorado: Am. Assoc. Petroleum Geologists Bull., vol. 13, pp. 1413–1448, 1929.

brick-red. There are many layers of gray to white thin-bedded to massive fossiliferous marine limestone interbedded with the sandstone. Some light-red to lavender shale and mudstone are also present in the formation. The brown-weathering massive sandstone and the red thin-bedded sandstone, shale, and mudstone impart a somber red tone to the formation, in contrast to the gray color of the underlying Hermosa formation and the more brilliant red of the overlying Halgaito tongue of the Cutler formation. The Rico formation in general is thinner-bedded and contains more sandstone than the Hermosa formation. The thickness of the Rico is 473 feet as measured in secs. 35 and 36, T. 41 S., R. 17 E. The upper 458½ to 468½ feet of the Goodridge formation at the Honaker Trail and the upper 462 feet at the mouth of Slickhorn Gulch, as shown in sections measured by Miser,[25] are here included in the Rico formation.

Section of Rico formation measured in secs. 35 and 36, T. 41 S., R. 17 E.

Halgaito tongue of the Cutler formation.	
Rico formation:	*Feet*
1. Limestone, massive, gray, fossiliferous, bench-forming (fossil lot 6594)	6
2. Sandstone, red, thin-bedded	27
3. Sandstone, massive, white, limy. ledge-forming (Baby oil sand)	9
4. Sandstone, red, thin-bedded	33
5. Sandstone, massive, white, limy, medium-grained; weathers brown	4
6. Shale and interbedded sandstone, orange-red to lavender-red (Goodridge oil sand)	30
7. Limestone, white, sparsely fossiliferous; weathers brown	14
8. Sandstone, thin-bedded to massive, orange-red to lavender-red	66
9. Limestone, gray, sandy; weathers light brown (Third oil sand)	9
10. Sandstone, fine-grained, thin-bedded to massive, dark red	45
11. Limestone, gray, sandy; weathers brown (Mendenhall oil sand)	8
12. Sandstone, fine-grained, thin-bedded to massive, salmon-red to brick-red	66
13. Limestone, brown	11
14. Sandstone, salmon-red to purplish red	27
15. Limestone, thin-bedded, gray, cherty	11
16. Limestone, massive, gray, fossiliferous (Little Loop oil sand) (fossil lot 6593e)	10
17. Sandstone interbedded with shale and mudstone, light red to purplish red; sparsely fossiliferous (fossil lot 6593d)	41

[25] Miser, H. D., Geologic structure of San Juan Canyon and adjacent country, Utah: U. S. Geol. Survey Bull. 751, pp. 127–130, 1925.

Rico formation—Continued.	*Feet*
18. Limestone, light gray, fossiliferous (fossil lot 6593c)	12
19. Sandstone, pale lavender, sandy at base, grading upward into massive gray sandy fossiliferous limestone	44
	473

Hermosa formation.

Fossils collected from the Rico formation in this section were determined by G. H. Girty as follows:

Lot 6594, from bed 1:

Pustula nebraskensis
Plagioglypta canna
Bellerophon crassus
Euphemus subpapillosus?
Bulimorpha chrysalis?

Lot 6593e, from bed 16:

Domatoceras aff. D. militarium

Lot 6593d, from bed 17:

Allerisma terminale

Lot 6593c, from bed 18:

Stenopora sp.
Rhombopora sp.
Derbya multistriata?
Derbya? n. sp.
Productus cora
Spirifer triplicatus
Composita subtilita
Aviculipecten fasciculatus
Deltopecten occidentalis?
Myalina wyomingensis

Fossils collected by Woodruff [26] at the Honaker Trail from the part of the Goodridge formation which is here included in the Rico formation were described by Girty as follows:

Lot 152, 100 to 125 feet below top of Rico formation:

Echinocrinus aff. E. ornatus
Composita subtilita?
Bellerophon sp.
Platyceras parvum

Lot 179, 100 to 125 feet below top of Rico formation:

Productus cora
Myalina permiformis
Small gastropod

Lot 178, 190 to 196 feet below top of Rico formation:

Productus nebraskensis
Edmondia gibbosa
Cardiomorpha? sp.
Deltopecten occidentalis
Myalina sp.
Pleurophorus subcostatus?
Schizodus meekanus
Monopteria polita?
Bellerophon sp.

Lot 177, 231 to 266 feet below top of Rico formation:

Leda arata
Deltopecten occidentalis
Myalina aff. M. parattenuata
Allerisma terminale
Pleurophorus sp.
Bellerophon tricarinatus
Bellerophon sp.
Euphemus carbonarius
Naticopsis sp.

[26] Woodruff, E. G., op. cit. (Bull. 471), pp. 81–85.

Lot 176, 358 to 377 feet below top of Rico formation:

Stenopora sp.	Productus cora

Lot 175, 384 to 469 feet below top of Rico formation:

Hydreionocrinus sp.	Productus nebraskensis
Stenopora sp.	Pugnax osagensis
Polypora sp.	Spirifer cameratus
Rhombopora lepidodendroides?	Spiriferina solidirostris
Productus cora	Composita subtilita

In his discussion of Woodruff's collections, Girty states [27] that the fossils in lots 175 and 176 "present the Hermosa facies, while lots 177 to 179 are more like the Rico facies." As the distinction between fossils of Rico and Hermosa facies rests upon the preponderance of brachiopods in the Hermosa as contrasted with a preponderance of pelecypods in the Rico, it is conceivable that a single small collection from the Rico formation might include more brachiopods than pelecypods and therefore be confused with a Hermosa fauna. It seems more probable, however, that the difference in facies reflects an environmental difference at the time the sediments were deposited, and that the fossils in lots 175 and 176 lived under conditions that represented a temporary recurrence of conditions that existed during Hermosa time.

The Rico formation is conformable with the underlying Hermosa formation and the overlying Cutler formation. The lower contact has been discussed in connection with the Hermosa formation. The upper contact is placed at the top of a thin fossiliferous dull-gray limestone. There are several very thin beds of unfossiliferous limestone in the Halgaito tongue of the Cutler formation, but the highest observed fossiliferous limestone marks an abrupt change in lithology. It is possible that this limestone does not always occur at the same horizon and that there may be slight intertonguing of the marine beds of the Rico formation with the continental beds of the Cutler formation, such as has been observed in the Moab district.[28] I believe, however, that the contact between these two formations in the Monument Valley-Navajo Mountain region is a single definite horizon within the small area in which the formation is exposed.

The Rico was formerly included with the Hermosa in the Goodridge formation,[29] but on the basis of lithologic and faunal differences the Rico formation can be separated from the underlying Hermosa formation. The fossils in the Rico established its correlation with the Rico formation of the Moab district and of the type

[27] Woodruff, E. G., op. cit., p. 83.

[28] Baker, A. A., Geology and oil possibilities of the Moab district, Utah: U.S. Geol. Survey Bull. 841, p. 29, 1933.

[29] Woodruff, E. G., Geology of the San Juan oil field, Utah: U. S. Geol. Survey Bull. 471, pp. 80–85, 1912.

locality in southwestern Colorado.[30] West of this area, in the Grand Canyon region, the Rico formation appears to be unrepresented, although the lower part of the Supai formation may represent Rico time.

The fossils that are present in many of the beds of the Rico formation are of marine types and prove the marine origin of a large part of the formation, but some of the interbedded red shale and sandstone was probably deposited under fluviatile conditions. Evidence obtained in the Moab district[31] indicated that marine beds intertongued with fluviatile beds and that recurrent invasions of sea water covered an aggraded slope extending from high lands in western Colorado. The maximum withdrawals of the sea during Rico time and the distance the continental deposits extend westward has not been determined, but the Monument Valley-Navajo Mountain region is probably in the zone in which the alternating marine and continental conditions prevailed.

CUTLER FORMATION

All the strata between the top of the Rico formation and the base of the Moenkopi formation, of Lower Triassic age, are included in the Cutler formation. The Cutler at its type locality in southwestern Colorado is composed of red arkosic conglomerates, which become fine-grained toward the west, as the formation is traced into Utah. In the Moab and Monument Valley districts massive white sandstones appear in the Cutler formation. West of the Monument Valley-Navajo Mountain region the Permian sediments are concealed under younger formations until they reappear near Lees Ferry, Ariz., where the sequence of strata is essentially that exposed at the Grand Canyon. Because of stratigraphic differences on opposite sides of the concealed interval and the impossibility of making detailed correlations across it, the terminology of the Grand Canyon region is not applicable to the Monument Valley section.

The Cutler formation crops out in the greater part of the Monument Valley-Navajo Mountain region east of Copper Canyon. It also crops out in small areas in the upper portion of the canyon of Nokai Creek and on the crest of the Balanced Rock anticline, near the mouth of Nokai Creek. Most of the monuments of Monument Valley are carved from the rocks of this formation, although most of them are capped by rocks of Triassic age.

The Cutler formation is divided into five distinct units, which, from oldest to youngest, are the Halgaito tongue, Cedar Mesa sandstone member, Organ Rock tongue, De Chelly sandstone member,

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[30] Baker, A. A., and others, Notes on the stratigraphy of the Moab region, Utah: Am. Assoc. Petroleum Geologists Bull., vol. 11, pp. 793–794, 1927.

[31] Baker, A. A., op. cit. (Bull. 841), p. 29.

and Hoskinnini tongue. The Halgaito, Organ Rock, and Hoskinnini tongues consist of red fine-grained muddy sandstone, shale, and mudstone, and the Cedar Mesa sandstone and De Chelly sandstone members consist of massive cross-bedded gray to buff or brown sandstone. The De Chelly sandstone wedges out toward the north on the east side of Monitor Butte, but the other units of the Cutler are persistent within the area that I have mapped, although they vary considerably in thickness. There is usually a thin transitional zone at the contact between the red beds and the massive sandstones, and deposition seems to have been continuous during Cutler time.

The assignment of the Cutler formation to the Permian is based on fossil evidence supported by regional stratigraphic relations. Plant and vertebrate fossils collected in Monument Valley have been determined to be of Permian age. The Rico formation, conformably underlying the Cutler formation, is of Permian age, and the Moenkopi formation, of Lower Triassic age, unconformably overlies the Cutler formation in Monument Valley. The Cutler is correlated in part with the Coconino sandstone, which in the San Rafael Swell, Waterpocket Fold, Grand Canyon district, and numerous other localities north, west, and south of the Monument Valley-Navajo Mountain region is overlain by the Kaibab limestone, of Permian age. Although not similar in lithology, it seems probable that the upper part of the Cutler formation of Monument Valley is the time equivalent of the Kaibab limestone.

HALGAITO TONGUE

The lowest unit of the Cutler formation has been named the "Halgaito tongue", from Halgaito Spring, which issues from the rocks of this unit in sec. 35, T. 42 S., R. 17 E.[32] The unit is completely exposed on the face of Douglas Mesa, a few miles north of the spring. It is composed of red to chocolate-brown fine-grained silty sandstone and shale with several thin beds of gray unfossiliferous limestone and scattered lenses of clay-pellet conglomerates. The red-brown Halgaito tongue usually forms a steep slope and thus a narrow belt between the overlying gray massive Cedar Mesa sandstone and the bench at the top of the Rico formation (pl. 7, *A*), but south of Halgaito Spring, where the protecting Cedar Mesa sandstone has been eroded, it forms a broad valley. It crops out only in the eastern part of the region and dips below the San Juan River in sec. 29, T. 40 S., R. 15 E., near the mouth of Oljeto Wash. The thickness ranges from 380 feet near the mouth of

[32] Baker, A. A., and Reeside, J. B., Jr., Correlation of the Permian of southern Utah, northern Arizona, northwestern New Mexico, and southwestern Colorado: Am. Assoc. Petroleum Geologists Bull., vol. 13, no. 11, p. 1443, 1929.

Slickhorn Gulch to 465 feet in Johns Canyon. The tongue is 425 feet thick in sec. 34, T. 41 S., R. 17 E., and has the same thickness in sec. 17, T. 41 S., R. 18 E.

The following section of the Halgaito tongue shows its lithology:

Section of Halgaito tongue of Cutler formation in sec. 34, T. 41 S., R. 17 E.

	Feet
Cedar Mesa sandstone member of the Cutler formation.	
Halgaito tongue of the Cutler formation:	
1. Mudstone, purplish red	4
2. Limestone, greenish gray	2
3. Sandstone, yellowish brown, gypsiferous at base	14
4. Sandstone and shale, light chocolate-brown to cherry-red, thin-bedded, slope-forming, with a few ledges of more resistant sandstone	190
5. Limestone, light gray, unfossiliferous	1
6. Sandstone and shale, like no. 4	74
7. Sandstone, limy, reddish brown, with 6-inch bed of light-gray unfossiliferous limestone at top	2
8. Sandstone and shale, like no. 4	48
9. Limestone, light gray	½
10. Sandstone, limy, purplish red, ledge-forming	4
11. Sandstone, thin-bedded, light chocolate-brown, with a few thin beds of limy ledge-forming sandstone	48
12. Sandstone, fine-grained, limy, purplish red	38
	425½
Rico formation.	

Fossils were collected from the Halgaito tongue at only one locality. Vertebrate remains embedded in a red clay-pellet and limestone conglomerate on a small butte in the SW¼ sec. 26, T. 41 S., R. 17 E., were examined by Dr. E. C. Case, who states that they include a caudal vertebra of a pelycosaur, probably *Ephiacodon* or *Sphenacodon*, and unidentifiable fragments of skull and other bones.

The Halgaito tongue was at one time included in the Moenkopi formation, which was formerly considered to be of Permian age.[33] Subsequently the Halgaito tongue was tentatively considered to be equivalent to the Supai formation,[34] and although it is still recognized that the Halgaito may be continuous with and partly equivalent to the Supai formation of the Grand Canyon, it does not now seem possible to make a sufficiently precise correlation to extend the name "Supai" into the Monument Valley region.

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[33] Woodruff, E. G., Geology of the San Juan oil field, Utah: U. S. Geol. Survey Bull. 471, p. 86, 1912. Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, p. 29, 1917.

[34] Longwell, C. R., and others, Rock formations in the Colorado Plateau of southeastern Utah and northern Arizona: U. S. Geol. Survey Prof. Paper 132, p. 7, 1923. Darton, N. H., A résumé of Arizona geology: Arizona Univ. Bull. 119, p. 207, 1925.

CEDAR MESA SANDSTONE MEMBER

The Cedar Mesa sandstone member of the Cutler formation makes prominent cliffs along the canyon of the San Juan River east of Clay Hill Crossing (pls. 7, *A*, and 8, *C*), and it floors broad, nearly flat plateaus and caps mesas on both sides of the canyon. The plateau north of the river is trenched by Johns Canyon, Slickhorn Gulch, and Grand Gulch, and local names have been given to the intervening flat divides. The tableland east of Johns Canyon is known as " Cedar Mesa " and has been taken as the type locality of the sandstone, which is well exposed in the cliffs around the mesa. South of the San Juan River the Cedar Mesa sandstone floors the country extending about 20 miles east from upper Copper Canyon and Clay Hill Crossing and 12 to 19 miles south from the river. Most of the natural monuments of Monument Valley rise above a platform made by this sandstone. Douglas Mesa marks the northeastern limit of this sandstone south of the San Juan River. Westward from the east rim of the mesa the sandstone makes a long westward-inclined dip slope extending to the axis of the Oljeto syncline near Oljeto Wash, beyond which the dip slope arches over the Organ Rock anticline and the sandstone passes below the surface on the east side of Monitor Butte and in upper Copper Canyon (pl. 4, *A*). A small isolated exposure is present on the San Juan River just west of the mouth of Nokai Creek, where it appears at the crest of the Balanced Rock anticline. The San Juan River, lower Oljeto Wash, and many small tributaries of Oljeto Wash have cut narrow steep-walled canyons in this massive sandstone, and these, combined with innumerable ledges, make travel difficult across the greater part of its outcrop.

The Cedar Mesa sandstone is fairly uniform in color and composition. It is a light-colored formation, dominantly light gray to buff but with some beds of light-brown, brownish-red, or salmon-red color. The top of a massive bed of light-brown sandstone about 75 feet below the top of the member served as a key bed in mapping the geologic structure of the large area in which the Cedar Mesa sandstone is the only formation exposed. The Cedar Mesa sandstone is massively bedded, and the individual beds show large-scale tangential cross-bedding. The quartz sand of which the sandstone is composed is medium- to fine-grained, and the grains are subangular to rounded. Locally, fine-grained thin-bedded red sandstone and greenish-gray or red micaceous sandstone separate the thick beds. Thin lenses of blue-gray unfossiliferous limestone are present here and there in the sandstone and are particularly abundant near the top of the member on the north side of Monument Pass.

The thickness of the Cedar Mesa sandstone cannot be determined accurately because of the great width of its outcrop and the difficulty of identifying and tracing key horizons. The greater part of the member is exposed in a vertical cliff at the edge of Douglas Mesa, where it was measured instrumentally. The remainder of the member was measured at the western edge of its area of exposure. The total thickness thus obtained is about 500 feet, but the actual thickness in different parts of the area may vary considerably from this figure because of the relation of the sandstone to the enclosing red beds. At its upper and lower contacts the sandstone is not sharply separated from the adjacent red beds but merges with them by lateral and vertical change in lithology. It is therefore possible that the base of the sandstone beneath the west edge of the outcrop of the member is not at the same stratigraphic position as at its outcrop on the east face of the Douglas Mesa. An interpretation of the log of the well drilled by Wilson-Cranmer & Co. in sec. 35, T. 42 S., R. 14 E., indicates that the Cedar Mesa sandstone has thinned at least 50 feet between Douglas Mesa and the well.

North of the San Juan River the Cedar Mesa sandstone is continuous across Elk Ridge with the massive sandstone that is present in the Cutler formation in the southern part of the Moab district, Utah. Largely on the basis of stratigraphic sequence, some previous workers applied the name "Coconino sandstone" to the unit here designated the "Cedar Mesa sandstone",[35] and they included the upper part of the Cutler formation in the Moenkopi formation. Darton considered a local thin limestone at the top of the Cedar Mesa sandstone on Oljeto Wash, about 6 miles north of the Arizona line, to be equivalent to the Kaibab limestone and reported that it contained Kaibab fossils.[36] I found no fossils in this limestone, though the red beds overlying the Cedar Mesa sandstone that were formerly considered to be part of the Moenkopi formation contain Permian fossils in Monument Valley. The Cedar Mesa sandstone would probably prove to be continuous with the Coconino sandstone of the Grand Canyon if it could be traced through southern Utah, although it is probably not of precisely the same age. Also, the De Chelly sandstone, which in Monument Valley is separated from the underlying Cedar Mesa sandstone by 385 to 700 feet of red beds, appears to be continuous with the Coconino sandstone of the Grand Canyon when correlated through northern Arizona.[37]

[35] Longwell, C. R., and others, Rock formations in the Colorado Plateau of southeastern Utah and northern Arizona: U. S. Geol. Survey Prof. Paper 132, p. 8, 1923. Darton, N. H., A résumé of Arizona geology: Arizona Univ. Bull. 119, p. 207, 1925.

[36] Darton, N. H., op. cit., p. 207.

[37] Darton, N. H., op. cit., p. 91. Baker, A. A., and Reeside, J. B., Jr., Correlation of the Permian of southern Utah, northern Arizona, northwestern New Mexico, and southwestern Colorado: Am. Assoc. Petroleum Geologists Bull., vol. 13, p. 1438, 1929.

The Cedar Mesa and De Chelly sandstones, therefore, are believed to converge toward the west to form the Coconino sandstone.

East of Cedar Mesa, outside the area here described, the Cedar Mesa sandstone changes into red beds, as reported by Woodruff.[38] Toward the southeast the same change apparently occurs, as no member similar to the Cedar Mesa sandstone is present in the Cutler formation where it crops out near Fort Defiance, Ariz., although it is possible that the Cedar Mesa sandstone converges with the De Chelly sandstone in that direction. Northwest and north from Monument Valley the sandstone continues for many miles and is present in the Waterpocket Fold and along the Cataract Canyon of the Colorado River.

ORGAN ROCK TONGUE

The Organ Rock tongue of the Cutler formation is composed of a series of red beds separating two massive light-colored sandstones—the Cedar Mesa and De Chelly sandstone members of the Cutler formation. It forms a steep slope that rises from the platform of the Cedar Mesa sandstone and is surmounted by the sheer cliff of the De Chelly sandstone (pl. 4, A), but where the De Chelly sandstone is absent the Organ Rock tongue forms the lower and steeper part of the slope that extends to the base of the Shinarump conglomerate. Several tall, slender fluted spires, such as Organ Rock (height 350 feet), in sec. 21, T. 42 S., R. 14 E., and Jacobs Monument (height 253 feet), in sec. 27, T. 42 S., R. 13 E. (pl. 8, *A*, *B*), are carved entirely from this series of red beds, and it forms the lower part of most of the picturesque buttes and monuments of Monument Valley. Its main outcrop is a narrow band bordering the broad area of Cedar Mesa sandstone and extending from Clay Hill Crossing southward along the east side of Monitor Butte to upper Copper Canyon and thence eastward around Hoskinnini and Oljeto Mesas to Monument Pass. A small isolated exposure of the Organ Rock tongue is present on the San Juan River just west of the mouth of Nokai Creek, where the strata are arched in the Balanced Rock anticline.

In composition the red beds of the Organ Rock tongue closely resemble the other red-bed tongues of the Cutler formation. They consist of nodular-weathering red-brown sandy mudstone, red fine-grained sandstone, and red shale with some interbedded lavender shale, limestone and mud-pellet conglomerate, gray sandstone, and blue-gray limestone. The following section measured in sec. 18, T. 43 S., R. 17 E., shows the lithology of the Organ Rock tongue:

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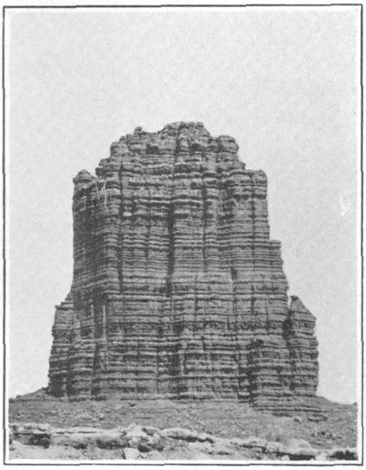
[38] Woodruff, E. G., Geology of the San Juan oil field, Utah: U. S. Geol. Survey Bull. 471, pp. 86–87, 1912.

Section of Organ Rock tongue of Cutler formation on east side of Monument Pass

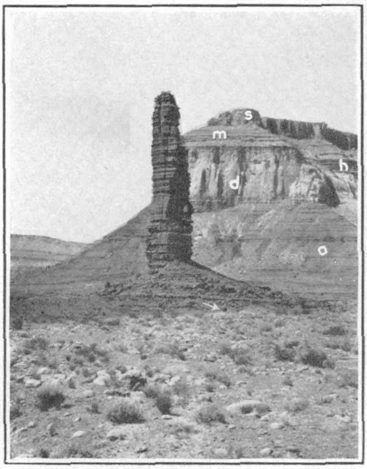
De Chelly sandstone member of Cutler formation.	
Organ Rock tongue of Cutler formation:	*Feet*
1. Mudstone, red-brown, sandy, nodular-weathering, and subordinate red sandstone and shale	363
2. Sandstone, cross-bedded, red-brown, with 6-inch bed of greenish-gray pellet conglomerate at base	6
3. Mudstone, sandstone, and shale, like no. 1	165
4. Sandstone and shale interbedded; sandstone dull brown to gray in three ledges about 3 feet thick, separated by dark lavender-red shale; upper sandstone capped by a thin pellet conglomerate	22
5. Sandstone, dull brown to gray, with thin beds of sandy limestone; base irregular	11
6. Shale, purple-red, with some red-brown mudstone	10
7. Sandstone, massive, cross-bedded, pale lavender-brown, medium-grained, quartzose, ledge-forming	6½
8. Mudstone, red sandy	12
9. Conglomerate, greenish gray, quartz matrix with pebbles of gray limestone, sandstone and clay pellets	½
10. Mudstone, red-brown, irregularly bedded, with some thin beds of red sandstone	22
11. Sandstone, medium-grained, limy, grading to lavender; contains stemlike masses of limestone	½
12. Sandstone, red-brown, thin-bedded, lenticular	5
13. Sandstone, massive, red-brown, lenticular	5½
14. Sandstone, sandy mudstone, and shale, red-brown to lavender; sandstone fine-grained, quartzose, muddy, lenticular, in beds 1 to 5 feet thick, separated by thicker units of sandy mudstone with subordinate shale	67
	696
Cedar Mesa sandstone member of Cutler formation.	

The Organ Rock tongue shows considerable variation in thickness. It is thinnest at the isolated exposure near the mouth of Nokai Creek, where it is 385 feet thick. It thickens eastward and southeastward from this locality. On the east side of Monitor Butte it is 500 feet thick, although here the overlying De Chelly sandstone is absent and the thin Hoskinnini tongue is included with the Organ Rock tongue. At the northeast point of Hoskinnini Mesa the thickness of the Organ Rock tongue is 540 feet, and at Monument Pass 696 feet. Still farther east, on the west side of Comb Ridge near the mouth of Comb Creek and beyond the limits of the area mapped, the Organ Rock tongue is about 800 feet thick.



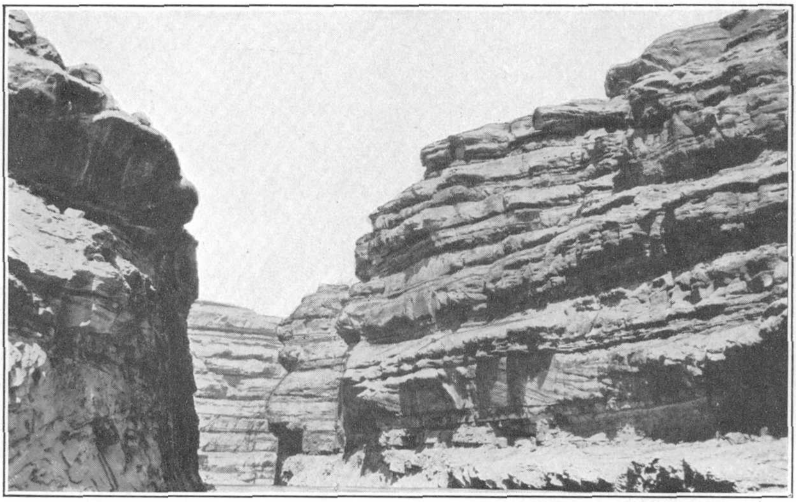
A. ORGAN ROCK, IN SEC. 21, T. 42 S., R. 14 E.

An outlier of the Organ Rock tongue of the Cutler formation 350 feet high, showing the banded, fluted character of the steep faces into which it weathers. Photograph by H. D. Miser.



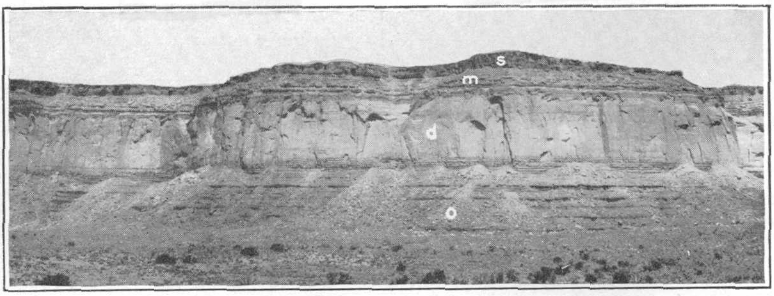
B. JACOBS MONUMENT, IN SEC. 27, T. 42 S., R. 13 E.

An outlier of the Organ Rock tongue of the Cutler formation 253 feet high. Scale is shown by horseman at foot of slope in front of spire (indicated by white arrow). Cliff in background is west wall of Copper Canyon. *o*, Organ Rock tongue of Cutler formation; *d*, De Chelly sandstone member of Cutler formation; *h*, Hoskinnini tongue of Cutler formation; *m*, Moenkopi formation; *s*, Shinarump conglomerate.



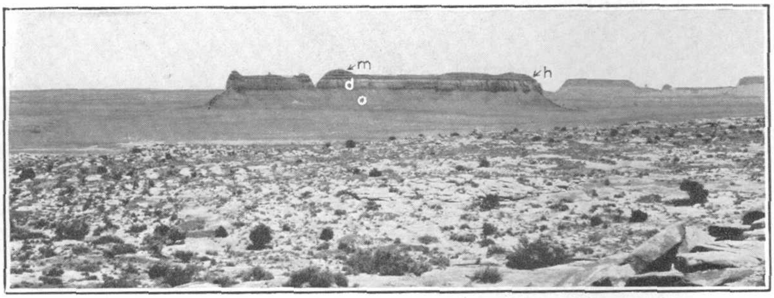
C. NARROW CANYON CUT IN CEDAR MESA SANDSTONE MEMBER OF THE CUTLER FORMATION BY THE SAN JUAN RIVER BELOW THE MOUTH OF OLJETO WASH.

Photograph by H. D. Miser.



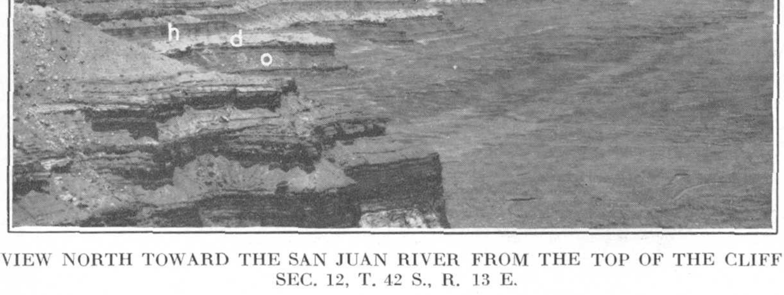
A. VIEW OF EAST SIDE OF WIDE BUTTE, IN SEC. 14, T. 43 S., R. 16 E.

Shows the group of formations from which most of the monuments of Monument Valley have been carved. The Hoskinnini tongue of the Cutler formation is very thin or absent. Symbols same as in *C*.



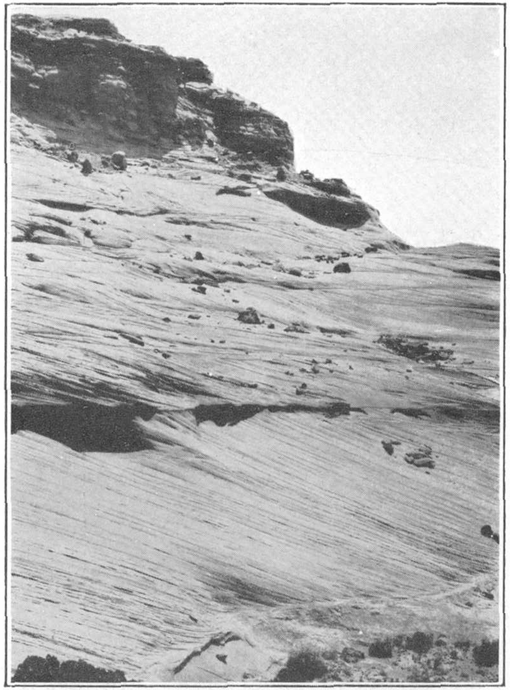
B. TRAIN ROCK, ONE OF THE MONUMENTS OF MONUMENT VALLEY, IN SEC. 33, T. 42 S., R. 15 E., AND SEC. 4, T. 43 S., R. 15 E.

Rocks in foreground are in the upper part of the Cedar Mesa sandstone member of the Cutler formation near the crest of the Organ Rock anticline. Symbols same as in *C*.



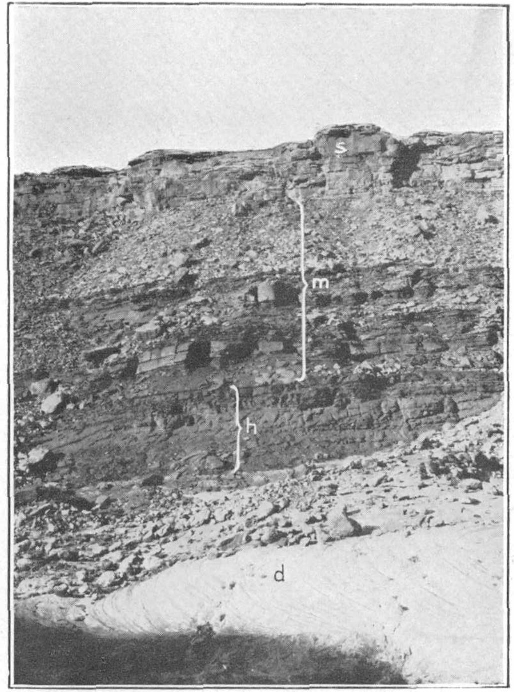
C. VIEW NORTH TOWARD THE SAN JUAN RIVER FROM THE TOP OF THE CLIFF IN SEC. 12, T. 42 S., R. 13 E.

Shows Monitor Butte at the left, the canyon of the San Juan River in the distance, and the wedging out of the De Chelly sandstone east of Monitor Butte. *o*, Organ Rock tongue of the Cutler formation; *d*, De Chelly sandstone member of the Cutler formation; *h*, Hoskinnini tongue of the Cutler formation; *m*, Moenkopi formation; *s*, Shinarump conglomerate; *c*, Chinle formation; *w*, Wingate sandstone; *k*, Kayenta formation; *n*, Navajo sandstone. Photograph by J. B. Reeside, Jr.



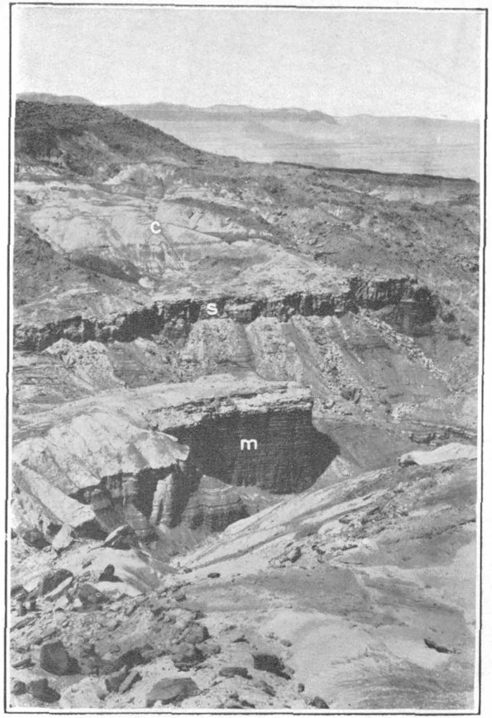
A. CROSS-BEDDING IN THE DE CHELLY SANDSTONE MEMBER OF THE CUTLER FORMATION ON THE EAST SIDE OF THE ROCK DOOR, IN SEC. 35, T. 43 S., R. 15 E.

Photograph by J. B. Reeside, Jr.



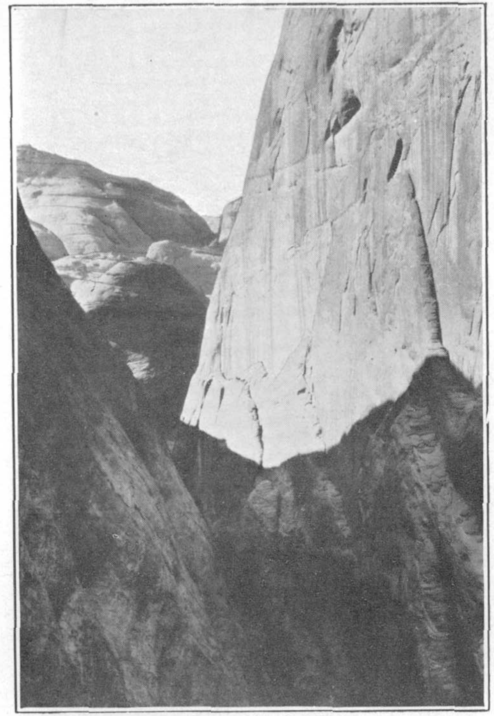
B. EAST SIDE OF THE CANYON OF NOKAI CREEK, IN SEC. 11, T. 43 S., R. 12 E.

Shows the ledgy slope formed by the weathering of the Moenkopi formation contrasted with the homogeneous lithology of the Hoskinnini tongue of the Cutler formation. *d*, De Chelly sandstone member of the Cutler formation; *h*, Hoskinnini tongue of the Cutler formation; *m*, Moenkopi formation; *s*, Shinarump conglomerate.



A. MASSIVE SHINARUMP CONGLOMERATE (*s*) GRADING LATERALLY INTO BANDED VARIEGATED SHALE OF THE CHINLE FORMATION (*c*), IN SEC. 22, T. 41 S., R. 13 E., SOUTHEAST OF MONITOR BUTTE.

Note the thin regular bedding of the Moenkopi formation (*m*). Photograph by J. B. Reeside, Jr.



B. WEST SIDE OF REDBUD PASS, A NARROW CLEFT IN THE NAVAJO SANDSTONE WEST OF NAVAJO MOUNTAIN.

The trail that encircles Navajo Mountain follows this narrow cleft between Cliff and Redbud Canyons. The Carmel formation crops out above the Navajo sandstone on the butte in the distance.

The variation in thickness of the Organ Rock tongue is probably due in part to variations in the amount of sediments deposited but may also be due in part to lateral change in lithology, from red beds to light-colored sandstones. Both the upper and lower contacts of the Organ Rock tongue are gradational, and these contacts probably do not have everywhere the same time significance. At the northeast point of Hoskinnini Mesa there is irregularity at the contact of the Organ Rock tongue and the De Chelly sandstone, a feature not noted elsewhere in the area. Red beds typical of the Organ Rock tongue extend 145 feet into the overlying De Chelly sandstone, but 1,000 feet away on each side the normal regular contact is found. This feature is interpreted as a phenomenon of deposition and not the result of erosion before the deposition of the De Chelly sandstone.

Fossil plants determined by David White to be *Walchia piniformis* and *Yakia heterophylla*, of Permian age, were collected from the top of the Organ Rock tongue along the trail on the west side of Copper Canyon in Arizona about 1,000 feet south of the Utah line, at the southeast corner of sec. 33, T. 43 S., R. 13 E. Fragmental vertebra remains were collected at two localities and were determined by Dr. E. C. Case to be of Permian age. A vertebra, probably of *Notodon* sp., was found in a small outlier of the Organ Rock tongue, at a horizon about 72 feet above the base, in the NE¼ sec. 11, T. 43 S., R. 15 E. Another collection, which included rib, vertebra, scapula, and neural spine fragments of a pelycosaur, *Sphenacodon?*, was obtained at the indefinite contact between the Organ Rock tongue and the Cedar Mesa sandstone in the NW¼ sec. 28, T 42 S., R. 15 E.

A specific age determination of the Organ Rock tongue is of particular stratigraphic value, because this member, together with the overlying De Chelly sandstone member and the Hoskinnini tongue of the Cutler formation, has previously been included in the Moenkopi formation.[39] The typical Moenkopi formation is of Lower Triassic age. The above-mentioned fossil collections thus show that the Permian-Triassic boundary is in the midst of the beds hitherto designated the Moenkopi formation in the Monument Valley region.

DE CHELLY SANDSTONE MEMBER

The De Chelly sandstone member of the Cutler formation crops out in the monuments of Monument Valley and along the cliffs extending south from the San Juan River near Clay Hill Crossing to the State line. There are isolated exposures along the San Juan River near the mouth of Nokai Creek, where it has been brought to the

[39] Longwell, C. R., and others, Rock formations in the Colorado Plateau of southeastern Utah and northern Arizona: U. S. Geol. Survey Prof. Paper 132, p. 9, 1923. Darton, N. H., A résumé of Arizona geology: Arizona Univ. Bull. 119, p. 207, 1925. Woodruff, E. G., Geology of the San Juan oil field, Utah; U. S. Geol. Survey Bull. 471, p. 87, 1912.

surface by an anticlinal fold (pl. 16, *A*), and in the upper part of the canyon of Nokai Creek. It commonly crops out as a light-colored band and nearly vertical face on the steep sides of the monuments and mesas (pls. 4, *A*, 9, *A*, *B*). The De Chelly sandstone is part of the stratigraphic series from which the picturesque buttes, mesas, and spires of Monument Valley have been carved, but it is not particularly resistant to erosion and rarely forms isolated spires unless protected by a resistant capping of younger beds. Where the sandstone forms vertical walls they are usually marked by numerous vertical joints. In many parts of its outcrop the sandstone weathers into rounded forms.

The sandstone is massive, is highly cross-bedded (pl. 10, *A*), and ranges in color from gray to tan and pinkish brown, although its color is sometimes obscured by red wash from the overlying red beds. It consists of poorly sorted medium to fine-grained well-rounded to subangular poorly cemented quartz grains, which are commonly coated with a thin film of red iron oxide. Here and there a thin lens, a few feet in extent, of red siltstone is interbedded in the massive sandstone. The De Chelly sandstone appears to be largely an eolian deposit, with some water-laid beds and some beds that are probably eolian sediments which have been reworked by water.

The De Chelly sandstone thins toward the northwest. Its maximum observed thickness is 375 feet, in Wide Butte, in the northeastern part of T. 43 S., R. 16 E. It is 300 feet thick near the east end of Oljeto Mesa, 310 feet near the northeast corner of Hoskinnini Mesa, 102 feet on the east side of Copper Canyon in the northern part of T. 42 S., R. 13 E., and 90 feet on the San Juan River near the mouth of Nokai Creek. It wedges out on the cliffs northeast of Monitor Butte in sec. 23, T. 41 S., R. 13 E. (pl. 9, *C*), and is absent near the San Juan River in the vicinity of Clay Hill Crossing. About 10 miles east of the area mapped the De Chelly sandstone is about 500 feet thick in Comb Ridge, near the Arizona-Utah State line, but it is only about 100 feet thick a few miles to the north, near the mouth of Comb Wash.

The determination of a precise boundary between the De Chelly sandstone and the underlying red beds of the Organ Rock tongue is usually impossible. An irregularity in the contact is present at the northeast point of Hoskinnini Mesa, where a hill of the red beds of the Organ Rock tongue, 1,000 feet long and 145 feet high, extends into the overlying De Chelly sandstone, but there is no evidence of erosion, and the knob of Organ Rock red beds grades laterally into massive sandstone, so that the irregularity of contact is considered a depositional rather than an erosional phenomenon. The contact is usually marked by a series of strata as much as 30 feet thick through which there is a gradual change in bedding and lithology from the horizontally bedded red mudstone and siltstone of the Organ Rock tongue to the massive cross-bedded quartz sandstone of the overlying De Chelly sandstone (pls. 8, *B*, and 9, *A*). Similarly, at the top of the De Chelly sandstone there may be a series of strata 20 feet or more thick that show a gradual change in lithology and bedding from the massive sandstone to the red beds of the overlying Hoskinnini tongue of the Cutler formation. In the eastern part of the area, where the intervening Hoskinnini tongue is absent, the Moenkopi formation rests unconformably upon the De Chelly sandstone.

No fossils have been found in typical De Chelly sandstone within the area, but some of the specimens of *Walchia piniformis* and *Yakia heterophylla*, of Permian age, from the top of the Organ Rock tongue in Copper Canyon near the Arizona-Utah State line, were collected from the lower part of the transition beds that grade upward into the De Chelly sandstone. The age of the Organ Rock tongue, shown to be Permian by vertebrate and plant fossils, unquestionably indicates the age of the entire red-bed series between the top of the Cedar Mesa sandstone and the base of the Moenkopi formation east of Monitor Butte, where the De Chelly sandstone is absent, and therefore shows that the De Chelly sandstone, which is included in the series a few miles to the south, is also of Permian age.

The De Chelly sandstone was included by Woodruff [40] in the Oljeto sandstone, named from the cliffs in the valley of Oljeto Wash near Oljeto. Concerning the age of the sandstone he says: "The Oljeto sandstone is tentatively assigned to the Moencopie, though there is meager evidence for so doing, and it is recognized that a study of this sandstone over a greater region may develop evidence to show that it is a distinct formation and later in age than the Moencopie." Gregory [41] abandoned the name "Oljeto sandstone" and correlated the massive sandstone with the sandstone that forms the walls of De Chelly Canyon, in northeastern Arizona, which he named the "De Chelly sandstone." Gregory considered the De Chelly to be younger than the Moenkopi but included both of these formations in the Permian. He classed the Moenkopi formation as Permian, as he believed Permian plant-bearing beds found by him underneath the De Chelly sandstone near Fort Defiance, Ariz., to be of the same age as the type Moenkopi beds near Moenkopi Wash in northern Arizona. Miser [42] included all the rocks between his Coconino sandstone (Cedar Mesa sandstone of this report) and the base of the Shinarump conglomerate

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

[41] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, pp. 32–33, 1917.

[42] Miser, H. D., and others, Rock formations in the Colorado Plateau of southeastern Utah and northern Arizona: U. S. Geol. Survey Prof. Paper 132, pl. 1, 1923.

in the Moenkopi formation. He recognized the De Chelly sandstone but questioned its correlation with the typical De Chelly sandstone. Darton [43] followed Miser in his definition of the Moenkopi formation in Monument Valley and described a massive sandstone member, but he followed Woodruff's designation " Oljeto " for it.

After detailed work in the Moab district [44] and in connection with the detailed mapping in the Monument Valley-Navajo Mountain region, J. B. Reeside, Jr., and I made reconnaissance stratigraphic studies of the Permian formations in southeastern Utah and adjacent parts of Arizona, New Mexico, and Colorado.[45] We concluded that the De Chelly sandstone of Monument Valley is continuous with the De Chelly sandstone of De Chelly Canyon, as stated by Gregory, and that it is continuous through northern Arizona with the Coconino sandstone of the Grand Canyon, as stated by Darton.[46] Several geologists had correlated the Cedar Mesa sandstone of this report with the Coconino sandstone of the Grand Canyon district,[47] and Reeside and I accepted this correlation to the extent of agreeing that these units were probably continuous when correlated through southern Utah. The Coconino sandstone of the Grand Canyon district, therefore, seems to split toward the east into two massive sandstones separated by red beds. In northeastern Arizona the upper massive sandstone (De Chelly sandstone) is the thicker one, whereas in southeastern Utah the lower massive sandstone is the thicker one. In Monument Valley both sandstones are present. A few miles east of the area shown on plate 1 the De Chelly sandstone dips beneath younger formations, and it is absent where the Cutler formation reappears at the surface in southwestern Colorado. Toward the northeast across Elk Ridge and along the canyon of the Colorado River the Cutler formation crops out almost continuously nearly to the Colorado State line, and the De Chelly or a similar sandstone at approximately the same stratigraphic horizon crops out, though not as a continuous bed.[48]

HOSKINNINI TONGUE

The Hoskinnini tongue of the Cutler formation, named from its outcrop on the sides of Hoskinnini Mesa, is the highest of the three

[43] Darton, N. H., A résumé of Arizona geology: Arizona Univ. Bull. 119, p. 112, 1925.

[44] Baker, A. A., Geology and oil possibilities of the Moab district, Utah: U. S. Geol. Survey Bull. 841, pp. 29–33, 1933.

[45] Baker, A. A., and Reeside, J. B., Jr., Correlation of the Permian of southern Utah, northern Arizona, northwestern New Mexico, and southwestern Colorado: Am. Assoc Petroleum Geologists Bull. vol. 13, pp. 1413–1448, 1929.

[46] Darton, N. H., op. cit., p. 91.

[47] Longwell, C. R., and others, Rock formations in the Colorado Plateau of southeastern Utah and northern Arizona: U. S. Geol. Survey Prof. Paper 132, p. 8, 1923. Darton, N. H., op. cit., p. 207.

[48] Baker, A. A., Geology of the Green River Desert and the east flank of the San Rafael Swell: U. S. Geol. Survey Bull. (in preparation).

red-bed tongues of the Cutler formation. It usually crops out in a steep face just above and almost continuous with that of the De Chelly sandstone (pls. 4, *A*, and 8, *B*), but locally, as in Copper Canyon (pl. 4, *B*) the Hoskinnini tongue may weather back to form a bench at the top of the De Chelly sandstone. As the Hoskinnini is thin everywhere in the region, the distribution of its outcrop is practically coincident with that of the De Chelly sandstone. It crops out in some of the monuments of Monument Valley, on the walls of Oljeto and Hoskinnini Mesas, and along the cliffs extending south from Clay Hill Crossing on the San Juan River. It crops out also along the San Juan near the mouth of Nokai Creek and in the upper part of Nokai Creek.

The Hoskinnini tongue is composed of red beds similar to those of the Organ Rock and Halgaito tongues of the Cutler formation. It consists of nodular-weathering, regularly bedded sandy mudstone and siltstone, with many streaks of grit, and is deep red-brown to maroon with irregular streaks of gray. At its outcrop in Copper Canyon in the northern part of T. 42 S., R. 13 E., there is a persistent bed of gray-white fine-grained sandstone 2 feet thick 25 feet above the base.

The Hoskinnini tongue where present is less than 100 feet thick. It thins somewhat irregularly toward the east and is either absent or thin and unrecognizable at the top of the inaccessible buttes and mesas near Monument Pass, at the east line of T. 43 S., R. 16 E. Its thickness is 55 feet in the canyon of the San Juan River near the mouth of Nokai Creek; 58 feet in the upper part of the canyon of Nokai Creek in sec. 11, T. 43 S., R. 12 E.; 88 feet on the east side of Copper Canyon in sec. 9, T. 42 S., R. 13 E.; 50 feet at the northeast corner of Hoskinnini Mesa in sec. 17, T. 43 S., R. 14 E.; and 34 feet at the Utah-Arizona State line in the southeast corner of T. 43 S., R. 15 E.

Where the De Chelly sandstone wedges out in sec. 23, T. 41 S., R. 13 E., east of Monitor Butte, the Hoskinnini is inseparable from the Organ Rock tongue of the Cutler formation, and from that point north to the limits of the mapped area all the red beds between the Moenkopi formation and the Cedar Mesa sandstone were mapped as the Organ Rock tongue.

The contact of the Hoskinnini with the overlying Moenkopi formation, of Lower Triassic age, is a sharp lithologic boundary where both constitution and color change (pl. 4, *B*). At 8 to 11 feet below the top of the Hoskinnini there is a persistent thin zone of crinkled bedding with irregular thin beds of gray to tan limestone marked with crystalline crusts and small masses of gray and rose quartz. Similar siliceous crusts and masses were also observed, but less commonly, at the top of the Hoskinnini tongue. Above the crinkled zone are numerous lenses of grit. Possibly the crinkled zone marks the contact between the Hoskinnini tongue and the Moenkopi formation, and the grit-bearing dull-red beds above the crinkled zone may represent a basal unit of the Moenkopi formation composed of reworked material. I consider, however, that the sharp lithologic boundary 8 to 11 feet above the thin crinkled zone is the upper boundary of the Hoskinnini tongue and hence of the Cutler formation. Although no discordance was observed at this horizon within the region shown on plate 1, an erosional discontinuity, marked by an irregular surface at the top of the Cutler formation and grits in the base of the Moenkopi formation, was observed a few miles south of the region, in northern Arizona near the Kayenta road; also east of the region, near Comb Ridge at the Utah-Arizona State line and at the mouth of Comb Wash where Comb Ridge crosses the San Juan River.

No fossils were found in the Hoskinnini tongue, but it is included in the Cutler formation on the basis of its lithology. The Hoskinnini differs in lithology from the overlying Moenkopi formation, of Lower Triassic age, and is inseparable from the Organ Rock tongue east of Monitor Butte, where the De Chelly sandstone is absent. The Hoskinnini tongue is not a conspicuous part of the Cutler formation beyond the limits of the region described in this report. In the eastern part of the region it thins out, and to the north it merges with the thick Organ Rock tongue and cannot be traced as a separate unit. Toward the west and south the Hoskinnini tongue dips beneath younger formations, and where Permian formations reappear at the surface it cannot be differentiated.

TRIASSIC SYSTEM

LOWER TRIASSIC SERIES

MOENKOPI FORMATION

The Moenkopi formation, of Lower Triassic age, is the lowest of the Mesozoic formations and unconformably overlies the Permian Cutler formation. It forms a slope between the cliffs of underlying Permian sediments and the overlying ledge-forming Shinarump conglomerate (pl. 4, *B*). The Moenkopi crops out near the top of the monuments of Monument Valley immediately beneath the thin resistant cap of Shinarump conglomerate (pl. 9, *A*, *B*). It crops out also high on the sides of the buttes and mesas near the Utah-Arizona line between Copper Canyon and the southeast corner of T. 43 S., R. 15 E., and on the cliffs extending south from Clay Hill Crossing on the San Juan River. There are small outcrops of the formation in upper Nokai Creek and along the San Juan River west of the mouth of Nokai Creek.

The Moenkopi formation is easily differentiated from other formations that crop out in the region. It is composed of thin, evenly bedded dark-brown to chocolate-brown sandy shale with a great many thin beds of red-brown ripple-marked sandstone and some irregularly bedded blocky-weathing, platy to massive red-brown medium-grained sandstone containing lenses of grit. Nodules and seams of gypsum are common, and thin beds of gypsum were observed here and there. At a few places beds of purplish-red dense nodular limestone a few inches thick are present near the base of the formation. In fresh exposures the Moenkopi formation usually crops out in a steep face, is dark reddish brown, with thin horizontal bands of gray, and is characterized by its even bedding (pl. 11, *A*). Where weathered it forms light chocolate-brown slopes with numerous bands of blocky-weathering sandstone (pls. 4, *B*, and 10, *B*). The abundance of ripple-marked, rain-pitted, and sun-cracked platy sandstones is perhaps the most characteristic feature of the Moenkopi formation.

The following sections of the Moenkopi show the lithologic character of the formation:

Section of Moenkopi formation measured on east side of Copper Canyon in sec. 9, T. 42 S., R. 13 E.

	Feet
Shinarump conglomerate.	
Unconformity.	
Moenkopi formation:	
Shale, chocolate-brown, sandy, with interbedded platy ripple-marked reddish-brown sandstone	77
Sandstone, fine-grained, light reddish brown, ledge-forming, massive in lower part and thin-bedded in upper part	15
Shale, chocolate-brown, sandy, with interbedded platy ripple-marked reddish-brown sandstone	28
Sandstone, ledge-forming, blocky-weathering, ripple-marked, reddish-brown	2
Shale, chocolate-brown, sandy, with interbedded platy ripple-marked reddish-brown sandstone	16
Sandstone, ledge-forming, blocky-weathering, ripple-marked, reddish-brown	10
Shale, chocolate-brown, sandy, with interbedded platy ripple-marked reddish-brown sandstone	49
Sandstone, ledge-forming, blocky-weathering, ripple-marked, reddish-brown	5
Shale, chocolate-brown, sandy, with interbedded platy ripple-marked reddish-brown sandstone and a zone of gypsum nodules 30 feet above base	52
	254
Unconformity.	
Hoskinnini tongue of Cutler formation.	

Section of Moenkopi formation measured on east side of Nokai Canyon in the southern part of sec. 11, T. 43 S., R. 12 E.

Shinarump conglomerate.
Unconformity.
Moenkopi formation:

	Feet
Shale, thin-bedded, reddish-brown, streaked with gray; contains some interbedded platy ripple-marked reddish-brown sandstone	132
Sandstone, brownish red to lavender-red, thin-bedded to massive, medium-grained, with streaks of grit	33
Shale, thin-bedded, chocolate-brown gypsiferous, interbedded with soft platy reddish-brown sandstone showing ripple marks and raindrop impressions	36
Sandstone, yellowish brown, medium-grained, thin-bedded to massive	21
Shale, thin-bedded, chocolate-brown, streaked with gray, interbedded with reddish-brown ripple-marked platy sandstone	25
	247

Unconformity.
Hoskinnini tongue of Cutler formation.

Section of Moenkopi formation measured at east end of Oljeto Mesa, in sec. 35, T. 43 S., R. 15 E.

Shinarump conglomerate.
Unconformity.
Moenkopi formation:

	Feet
Shale, dark red, and thin-bedded sandstone	60
Sandstone, massive, cross-bedded, fine-grained, weathering brownish pink	8
Shale and thin sandstone, dark red and gray-white; sandstone ripple-marked; locally bed is a mass of nodules of sandy clay with maximum diameter of 2 inches	2
Sandstone, massive, cross-bedded, fine-grained, mauve	3
Shale, dark red, with thin beds of blocky-weathering reddish-brown sandstone	33
Sandstone, fine-grained, pinkish brown, in massive beds 2 to 5 feet thick; bench-forming; lower part locally contains clay balls with a maximum diameter of 6 inches and a few lenses of maroon mudstone streaked with greenish gray	54
Limestone, purplish red, dense, fine-grained, nodular-weathering	½
Mudstone, sandy, maroon, streaked with greenish gray; includes several beds of greenish-gray, dense, fine-grained limestone, 1 inch thick	8
Shale, brownish red, sandy, interbedded with platy, ripple-marked, brownish-red sandstone	12
	180½

Unconformity.
Hoskinnini tongue of Cutler formation.

The Moenkopi formation decreases in thickness toward the east across the Monument Valley-Navajo Mountain region. Its thickness is 325 feet near the San Juan River west of Nokai Creek, in sec. 28, T. 41 S., R. 12 E.; 340 feet northeast of Monitor Butte, in the northeastern part of T. 41 S., R. 13 E.; 254 feet on the east side of Copper Canyon in sec. 9, T. 42 S., R. 13 E.; 247 feet on the east side of the canyon of Nokai Creek in sec. 11, T. 43 S., R. 12 E.; 167 feet at the northeast corner of Hoskinnini Mesa, in sec. 17, T. 43 S., R. 14 E.; 180 feet at the east end of Oljeto Mesa, in the southeastern part of T. 43 S., R. 15 E.; and 130 feet at the south tip of Wide Butte, in sec. 22, T. 43 S., R. 16 E. The Moenkopi formation continues to thin toward the east, as it is 80 feet thick on the east side of Comb Ridge, at the Arizona-Utah State line about 8 miles east of the region shown on the map. North of the San Juan River the Moenkopi formation increases in thickness toward the north.

Invertebrate fossils found in the Moenkopi formation in southwestern Utah,[49] near the junction of the Green and Colorado Rivers,[50] and in the San Rafael Swell[51] have established its age as Lower Triassic. No fossils were found in the Moenkopi in the Monument Valley-Navajo Mountain region, but more or less continuous outcrops connect the exposures in this region with those of the fossil locality at the junction of the Green and Colorado Rivers. The correlation of the formation between the Monument Valley region and the type locality at Moenkopi Wash, in northern Arizona,[52] is based on reconnaissance observations by J. B. Reeside, Jr., and me. Further evidence of the age of the Moenkopi formation is afforded by its unconformable relations with the enclosing formations. It unconformably overlies rocks of Permian age, and though the unconformity is poorly displayed in the Monument Valley-Navajo Mountain region, it has been recognized in adjoining areas and over a wide region in the plateau country of southern Utah and northern Arizona.[53] A marked erosional unconformity at the top of the Moenkopi formation separates it from the Shinarump conglomerate of Upper (?) Triassic age.

No part of the Moenkopi formation is known to be of marine origin in the Monument Valley-Navajo Mountain region, although north

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[49] Reeside, J. B., Jr., and Bassler, Harvey, Stratigraphic sections in southwestern Utah and northwestern Arizona: U. S. Geol. Survey Prof. Paper 129, pp. 67–68, 1922.

[50] Baker, A. A., Dobbin, C. E., McKnight, E. T., and Reeside, J. B., Jr., Notes on the stratigraphy of the Moab region, Utah: Am. Assoc. Petroleum Geologists Bull., vol. 11, p. 797, 1927.

[51] Gilluly, James, Geology and oil and gas prospects of part of the San Rafael Swell, Utah: U. S. Geol. Survey Bull. 806, pp. 86–87, 1929.

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

[53] Longwell, C. R., and others, Rock formations in the Colorado Plateau of southern Utah and northern Arizona: U. S. Geol. Survey Prof. Paper 132, p. 9, 1923.

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and west of this region the formation includes marine sediments. The thin regular bedding and abundance of ripple marks of both current and oscillation type show that the Moenkopi formation was water-laid, but the sun-cracked and rain-pitted surfaces indicate that the accumulating sediments were frequently above water. The sediments perhaps accumulated partly in shallow marine water and partly under terrestrial conditions on a surface sloping gently seaward from a highland in southwestern Colorado and eastern Utah. The source of the sediments that were deposited in the vicinity of Monument Valley is unknown, but one source of Moenkopi sediments is indicated by the increasing thickness of the formation and the increase in coarseness of material toward the pre-Cambrian rocks of the Uncompahgre Plateau.[54]

UPPER (?) TRIASSIC SERIES

SHINARUMP CONGLOMERATE

The Shinarump conglomerate crops out in the central and southeastern part of the region. It caps the mesas and buttes and many of the monuments in Monument Valley, and it floors a broad dissected platform which includes the surface of Hoskinnini Mesa and the plateau surfaces south of No Man's Mesa and Monitor Butte. Monitor Butte (pl. 9, *C*) and No Man's Mesa (pl. 4, *B*) rise 1,200 feet or more above this platform. The inner gorges of lower Copper Canyon, Nokai Creek, and the San Juan River between the mouths of Copper Canyon and Nokai Creek are rimmed by the Shinarump conglomerate. There is an isolated exposure of the Shinarump conglomerate northwest of Piute Mesa, in the southeastern part of T. 41 S., R. 11 E. Miser[55] reports isolated outcrops of this formation on Piute Creek that were not visited by me and are not shown on plate 1. The underlying Moenkopi formation, Hoskinnini tongue of the Cutler formation, and De Chelly sandstone member of the Cutler formation are much less resistant to erosion than the Shinarump conglomerate, and these formations usually crop out in a steep slope beneath the resistant Shinarump cap (pl. 4, *B*). The cliffs formed by it can usually be scaled, but only with difficulty. The surface of the bench floored by Shinarump conglomerate is marked by many ledges and small gulches, so that it is difficult to traverse, but near the foot of the slope of the overlying Chinle formation the bench is relatively smooth. Several trails approximately follow the foot of the Chinle slope. The road around the north end of No Man's Mesa is similarly located.

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[54] Dane, C. H., Geology of the Salt Valley anticline and the northwest flank of the Uncompahgre Plateau, Grand County, Utah: U. S. Geol. Survey Bull. 863 (in press).

[55] Miser, H. D., The San Juan Canyon, southeastern Utah: U. S. Geol. Survey Water-Supply Paper 538, pl. 15, 1924.

The Shinarump conglomerate is composed of sandstone with lenses of grit and conglomerate and interbedded shale. The sandstone is gray, fine- to coarse-grained, irregularly bedded (pl. 12, *A*), and composed largely of quartz. Its gray color is commonly obscured by a brownish black coating of desert varnish on weathered surfaces. Massive beds are irregularly cross-bedded. The sandstone contains scattered quartz pebbles with a maximum observed diameter of 4 inches and lenses of grit and conglomerate containing pebbles of quartzite, varicolored chert, and quartz. Greenish-gray sandy shale, in beds of moderate extent, is interbedded with the sandstone and grades laterally and vertically into the sandstone. At the top of the Shinarump conglomerate there is usually a zone a few feet thick of thin-bedded medium- to fine-grained yellowish brown sandstone, which grades into the overlying Chinle formation.

The following partial section of the lower part of the Shinarump conglomerate, measured in the northern part of sec. 35, T. 43 S., R. 15 E., is typical of the lithology of the formation:

Partial section of Shinarump conglomerate on west side of Rock Door

	Feet
Shinarump conglomerate:	
Sandstone, medium- to fine-grained, gray, cross-bedded, composed of quartz sand; weathers into thin yellowish-brown slabs	14
Conglomerate, yellowish brown; pebbles of quartzite, vari-colored chert, and quartz, with maximum diameter of 1½ inches, are rounded and poorly sorted and are embedded in a matrix of siliceous grit; contains complete logs of silicified wood	2
Sandstone, coarse-grained, yellowish brown, containing scattered siliceous pebbles, a few lenses of conglomerate, and much silicified wood; average diameter of pebbles about 1 inch and maximum diameter about 3 inches	10
Shale, greenish gray, sandy, with a thin zone of platy sandstone near middle	5
	31
Unconformity.	
Moenkopi formation.	

The thickness of the Shinarump conglomerate varies iregularly. Its maximum observed thickness is 210 feet south of Monitor Butte, in the southcentral part of T. 41 S., R. 13 E. About 2 miles to the east, near the trail in sec. 23, T. 41 S., R. 13 E., the Shinarump conglomerate is a thin bed of sandstone a few inches thick (pl. 11, *A*). North of the San Juan River the formation wedges out in the western part of T. 40 S., R. 14 E. It is 105 feet thick along the San Juan River in the western part of T. 41 S., R. 12 E. The average thickness of the Shinarump conglomerate in the Monument Valley-

Navajo Mountain region is probably between 100 and 140 feet. Variations in thickness are due in part to the erosional unconformity at the base but more largely to the character of its contact with the overlying Chinle formation.

The lower contact of the Shinarump conglomerate is a marked erosional unconformity. At its upper contact sandstone beds of the formation grade into the Chinle formation, and there is usually a thin series of light-brown platy sandstone and interbedded shale which could be included with either formation. Locally, however, the Shinarump conglomerate grades laterally into variegated shale identical in lithology with shale beds of the Chinle formation and consequently is inseparable from them. Such changes may occur within short distances, as in sec. 22, T. 41 S., R. 13 E., where the entire Shinarump conglomerate, about 100 feet thick, changes to shale in a distance of not more than 1,000 feet. Less conspicuous changes involving only the upper part of the Shinarump conglomerate probably occur elsewhere in the region. The upper contact of the conglomerate is therefore not everywhere at the same horizon.

Silicified logs, some of which are 20 or 30 feet in length and 2 or 3 feet in diameter, are very plentiful in the Shinarump conglomerate in the Monument Valley-Navajo Mountain region. The only other fossils found in the formation in this region were several cycad fronds of a new species, to which the name *Pterophyllum bakeri* had been applied by Berry.[56] These plant remains were collected at a locality about 1,000 feet southeast of the northwest corner of sec. 35, T. 42 S., R. 12 E., from the transition zone at the top of the formation. Neither the fronds nor the silicified wood are diagnostic of the age of the formation. Another collection of fronds (*Otozamites powelli*), obtained by R. C. Moore from the Shinarump conglomerate in the Waterpocket Fold, about 50 miles north of Navajo Mountain, was described by Berry.[57] Vertebrate and invertebrate fossils of Upper Triassic age have been found in the overlying Chinle formation at numerous places in the plateau province. Because of the close relationship between these formations I consider that the Shinarump conglomerate is a basal conglomerate of the Chinle formation and that both are of Upper Triassic age. In the absence of organic remains that specifically determine the age of the Shinarump conglomerate, the usual tentative assignment to the Upper (?) Triassic is followed in this report.

The thin Shinarump conglomerate has been traced over thousands of square miles in southern Utah and northern Arizona. Nowhere

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[56] Berry, E. W., A new *Pterophyllum* from the Shinarump conglomerate in Utah: Washington Acad. Sci. Jour., vol. 20, pp. 458–463, 1930.

[57] Berry, E. W., Cycads in the Shinarump conglomerate of southern Utah: Washington Acad. Sci. Jour., vol. 17, pp. 303–307, 1927.

does it appreciably exceed the maximum thickness observed in the Monument Valley-Navajo Mountain region, and throughout its extent its lithology is essentially the same. The irregular bedding, poorly sorted sediments, and cross-bedding indicate deposition in shifting streams. The source of the coarse sediments that were distributed so widely is not known.

UPPER TRIASSIC SERIES

CHINLE FORMATION

The Chinle formation crops out in the part of the region lying west of Monument Valley and west of Grand Flat, which is north of the San Juan River. Almost continuous exposures extend along the canyon of the San Juan River from a point near Clay Hill Crossing, in the western part of T. 40 S., R. 14 E., nearly to the junction of the San Juan and Colorado Rivers. Belts of exposure follow the canyons of Piute and Nokai Creeks and encircle the sides of No Man's Mesa and Monitor Butte. There is a small isolated exposure of the formation in Horse Canyon, a deep canyon that drains the southwest slope of Navajo Mountain. The Chinle forms steep slopes below the palisadelike wall of Wingate sandstone that forms the rims of canyons and mesas (pl. 4, *B*). These steep slopes have been dissected into badlands; they are strewn with blocks of the sandstone that have fallen from the high cliffs, and many landslides involving the Chinle and the overlying Wingate sandstone form rounded hills that are composed of jumbled Chinle beds capped by sandstone debris. The inner gorge of Copper Canyon in sec. 19, T. 41 S., R. 13 E., was dammed by an ancient landslide from the mesa to the east, and the creek was thereby diverted a short distance to the west, where a second inner canyon, about 45 feet deeper than the obstructed channel, has been cut around the west margin of the slide.

The Chinle formation is composed chiefly of variegated shale which weathers into a stiff clay roughly banded in vivid colors (pl. 11, *A*) and produces a barren surface. A desolate but brilliantly colored landscape is produced by this formation at many places in the region, and such a landscape east of the Grand Canyon in northern Arizona has received the well-known name "Painted Desert." Interbedded with the shale are a few thin beds of cherty limestone and conglomerate with angular pebbles of limestone and pellets of mud. The upper part of the formation contains reddish-brown sandstone, similar in composition to the overlying Wingate sandstone, into which it grades without apparent break. Silicified wood is present but is less abundant than in the underlying Shinarump conglomerate. The thickness of the Chinle formation is 825 feet on the north side of Monitor Butte and 925 feet at the north end of Piute Mesa, in the southern part of T. 41 S., R. 12 E.

No fossils were collected from the Chinle formation, but Miser [58] observed leaves in the lower part of the formation at its outcrop in Piute Creek near the San Juan River. At many places in the Colorado Pleateau the Chinle contains vertebrate fossils which show it to be of Upper Triassic age.[59] Both vertebrate and invertebrate fossils collected from the Chinle formation are forms that inhabit fresh water. It is therefore of continental origin. The evenly bedded shale is probably a lacustrine deposit, but the irregularly bedded sandstone in the upper part of the formation is believed to be of fluviatile origin.

The source of the sediments of the Chinle formation is uncertain. Camp [60] has shown that beds of bentonite derived from the alteration of volcanic ash are a common constituent of the formation in Arizona, and bentonite has been reported from outcrops of the Chinle formation near the Kaiparowits Plateau.[61] Although bentonite is probably present in the Monument Valley-Navajo Mountain region, it was not recognized in the course of the field studies, and no thin sections of the Chinle were made for the detection of bentonite. The sediments become coarser-grained toward the pre-Cambrian rocks of western Colorado and eastern Utah, and it seems possible that these rocks were a source of material during at least part of Upper Triassic time.

JURASSIC (?) SYSTEM

GLEN CANYON GROUP

WINGATE SANDSTONE

The Wingate sandstone is the lowest formation of the Glen Canyon group and one of the most conspicuous formations in the Monument Valley-Navajo Mountain region, for it forms a sheer palisade-like wall along the canyon rims above the badland slopes of the shales of the Chinle formation (pl. 4, *B*). This wall, which includes the full thickness of the sandstone and usually exceeds 300 feet in height, is impassable for stretches of many miles and can be scaled at few places except by means of built trails. The Wingate sandstone is exposed almost continuously along the San Juan River from a point near Clay Hill Crossing, in the western part of T. 40 S., R. 14 E., to a point within half a mile of the junction of the San Juan and Colorado Rivers. In the eastern part of its

[58] Miser, H. D., oral communication.

[59] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, pp. 46–47, 1917. Camp, C. L., A study of the phytosaurs: California Univ. Mem., vol. 10, p. 4, 1930.

[60] Camp, C. L., op. cit., p. 2.

[61] Hewett, D. F., oral communication.

outcrop it forms a high rim along the canyon of the San Juan and its tributaries, but in general the height of the rim above river level becomes progressively lower toward the west. Where streams have not cut into the soft beds of the underlying Chinle formation, as in Deep and Desha Canyons, narrow gorges that may be more than 200 feet deep are usually cut in the Wingate sandstone. There are isolated exposures of the sandstone in the beds of Cha and Bridge Canyons and in the three forks of Tsagieto Canyon, all of which are part of the drainage system radiating from Navajo Mountain.

The Wingate sandstone is nearly homogeneous and is composed of medium- to fine-grained quartz sand cemented largely with calcium carbonate. The sand grains are rounded to angular and are commonly coated with a red film of iron oxide. Rarely there are thin lenses of brownish-gray unfossiliferous limestone of local extent in the sandstone. Pebbles of sandstone and shale with a maximum diameter of 2 inches were observed at the base of the sandstone at one locality, and discontinuous stringers of quartz grit also are present locally at the base. The sandstone crops out in a cliff as a single massive, vertically jointed unit (pls. 9, *C*, and 12, *B*), in which bedding is indistinct and discontinuous except at the very base of the formation, where it is irregularly bedded. It is cross-bedded on a large scale, but the cross-bedding is less apparent in the vertical cliffs than on local rounded surfaces, where it has been emphasized by the etching effect of weathering. On unweathered surfaces the sandstone is pinkish red to buff, but when weathered it acquires a deep-red to black color due to a coating of desert varnish.

The thickness of the Wingate sandstone is fairly uniform throughout the area. It is 293 feet in Horse Canyon, southwest of Navajo Mountain; 302 feet in the canyon of the San Juan River at the mouth of Wilson Creek; 337 feet on the west side of Piute Canyon at the southwest corner of sec. 4, T. 42 S., R. 11 E.; 328 feet on the north side of the canyon of the San Juan River near the southeast corner of sec. 28, T. 41 S., R. 11 E.; and 320 feet at the north and south ends of No Man's Mesa.

The Wingate sandstone appears to rest conformably upon the underlying Chinle formation. This contact elsewhere in the plateau region shows an erosional unconformity that has been interpreted as marking an important stratigraphic break.[62] In the Monument Valley-Navajo Mountain region, however, irregularly bedded sandstones at the top of the Chinle formation grade into the Wingate sandstone. Locally there probably were minor breaks in sedi-

[62] Gilluly, James, Geology and oil and gas prospects of part of the San Rafael Swell, Utah: U.S. Geol. Survey Bull. 806, p. 94, 1929.

mentation between the formations, but in my opinion deposition was essentially continuous. The conglomerate and grit-bearing beds that occur locally in the base of the Wingate sandstone are considered to be of fluviatile origin and therefore do not necessarily indicate an unconformity involving the lapse of a long interval of time.

The irregularly bedded sandstone at the base of the formation is obviously waterlaid and presumably represents a continuation of the fluviatile conditions that existed in the later part of Chinle time. The homogeneous lithology and the large-scale cross-bedding suggest an eolian origin for the massive sandstone.

No fossils were collected from the Wingate sandstone, but Miser [63] observed dinosaur tracks on surfaces of the lower lenticular beds in sec. 30, T. 41 S., R. 11 E. The formation is tentatively classified as Jurassic (?), although there is no specific evidence bearing on its age. It is part of the Glen Canyon group, which is underlain by rocks of Upper Triassic age and overlain by rocks of Upper Jurassic age.

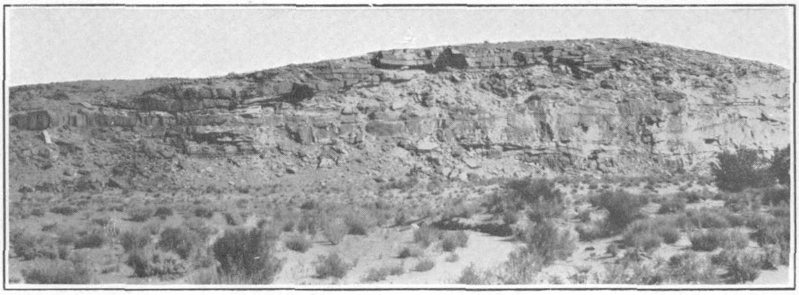
The correlation of the Wingate sandstone is discussed in another paper [64] but may be briefly summarized here. From its type locality, near Fort Wingate, in northern New Mexico, it has been found to extend over a large part of the Colorado Plateau. It thins toward the east and is represented by an upper sandstone member of the Dolores formation in Colorado west of Ouray. West of the Monument Valley-Navajo Mountain region it appears to wedge out and not to be represented in the thick sandstone that represents the Glen Canyon group near Lees Ferry, Ariz., and farther west. Its northern limit is unknown, but it is apparently absent in the Wasatch and Uinta Mountains.

KAYENTA FORMATION

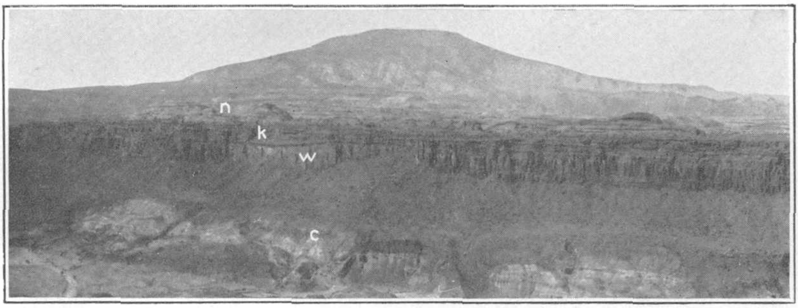
The middle formation of the Glen Canyon group is the Kayenta, which consists largely of irregularly bedded sandstones that separate the two massive sandstones of the group. Approximately the lower half of the Kayenta crops out at the top of the cliff of Wingate sandstone, forming the resistant rim rock that protects the underlying Wingate sandstone from erosion. It is readily distinguished from the Wingate sandstone portion of the cliff by its pronounced bedding, which contrasts with the massive character of the underlying sandstone (pl. 12, *B*, *C*). The upper part of the Kayenta formation is less resistant to erosion than the lower part and weathers back from

[63] Miser, H. D., and others, Rock formations in the Colorado Plateau of southeastern Utah and northern Arizona: U. S. Geol. Survey Prof. Paper 132, p. 13, 1923.

[64] Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., Correlation of the Jurassic formations of parts of Utah, Arizona, New Mexico, and Colorado: U. S. Geol. Survey Prof. Paper 183 (in press).

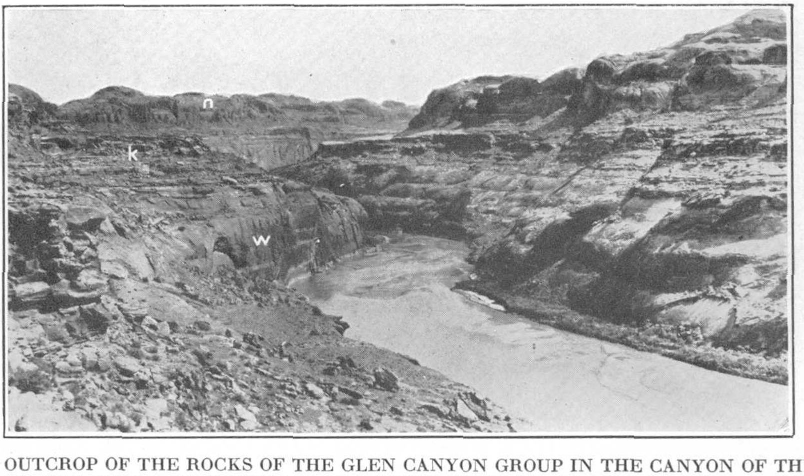


A. AN OUTCROP OF THE SHINARUMP CONGLOMERATE IN SEC. 29, T. 41 S., R. 13 E., SHOWING THE IRREGULAR BEDDING OF THE FORMATION.



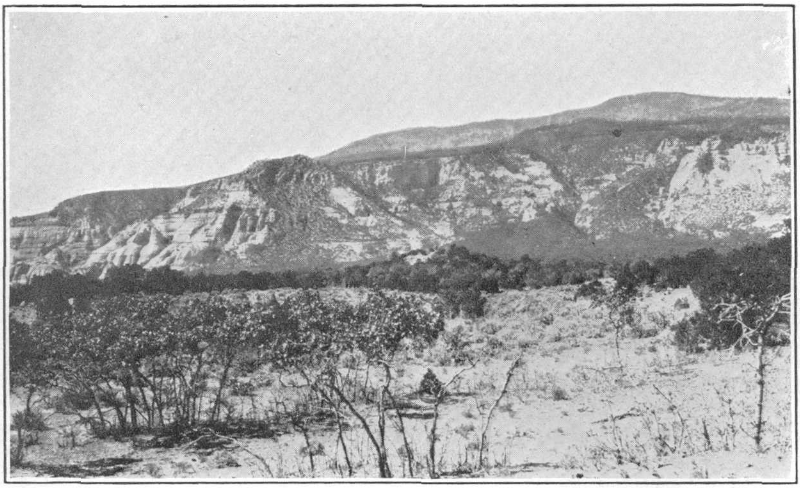
B. WEST WALL OF PIUTE CANYON IN THE SOUTHERN PART OF T. 42 S., R. 11 E.

Shows the talus-strewn slopes of the Chinle formation (*c*) overlain by the vertically jointed cliff-forming Wingate sandstone (*w*). The sandstone of the Kayenta formation (*k*) forms the upper part of the cliff, and the Navajo sandstone (*n*) forms rounded domes on the upland surface. Navajo Mountain appears in the background.



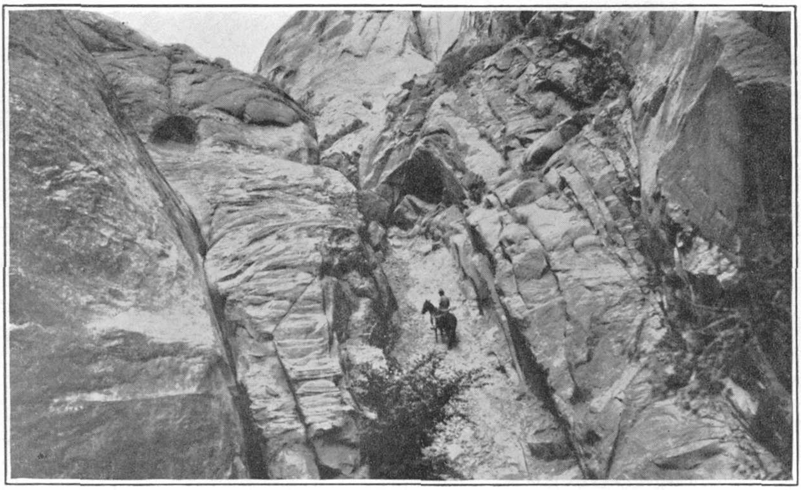
C. OUTCROP OF THE ROCKS OF THE GLEN CANYON GROUP IN THE CANYON OF THE SAN JUAN RIVER SOUTHEAST OF THE SOUTH QUARTER CORNER OF SEC. 4, T. 41 S., R. 11 E.

Shows the steep canyon wall formed by the massive Wingate sandstone (*w*), the bench formed by the thin-bedded Kayenta formation (*k*), and the rounded domes formed by the massive Navajo sandstone (*n*).



A. EAST SIDE OF NAVAJO MOUNTAIN FROM THE WETHERILL TRADING POST.

Shows the bare, rugged lower slopes carved from the Navajo sandstone and the long smooth slopes formed by the overlying Carmel formation. The Entrada sandstone, Morrison formation, and Dakota (?) sandstone are poorly exposed in the steep upper slopes.



B. JOINTS IN THE NAVAJO SANDSTONE ON THE EAST SIDE OF REDBUD PASS.

At several places such joints have facilitated the construction of the trail northwest of Navajo Mountain.

the cliffs, forming broad benches and platforms that rise gradually to the foot of the cliffs formed by the overlying Navajo sandstone. These benches are marked by numerous ledges and low cliffs. The Kayenta formation crops out along the canyon of the San Juan River in the west half of the region and extends about 2 miles down the Colorado River from its junction with the San Juan. It caps No Man's and Piute Mesas and crops out extensively on the Rainbow Plateau. There are isolated exposures of the formation in most of the canyons radiating from Navajo Mountain. At Rainbow Bridge the inner gorge of Bridge Canyon, which passes under the arch, is cut in this formation (pl. 16, *B*).

The Kayenta formation is composed of irregularly bedded fine- to coarse-grained sandstone with some interbedded shale, limestone, and conglomerate. The sandstone is purplish red to buff, but surfaces of the lower cliff-forming part are usually dark reddish brown, owing to a coating of desert varnish. Individual beds of the sandstone are commonly cross-bedded and range from a few inches to tens of feet in thickness, but the beds are lenticular and discontinuous. Some of the sandstone is coarse-grained and micaceous and is locally a grit or fine conglomerate with small pebbles of quartz and sandstone. Beds of conglomerate composed of angular fragments of limestone and shale, with a maximum observed diameter of 1 inch, imbedded in a sandy matrix, are distributed sparsely through the formation. Thin beds of shale interbedded with the sandstone are gray to purplish red and are usually sandy. Beds of gray sandy unfossiliferous limestone a few inches thick are rare.

The thickness of the Kayenta formation is 225 feet in Horse Canyon, southwest of Navajo Mountain; 148 feet on the north side of the canyon of the San Juan River at the mouth of Cha Canyon; 140 feet on the west side of Piute Canyon at the southwest corner of sec. 4, T. 42 S., R. 11 E.; and 157 feet on the east side of Piute Mesa in sec. 28, T. 42 S., R. 12 E.

Some of the variation in thickness is perhaps due to the difficulty of selecting a boundary between the irregularly bedded sandstone and the massive sandstones that overlie and underlie it. The sandstone in the lower part of the Kayenta formation is similar in color and composition to the underlying Wingate sandstone, and the character of the bedding is the only criterion that can be used in selecting a contact between them. All the beds that showed distinct bedding were placed in the Kayenta formation. The precise boundary is largely a matter of personal opinion, and it is possible that the same horizon was not selected by the various geologists who mapped different parts of the region. In sec. 1, T. 43 S., R. 11 E., on the north side of the trail from Piute Mesa to Piute Canyon, there is an erosional unconformity between the Wingate sandstone and the

Kayenta formation, but it is of slight extent and probably does not indicate a stratigraphic break at this horizon throughout the area. At the top of the formation the lithology is not greatly different from that of the overlying massive Navajo sandstone, and the presence of distinct bedding planes in the Kayenta formation is the principal criterion for separating the two formations.

The Kayenta formation is tentatively classified as Jurassic(?). No fossils were collected from it in the Monument Valley-Navajo Mountain region, and none that have definite age significance have been collected from it elsewhere. Gregory observed dinosaur tracks in this formation in Navajo Canyon, in Arizona about 12 miles south of Navajo Mountain. R. S. Lull examined photographs and measurements of these tracks and reported that they are not older than latest Triassic.[65]

The name "Kayenta formation" has recently been adopted to replace the name "Todilto (?)" for this formation. The type locality is about a mile north of Kayenta, Ariz., and about 20 miles south of the Monument Valley-Navajo Mountain region. At the type locality of the Todilto formation, in Todilto Park, N. Mex., that formation is a thin limestone, and it was with considerable uncertainty that Gregory correlated the irregularly bedded sandstones between the massive Wingate and Navajo sandstones of Monument Valley with that limestone. The name "Todilto" has therefore been used with a query in several published reports dealing with Utah and Arizona. Reconnaissance stratigraphic observations[66] have led to the conclusion that the Todilto limestone of Todilto Park is much younger than the Kayenta formation and that the Kayenta is not present in New Mexico. The Kayenta formation maintains a fairly constant lithology and thickness in a large area in southeastern Utah, but it thins toward the east and wedges out in western Colorado near the Utah State line. It is thin or absent in northern Arizona near Tuba. West of the Monument Valley-Navajo Mountain region, near Lees Ferry, Ariz., where the Jurassic (?) beds reappear from beneath the cover of younger formations, the Kayenta formation cannot be recognized. It appears to have wedged out in that direction, although it may be represented by thin-bedded sandstones beneath the single massive sandstone that forms the Echo Cliffs, near Lees Ferry.

The irregularly bedded sediments of the Kayenta formation were obviously deposited in water and are probably fluviatile sediments

[65] Gregory H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, p. 56, 1917.

[66] Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., Correlation of the Jurassic formations of parts of Utah, Arizona, New Mexico, and Colorado: U. S. Geol. Survey Prof. Paper 183 (in press).

laid down by shifting streams. Three lots of Unios, collected near Moab, Utah,[67] were reported by J. B. Reeside, Jr., to show that the Kayenta formation accumulated in fresh water. The source of the sediments is not known, but they were perhaps derived in part from highlands in southwestern Colorado.

NAVAJO SANDSTONE

The Navajo sandstone is the upper formation of the Glen Canyon group. Except for a few isolated knobs, all the exposures of this sandstone south of the San Juan River lie west of Piute Creek. North of the San Juan River the sandstone crops out almost continuously along the canyon rim west of Clay Hill Crossing, in sec. 19, T. 40 S., R. 14 E. The Navajo sandstone forms the steep, rugged lower flanks of Navajo Mountain (pl. 13, A) and is the principal surface rock west of Piute Creek. Near the west rim of Piute Canyon the sandstone crops out as a series of gently rounded knobs rising above the bench formed by the Kayenta formation. Toward the west the topography becomes increasingly rugged, and in the area north and west of Navajo Mountain where this sandstone forms the surface rock there is an indescribable maze of high rounded, closely-spaced domes and deep, narrow canyons (pls. 11, *B*, 14, *A*, *B*). The canyons and domes resulting from the dissection of this sandstone when seen from the top of Navajo Mountain create the impression of a billowy barren waste and yet one of remarkable scenic grandeur. The Colorado River crosses this barren area in a canyon cut in the Navajo sandstone. Rainbow Bridge (pl. 16, *B*), which lies in its midst, and the Owl and Hawkeye natural bridges have also been carved from this sandstone. The greater part of the outcrop of the Navajo sandstone has so rugged a surface that travel across it, even on foot, is practically impossible except along a single trail that circles the base of Navajo Mountain.

The Navajo sandstone is composed of medium-sized, rounded to subangular quartz grains, loosely cemented with calcium carbonate. Horizontal bedding planes are rare, but the sandstone is intricately cross-bedded with many tangential bedding planes. The color of the sandstone is gray to buff or tan, although on the flanks of Navajo Mountain it is pink to bright red in irregular patches of slight extent. Silicification of the sandstone was also observed on the flanks of Navajo Mountain. Thin beds of unfossiliferous greenish-gray sandy limestone occur here and there as lenses perhaps a mile in maximum diameter at several horizons in the sandstone. They usually crop out as a resistant capping on mesas. On the west side of Cha Canyon about 3 miles from its mouth, a thin bed of limestone conglomerate is

[67] Baker, A. A., Geology and oil resources of the Moab district, Utah: U. S. Geol. Survey Bull. 841, p. 46, 1933.

present in the Navajo sandstone about 100 feet above the base. The matrix of the conglomerate is red-brown quartz sandstone with angular slabs of greenish-gray sandy limestone, 18 inches or more in diameter, embedded in it.

The thickness of the Navajo sandstone as measured northeast of Navajo Mountain, at Navajo Begay, and at Rainbow Bridge is 1,100 feet.

The Navajo sandstone is unfossiliferous, and its exact age is unknown. There appears to have been continuous deposition during the accumulation of the Glen Canyon group, but none of the three formations of the group has yielded fossils that determined its age. The Glen Canyon group is underlain by the Chinle formation, of Upper Triassic age, and is overlain by the Carmel formation, of Upper Jurassic age. The entire group is tentatively considered to be of Jurassic age and is therefore designated "Jurassic (?)."

The correlation of the Navajo sandstone presents little difficulty in a large area in southeastern Utah and northeastern Arizona where the sequence of formations is essentially the same as in the Monument Valley-Navajo Mountain region. A detailed discussion of a more widespread correlation of the formation is presented in another paper,[68] but the principal points of the correlation are here summarized. The Navajo sandstone wedges out toward the east near the southeast corner of Utah and in western Colorado near the Uncompahgre Plateau. It is not represented by any part of the La Plata sandstone of Cross in the San Juan Mountains of southwestern Colorado. The Dolores formation which there underlies the La Plata, is older than the Navajo sandstone, and the La Plata is younger than this sandstone. The Navajo sandstone is absent in northwestern New Mexico, and the hiatus corresponding to it and the Kayenta formation falls between the Todilto limestone and the underlying Wingate sandstone. The Navajo sandstone thickens toward the west and is believed to include all of the massive Jurassic (?) sandstone that crops out in northern Arizona and southern Utah west of a line through Lees Ferry, Ariz.

The Navajo sandstone is considered to be of eolian origin. The intricate large-scale cross-bedding, scarcity of true bedding planes, absence of silt, and total lack of fossils support this interpretation. The presence of scattered pebbles in the Navajo in the San Rafael Swell and Green River Desert,[69] which show polishing and scouring

[68] Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., Correlation of the Jurassic formations of parts of Utah, Arizona, New Mexico, and Colorado: U. S. Geol. Survey Prof. Paper 183 (in press).

[69] Gilluly, James, and Reeside, J. B., Jr., Sedimentary rocks of the San Rafael Swell and some adjacent areas in eastern Utah: U. S. Geol. Survey Prof. Paper 150, p. 72, 1928. Baker, A. A., Geology of the Green River Desert and the eastern flank of the San Rafael Swell: U. S. Geol. Survey Bull. (in preparation).

attributed to wind action, also accords with this interpretation. The thin beds of limestone and a few beds of horizontally bedded sandstone show that some of the sediments were deposited from water. The source of the sediments is not definitely known, but because of the westward thickening of the formation the source presumably lay to the west.

JURASSIC SYSTEM

UPPER JURASSIC SERIES

SAN RAFAEL GROUP

CARMEL FORMATION

The Carmel formation is the lower of the two formations of the San Rafael group that are present in the Monument Valley-Navajo Mountain region. It crops out only in the extreme western part of the region, on the flanks of Navajo Mountain, on a few isolated buttes, and along the foot of Cummings Mesa and the Kaiparowits Plateau. It is a soft formation that weathers back on a bench formed at the top of the Navajo sandstone. The bench is usually a relatively narrow one (pl. 14, *A*, *C*) between the cliffs formed by the Navajo sandstone and those of the overlying Entrada sandstone, but on the sides of Navajo Mountain the formation caps long sloping benches that are essentially dip slopes on the top of the Navajo sandstone (pl. 13, *A*). The exposure of the Carmel formation on Navajo Mountain is largely concealed by vegetation and talus from overlying formations. Most of the exposures are practically devoid of vegetation but are accessible at few places.

When the various inaccessible exposures of the Carmel formation are viewed from a distance the formation appears to be composed of soft red sandstone, shale, and mudstone, with some thin ledges of gray sandstone. Gregory and Moore [70] describe the Carmel formation near the mouth of Rock Creek, which enters the Colorado River from the north about 10 miles west of the area shown on plate 1, as follows:

> Immediately above the Navajo lies 35 feet of red crumbly, very unevenly bedded calcareous sandy shale that includes patches of lumpy sandstone. These beds are succeeded upward by 94 feet of red sandstone, mottled with white, alternating with unevenly bedded sandy red shale that presents many smooth and rippled foliation surfaces. Toward the top these beds become increasingly irregular in thickness and extent.

The thickness of the Carmel formation on the butte that lies west of Surprise Valley, northwest of Navajo Mountain, is 130 feet.

The contact between the Carmel formation and the Navajo sandstone was usually observed only from a distance. As thus viewed it appeared to be even and apparently conformable. In some sections

[70] Gregory, H. E., and Moore, R. C., The Kaiparowits region: U. S. Geol. Survey Prof. Paper 164, p. 87, 1931.

in the Colorado Plateau [71] minor relief has been observed on the top of the Navajo sandstone, suggesting that a period of erosion preceded the deposition of the Carmel formation. From my observations over a wide area in the Colorado Plateau it appears that there is little evidence of an extended lapse of time or of erosion of the Navajo before the overlying Carmel formation was deposited. The slight relief at the top of the dune-sand deposit of the Navajo sandstone is believed to represent surface irregularities that were incompletely erased before the overlying water-laid sediments were deposited.

The Carmel formation is of Upper Jurassic age. No fossils were collected from it in the Monument Valley-Navajo Mountain region, but elsewhere the formation contains Upper Jurassic invertebrate fossils. It is fossiliferous in the San Rafael Swell [72] and at the type locality near Mount Carmel, in southwestern Utah.[73] Although the formation has not been traced from Navajo Mountain to the San Rafael Swell, its characteristic lithology and stratigraphic position between the massive Navajo and Entrada sandstones make the correlation unquestionable. Toward the west Gregory and Moore [74] have correlated it between the Monument Valley-Navajo Mountain region and the type locality of the formation. As a result of recent reconnaissance stratigraphic studies, however, it seems probable that the original Carmel formation near Mount Carmel, Utah, contains not only rocks that are equivalent to the formation in southeastern Utah,[75] but also younger rocks. East and south of the Monument Valley-Navajo Mountain region the Carmel formation thins rapidly and wedges out in northeastern Arizona and western Colorado.

The sediments composing the Carmel formation were water-laid, and it is inferred that they are marine and accumulated near the southeast margin of an arm of the sea. Marine limestone and abundant gypsum are present in the formation in the Green River Desert, in the Waterpocket Fold, and near Mount Carmel, north and west of the Monument Valley-Navajo Mountain region. They disappear toward the southeast, gradually changing to soft silty sandstone and shale, which in turn wedge out toward the south and east. The margin of

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[71] Baker, A. A., Geology and oil possibilities of the Moab district, Utah: U. S. Geol. Survey Bull. 841, pp. 47–48, 1933. Longwell, C. R., and others, Rock formations in the Colorado Plateau of southeastern Utah and northern Arizona: U. S. Geol. Survey Prof. Paper 132, p. 14, 1923.

[72] Gilluly, James, Geology and oil and gas prospects of part of the San Rafael Swell, Utah: U. S. Geol. Survey Bull. 806, p. 100, 1929.

[73] Gregory, H. E., and Moore, R. C., The Kaiparowits region: U. S. Geol. Survey Prof. Paper 164, p. 73, 1931.

[74] Idem, pp. 72–77.

[75] Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., Correlation of the Jurassic formations of parts of Utah, Arizona, New Mexico, and Colorado: U. S. Geol. Survey Prof. Paper 183 (in press).

the silty sediments in these directions is believed to mark the extent of the marine incursion.

ENTRADA SANDSTONE

The Entrada sandstone overlies the Carmel formation and is the upper of the two formations of the San Rafael group that are present in this region. It crops out only in the extreme western part of the region, high on the slopes of Navajo Mountain, on a few isolated buttes, and along the sides of Cummings Mesa and the Kaiparowits Plateau. It usually makes a steep cliff, which rises above the slope-forming Carmel formation (pl. 14, *A*, *C*), but it is poorly exposed on Navajo Mountain, where it underlies a steep forested and debris-strewn slope.

The Entrada is a massive medium- to fine-grained quartz sandstone. Horizontal bedding planes are present but are not always conspicuous, and the formation may crop out as a single massive bed or as a series of thick beds. It is tangentially cross-bedded. The color of the sandstone is a light brownish red to tan, which serves to distinguish it from the similarly bedded light-colored Navajo sandstone. The thickness of the Entrada is 440 feet as measured at the west end of the butte between Nasja and Oak Canyons, northwest of Navajo Mountain.

Although the contact between the Carmel formation and the Entrada sandstone could not be closely examined because of its inaccessibility, it appears to be conformable. Throughout a large part of southeastern Utah the contact is notably irregular, being characterized by crinkly bedding, wedges of sandstone extending down into the underlying shaly beds, and the presence in the upper part of the Carmel formation of sandstone that is identical in lithology with the Entrada sandstone.[76] Although some of these features have been considered by Gregory and Moore[77] and by Lee[78] to indicate an unconformity, other geologists[79] have concluded that the contact is essentially conformable over a wide area, and it is also inferred to be conformable in the Monument Valley-Navajo Mountain region.

The Entrada sandstone is of Upper Jurassic age. No fossils have been collected from it in southeastern Utah, but its age is fixed at its

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[76] Gilluly, James, and Reeside, J. B., Jr., Sedimentary rocks of the San Rafael Swell and some adjacent areas in eastern Utah: U. S. Geol. Survey Prof. Paper 150, p. 78, 1928. Baker, A. A., Geology and oil possibilities of the Moab district, Utah: U. S. Geol. Survey Bull. 841, p. 48, 1933; Geology of the Green River Desert and the east flank of the San Rafael Swell: U. S. Geol. Survey Bull. (in preparation).

[77] Gregory, H. E., and Moore, R. C., The Kaiparowits region: U. S. Geol. Survey Prof. Paper 164, p. 87, 1931.

[78] Lee, W. T., unpublished manuscript.

[79] Gilluly, James, and Reeside, J. B., Jr., op. cit., p. 46. Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., Correlation of the Jurassic formations of parts of Utah, Arizona, New Mexico, and Colorado: U. S. Geol. Survey Prof. Paper 183 (in press). McKnight, E. T., oral communication.

type locality in the San Rafael Swell, where it is enclosed between formations that contain Upper Jurassic marine fossils.[80]

The regional correlation of the Entrada sandstone has been discussed in another paper [81] but is briefly as follows:

It is a conspicuous lithologic unit in a large area in southeastern Utah, but thins to the east and is equivalent to the †Lower LaPlata sandstone in southwestern Colorado. It also thins to the south and wedges out in northeastern Arizona. Toward the northeast it is probably equivalent to beds in northeastern Utah which have been called "Nugget sandstone" but which are younger than the true Nugget sandstone. Its westward extent is uncertain, but it may be represented in the upper part of the Carmel formation at the type locality near Mount Carmel, in southwestern Utah.

The long, sweeping tangential cross-bedding of the Entrada sandstone combined with horizontal bedding planes suggests that the sandstone is in part of eolian origin and in part water-laid.

MORRISON FORMATION

The Morrison formation overlies the Entrada sandstone and is present only in the extreme western part of the region. Its most extensive outcrops are in the nearly vertical cliffs along the east side of Cummings Mesa and the cliffs of the Kaiparowits Plateau north of the Colorado River. The Morrison formation also crops out in the upper slopes of Navajo Mountain, and the lower part of the formation caps two isolated buttes west and northwest of the mountain.

The outcrop of the Morrison formation on Navajo Mountain is mantled with talus and vegetation, which conceal the lithology. Observed from a distance the formation as exposed along Cummings Mesa and the Kaiparowits Plateau appears to consist of irregularly bedded gray and brown sandstone with perhaps minor amounts of interbedded shale. In a section measured near the mouth of Last Chance Creek, which is about 13 miles west of the area described in this report, Moore [82] found the Morrison to be 393 feet thick and to consist of distinctly but massively bedded vertical jointed greenish-gray gritty sandstone with some purplish and brown layers (pl. 14, *C*). The formation is 480 feet thick on the east side of Cummings Mesa opposite the junction of Cliff and Forbidding Canyons as measured with a telescopic alidade.

An uncomformity at the base of the Morrison has been reported at several localities in the Colorado Plateau and elsewhere, and there

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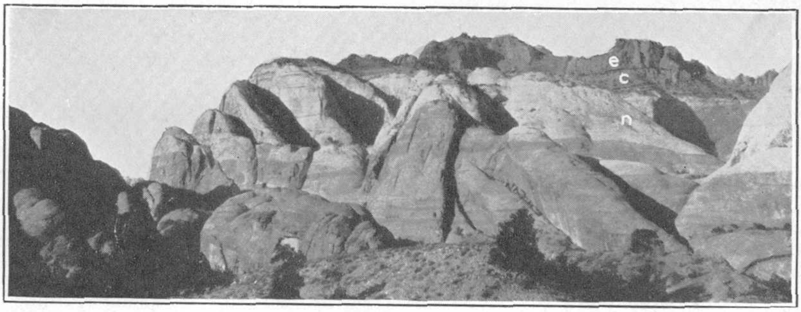
[80] Gilluly, James, Geology and oil and gas prospects of part of the San Rafael Swell, Utah: U. S. Geol. Survey Bull. 806, pp. 99–108, 1929.

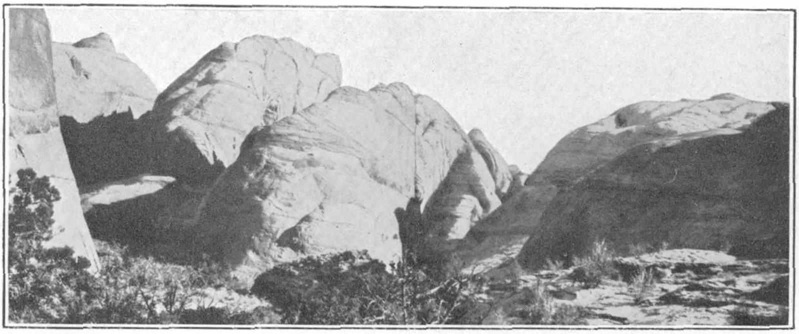
[81] Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., op. cit.

[82] Gregory, H. E., and Moore, R. C., The Kaiparowits region: U. S. Geol. Survey Prof. Paper 164, p. 88, 1931.



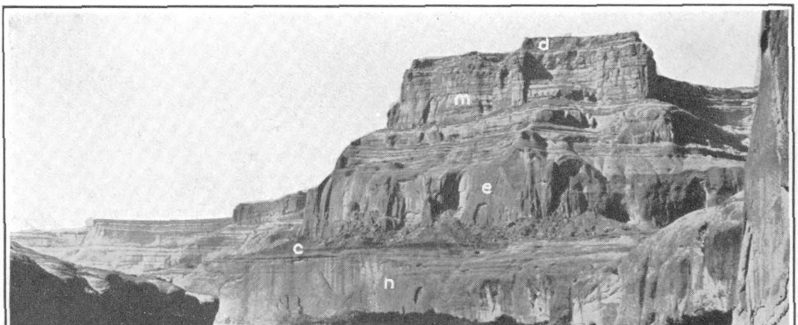
A. AN OUTCROP OF THE NAVAJO SANDSTONE IN A BUTTE ON THE WEST SIDE OF SURPRISE VALLEY.

Shows the rounded forms produced by erosion of the Navajo sandstone (*n*). The Entrada sandstone (*e*) crops out in the darker cliff at the top of the butte and is separated from the Navajo by the slope-forming Carmel formation (*c*). The trail to Rainbow Bridge follows the narrow pass at the left of the butte.



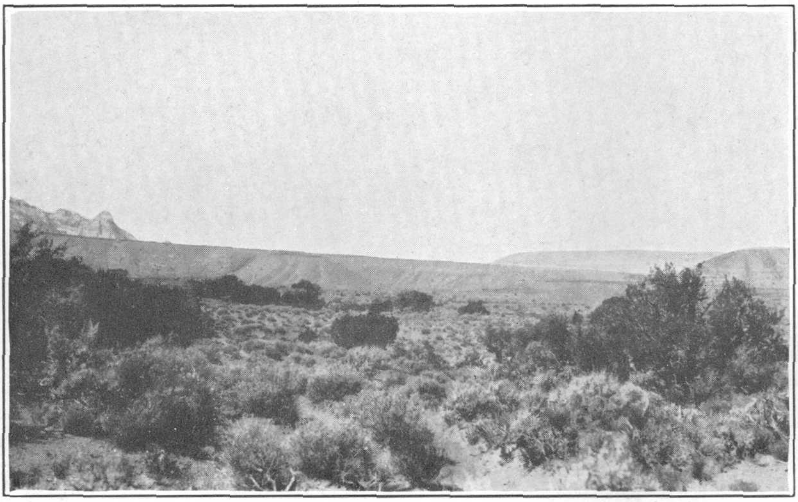
B. CLOSELY SPACED ROUNDED DOMES OF NAVAJO SANDSTONE ON THE NORTH SIDE OF REDBUD CANYON ABOUT 1 MILE FROM ITS JUNCTION WITH BRIDGE CANYON.

Erosion along parallel joint planes has produced the deep, narrow, impassable clefts separating the high rounded domes.



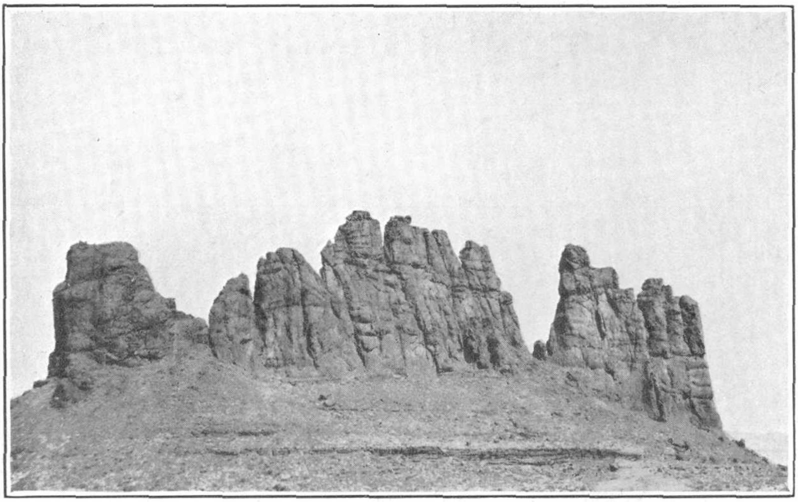
C. NORTH WALL OF THE CANYON OF THE COLORADO RIVER ABOUT 9 MILES WEST OF THE MONUMENT VALLEY-NAVAJO MOUNTAIN REGION.

Shows the Navajo sandstone (*n*) cropping out in a sheer wall, the overlying Carmel formation (*c*) forming a slope, the Entrada sandstone (*e*) and the Morrison formation (*m*) cropping out in a cliff, and the Dakota (?) sandstone (*d*) forming the rim rock. Photograph by R. N. Allen.



A. A REMNANT OF AN OLD EROSION SURFACE, POSSIBLY OF TERTIARY AGE, NORTH OF NAVAJO MOUNTAIN.

The surface bevels the Navajo sandstone and is covered by a veneer of gravel.



B. ALHAMBRA ROCK, A DIKE OF IGNEOUS ROCK THAT MAKES A PROMINENT LANDMARK NEAR THE CANYON OF THE SAN JUAN RIVER AT THE EAST EDGE OF THE AREA.

Photograph by H. D. Miser.

may be a stratigraphic break at this horizon in the Monument Valley-Navajo Mountain region, but it was not observed in distant outcrops nor on Navajo Mountain, where the contact is poorly exposed.

No fossils were collected from the Morrison formation in the Monument Valley-Navajo Mountain region, but vertebrate and invertebrate fossils have been collected from this formation at many localities in the Western States. Until recently it was considered tentatively by some geologists that the vertebrate fossils were of Lower Cretaceous age and that the unconformity at the base of the Morrison marked a break between Jurassic and Cretaceous rocks. An examination of the various lines of evidence used as a basis for an age assignment of the formation has led to the conclusion that the Morrison is Jurassic.[83]

The Morrison formation is the upper part of the †McElmo formation of Gregory[84] and is equivalent to the †McElmo formation of Longwell and others.[85] The name † " McElmo formation " was abandoned by the Geological Survey as a result of the work of Gilluly and Reeside,[86] who found that it was applied to different groups of beds at different places and was therefore an ambiguous name. They subdivided the †McElmo formation as previously used in the vicinity of the San Rafael Swell and applied the older name "Morrison formation " to a series of conglomeratic sandstones and variegated shale in the upper part of the †McElmo formation. Subsequently the Morrison formation was traced over most of the Colorado Plateau.[87] In southwestern Colorado the †Middle La Plata limestone and the †Upper La Plata sandstone are believed to represent the lower part of the Morrison formation, and in northwestern New Mexico the base of the Todilto limestone is believed to mark the base of the Morrison formation.

CRETACEOUS SYSTEM

UPPER CRETACEOUS SERIES

DAKOTA (?) SANDSTONE

The Dakota (?) sandstone crops out above the Morrison sandstone near the western edge of the region. The lower part of the formation is resistant to erosion and caps Cummings Mesa and also forms

[83] Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., Correlation of the Jurassic formations of parts of Utah, Arizona, New Mexico, and Colorado: U. S. Geol. Survey Prof. Paper 183 (in press).

[84] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, p. 59, 1917.

[85] Longwell, C. R., and others, Rock formations in the Colorado Plateau of southeastern Utah and northern Arizona: U. S. Geol. Survey Prof. Paper 132, p. 14, 1923.

[86] Gilluly, James, and Reeside, J. B., Jr., Sedimentary rocks of the San Rafael Swell and some adjacent areas in eastern Utah: U. S. Geol. Survey Prof. Paper 150, p. 82, 1928.

[87] Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., op. cit.

a bench north of the Colorado River along the side of the Kaiparowits Plateau (pl. 14, *C*). It is shown on plate 1 as forming the cap of Navajo Mountain, but the identification of the formation at that place is questionable, and the rocks at the summit should perhaps be included in the Morrison formation. These rocks are a gray-white silicified conglomeratic sandstone containing rounded pebbles of white quartz which range from a fraction of an inch to 3 inches in diameter. The extensive outcrops at the western border of the region were observed only from a distance, and details of the lithology could not be distinguished. Gregory and Moore [88] describe the Dakota (?) sandstone as an irregularly bedded coarse- to medium-grained brown or buff, more or less cross-bedded sandstone, which is locally conglomeratic and contains some sandy and carbonaceous shale and poor coal. The pebbles in the conglomeratic phase of the sandstone consist of quartz, quartzite, and chert of various colors and are as much as 2 inches in diameter. According to Gregory and Moore the upper part of the formation is commonly less resistant to erosion than the lower part and is stripped back from the edge of the lower ledge-forming conglomeratic sandstone. An average thickness of the Dakota (?) sandstone is about 100 feet.

The Dakota (?) sandstone overlies the Morrison formation unconformably [89] but grades upward into the overlying Cretaceous shale. Fossils that have been collected from the Dakota (?) sandstone elsewhere in the Colorado Plateau show that it is of Upper Cretaceous age,[90] though there are suggestions that at some localities beds of Lower Cretaceous age have also been included under the name.[91]

TROPIC SHALE AND STRAIGHT CLIFFS SANDSTONE

The Tropic shale and Straight Cliffs sandstone, of Upper Cretaceous age, crop out only in the southeast tip of the Kaiparowits Plateau in the extreme northwest corner of the region, north of the Colorado River. I did not visit the outcrops, and for a detailed description of them the reader is referred to the description by Gregory and Moore.[92]

The Tropic shale conformably overlies the Dakota (?) sandstone and consists of a fairly uniform dark-drab, more or less sandy marine shale. It weathers into a slope that rises from the bench underlain by the Dakota (?) sandstone to the cliffs formed by the over-

[88] Gregory, H. E., and Moore, R. C., The Kaiparowits region: U. S. Geol. Survey Prof. Paper 164, p. 95, 1931.

[89] Idem, p. 95. Longwell, C. R., and others, Rock formations in the Colorado Plateau of southeastern Utah and northern Arizona: U. S. Geol. Survey Prof. Paper 132, p. 15, 1923.

[90] Richardson, G. B., Reconnaissance of the Book Cliffs coal field between Grand River, Colorado, and Sunnyside, Utah: U. S. Geol. Survey Bull. 371, p. 14, 1909.

[91] Reeside, J. B., Jr., oral communication.

[92] Gregory, H. E., and Moore, R. C., op. cit., pp. 98–104.

lying Straight Cliffs sandstone. The thickness of the Tropic shale is about 600 feet.

The Straight Cliffs sandstone conformably overlies the Tropic shale and crops out in the high cliffs that form the rim at the southeast tip of the Kaiparowits Plateau. It consists of massively bedded light-yellowish or buff-brown fine- to medium-grained sandstone that contains some interbedded shale and carbonaceous beds. The total thickness of the Straight Cliffs sandstone in the southeastern part of the Kaiparowits Plateau is reported by Gregory and Moore to be about 1,200 feet, but the full thickness of the formation probably is not present in the area shown on plate 1.

TERTIARY (?) SYSTEM

Gravel deposits near Navajo Mountain and Monument Pass which floor remnants of old erosion surfaces may possibly be of late Tertiary age, but at present evidence to fix their age is lacking. Their distribution is not shown on the map.

Several ridges and buttes north and east of Navajo Mountain are capped by gravel deposits that are remnants of a thin deposit that formerly sloped away from the mountain (pl. 15, *A*). The deposits weather greenish gray and are thus conspicuous in this country of white, buff, and red rocks. They are composed of sandstone boulders derived from the rocks on the mountain. They are high above the present drainage courses and probably represent a former continuous apron that sloped from the mountain to the Colorado and San Juan Rivers when those rivers occupied channels high above the present streams. Gregory and Moore [93] discuss an old graded surface which existed in the later part of an erosion cycle that preceded the present cycle of canyon cutting and which was about 1,800 feet higher than the present river level at the junction of the San Juan and Colorado Rivers. A few altitudes upon the remnants of the gravel-covered surface indicate that if projected it would be about 1,400 feet above the Colorado River at the mouth of the San Juan, but it may be a part of the graded surface described by Gregory and Moore.

Another gravel deposit that appears to be of similar origin and age is crossed by the road that runs from Mexican Hat to Kayenta, in the eastern part of the region. It was observed only in the northern part of T. 43 S., R. 17 E., where it caps a bench that rises gradually toward the monuments near Monument Pass. The gravel consists of fragments of sedimentary rock of the type that forms the monuments, and it is cemented in a sandy matrix. This deposit is not directly related to present drainage and appears to have accumu-

[93] Gregory, H. E., and Moore, R. C., The Kaiparowits region: U. S. Geol. Survey Prof. Paper 164, pp. 138–139, 1931.

lated on a sloping surface extending to cliffs of which the present monuments are remnants. The altitude of the northeast end of this gravel bench is 5,300 feet, or about 1,300 feet above the level of the San Juan River, which is about 7 miles distant.

QUATERNARY SYSTEM

The Quaternary deposits of the region consist of gravel beds capping several terraces along the San Juan River and alluvial fill along some of the major stream courses. None of these deposits are shown on plate 1.

Gravel-covered terraces are numerous along the San Juan River, but no attempt was made to map or correlate them. They occur at different altitudes above the river up to about 600 feet. The composition of the pebbles and boulders shows that some were derived from the sedimentary rocks that crop out in or near the area, but many of them are igneous or metamorphic rocks derived from the San Juan Mountains, at the headwaters of the river in southwestern Colorado.

The alluvial fill is of slight extent and is found principally as narrow strips of bottom land in the canyons of the San Juan and Colorado Rivers. Through most of their courses these rivers flow on a bed of alluvium of unknown thickness. Miser [94] has estimated that its maximum thickness is about 80 feet near the mouths of the larger tributary streams.

IGNEOUS ROCKS

Dikes and volcanic plugs of igneous rock crop out at three localities in Monument Valley within the region shown on plate 1. The area occupied by them is the northern portion of a large area, mostly in northern Arizona, that has been described by Gregory [95] as the "Monument Valley volcanic field." He considered many of the pluglike masses to be volcanic necks, but any extrusive material that may have reached the surface through these conduits has been eroded. Gregory concluded also that the volcanic activity occurred in the Tertiary period but that the lavas were probably poured out on a maturely eroded surface from which early Tertiary and Cretaceous sediments had already been removed.

Alhambra Rock (pl. 15, *B*) is a volcanic plug that protrudes above a bench formed by the Rico formation near the south rim of the canyon of the San Juan River at the east boundary of the region. The black jagged peak is a conspicuous landmark in this country of red rocks.

[94] Miser, H. D., The San Juan Canyon, southeastern Utah: U. S. Geol. Survey Water-Supply Paper 538, pp. 67–71, 1924.

[95] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, p. 100, 1917.

The dike of which Alhambra Rock is a part is about a mile in length and for the most part 2 to 20 feet in width, but it widens to about 100 feet at the rock. As described by E. S. Larsen,[96] the porphyritic greenish gray igneous rock is an augite minette composed of phenocrysts of biotite and augite in nearly equal proportions, with a few phenocrysts of orthoclase and sodic plagioclase embedded in a groundmass of orthoclase, diopside, biotite, and opacite. Angular fragments of granite, sandstone, and limestone are enclosed by the igneous rock.

A circular plug of igneous rock about 200 feet in diameter crops out in the SE¼ sec. 14, T. 43 S., R. 17 E. It forms a low sharp greenish-gray cone that rises above the broad valley formed by the Halgaito tongue of the Cutler formation south of Halgaito Spring. This conspicuous topographic feature has been named "Tse Ajai" (rock heart) by the Navajo Indians. The rock is coarse-grained and was identified by M. N. Short as a hornblende gabbro consisting of labradorite, brown hornblende, and augite in approximately equal proportions. The ferromagnesian minerals are somewhat altered to serpentine. Boulders of gray granite consisting of orthoclase, oligoclase, quartz, and biotite, with subordinate titanite, are present in the hornblende gabbro and apparently are fragments of underlying rock through which the magma passed.

Disconnected exposures of igneous rock on the south side of Oljeto Mesa, in the SE¼ sec. 29, T. 43 S., R. 15 E., are probably apophyses of an elongated plug or dike. The igneous rock is intruded into the De Chelly sandstone member and the Hoskinnini tongue of the Cutler formation and the Moenkopi formation. The group of exposures is about one-third of a mile in length, and the largest body has a maximum width of about 150 feet. The rock is a grayish-black porphry which M. N. Short identified as a lamprophyre consisting predominantly of augite and biotite phenocrysts in a highly altered groundmass. Feldspar is absent. The groundmass seems to be, in part, at least, a devitrified glass.

No igneous rocks crop out in Navajo Mountain, but, as described on page 71, it is inferred that they underlie the mountain at depth and that the domal structure of the mountain was formed by a laccolithic intrusion.

STRUCTURE

GENERAL FEATURES

The rocks of the Monument Valley-Navajo Mountain region have a low westerly dip which is modified by the Navajo Mountain dome and by several northward-trending anticlines and synclines. The re-

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[96] Woodruff, E. G., Geology of the San Juan oil field, Utah: U. S. Geol. Survey Bull. 471, pp. 90–91, 1912.

gion lies on the west flank of the Monument upwarp,[97] which is a regional upwarp with a north-south trend and whose length north of the San Juan River is about 75 miles. It plunges to the south and disappears in northern Arizona about 20 miles south of the Utah State line. The axis of the upwarp splits into two subordinate axes in the southern part of the fold, and the axis of the Halgaito anticline, near the eastern limit of the Monument Valley-Navajo Mountain region, is the western one of these subordinate axes.

The Monument upwarp, like the Waterpocket Fold and the San Rafael Swell, which are also regional upwarps in southeastern Utah, and the De Chelly upwarp, in northeastern Arizona, is an asymmetric fold with a short, steep east flank and a long, gently dipping west flank. West of the Halgaito anticline three anticlines are present on the west slope of the Monument upwarp in the region here described. These four folds are also characterized by steeply dipping east flanks and more gently dipping west flanks, but plate 1 does not extend far enough to the east to show the steep flank of the Halgaito anticline. The east flank of each anticline is terminated at the axis of an asymmetric syncline which is parallel to the anticline and lies from 1 to 3 miles east of the anticlinal axis and 10 to 17 miles west of the adjacent anticlinal axis to the east. Although the Navajo Mountain dome is a conspicuous feature of the geologic structure of the region, it was presumably formed by a laccolithic intrusion and is thus apparently unrelated in origin to other structural features of the region.

The rocks of the Monument Valley-Navajo Mountain region are cut by a few normal and reverse faults, all of small displacement.

METHODS OF REPRESENTING STRUCTURE

The attitude of the strata in the region is shown on plate 1 by strike and dip symbols and by contour lines drawn between points of equal altitude above sea level on the stratigraphic horizon selected as a datum plane. A contour map is constructed by observing numerous altitudes on known geologic horizons and then reducing the altitudes to a selected horizon by adding or subtracting the intervening stratigraphic interval. Lines are then drawn between points of equal altitude. To represent the geologic structure near the surface most accurately the horizon to be contoured should be one that is extensively exposed in the region. In the Monument Valley-Navajo Mountain region the youngest formations are exposed in the western part, and progressively older formations appear at the surface toward the east, so that no single horizon is exposed in the greater part of the region. The top of a widely exposed ledge

[97] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, p. 113, 1917.

of brown sandstone 50 to 75 feet below the top of the Cedar Mesa sandstone member of the Cutler formation was selected for contouring in the eastern part of the region. In the western part the depth to this standstone could not be accurately determined, because of the presence of an unconformity at the top of the Permian and also because of changes in thickness of the upper Permian and Triassic rocks that probably occur beneath the cover of younger rocks. The base of the Wingate sandstone was therefore selected for contouring in the portion of the region west of a line (shown on pl. 1) which extends south from the San Juan River in T. 40 S., R. 14 E., to the Utah-Arizona boundary. The stratigraphic interval between the horizon contoured in the western part of the region and the horizon contoured in the eastern part increases from 1,750 feet near the San Juan River to 2,200 feet near the State line.

The geologic structure is also indicated by two cross sections (pl. 1) along lines shown on the map. The cross sections are drawn with the same vertical and horizontal scale, so that the structural features are not exaggerated. Minor details of the structure and of the surface are generalized because of the small scale of the cross sections. In addition to the geologic structure the cross sections serve to illustrate the topographic expression of the various formations and the character of the surface of the region.

In constructing the cross sections it has been necessary to extend the different members and tongues of the Cutler formation for many miles beneath a covering of younger formations where changes in thickness cannot be observed. The total thickness of the Cutler formation and the thickness of its different members and tongues varies along the outcrop and undoubtedly varies where these units are not exposed, but it is impossible to predict these changes, so that the thickness of these units as determined at the nearest outcrop is arbitrarily assumed to remain unchanged under cover. Other formations possibly vary in thickness under cover also, but they are known either to maintain a fairly uniform thickness over a wide area or to show a definite regional trend in change of thickness, so that the thickness as shown on the cross sections are believed to be approximately correct.

DETAILS OF FOLDS

Halgaito anticline.—The Halgaito anticline is a broad, somewhat irregular arch extending northward from the Utah-Arizona State line to and beyond the San Juan River near the eastern border of the region. Gregory[98] applied the name "Mitten Butte anticline" to this fold, but as Mitten Butte, which is south of the area here

[98] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, p. 114, 1917.

described, lies several miles west of the axis of the anticline and is not obviously related to any anticlinal fold, the name "Halgaito anticline", from Halgaito Spring, in sec. 35, T. 42 S., R. 17 E., which lies nearer the crest of the fold, seems more appropriate. Most of the east limb of the Halgaito anticline lies east of the area mapped. The anticline is incompletely shown, therefore, on the contour map and cross section A–A′ (pl. 1).

The slightly sinuous axis of the Halgaito anticline, an elongated fold, trends nearly due north through the eastern parts of Tps. 41 and 42 S., R. 17 E. The eastern flank of the anticline has an average dip of about ½° for a distance of 2½ miles east of the axis and then steepens to a maximum observed dip of 6½°. The west flank of the anticline is less regular than the east flank. Near the San Juan River there is an uninterrupted westerly dip of 1° to 3½° extending for about 15 miles from the crest of the anticline to the axis of the Oljeto syncline. In the eastern part of T. 42 S., R. 17 E., however, the gently dipping west flank of the anticline is modified by a narrow belt of steep west dips extending from sec. 2 to sec. 36, in which the maximum observed dip is 24°. The steep dips are terminated by a small syncline, whose axis extends from sec. 3 to sec. 27, T. 42 S., R. 17 E. West of this syncline the beds rise at an angle of about 2° to the crest of a southward-plunging anticlinal nose which extends from sec. 4 to sec. 32, T. 42 S., R. 17 E. West of this nose the beds dip 1°–4° W., to the axis of the Oljeto syncline. There are two distinct structurally high points on the Halgaito anticline, both of them rising to about the same altitude. The center of the south dome is near the west quarter corner of sec. 13, T. 42 S., R. 17 E., and the center of the north dome is north of the San Juan River in the eastern part of sec. 14, T. 41 S., R. 17 E. The low point in the saddle between these domes is in sec. 25, T. 41 S., R. 17 E., and is about 100 feet below the apices of the domes. At the south end of the anticline the strata dip southward from the top of the south dome to the Utah-Arizona State line. On the north side of the north dome the axis of the anticline plunges to the northwest, but the extent of the anticline north of the San Juan River is unknown.

The surface rocks over much of the anticline are in the Rico formation and the Halgaito tongue of the Cutler formation, but the Cedar Mesa sandstone member of the Cutler formation floors a long dip slope on the west flank of the anticline west of the rim of Douglas Mesa. The oldest rocks exposed at the crest of the anticline in the canyon walls of the San Juan River are about 1,020 feet below the top of the Hermosa formation, of Pennsylvanian age.

Oljeto syncline.—The axis of the Oljeto syncline approximately follows the course of Oljeto Wash, from which it derives its name. The slightly sinuous axis trends a few degrees east of north and extends across the region from the Utah-Arizona State line at the southeast corner of sec. 35, T. 43 S., R. 14 E., to the San Juan River at the mouth of Oljeto Wash, near the northeast corner of sec. 30, T. 40 S., R. 15 E. The length of the part of the syncline included within the area mapped is about 20 miles. The syncline is an asymmetric fold with a long gently dipping east limb rising to the Halgaito anticline and a short more steeply dipping west limb rising to the Organ Rock anticline, which adjoins it on the west. From a locality in sec. 19, T. 42 S., R. 15 E., which lies northeast of a closed dome on the Organ Rock anticline, the axis of the syncline plunges toward the south about 750 feet in a distance of 8½ miles and toward the north about 550 feet in a distance of 11½ miles. The maximum structural relief between the axis of the Oljeto syncline and the axis of the Halgaito anticline is about 2,350 feet.

The Cedar Mesa sandstone member of the Cutler formation is the surface rock across most of the syncline. Near the Arizona-Utah State line younger rocks, including the upper part of the Cutler, the Moenkopi, and the Shinarump, crop out in the trough of the syncline.

Organ Rock anticline.—The Organ Rock anticline is in the east-central part of the region and trends a few degrees east of north from the Utah-Arizona State line at the south boundary of T. 43 S., R. 14 E., to the San Juan River in the eastern part of T. 40 S., R. 14 E. Its length is about 21 miles within the area mapped, and it extends unknown distances both to the south and north beyond the borders of the area. It is named from Organ Rock, which stands on the west flank of the anticline in sec. 21, T. 42 S., R. 14 E., about 2 miles west of the axis (pl. 4, *A*.) The axis of the anticline, which is slightly sinuous, is approximately parallel to the axis of the Oljeto syncline and 1¼ to 3 miles west of it. Except for a slight saddle in the northern part of T. 43 S., R. 14 E., the anticline plunges to the north and gradually flattens in that direction. A closed dome, which centers in sec. 35, T. 42 S., R. 14 E., lies northeast of the saddle and has a closure of about 150 feet. The Organ Rock anticline is asymmetric with a steep east flank and a more gently dipping west flank.

The east flank, which was described as the Hoskinnini monocline by Gregory,[99] has a maximum observed dip of 18° a quarter of a mile south of the State line, and dips of 10° to 15° near Oljeto trading post in Utah, but the steepness of the dip decreases toward the north to 5° in the southeast corner of T. 42 S., R. 14 E., and to about

[99] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, p. 114, 1917.

2° in the northeast corner of that township. The maximum structural relief between the crest of the Organ Rock anticline and the trough of the Oljeto syncline is nearly 1,400 feet at the Utah-Arizona State line. At the San Juan River the structural relief between these folds is about 200 feet.

The west flank of the Organ Rock anticline is 9 to 13 miles long and dips 1° to 3½° to the trough of the Nokai syncline. There are minor undulations on this flank of the anticline, which are expressed as a shallow northwestward-plunging syncline along lower Copper Canyon and a low northwestward-plunging anticlinal nose about a mile farther west.

The Cedar Mesa sandstone member of the Cutler formation floors dip slopes on the Organ Rock anticline, and the upper part of this member includes the oldest exposed rocks. Near the State line the Shinarump conglomerate, the Moenkopi formation, and the upper part of the Cutler formation crop out on the crest and flanks of the anticline.

Nokai syncline.—The Nokai syncline is the next conspicuous fold west of the Organ Rock anticline. The axis of the fold trends nearly due north, approximately following the bed of Nokai Creek through Tps. 41, 42, and 43 S., R. 12 E., from the Utah-Arizona State line north to the San Juan River, where the axis swings to the northeast. Near the State line the syncline is a nearly symmetrical shallow fold, with each flank dipping about 2°, but it plunges to the north and is a deep asymmetric fold where it crosses the San Juan River, with the short west limb dipping 30° or more and the long east limb dipping between 1° and 3½°. Between the State line and the river the axis of the syncline plunges to the north about 1,900 feet in a distance of 14 miles. The structural relief between the trough of the Nokai syncline and the crest of the Organ Rock anticline is about 1,100 feet along the State line and about 1,600 feet along the San Juan River. Between the high point on the Organ Rock anticline at the State line and the low point on the Nokai syncline at the San Juan River the structural relief is about 3,000 feet.

The Shinarump conglomerate floors the trough of the syncline at the San Juan River and in the lower part of the canyon of Nokai Creek, but the axis of the fold rises more steeply toward the south than the gradient of Nokai Creek, and progressively older rocks are exposed toward the south. The De Chelly sandstone crops out in the trough of the syncline at the State line. The lower part of the Chinle formation crops out on the west limb of the syncline. The Chinle formation, capped by the Wingate sandstone and the Kayenta formation, crops out on the east limb in the sides of No Man's

Mesa, and in the trough of the syncline on the north wall of the canyon of the San Juan River.

Balanced Rock anticline.—The Balanced Rock anticline has a northerly trend and extends entirely across the region. Its axis, which is approximately parallel to and about 1 mile west of the axis of the Nokai syncline, extends from the Utah-Arizona State line near the southwest corner of sec. 35, T. 43 S., R. 12 E., to the San Juan River at the northwest corner of sec. 22, T. 41 S., R. 12 E. Near the river the axis of the anticline swings to the northeast. The fold was mapped for about 1 mile north of the San Juan River but continues an unknown distance beyond the limits of the mapping. Toward the south the anticline probably flattens out and disappears in northern Arizona a short distance south of the State line. The Balanced Rock anticline was named by Miser [1] from a huge balanced rock near the crest of the anticline on the north side of the San Juan River.

The Balanced Rock anticline is an asymmetric fold with a steep east flank and a gently dipping west flank (pl. 16, *A*). The east flank dips about 2° near the State line but gradually steepens toward the north and dips 30° or more near the San Juan River. The structural relief between the axis of the anticline and the axis of the Nokai syncline, which adjoins it on the east, increases correspondingly from about 50 feet at the State line to about 1,100 feet at the river. The west flank of the anticline extends 10 miles to the axis of the Rapid syncline. The maximum observed dip on the west flank is about 5°. The crest of the anticline plunges to the north about 900 feet in a distance of 12 miles from the State line to a low saddle in the southern part of T. 41 S., R. 12 E., beyond which it rises to the north or northeast about 200 feet in a distance of 4 miles. There are no closed domes on the crest of the anticline within the area mapped.

The upper part of the Cedar Mesa sandstone member of the Cutler formation crops out in the canyon of the San Juan River at the crest of the anticline and is the oldest exposed formation. The part of the Cutler formation above the Cedar Mesa sandstone and the Moenkopi formation also crop out in a small area along the San Juan River where it crosses the anticline. The Chinle formation is the surface rock at the crest of the anticline throughout most of its length within the mapped area, but the Wingate sandstone and Kayenta formation crop out in the cliff at the east edge of Piute Mesa, which is about half a mile west of the axis, and the Kayenta formation is the surface rock on a large part of the long

[1] Miser, H. D., Geologic structure of San Juan Canyon and adjacent country, Utah: U. S. Geol. Survey Bull. 751, pp. 134–135, 1925.

west flank of the anticline. The Wingate and Chinle are extensively exposed on the west flank, however, along the canyon of the San Juan River and in tributary canyons. The Shinarump conglomerate crops out for a distance of 4 miles along the San Juan River west of the axis and forms dip slopes on the steep east flank of the anticline.

Rapid syncline.—The Rapid syncline is a shallow northward-plunging synclinal trough whose axis trends nearly due north and approximately follows the course of Desha Creek. It was named the Rapid syncline by Miser[2] from a rapid in the San Juan River near the axis of the fold. The syncline, which extends an unknown distance north of the San Juan River, extends about 6 miles south from the river; it flattens out about a mile west of the southwest corner of T. 42 S., R. 11 E. The trough of the syncline plunges northward about 1,200 feet in the part of the fold lying south of the river. A normal fault of slight displacement follows the axis of the syncline for 2½ miles at its south end. The east limb of the syncline rises for 10 miles with an average dip of about 3° to the axis of the Balanced Rock anticline. The west limb rises with a maximum dip of 8° to 10° to the crest of the Beaver anticline, which is about 2 miles west of the axis of the syncline. The maximum structural relief between the axes of the Rapid syncline and the Beaver anticline is about 600 feet, and that between the syncline and the Balanced Rock anticline is about 2,100 feet.

The oldest rocks exposed along the axis of the syncline are the upper 20 feet of the Chinle formation, which crops out in the canyon of the San Juan River. The Kayenta formation is the surface rock of a large part of the syncline, but the Wingate sandstone and Chinle formation are extensively exposed in canyons, and the Shinarump conglomerate crops out in Piute Canyon and along the San Juan River about 6 miles east of the axis. The Navajo sandstone crops out as knobs and ridges on the stream divides near the trough of the syncline.

Beaver anticline.—The Beaver anticline is a northward-plunging anticlinal nose that lies northeast of Navajo Mountain. Its axis crosses the San Juan River about a mile east of the mouth of Cha Canyon. Miser[3] described this fold as the Navajo Mountain anticline, as it appeared to be a spur of the Navajo Mountain uplift. Detailed mapping has shown, however, that this fold is not connected with the dome of Navajo Mountain, so the fold is here renamed the "Beaver anticline", from the English translation of the

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[2] Miser, H. D., Geologic structure of San Juan Canyon and adjacent country, Utah: U. S. Geol. Survey Bull. 751, p. 137, 1925.

[3] Idem, p. 136.

Navajo Indian name of the canyon (Cha Canyon) that crosses its west flank.

The axis of the Beaver anticline, which is approximately parallel to and about 2 miles west of the axis of the Rapid syncline, extends about 6 miles south of the San Juan River. Miser observed that in distant view the anticline appeared to die out a few miles north of the river. The axis of the anticline trends a few degrees west of north and plunges to the north about 700 feet in 6 miles. The anticline, like others in the region, is an asymmetric fold. The east flank has a maximum dip of 8° to 10° and the west flank, which extends to the western limit of the region, has an average dip of about 4°.

The Kayenta formation is the principal surface formation on the anticline, but the upper 700 feet of the Chinle formation is exposed at the crest of the anticline in the canyon of the San Juan River, and the Chinle and Wingate are exposed on the flanks in Cha Canyon and the canyon of the San Juan. The Navajo sandstone crops out as isolated knobs near the crest of the anticline but is the principal surface rock on the west flank.

Navajo Mountain dome.—Navajo Mountain is a nearly circular dome, whose center lies about 2½ miles north of the Utah-Arizona State line and about 7 miles east of the west border of the region. The uplift is so local in extent that the regional dip is not disturbed beyond a radius of about 5 miles from the center of the dome. The observed dips on the flanks range from 4° to 21°, with the steeper dips on the west and northwest flanks. The Utah-Arizona line crosses the south flank of the dome, and as that line was the approximate limit of mapping, the full extent of the dome in that direction is not shown on plate 1. The rocks have a low dip, however, a short distance south of the State line. Owing to the regional northwest dip and the steepness of the northwest flank of the dome, the structural relief is about 4,800 feet in a distance of 8 miles between the crest of the Navajo Mountain dome and a locality on the Colorado River near the mouth of Forbidding Canyon. The structural rise on the southeast flank of the dome is about 1,900 feet in about 6 miles. The exact closure on the dome is unknown because of the incomplete mapping of its south flank. Rocks tentatively assigned to the Dakota (?) sandstone crop out at the crest of the dome, but the Morrison, Entrada, Carmel, Navajo, Kayenta, and Wingate formations are exposed on the flanks or in the numerous canyons that radiate from the mountain. The uppermost beds in the Chinle formation appear in a small outcrop in the bottom of Horse Canyon, on the southwest side of the mountain, and are the oldest rocks exposed.

No igneous rocks crop out in Navajo Mountain, but it is inferred that they underlie the mountain at depth and that the dome, as suggested by Gilbert,[4] was formed by a laccolithic intrusion of igneous rock, like the La Sal, Abajo, El Late (Ute), Carrizo, and Henry Mountains. Gregory [5] also concluded that the mountain was of laccolithic origin and in a cross section shows the igneous rock intruded at the base of the Chinle formation. Certain features of the Navajo sandstone observed in the exposures of that formation on the flanks of Navajo Mountain are abnormal for the formation and may be due to metamorphism resulting from the intrusion of igneous rock. The normally gray to tan sandstone is in part bleached to light gray or nearly white, and in other places it has a pink to bright-red color in irregular patches of moderate extent. Furthermore, the calcium carbonate cement of the sandstone is locally replaced by a siliceous cement. The shape of the dome and the lack of any apparent relation to the regional structure are perhaps the best indications of a laccolithic origin.

The stratigraphic position of the intrusion cannot be determined, but because of the almost complete absence of metamorphism of the surface rocks and the absence of dikes of igneous rocks at the surface I am inclined to believe that the laccolith is deeper than it would be if intruded in the Chinle formation. The end groups of laccoliths of the La Sal Mountains were intruded into the Cutler formation,[6] and the deepest known laccolith of the Henry Mountains was intruded into rocks of Permian age,[7] which have essentially the same stratigraphic position as the upper part of the Cutler formation. On cross section ABC, plate 1, the stratigraphic position of the intrusion is shown as at the base of the Cutler formation. Its position may be higher in the thick series of relatively incompetent or weak strata that lie between the Rico formation and the Wingate sandstone, but that its position is deeper than the base of the Cutler formation seems less probable. Gilbert has shown that practically all the known laccoliths of the Henry Mountains are intruded into relatively incompetent beds, and if the same relation holds for Navajo Mountain, it would follow that the thick series of competent beds in the Rico, Hermosa, and possibly older formations would not be favorable for intrusion.

Minor folds.—A low anticlinal nose plunges to the northwest from the north-central part of T. 43 S., R. 13 E., and its axis crosses the San Juan River less than a mile below the mouth of Copper Canyon. The northwestward-plunging axis of a shallow syncline is parallel to and about 1 mile northeast of the axis of the anticlinal nose. The

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[4] Gilbert, G. K., Geology of the Henry Mountains, p. 69, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1877.

[5] Gregory, H. E., op. cit., (Prof. Paper 93), p. 11, pl. 22.

[6] Gould, L. M., The role of orogenic stresses in laccolithic intrusions: Am. Jour. Sci., 5th ser., vol. 12, p. 122, 1926.

[7] Gilbert, G. K., Geology of the Henry Mountains, p. 57, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1877.

maximum structural relief between the trough of the syncline and the crest of the anticline, at right angles to the axes, is about 200 feet. The creek in Copper Canyon follows the trough of the syncline in the lower part of its course. Toward the northwest these folds disappear near the trough of the Nokai syncline on the north side of the San Juan River, and toward the southeast they flatten and merge with the west flank of the Organ Rock anticline.

On the Rainbow Plateau the axis of a low northward-plunging anticlinal nose trends approximately north parallel to and about 1 mile east of the axis of the Rapid syncline. The length of the anticlinal nose is about 4 miles, and its north end is about 1 mile south of the San Juan River. A shallow syncline whose axis lies about 1 mile east of the axis of this anticline extends from the San Juan River to the State line. The middle fork of Piute Creek follows the trough of the syncline near the State line, but on the Rainbow Plateau it is followed by Deep Canyon. Near the river the maximum relief between the syncline and the anticlinal nose adjacent on the west is slightly more than 50 feet. Toward the State line the syncline becomes deeper and is the structural trough between the Balanced Rock anticline on the east and the Navajo Mountain dome on the west. The structural relief between the axis of the syncline and the crest of the Balanced Rock anticline at the State line is about 1,100 feet.

Neski Creek follows the trough of a shallow northward-plunging syncline for about 12 miles on Piute Mesa, from a point about 2 miles north of the State line to the rim of the mesa in sec. 18, T. 42 S., R. 12 E.

FAULTS

Faults are an unimportant feature of the geologic structure of the Monument Valley-Navajo Mountain region, as the longest fault is less than 5 miles long, and the maximum displacement of any of the faults is about 100 feet. All the larger faults are shown on plate 1, but a few of the smaller ones have been omitted. Faults that cut the strata in San Juan Canyon include thrust faults and normal faults which have vertical displacements ranging from a few inches to a maximum of 10 feet. Most of these faults are not shown on the map but have been described in detail by Miser.[8] Most of them are strike faults. The dip of the normal fault planes ranges from 75° E. to vertical. The planes of the thrust faults dip 10°–20° E. All the faults observed south of the canyon of the San Juan River are steeply dipping normal faults.

No faults are associated with the Navajo Mountain dome, but there are conspicuous northeastward-trending joints on the north-

[8] Miser, H. D., Geologic structure of San Juan Canyon and adjacent country, Utah: U. S. Geol. Survey Bull. 751, pp. 137–139, 1925.

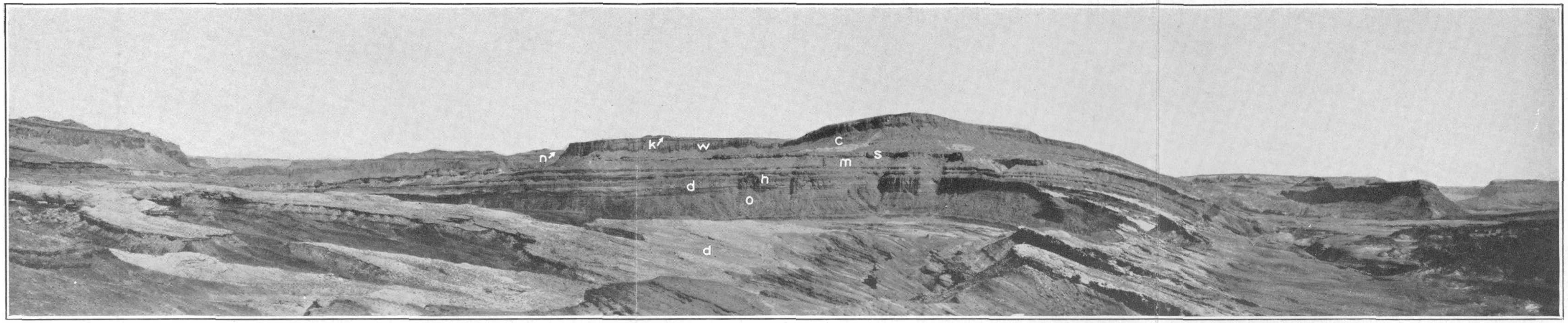
west flank of the dome. The crevices in the Navajo sandstone formed by erosion along these joints have been utilized in building the trail through the nearly impassable country that lies on that side of the mountain (pl. 13, *B*).

PERIODS OF DEFORMATION

The rock strata of the Monument Valley-Navajo Mountain region, which range in age from Pennsylvanian to Upper Cretaceous, are essentially parallel, although the sequence is broken by some unconformities. As all the strata have been involved in the folding and faulting that has been described above, and no rocks younger than Cretaceous are found in the region, except gravel of possible late Tertiary and Quaternary age, the folding and faulting, as shown by evidence in this region, took place near the end of the Cretaceous period or later. Conclusions concerning the precise date of this folding and faulting, as well as of earlier deformations that produced stratigraphic breaks, must be based largely on stratigraphic relations exhibited elsewhere in the Colorado Plateau and on similarity of the type of folds to that of other folds in the plateau.

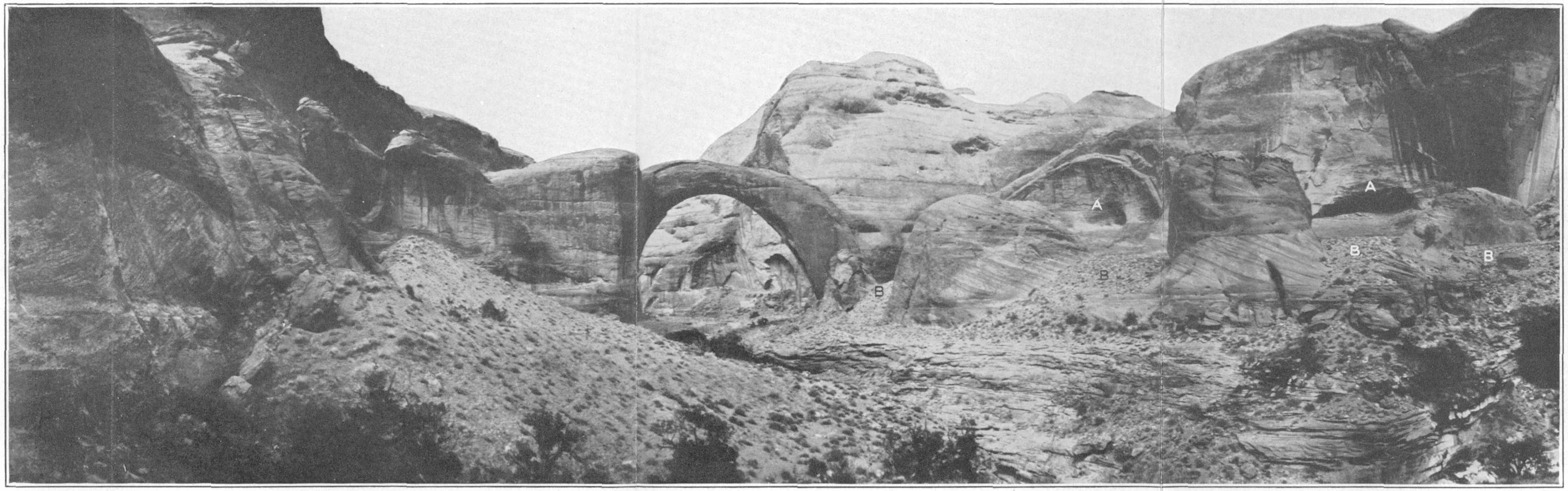
The earliest record of deformation in southeastern Utah is found at Moab,[9] where angular discordance between the Cutler formation, of Permian age, and the Moenkopi formation, of Lower Triassic age, shows local folding at the end of the Permian. A widespread erosional unconformity is present at the base of the Triassic in southern Utah and probably represents erosion following a regional upwarping near the end of Permian time. No evidence of this upwarping is apparent in the Monument Valley-Navajo Mountain region except perhaps the eastward thinning of the Hoskinnini tongue, the uppermost division of the Cutler formation, but this thinning is not clearly due to tilting and erosion and may be equally well explained by changes in conditions of sedimentation during Cutler time. Angular discordance between the Moenkopi formation, of Lower Triassic age, and the Chinle formation, of Upper Triassic age, near Moab[9] shows that folding occurred at least locally in southeastern Utah at the end of the Lower Triassic or in the Middle Triassic. A widespread unconformity has also been recognized at the top of the Lower Triassic in southern Utah. The eastward thinning of the Moenkopi formation beneath this unconformity in the vicinity of Monument Valley may be due to tilting and erosion prior to the Upper Triassic, but if such tilting of the strata occurred the angular discordance is so slight that it cannot be readily detected. From the beginning of Upper Triassic time the rocks were relatively undis-

[9] Baker, A. A., Geology and oil possibilities of the Moab district, Utah: U. S. Geol. Survey Bull. 841, p. 77, 1933.



A. PANORAMIC VIEW OF THE BALANCED ROCK ANTICLINE LOOKING NORTH FROM THE TRAIL TO PIUTE MESA NEAR THE SOUTHEAST CORNER OF SEC. 28, T. 41 S., R. 12 E.

Shows at the right the narrow gorge cut in the Shinarump conglomerate by Nokai Creek and in the foreground the dip slopes of the Shinarump conglomerate and the De Chelly sandstone. In the cliff at the crest of the anticline the color of the De Chelly sandstone is concealed by wash from the overlying beds. The butte at the left capped with Navajo sandstone lies within the Great Bend of the San Juan River. Note the sheer cliff formed by the vertically jointed Wingate sandstone. *o*, Organ Rock tongue of the Cutler formation; *d*, De Chelly sandstone member of the Cutler formation; *h*, Hoskinnini tongue of the Cutler formation; *m*, Moenkopi formation; *s*, Shinarump conglomerate; *c*, Chinle formation; *w*, Wingate sandstone; *k*, Kayenta formation; *n*, Navajo sandstone. Photograph by J. B. Reeside, Jr.



B. UPSTREAM SIDE OF RAINBOW NATURAL BRIDGE.

Shows the cliffs of Navajo sandstone, from which the arch has been carved, and the inner gorge of Bridge Canyon, which has been cut in the thin-bedded Kayenta formation. Note the meander scars (*A*) in the cliff at the right and the gravel terrace (*B*) marking a former position of the channel of Bridge Creek. Photograph by E. C. La Rue.

turbed by folding or faulting until the end of the Cretaceous, when the principal deformation is believed to have occurred. This age assignment of the deformation is based partly on the structural analogy of many of the other folds in southeastern Utah to the Waterpocket Fold and to the De Chelly upwarp of northeastern Arizona. On the west flank of the Waterpocket Fold the Wasatch formation, of Eocene age, rests with angular discordance upon older rocks.[10] On the east flank of the De Chelly upwarp in the Chuska Mountains and on the west flank near Ganado the flat-lying Tohachi shale, of probable Eocene age, rests upon tilted older strata.[11] Wherever the Cretaceous formations have not been removed by erosion they have been folded with the underlying rocks. These stratigraphic relations show that the Waterpocket Fold and the De Chelly upwarp were formed after the deposition of the Cretaceous rocks and before the deposition of early Tertiary rocks. The Waterpocket Fold, the San Rafael Swell, and the Monument upwarp, in southeastern Utah, and the De Chelly upwarp, in northeastern Arizona, are regional folds of similar size, trend, and shape and were doubtless formed contemporaneously. As explained on page 64, the Monument Valley-Navajo Mountain region lies on the west flank of the Monument upwarp, and most of the folds in the region exhibit on a smaller scale the same cross section and trend that characterize the larger folds. It is inferred, therefore, that most of the deformation in this area was produced during this period of regional folding.

The Navajo Mountain dome appears to have been raised on a preexisting monoclinal slope. There is, as previously stated, little doubt that it is of laccolithic origin and one of the group of laccolithic mountains on the Colorado Plateau in southeastern Utah and northeastern Arizona, which are believed to be of contemporaneous origin. The Henry Mountains, which are members of this group, were studied by Gilbert,[12] who deduced that the laccolithic intrusion occurred after the accumulation of the Tertiary formations and before subsequent degradation had made great progress. As the Tertiary formations that appear to have been continuous across the Colorado Plateau are of Eocene age, the uplift of the Henry Mountains would thus have occurred early in the Tertiary period. Other members of the group of laccolithic mountains, including Navajo Mountain, are therefore considered to have been formed early in the Tertiary, possibly near the end of the Eocene.

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[10] Gregory, H. E., and Moore, R. C., Geology of the Kaiparowits region: U. S. Geol. Survey Prof. Paper 164, pp. 116, 139, 1931.

[11] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, pp. 80, 81, 112, 1917.

[12] Gilbert, G. K., Geology of the Henry Mountains, p. 94, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1877.

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GEOMORPHOLOGY

EARLY GEOMORPHIC HISTORY

The presence of a considerable thickness of rocks of Eocene age at several widely spaced localities on the Colorado Plateau clearly shows that it was formerly covered by a mantle of these rocks, possibly to a depth of several thousand feet. As no extensive deposits younger than the Eocene are known on the plateau, it seems probable that the accumulation of Eocene rocks was terminated by regional uplift, which initiated a period of erosion that has continued to the present time. Thus the shaping of the land forms in the Colorado Plateau apparently has been in progress since the Eocene epoch. The Colorado River and its principal tributaries, flowing in channels developed on the uplifted surface, were gradually let down upon folded pre-Tertiary rocks but were so firmly established in their courses that at few places were they diverted by the belts of harder rock which they encountered; they cut downward directly across anticlines and synclines regardless of the attitude of the resistant strata.

Degradation of the region did not, however, proceed at a uniform rate, for remnants of erosion surfaces that have been observed at many places on the plateau indicate that there were probably several periods when the streams practically stopped downcutting and consequently produced graded surfaces or surfaces of slight relief. Two or more cycles of erosion appear to have been involved in the sculpturing of the surface features of the Monument Valley-Navajo Mountain region.

EROSION SURFACES AND TERRACES

There are no large remnants of old erosion surfaces in the Monument Valley-Navajo Mountain region, but small remnants are found northeast of Monument Pass and north and east of Navajo Mountain.

The remnant northeast of Monument Pass, principally in sec. 3, T. 43 S., R. 17 E., is less than 1½ miles long. It bevels the Cedar Mesa sandstone and rises gradually toward the southwest from an altitude of about 5,300 feet at its northeast end. The surface is covered with a thin mantle of gravel, which consists of angular pebbles of sedimentary rock that were derived from the rocks that form the monuments near Monument Pass. This remnant seems to be, therefore, a part of a surface that formerly sloped away from the base of the adjacent cliffs before they had receded to their present position. Although no other clearly defined remnants were observed nearby, the original surface probably extended over the part of the Monument Valley-Navajo Mountain region lying east of

Douglas Mesa and also probably extended several miles east of the boundary of the region. This surface must have been graded with respect to the San Juan River when the river was flowing at a level about 1,250 feet above the present stream, or at an altitude that is now about 5,200 feet above sea level.

The gravel-capped ridges, mesas, and buttes east and north of Navajo Mountain from the State line to Rainbow Bridge are remnants of a surface that formerly sloped away from Navajo Mountain. An approximate restoration of this surface shows that it slopes gently away from the foot of the steep slopes of the mountain (pl. 15, *A*) from an altitude of over 6,000 feet on the sides of the mountain to an altitude of about 4,600 feet at the mouth of the San Juan River (about 1,350 feet higher than the present channel) and a slightly higher altitude along Piute Creek. It bevels the Navajo sandstone. Within the Monument Valley-Navajo Mountain region this surface is of moderate extent, for it is bounded on the west by Cummings Mesa, which rises about 1,000 feet above it, and northwest of the Colorado River it is bounded by the cliffs that encircle the Kaiparowitz Plateau; east of Navajo Mountain it extends to Piute Creek. The surface may be a portion of a hypothetical surface that Gregory and Moore [13] placed about 1,800 feet above the junction of the Colorado and San Juan Rivers.

The remnants of the erosion surface adjacent to Navajo Mountain and the remnant northeast of Monument Pass are smooth rock plains which are covered with a thin veneer of gravel and slope gently valleyward from the foot of cliffs or steep slopes. They belong, therefore, to the class of surfaces to which Bryan [14] has applied the term "mountain pediment."

During the erosion of these old surfaces the stretches of the rivers that crossed them were not rapidly eroding their channels, and it appears probable that the rivers were essentially graded streams which had acquired stable channels during an erosion cycle that immediately preceded the present period of canyon cutting. The development of these surfaces during a former cycle of erosion is suggested by the presence of erosion surfaces at about the same altitude at other localities on the Colorado Plateau.[15] A hypothetical stream profile drawn between the surface northeast of Monument Pass and the surface near Navajo Mountain has a fall of about 600 feet, or about 100 feet less than the gradient of the present San Juan River. The name "Rainbow stage" is here applied to the former level of the

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[13] Gregory, H. E., and Moore, R. C., The Kaiparowits region, Utah and Arizona: U. S. Geol. Survey Prof. Paper 164, p. 138, 1931.

[14] Bryan, Kirk, The Papago country, Arizona: U. S. Geol. Survey Water-Supply Paper 499, pp. 93–100, 1925.

[15] Gregory, H. E., and Moore, R. C., The Kaiparowits region, Utah and Arizona: U. S. Geol. Survey Prof. Paper 164, pp. 133–135, 1931.

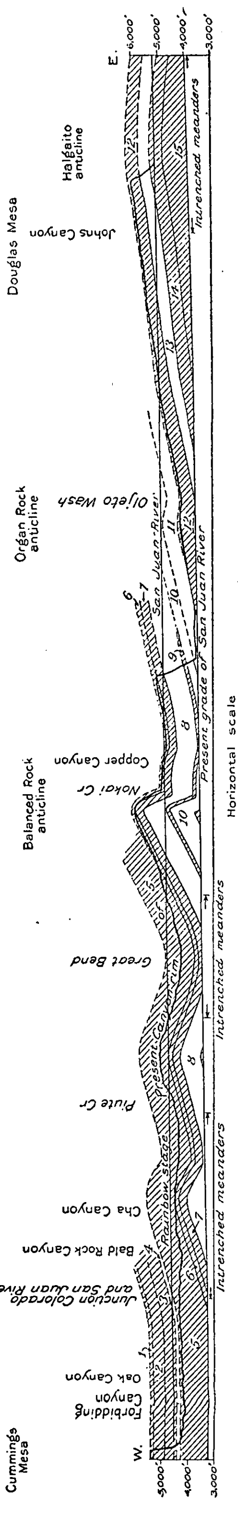


FIGURE 3.—Restored cross section along the Colorado and San Juan Rivers showing the stream profile at the Rainbow stage and its relation to the present surface. Resistant rocks are indicated by diagonal ruling. 1, Dakota (?) sandstone; 2, Morrison formation; 3, Entrada sandstone; 4, Carmel formation; 5, Navajo sandstone; 6, Kayenta formation; 7, Wingate sandstone; 8, Chinle formation; 9, Shinarump conglomerate; 10, Moenkopi formation; 11–13, Cutler formation (11, Organ Rock tongue; 12, Cedar Mesa sandstone member; 13, Halgaito tongue); 14, Rico formation; 15, Hermosa formation.

San Juan and Colorado Rivers that controlled the development of these surfaces.

At the Rainbow stage the rivers did not flow in open valleys in all parts of their courses across the Monument Valley-Navajo Mountain region. The rims of the present canyons locally rise hundreds of feet above the position of the stream profile of the Rainbow stage (fig. 3), and at two localities it is evident that the rivers flowed through narrow canyons at that time. For a distance of about 11 miles from the mouth of Slickhorn Gulch to the east rim of Douglas Mesa the westward-sloping plateau floored by the Cedar Mesa sandstone rises above the Rainbow level with a maximum height of over 800 feet. Although the upper part of the present canyon has probably been widened slightly during the present cycle of erosion, it is obvious that this part of the San Juan was in a narrow canyon when flowing at the Rainbow level. Near the west boundary of the region the plateau (floored by the Dakota (?) sandstone) of which Cummings Mesa is a part rises about 1,000 feet above the Rainbow level, and the closeness of the present canyon walls shows that the Colorado River flowed through a narrow canyon at that stage. Near the mouth of Nokai Creek the San Juan River at the Rainbow stage was flowing through a canyon about 1,000 feet deep, but the Canyon walls, although rimmed by the Wingate and Kayenta formations, were composed largely of the soft rocks of the Chinle formation; the canyon probably was wide, and the river may have been flowing on a rather wide flood plain.

The presence of narrow canyons along some stretches of the rivers and erosion surfaces of slight relief adjacent to other stretches suggests that local barriers of resistant rocks across the channels might have formed local base levels that controlled the graded condition of the rivers across the erosion surfaces, while downstream from the barriers the rivers were corrading their channels through canyons. The rocks exposed in the region do not include any exceptionally resistant rocks and none that appear sufficiently resistant or properly located to have been effective as local barriers at the downstream side of the erosion surfaces.

For a distance of about 30 miles downstream from the erosion surface near Monument Pass the Cedar Mesa sandstone is the most resistant rock that crossed the river at the altitude of the erosion surface. This sandstone crossed the ancient channel at the lower end of the narrow canyon through which the river flowed north of Douglas Mesa. If it had formed the barrier that controlled the development of the erosion surface, lateral corrasion by the graded stream would have widened the canyon, especially as the soft rocks of the Halgaito tongue cropped out in the lower canyon walls. Because this sandstone bed crossed the river several miles downstream from the erosion surface and because there is no evidence of significant widening of the canyon along the intervening stretch of the river, it is inferred that this sandstone bed did not form a local barrier that controlled the planation of the erosion surface.

The hard sandstones of the Morrison and Dakota (?) formations crossed the Colorado River at the level of the erosion surface about 20 miles west of the boundary of the Monument Valley-Navajo Mountain region. These relatively resistant sandstones doubtless retarded the rate of channel deepening, but whether the barrier was sufficiently effective to control the planation of the surface near Navajo Mountain cannot be definitely determined from the evidence available to me. As the surface near Monument Pass appears to have been formed independently of local barriers, it is inferred that both that surface and the surface near Navajo Mountain were formed during a regional pause in the downcutting of the rivers.

Gravel-covered terraces are present at several localities along the San Juan River and occur at different altitudes up to about 600 feet above the river.[16] They are particularly abundant between the mouth of Oljeto Wash and Spencer Camp. In this part of its course the river was flowing principally upon soft beds at the time the terraces were formed, but a few miles downstream, at and near the Great Bend, it was flowing across more resistant rocks. These relations suggest that the slowly eroded, more resistant rocks caused the formation of local baselevel, so that for a short distance upstream the river was graded and corraded its banks. It thus formed a narrow flood plain upon which meanders developed, and the slow lower-

[16] Miser, H. D., Geologic structure of the San Juan Canyon and adjacent country, Utah: U. S. Geol. Survey Bull. 751, p. 126, 1925.

ing of the local baselevel then permitted slow deepening of the meandering channel. According to this explanation, the terraces represent different positions of the meandering channel and are features of the local history of the river but apparently do not indicate pauses of regional significance in the downcutting of the river.

Little information is available concerning terraces along the part of the Colorado River included in this region. They probably are not numerous, as the river has been closely confined by canyon walls composed of massive sandstone during the present cycle of canyon cutting, and terraces would not have been likely to form. Gravel-covered terraces were observed at many places along smaller streams but were not studied in detail.

SAN JUAN AND COLORADO RIVERS

The westerly courses of the Colorado and San Juan Rivers across the Monument Valley-Navajo Mountain region show practically no relation to the attitude of the underlying rocks. In the part of its course included in the region the Colorado River follows a diagonal course across a northwestward-sloping monocline. The San Juan River flows across belts of hard and soft rocks, and its course is not deflected by the resistant beds which it encounters; it crosses anticlines and synclines nearly at right angles to their axes. The general courses of these rivers have apparently been inherited from the courses developed upon the nearly flat-lying Tertiary formations that formerly extended across the region and have remained practically unchanged throughout the greater part of the period of erosion.

In detail the courses of the rivers show more or less well-developed meander bends and loops enclosed in deep canyons whose parallel walls follow each meander bend. At most places both walls of the canyon are practically vertical, showing that there has been no significant change in the shape of the meanders during the canyon cutting, but at a few localities there are slip-off slopes which indicate that the form of the meander bends has changed during the deepening of the canyon. The rivers obviously have been confined to their present courses since they first trenched the rocks that form the canyon walls. Consequently, the meanders were developed at some earlier stage in the history of the rivers. Such a stage would have been provided when the rivers were relatively free to widen their flood plains on a surface of low relief or were able to cut laterally in belts of soft rock under favorable conditions of load and gradient.

Meanders enclosed by canyon walls are conspicuous along the portions of the San Juan River extending from its mouth to Piute Creek and from Johns Canyon to the east boundary of the region; the remainder of the San Juan River and the Colorado River follow winding courses through canyons, but the bends are not so closely compressed. The meanders were probably developed at the Rainbow stage of the San Juan River and subsequently were entrenched in deep canyons during the present cycle of canyon cutting. As shown by figure 3, the conspicuous enclosed meanders are found where the rivers have been cutting through hard rocks since the Rainbow stage, and meanders are poorly developed or absent where the rivers have cut through considerable thicknesses of soft strata during the present cycle of erosion. My observations agree in general with the following conclusion, expressed by Moore,[17] who described the enclosed meanders of the Colorado River and its principal tributaries:

> Construction of geological sections along the streams, restoring eroded rocks, suggests that where hard formations immediately underlay streams at the time regional uplift brought the earlier erosion cycle to a close, the courses of streams have been preserved with little change, but that where a considerable thickness of soft rocks has been encountered in downcutting the stream courses have been greatly modified, in some cases with obliteration of meanders. An empirical adjustment of a hypothetical, gently sloping stream profile to the restored geological section, so that meanders at the assumed profile elevation will find hard rocks below them where entrenched meanders actually occur and soft rocks where meanders are nontypical or absent, is commonly possible in only one position. This position presumably marks the stream profile before entrenchment in the present cycle.

It should be pointed out, however, that the absence of meanders is not necessarily due to the history of erosion subsequent to the trenching of the old stream valley. As explained above, the San Juan River was flowing in a narrow canyon north of Douglas Mesa at the Rainbow stage, and the relatively straight course through this narrow canyon obviously antedated the Rainbow stage; it has persisted unchanged into a later cycle of erosion and has not been greatly changed during downcutting through hard and soft rocks. Similarly, the Colorado River was flowing in a canyon between Cummings Mesa and the Kaiparowits Plateau at the Rainbow stage, and it seems probable that the relatively straight course of the river extending for a few miles west of the boundary of the Monument Valley-Navajo Mountain region [18] was also in existence before the development of the erosion surface upon which meanders were developed at other places.

The evidence seems fairly clear that the Colorado and San Juan Rivers are deepening their channels, although nearly everywhere they flow upon a bed of alluvium that may be as much as 80 feet thick.[19] The sudden floods that occur in the rivers vary in size and

[17] Moore, R. C., Origin of enclosed meanders in streams of the Colorado Plateau: Jour. Geology, vol. 34, pp. 29–57, 1926; Significance of enclosed meanders in the physiographic history of the Colorado Plateau country: Idem, pp. 97–130.

[18] Gregory, H. E., and Moore, R. C., The Kaiparowits region, Utah and Arizona: U. S. Geol. Survey Prof. Paper 164, pl. 1, 1931.

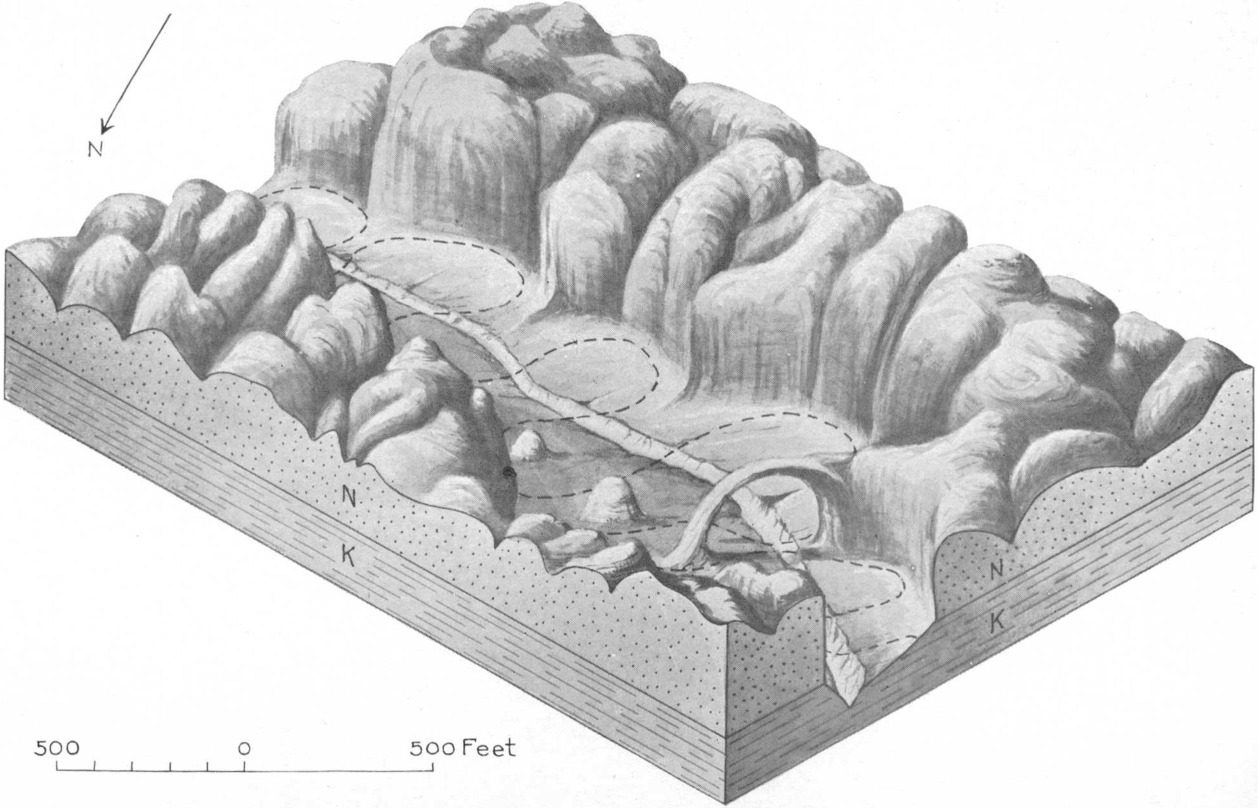
[19] Miser, H. D., The San Juan Canyon, southeastern Utah: U. S. Geol. Survey Water-Supply Paper 538, pp. 67–71, 1924.

carrying capacity, but the larger ones, which take place at long intervals—such as that in the San Juan River in 1911 which was reported [20] to be 50 feet deep in the narrower parts of the canyon—are probably capable of moving all the alluvial material down to bedrock for long distances. At such times the canyon would be deepened by the scouring effect of the moving material. The evidence that appears most significant that the rivers are corrading streams is the fact that the tributary streams have rock floors practically to their mouths. If the rivers had ever flowed at a much lower level and subsequently been raised by a deep filling of the channels, some of the tributary streams should also have filled their channels and should show considerable alluvial fill in the lower parts of their courses. Such deposits are not present except in small areas at the mouths of the tributaries. It therefore seems probable that the alluvial fill is relatively shallow and does not exceed the amount that the river is capable of transporting during unusually large floods.

TRIBUTARY STREAMS

The position of most of the tributaries of the San Juan and Colorado Rivers has been determined by the attitude of beds of resistant rock, and therefore they are unlike the Colorado and San Juan Rivers, which are superimposed streams that have maintained their courses across the region regardless of the attitude of the strata they cross. Monument Creek, which heads near the rim of the San Juan Canyon, makes a great bend to the south before joining the San Juan River. It follows the soft rocks of the Halgaito tongue of the Cutler formation around the outcrop of the resistant rocks of the Rico formation, which are exposed on the Halgaito anticline. Oljeto Wash, Nokai, Neski, and Piute Creeks, and the creeks in Copper, Deep, and Desha Canyons follow the troughs of synclines in part or all of their courses. Many of the streams have asymmetric drainage basins, with long east tributaries and short west tributaries, as is particularly well exemplified by Oljeto Wash. The drainage basin of Oljeto Wash is entirely confined to the structural trough of the Oljeto syncline; the east tributaries drain the long dip slopes on the wide east limb of this syncline, and the short west tributaries extend only to the nearby axis of the Organ Rock anticline. The drainage basins of the creek in Copper Canyon and Nokai Creek are similarly controlled by the asymmetric shape of the synclines which they drain. The unnamed stream draining the lowland east of Monitor Butte flows approximately along the strike of a westward-dipping monocline, and the asymmetry of its drainage basin is presumably due to down-dip shifting of the position of the stream. Similarly, Forbidding Canyon, which drains the west side

[20] Miser, H. D., The San Juan Canyon, southeastern Utah: U. S. Geol. Survey Water-Supply Paper 538, p. 62, 1924.



GENERALIZED BLOCK DIAGRAM OF A PART OF BRIDGE CANYON.

K, Kayenta formation; *N*, Navajo sandstone.

of Navajo Mountain, appears to have shifted down the west flank of the Navajo Mountain dome and to have crowded against the wall of resistant rocks which underlie Cummings Mesa; its principal tributaries are from the east and drain the flanks of Navajo Mountain.

Although Piute Creek follows the trough of a shallow syncline for a short distance north from the State line, the rest of its course northward across the region is not controlled by the attitude of the rocks which it crosses. About 2 miles north of the State line it diverges from the axis of the syncline and flows northward in a great arc, which is convex to the east. As the synclinal trough which it follows in the upper part of its course extends to the San Juan River, and in view of the habits of other streams in the region, it is a reasonable assumption that this stream was formerly confined to the syncline and therefore emptied into the San Juan River near the mouth of Deep Canyon. A restoration of the old graded surface that formerly sloped away from Navajo Mountain shows that this eastward-sloping surface extended to approximately the present position of Piute Creek. The eastward shifting of the stream is believed to be related to the development of this surface. As the regional slope of the upland, of which Piute Mesa is a remnant, is to the west and the graded surface sloped eastward from Navajo Mountain, it follows that a valley existed where these surfaces merged, and it was probably this valley that was occupied by Piute Creek north of the mouth of Jackrabbit Fork. South of the mouth of Jackrabbit Fork, however, the upland surface projected above the level of the graded surface, so that near the State line the course of Piute Creek was determined by the synclinal structure of the rocks.

Most of the debris carried to Piute Creek probably came from the west, from the shifting streams that were producing the graded surface. The east limit of the drainage basin of Piute Creek probably lay near the axis of the Balanced Rock anticline, only a few miles to the east and only 500 or 600 feet higher than the stream bed, as compared with about 5,000 feet of relief between the stream bed and the top of Navajo Mountain in a comparable distance toward the west. The stream apparently tended to skirt the debris swept out from the mountain over the graded surface and was constantly forced eastward until it reached approximately its present position. With renewal of vertical corrasion the stream became entrenched in a canyon. As the present canyon is asymmetric, with the stream crowded against the west wall, it seems evident that the westward-dipping strata through which the canyon has been cut have induced a westward migration of the stream. This lateral migration will eventually bring the stream into adjustment with the structure, so that it will again flow along the axis of the syncline, as it presumably once did at a much higher level before the erosion surface was formed.

The tributaries to the San Juan and Colorado Rivers are rapidly eroding streams, nearly everywhere entrenched in canyons. Some of them have a very steep gradient, and others have a relatively low gradient, but most of them have a steplike profile, with steep sections alternating with sections of low gradient, owing to the fact that they cross belts of resistant rocks alternating with belts of easily eroded rocks. The resistant beds present a barrier to downcutting which forms a local baselevel, and upstream from the edge of the belt of resistant rocks each stream has a low gradient and a graded profile, whereas downstream it plunges into a canyon cut in the resistant rocks and has a steep gradient. If another belt of resistant rocks is encountered farther downstream, the stream again becomes graded with respect to a local baselevel, and another break in the profile occurs when the stream plunges into the canyon cut in the resistant rocks. Most of the streams empty into the rivers through canyons trenched in the rim of the river canyons and hence have a steep gradient in the lower parts of their courses.

Nokai Creek illustrates well the stepped profile characteristic of many of the tributary streams. It has a steep gradient near the State line, where it flows through a narrow gorge cut in the De Chelly sandstone. A few miles north of the line the valley widens, and the stream has a low gradient where it is adjusted to the local baselevel formed by the northward-dipping Shinarump conglomerate. Below the gorge cut in the Shinarump the stream again has a low gradient where it is flowing upon a surface that practically coincides with the top of the Shinarump conglomerate, but near its mouth the grade of the stream steepens where it has cut another canyon in the same formation. Oljeto Wash has a low gradient through a more or less open valley extending a few miles north from the State line, but opposite Train Rock it enters a canyon cut in the Cedar Mesa sandstone, in which it has a steep gradient and a waterfall near its mouth.

GENERAL SURFACE FEATURES

The surface features of the Monument Valley-Navajo Mountain region are typical of the Colorado Plateau: It is a region of bare rock mesas, buttes, plateaus, cliffs, steep slopes, and rounded domes. The relative resistance to erosion of the outcropping rocks has controlled the shaping of the surface features, and each of the major lithologic units in the thick series of stratified rocks that crop out in the region has a more or less characteristic surface expression. The rocks that are more resistant to erosion form cliffs and canyon walls, cap mesas and buttes, and commonly make long dip slopes from which the overlying less resistant rocks have been removed. The less resistant rocks crop out in cliffs and steep badland slopes beneath the protecting cap of more resistant rock.

The Rico and Hermosa formations are composed of sandstone and limestone and comprise the thickest group of resistant rocks that crop out in the region; the maximum thickness is about 1,500 feet. It is in these rocks that the San Juan River has carved the deep, narrow canyon in the eastern part of the region (pl. 7, *A*, *B*), and the broad surface of slight relief east of Douglas Mesa has been formed by the stripping of softer rocks from the top of the Rico formation. The Cedar Mesa sandstone member of the Cutler formation, the Shinarump conglomerate, the lower part of the Kayenta formation, and the Dakota (?) sandstone are also resistant to erosion and have had much influence in the development of the surface features. The Cedar Mesa sandstone forms a cliff at the east edge of Douglas Mesa and along the canyon of the San Juan River east of Clay Hill Crossing. Dip slopes floored by this sandstone form the surface in most of the east half of the region (pl. 4, *A*). The Shinarump conglomerate caps mesas, buttes, and cliffs and floors platforms from which the overlying Chinle shale has been removed and which slope in conformity with the dip of the formation; it is the resistant rim rock at the top of the cliffs in Monument Valley (pl. 9, *A*) and along upper Oljeto Wash, upper Copper Canyon (pl. 4, *B*), and upper Nokai Creek and rims the inner canyon of lower Copper Canyon and the canyon of the San Juan River near the mouth of Nokai Creek. The Kayenta formation caps No Man's and Piute Mesas and floors part of the Rainbow Plateau. It is the resistant rim rock at the top of the palisadelike cliffs of Wingate sandstone which are so conspicuous as surface features of the region. The Dakota (?) sandstone floors Cummings Mesa and a broad bench between the Kaiparowits Plateau and the Colorado River.

The massive Wingate sandstone (pl. 4, *B*) and De Chelly sandstone (pls. 8, *B*, and 9, *A*) are not especially resistant to erosion, but they usually crop out in conspicuous cliffs. The Wingate sandstone is protected by the overlying resistant Kayenta formation, and where it crops out in cliffs or canyon walls huge slabs break from the face of the more or less vertically jointed homogeneous sandstone, thus producing vertical cliffs. At outcrops near stream level the Wingate sandstone commonly weathers with rounded surfaces. Similarly, the De Chelly sandstone is protected by the resistant Shinarump conglomerate and forms cliffs produced by the same process. Much of the picturesqueness of Monument Valley is due to the sheer cliffs of De Chelly sandstone surrounding each of the monuments. Near Oljeto trading post and at other localities where it crops out near stream level, the De Chelly sandstone weathers into rounded surfaces, in contrast to the sheer cliffs formed by this sandstone in Monument Valley and other parts of the region where it crops out high on cliffs or canyon walls.

The Navajo sandstone is 1,100 feet thick and consists of a cross-bedded, practically homogeneous sandstone that is not especially resistant to erosion. As it is not protected by an overlying bed of resistant material, it commonly weathers into huge rounded domes. Where the surface is carved largely from this sandstone and the adjacent formations are not extensively exposed, the domes are closely spaced and are separated by deep, narrow clefts and canyons. The surface of a large part of Rainbow Plateau is made up of innumerable closely spaced domes. Numerous alcoves and several natural bridges, including Rainbow Natural Bridge, have been carved from this sandstone.

Rainbow Bridge, which is in Bridge Canyon northwest of Navajo Mountain, is a huge arch that spans an inner gorge of this canyon (p. 8). It has been carved from a sandstone shoulder projecting from the southwest wall of the canyon, as described by Miser [21] and others. Gravel deposits and meander scars on the canyon walls show that Bridge Creek when flowing in a channel 130 to 140 feet above the present channel followed a meandering course and that the sandstone shoulder separated two meander bends (pl. 17). Undercutting of this shoulder from opposite sides by the impinging of Bridge Creek against the outside of the meander bends resulted in the excavation of alcoves, which ultimately coalesced, forming an opening through the mass of sandstone; spalling from the sides of the alcoves doubtless served to enlarge the opening to its present size. The stream abandoned its old channel in order to follow the more direct course under the bridge, and by subsequent erosion it has excavated the inner gorge of Bridge Canyon.

Navajo Mountain is a dome-shaped peak that rises nearly 5,000 feet above the Rainbow Plateau and is the most prominent surface feature in the Monument Valley-Navajo Mountain region. Structurally the mountain is a nearly circular upfold (p. 71), and its general shape conforms to the outline of this fold. However, erosion has modified the shape imparted to the mountain by the upfold and has accentuated the relief. The siliceous rocks of the Dakota (?) and Morrison formations crop out only on the rounded peak of the mountain and have protected it from erosion, while less resistant underlying rocks have been removed from the flanks. Thus Navajo Mountain is a somewhat unusual example of an eroded upfold in that erosion has not uncovered older rocks at the crest of the fold than are exposed on the flanks.

MINERAL RESOURCES

The Monument Valley-Navajo Mountain region has been of interest as a possible source of oil, gold, and copper, but up to the present

[21] Miser, H. D., Trimble, K. W., and Paige, Sidney, The Rainbow Bridge, Utah: Geog. Review, vol. 13, p. 523, 1923.

time no commercially important deposits have been discovered. Coal is present in the Straight Cliffs sandstone, which crops out at the northwest corner of the region, north of the Colorado River, but as the coal at that place was not examined by me and is described in another report,[22] it will not be discussed here.

OIL

OIL SEEPS

Oil springs or seeps are present at several places in the canyon of the San Juan River. A sandstone 75 feet below the top of the Rico formation is impregnated with oil along joints and cracks at its outcrop at the Goodridge Bridge, 3 miles east of the region here described. A seep is reported on the right bank of the river in or near the Second Narrows, which is about three-quarters of a mile east of this region. The rocks at river level at this locality are about 565 feet below the top of the Hermosa formation. A small quantity of oil and gas emerges from a sandbar at the north edge of the river in sec. 33, T. 41 S., R. 18 E., about 1½ miles southeast of the head of the Honaker Trail. The rocks at river level at this locality are about 750 feet below the top of the Hermosa formation. A seep is reported in Johns Canyon about 2 miles above its mouth, but the stratigraphic position of the rocks from which the oil emerges is not known. The largest oil seep is near the mouth of Slickhorn Gulch, where oil appears in the river near the edge of the water and in the sand and boulders along the bank of the river for a distance of about 1¼ miles up the canyon from the mouth of the gulch. The rocks at river level at the oil seep are about 60 feet below the top of the Hermosa formation, but the oil may be derived from a somewhat lower portion of the Hermosa that is concealed by alluvial material.

Oil seeps from the Shinarump conglomerate on the north bank of the Colorado River opposite The Rincon, about 6 miles northwest of the great bend of the San Juan River.[23]

HISTORY OF DRILLING

The first wells drilled in the vicinity of the Monument Valley-San Juan region were east of the region in the vicinity of Mexican Hat. The early development of that area, then known as the San Juan oil field, is described by Woodruff,[24] as follows:

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[22] Gregory, H. E., and Moore, R. C., The Kaiparowits region, Utah and Arizona: U. S. Geol. Survey Prof. Paper 164, pp. 149–153, 1931.

[23] Miser, H. D., Geologic structure of San Juan Canyon and adjacent country, Utah: U. S. Geol. Survey Bull. 751, p. 141, 1925. Gregory, H. E., and Moore, R. C., The Kaiparowits region, Utah and Arizona: U. S. Geol. Survey Prof. Paper 164, p. 156, 1931.

[24] Woodruff, E. G., Geology of the San Juan oil field, Utah: U. S. Geol. Survey Bull. 471, pp. 98–99, 1912.

Though oil springs must have been seen by prospectors and traders who operated along San Juan River, they seem to have received only casual notice until 1882, when E. L. Goodridge made the first location of a claim. No drilling was done, however, until the fall of 1907, when the first well, Crossing No. 1, was begun. This well encountered oil March 4, 1908, at a depth of 225 feet. It was a gusher, throwing oil to a height of 70 feet above the floor of the derrick, and led to considerable excitement. Other wells followed in rapid succession in 1908 and 1909, but most of them were only prospect holes put down to validate the titles to claims and not with serious intention of determining the oil resources of the field. By the summer of 1910 considerable capital had been enlisted to exploit the field. One standard rig was in operation, and others were reported to have been ordered. There were 10 portable deep-well rigs in the area and several more on the way to it. During midsummer active development was somewhat retarded on account of the heat, but in the latter part of August preparations were made to renew operations with greater vigor than before. Reports received during the winter of 1910–11 indicate that the expectation of activity has been fully realized. On February 1, 1911, according to a report by A. L. Raplee, there were 27 drilling rigs in the field and equipment for more on the way. Two oil wells were brought in during the winter, and there was considerable improvement at old wells. A small town had been established near Mexican Hat, and the roads and general facilities much improved.

Most of the wells drilled in the San Juan field in the vicinity of Mexican Hat before 1911 were shallow wells. Of 37 wells listed by Miser [25] only 7 exceeded 600 feet in depth. Most of these wells were drilled with the hope of finding oil in the Rico formation or the top of the Hermosa formation, and the deeper wells were drilled to test deeper beds in the Hermosa formation which are impregnated with oil at their outcrops in the canyon of the San Juan River. All the wells that were drilled with the intent of testing for oil encountered showings of oil or gas at one or more horizons. Oil was produced from only 3 wells drilled before 1911—namely, the Hudson well of the Anderson Oil & Development Co., Bryce No. 2 well of the Western Investment Co., and the Crossing No. 1 well of the Oil Co. of San Juan—although the showings from other wells were reported to be large enough to permit bailing of several barrels of oil. The largest production was obtained from the Bryce No. 2 well, which was reported to have an average daily yield of about 25 barrels of oil. In 1910–11 this well produced about 5,000 barrels of oil which was used for fuel by other operators in the field. The Hudson and Crossing No. 1 wells produced only a few barrels.

Between 1911 and 1920 there was comparatively little drilling in the vicinity of the Monument Valley-Navajo Mountain region, but since that time several wells have been drilled in the San Juan field and the surrounding region. Most of these wells were deeper tests than the earlier wells drilled in this region. A well at Halgaito (formerly

[25] Miser, H. D., Geologic structure of San Juan Canyon and adjacent country, Utah: U. S. Geol. Survey Bull. 751, pp. 150–155, 1925.

spelled Hulkito) Spring, in sec. 35, T. 42 S., R. 17 E., was drilled by the Monumental Oil Co. about 1920 to a depth of 1,300 feet or more. This well, which was drilled on the southwest flank of the Halgaito anticline in the subsidiary syncline lying west of the belt of steep dips, started near the base of the Halgaito tongue of the Cutler formation and penetrated all but the deeper beds in which showings of oil or gas were obtained in the San Juan field. As far as known to me no showings of oil or gas were obtained.

The Mexican Hat Co. drilled a well in 1922 in the San Juan field 1½ miles southwest of the Mexican Hat town site and about 3 miles east of the region here described. The well was drilled to a depth of 362 feet and is said to have reached the Little Loop sand, in the lower part of the Rico formation, from which a daily production of 50 barrels of oil was obtained.[26]

A second well was drilled with a diamond drill by the Monumental Oil Co. between April 14 and June 9, 1923, in sec. 23, T. 42 S., R. 17 E., near the crest of the Halgaito anticline. The well was started near the top of the Rico formation and was drilled to a depth of 756 feet, penetrating the upper part of the Hermosa formation. No showings of oil or gas were reported. Difficulties were encountered in drilling this well, and another well was started near the same location. It was drilled with a diamond drill to a depth of 1,622 feet between June 9, 1923, and December 31, 1924, penetrating nearly 1,200 feet of the Hermosa formation, but no production was obtained. This well reached strata only about 180 feet deeper than the lowest rocks exposed in the canyon of San Juan River at the crest of the anticline.

The London-San Juan Oil Co. drilled a well 213 feet deep north of the San Juan River in sec. 13, T. 41 S., R. 18 E., in 1923. This well was started near the top of the Rico formation and was not drilled to sufficient depth to reach the Hermosa formation. No showings of oil or gas were reported.

During 1922–23 Wilson-Cranmer & Co. drilled a well on the crest of the Organ Rock anticline in sec. 35, T. 42 S., R. 14 E. The well, which was started near the top of the Cedar Mesa sandstone member of the Cutler formation, was drilled to a depth of 2,323 feet. It penetrated the Cedar Mesa sandstone, the Halgaito tongue of the Cutler formation, the Rico formation, and approximately the upper 1,000 feet of the Hermosa formation. Only one small showing of oil and gas in the upper part of the Rico formation, at a depth of 950 feet, was found in this well.

In 1924 the Utah Southern Oil Co. commenced drilling a well in the canyon of the San Juan River in sec. 27, T. 41 S., R. 19 E., about

[26] Miser, H. D., Geologic structure of San Juan Canyon and adjacent country, Utah: U. S. Geol. Survey Bull. 751, p. 154, 1925.

6 miles east of the region described in this report. It was abandoned in 1928 at a depth of 1,850 feet, after it had been drilled into mica schist. This well began in the Hermosa formation but may have been drilled through the Hermosa into an older limestone formation before reaching the crystalline rocks. It obtained one small showing of oil at a depth of 172 feet and several showings of oil and gas below 740 feet.

The San Juan Oil & Development Co. commenced drilling in 1923 in sec. 7, T. 41 N., R. 23 E., Arizona, about 1½ miles south of the Utah line and about 4 miles east of the region described in this report. Drilling was discontinued in 1924 after the well had reached a depth of 2,083 feet. The surface rock at this well is in the Cutler formation, and the well penetrated the Rico formation and probably the upper 1,000 feet or more of the Hermosa formation. A small showing of oil and gas was reported between the depths of 495 and 500 feet, possibly in the upper part of the Rico formation.

The Southwest Oil Co. in 1923 drilled a well in sec. 22, T. 43 S., R. 22 E., near Boundary Butte, about 25 miles east of the region described in this report. After the drill had reached a depth of 1,565 feet, where a promising showing of oil was obtained, mechanical difficulties developed which caused the abandonment of the well. A second well was started by the same company but was later taken over by the Continental Oil Co. and drilled to a depth of 5,612 feet. This well started in the Navajo sandstone and probably entered older rocks than the Hermosa formation. Several showings of oil and gas were found, but no production was obtained and the drilling was suspended in 1929.

The Utah Petroleum Corporation drilled a well at the crest of the Halgaito anticline in sec. 36, T. 41 S., R. 17 E., in 1926. This well was abandoned at a depth of 1,707 feet without obtaining any showings of oil or gas. The well was started near the top of the Rico formation and was drilled about 1,300 feet into the Hermosa formation. All but the lower 280 feet of the strata through which the well was drilled crop out in the canyon of the San Juan River, which is only about 1¼ miles north of the well site.

The Utah Southern Oil Co. commenced drilling a well in 1926 in sec. 28, T. 40 S., R. 18 E., about 10 miles north of Alhambra Rock. After going through the Rico formation the well penetrated about 3,000 feet of strata composed principally of limestone, which include the Hermosa formation and possibly older rocks that may be of lower Pennsylvanian or Mississippian age. A small showing of gas was obtained in the Hermosa formation. The well was abandoned at a depth of 3,633 feet after encountering mica schist.

During 1926 the Monumental Oil Co. drilled a fourth well, 1,140 feet deep on the southeast flank of the Halgaito anticline in sec. 19, T. 42 S., R. 18 E. (unsurveyed). The well was started near the top of the Rico formation and penetrated the principal oil-bearing beds of the San Juan field. A small showing of oil and gas was found at a depth of 800 to 812 feet and another at 890 to 900 feet. Both showings were in the upper part of the Hermosa formation, at horizons which cannot be precisely correlated with oil-bearing beds in the San Juan field.

In 1930 a new well was started by the Arcola Oil Co. in sec. 6, T. 42 S., R. 19 E., near the wells that had formerly produced oil in the San Juan field. This well is reported to have been drilled to a depth of 263 feet, where it obtained a small production of oil. In 1931 no drilling was in progress in the Monument Valley-Navajo Mountain region.

CHARACTER OF THE OIL

No samples of oil were collected from the seeps along the canyon of the San Juan River, but Woodruff [27] collected samples from four wells at Mexican Hat, which were analyzed under the direction of David T. Day, and the physical and chemical properties were described as follows. The stratigraphic determinations, which are mine, have been added to Woodruff's table.

Chemical and physical properties of oil in the San Juan oil field, Utah

Serial no.		Depth (feet)	Physical properties		
			Gravity		Color
			Specific	Degrees Baumé	
Utah 4	Well No. 4, Goodridge townsite; E. L. Goodridge, Goodridge	263	0.8264	39.4	Black.
Utah 5	Jackson well, sec. 5, T. 42 S., R. 19 E.; stray sand; Monumental Oil Co., Bluff.	625	.8314	38.4	Do.
Utah 6	Anderson well, sec. 5, T. 42 S., R. 19 E.; Baby or Goodridge sand, South Side Oil Co., Mexican Hat.	300	.8202	40.7	Do.
Utah 7	Arcola well No. 2, T. 42 S., R. 19 E.; Mendenhall sand; Bluff.	600	.8388	36.9	Dark green.

[27] Woodruff, E. G., Geology of the San Juan oil field, Utah: U. S. Geol. Survey Bull. 471, pp. 94–95, 1912.

Chemical and physical properties of oil in the San Juan oil field, Utah—Contd.

Serial no.	Distillation by Engler method								Sulphur (percent)	Paraffin (percent)	Asphalt (percent)	Unsaturated hydrocarbons (percent)	
	Begins to boil (° C.)	By volume											
		To 150° C.		150° to 300° C.		Residuum		Total (cubic centimeters)				Crude	100°-300° C.
		Cubic centimeters	Specific gravity	Cubic centimeters	Specific gravity	Cubic centimeters	Specific gravity						
Utah 4	70	12.0	0.7245	36.0	0.7941	49.3	0.8974	99.3	0.26	6.09	0.80	20.4	1.0
Utah 5	78	11.0	.7235	35.0	.7976	51.0	.8946	97.0	.18	5.29	.60	14.8	6.0
Utah 6	73	12.0	.7130	36.0	.7941	49.5	.8975	97.5	.20	3.25	1.11	14.4	8.0
Utah 7	97	10.0	.7395	37.0	.8021	52.0	.8986	99.0	.40	6.79	.49	19.2	6.0

4. From a sandstone in the Rico formation about 80 feet below the top.
5. Probably from a horizon in the Rico formation about 370 feet below the top.
6. From a horizon in the Rico formation between 30 and 100 feet below the top.
7. From a sandstone in the Rico formation about 240 feet below the top.

Concerning the character of the oil, Mr. Day remarked:

These oils, as shown by the analyses, are unusually light in specific gravity. They yield more than the average amount of gasoline and of burning oil. The light specific gravity of the burning-oil fraction compared to the average, the considerable amount of paraffin wax, and the comparatively low proportion of unsaturated hydrocarbons show that these oils are somewhat similar to the oil from Lima, Ohio, with a smaller proportion of sulphur. In fact, the amount of sulphur is less than in many oils in Illinois, which are refined without special apparatus for eliminating sulphur. Taken althogether, these oils are well suited for the manufacture of gasoline and kerosene, and there is every indication that the residuum would yield valuable lubricating oils.

POSSIBLE RESULTS OF FURTHER DRILLING

STRATIGRAPHIC EVIDENCE

The Hermosa formation, of Pennsylvanian age, and the Rico formation, of Permian age, formerly grouped as the Goodridge formation, are the only formations that crop out in the Monument Valley-Navajo Mountain region that are known to be oil-bearing. The presence of oil in these formations is shown by the seeps along the canyon of the San Juan River and the oil found in numerous wells drilled in the San Juan field. There is little question that these formations persist beneath the surface within the region here described and maintain essentially the same lithologic character as is displayed in their outcrop, for their known wide areal extent in southwestern Colorado and southeastern Utah argues against the rapid thinning of these formations that would be necessary if they wedged out in the relatively short distance between their westernmost outcrop and the west edge of the region here described. The formations eventually disappear toward the west, however, as they are absent in the Grand Canyon. Whether the Rico and Hermosa formations are petroliferous in the western part of this region has not been demonstrated, but it seems a fair assumption that they are petroliferous there to about the same degree as they are in the San Juan field. Drilling to date (1931) between the Organ Rock anticline and the San Juan field has failed to find oil in commercial quantities, but when it is considered that the drilling has been done on or near the crests of anticlines, whereas the wells in the San Juan field are near the axis of a syncline, it does not appear that the drilling so far done has thoroughly tested the petroleum possibilities of the region west of that field.

As the base of the Hermosa formation is not exposed in the Monument Valley-Navajo Mountain region nor in neighboring regions, the nature and petroleum possibilities of the underlying formations can be surmised only by an interpretation of the information obtained in a few wells and from distant outcrops. Several deep wells in the vicinity of Moab, Utah, on the Colorado River about 95 miles north of the San Juan River, were drilled through the Hermosa formation into the Paradox formation, consisting of a great thickness of saliferous strata, in which some showings of oil and gas were obtained.[28] The Paradox formation is now classified as lower Pennsylvanian. South from the Moab district the Paradox formation apparently wedges out, as only 650 feet of strata encountered in the Elk Ridge well of the Midwest Exploration Co., 43 miles north of Alhambra Rock, are correlated with the Paradox formation, and no saliferous beds that could be assigned to this formation were reported from the Cedar Mesa well of the Utah Southern Oil Co., 10 miles north of Alhambra Rock, or the Boundary Butte well of the Continental Oil Co., 25 miles east of Alhambra Rock. An almost unbroken series of limestone 1,700 feet thick was encountered in the Elk Ridge well below the beds correlated with the Paradox formation, and the Cedar Mesa and Boundary Butte wells were drilled through nearly 3,000 feet of limestone with some interbedded shale and sandstone below the Rico formation. It is inferred that the Paradox formation wedges out southward by overlap upon an older limestone, and that in the Cedar Mesa and Boundary Butte wells, where the Paradox formation is apparently absent, the Hermosa rests upon the older limestone, although it is not possible to subdivide the limestone series from the evidence supplied by these wells. This older limestone has not proved to be petroliferous in any of these three wells, and it does not appear that these beds will prove to be an important source of oil.

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[28] Baker, A. A., Geology and oil possibilities of the Moab district, Utah: U. S. Geol. Survey Bull. 841, p. 83, 1933.

The Rattlesnake no. 17 well of the Continental Oil Co., in sec. 2, T. 29 N., R. 19 W., in northwestern New Mexico, obtained a production of oil reported to be nearly 800 barrels a day at a depth of 6,769 feet, from a bed that is believed to be in the lower part of the Hermosa formation, but this production was not maintained, and drilling was continued to about 7,000 feet. A second well, Rattlesnake no. 24, in sec. 1, T. 29 N., R. 19 W., was reported to have had an initial production of oil of over 500 barrels a day from a bed found at a depth of 6,620 feet. After drilling to a total depth of 7,370 feet without finding additional oil, the well was plugged back to 6,620 feet and production was obtained. The Rattlesnake nos. 17 and 24 wells probably did not reach rocks as old as those encountered in the Boundary Butte well.

Southeastern Utah is probably underlain by rocks of Mississippian age. Rocks of this age crop out in the Grand Canyon district, to the west, as the Redwall limestone, and in southwest Colorado, to the east, as the Leadville limestone. Both of these formations consist largely of massive limestone that seems to offer little possibility for the production of petroleum. It is possible that the limestone encountered in the deep wells drilled at Elk Ridge, Cedar Mesa, and Boundary Butte, as described in a preceding paragraph, is the Mississippian limestone.

Some of the formations above the Permian Rico formation are petroliferous at their outcrops elsewhere in Utah, but none of them are petroliferous within the Monument Valley-Navajo Mountain region. The Permian Cutler formation consists of three tongues of red sandstone, mudstone, and shale with two massive light-brown to gray sandstone members. The stratigraphic equivalent of the De Chelly sandstone, the upper of the two sandstone members of the Cutler, on the west side of the Colorado River between the mouths of the Green and Fremont Rivers,[29] is lightly impregnated with oil at its outcrop. However, as no petroliferous beds have been reported at the outcrops of the Cutler formation between this portion of the Colorado River and the San Juan River, and equivalent strata west of the region here described are not known to be petroliferous,[30] there seems to be no possibility that this member of the Cutler formation contains oil within the region here described.

The Moenkopi formation, of Lower Triassic age, contains indications of oil at several places in Utah. A small production of oil has been obtained from this formation in southwestern Utah,[31] and at

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[29] Baker, A. A., Geology of the Green River Desert and the east flank of the San Rafael Swell: U. S. Geol. Survey Bull. (in preparation).

[30] Gregory, H. E., and Moore, R. C., The Kaiparowits region, Utah and Arizona: U. S. Geol. Survey Prof. Paper 164, p. 154, 1931.

[31] Bassler, Harvey, and Reeside, J. B., Jr., Oil prospects in Washington County, Utah: U. S. Geol. Survey Bull. 726, pp. 87–107, 1922.

outcrops in the Circle Cliffs it is impregnated with oil.[32] In the San Rafael Swell considerable detrital asphalt is present in the Sinbad limestone member of the Moenkopi formation.[33] The oil that seeps from the Shinarump conglomerate near the axis of the Waterpocket Fold on the Colorado River is probably derived from the Moenkopi formation.[34] At all these localities the Moenkopi formation contains marine beds that are presumably the source of the oil, but in the Monument Valley-Navajo Mountain region the Moenkopi contains no indications of petroleum and consists of red beds that may be in part marine but are not considered to be favorable source rocks. The Moenkopi formation, therefore, does not offer favorable possibilities for the production of oil within the region here described.

The Shinarump conglomerate and Chinle formation, both of Triassic age, and the overlying Jurassic formations show no indications of oil and are not believed to offer any possibility of oil production in the Monument Valley-Navajo Mountain region.

STRUCTURAL RELATIONS

An anticline presents a favorable type of geologic structure for the accumulation of oil, but oil may accumulate under other structural conditions. The most important factor bearing on the accumulation of petroleum in the Monument Valley-Navajo Mountain region may be the lack of abundant water in the strata that crop out or that have been reached in drilled wells. According to commonly accepted theories of oil migration, where the strata are only partly filled with water the oil will not move to the crests of the anticlines, and where there is a total lack of water the oil will accumulate in structural depressions or synclines. The lack of an adequate supply of water is believed to account for the occurrence of the oil in the San Juan field near the trough of a syncline.[35]

There are two anticlines within the region mapped that would normally be considered favorable locations for test wells. One of these, the Halgaito anticline, is an asymmetric fold with a closure of at least 100 feet. The exact amount of closure is uncertain, because the north end of the anticline is north of the San Juan River and was incompletely mapped during the present investigation. The uppermost beds of the Rico formation are the surface rocks over a large part of the anticline, but the canyon of the San Juan River crosses the north end of the fold, and there about 1,020 feet of the Hermosa formation is exposed. The Monumental Oil Co. drilled

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[32] Gregory, H. E., and Moore, R. C., op. cit., p. 154.

[33] Gilluly, James, Geology and oil and gas prospects of part of the San Rafael Swell, Utah: U. S. Geol. Survey Bull. 806, p. 128, 1929.

[34] Gregory, H. E., and Moore, R. C., op. cit., p. 154.

[35] Woodruff, E. G., Geology of the San Juan oil field, Utah: U. S. Geol. Survey Bull. 471, p. 96, 1912.

two wells and the Utah Petroleum Corporation one well near the crest of this anticline, and the Monumental Oil Co. drilled a third well nearly 2 miles east of the crest, on the gently dipping east flank. None of these wells can be considered thorough tests of the anticline, as none of them were drilled to sufficient depth. The well of the Utah Petroleum Corporation penetrated and tested about 280 feet of strata that are deeper than the rocks exposed in the canyon of the San Juan River and that would not have been drained of any oil they might have contained. The lower part of the Hermosa formation and the deeper limestone formations were not reached. Similarly, the deeper well of the Monumental Oil Co. in sec. 23, T. 42 S., R. 17 E., tested only about 180 feet of the Hermosa formation that is not exposed along the river.

The Organ Rock anticline is an asymmetric fold with a closure of about 150 feet. The upper part of the Cedar Mesa sandstone member of the Cutler formation is the surface rock over the crest of the anticline. The Wilson-Cranmer & Co. well was drilled at the crest of this anticline to a depth of 2,323 feet and passed through about 1,000 feet of the Hermosa formation without obtaining production. This well constitutes a good test of this anticline to the depth to which the well was drilled, but it failed to reach the lower part of the Hermosa formation and the deeper limestone formations.

The Balanced Rock anticline is a long, narrow asymmetric fold that crosses the San Juan River. The north end was not mapped, and it was not determined, therefore, whether or not there is a closure in that direction. The oldest formation exposed at the crest of the anticline is the Cedar Mesa sandstone member of the Cutler formation. The top of the Rico formation is probably about 800 feet below the level of the San Juan River at the crest of the anticline, and the Hermosa formation presumably underlies the Rico. This anticline has not been tested with a drill.

The Beaver anticline does not appear to be a favorable location for a test well, as it is a northward-plunging anticlinal nose on which there is no closure.

The Navajo Mountain dome is apparently underlain by igneous rock in the form of a laccolith that arched the rock strata of the mountain. The stratigraphic horizon at which the igneous rock spreads laterally from its feeder dikes has an important bearing on the possibility of oil in the dome, for in the laccolithic type of intrusion only the strata above the igneous rock are arched, and the strata beneath them may be relatively undisturbed. As discussed on pages 71–72, it seems probable that the laccolith was intruded somewhere between the base of the Cutler formation and the base of the Wingate sandstone. If this hypothesis is correct, the surface folding does not reflect the attitude of the Rico and Hermosa formations, the only known oil-bearing formations in the region, which presumably dip uniformly to the northwest beneath the mountain. There is therefore no reason to expect that Navajo Mountain is underlain by oil or gas. If the laccolith had been intruded in or just below the Rico or Hermosa formation, part or all of these formations would have been arched over the intrusion, but the heat and pressure of the intrusion would have altered the adjacent rocks and probably would have rendered them unfavorable for the accumulation of oil or gas.

In view of the apparent lack of water in the sediments the possibility of finding oil accumulations in the synclines should not be ignored. The Oljeto syncline trends north across the region. Its axis plunges both north and south from a structurally high point in the western part of T. 42 S., R. 15 E., to structurally low points at the Arizona State line and the San Juan River. I do not know how far the axis of the syncline continues to pitch beyond the limits of this region, but from the evidence obtained within the region it appears that any oil that might tend to accumulate in the trough of the syncline would drain out of the area either to the north or to the south. The top of the Rico formation is about 500 feet below the water level of the San Juan River in the trough of the syncline and about 1,900 feet below the surface where the axis of the syncline crosses the Arizona-Utah State line.

The axes of both the Nokai and Rapid synclines plunge to the north, and there appears to be nothing to prevent the migration beyond the limits of the region of any oil that might tend to accumulate in these synclines. At the point where the axis of the Nokai syncline crosses the San Juan River the top of the Rico is about 1,600 feet below the surface, and at a corresponding point on the Rapid syncline it is possibly 2,700 feet below the surface.

CONCLUSIONS

The Monument Valley-Navajo Mountain region is underlain by the Rico and Hermosa formations, which are oil-bearing, as is shown by oil seeps and by wells in the San Juan field at Mexican Hat. Other formations that crop out in the region do not appear to be source rocks of oil nor show any indication that oil has migrated into them along joints or faults from the underlying Rico and Hermosa formations. Deep wells drilled a few miles outside of this region may have penetrated rocks older than the Hermosa, possibly of Mississippian age, but failed to produce oil. Wells that have been drilled on the Halgaito and Organ Rock anticlines, which from surface indications appear to be the most favorable locations for tests, have found only slight showings of oil but these wells have not been drilled deep enough to test the lower part of the Hermosa formation. In view of the failure of these wells to find oil accumulations in the anticlines and the occurrence of oil near the trough of a syncline at Mexican Hat, it is inferred that lack of water in the oil-bearing strata has caused the oil to accumulate in the synclines rather than in the anticlines, and consequently that further drilling on the crests of the anticlines is not likely to prove successful. In the absence of additional geologic work to ascertain the extent and shape of the synclines beyond the limits of the region here described, it is not possible to determine whether the portions of the synclines included within the region offer sufficient possibilities of oil accumulation to warrant the drilling of test wells. Until test wells are drilled it is impossible to determine the extent to which water in the oil-bearing strata may have influenced the accumulation of oil. If the oil-bearing strata are partly filled with water the oil probably would migrate to the upper limit of the water, the position of which is unknown in the absence of systematic prospecting with the drill. Such systematic prospecting would not only be expensive but would meet with difficulties in this arid country remote from railroads.

GOLD

Placer gold in small amounts has been found in the gravel bars and terraces along the San Juan River. Gregory [36] gives the following description of the development work:

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 sandrock. Pierce riffles were used and gasoline power provided. The expense of installation was much increased by the necessity of procuring supplies and fuel from 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

[36] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, pp. 139–140, 1917.

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.

Miser[37] describes the search for gold along the San Juan River as follows:

Prospecting for gold in San Juan Canyon began in 1892, when tales of fabulously rich deposits caused 1,200 men to stampede to the canyon. After spending a few months there they went away empty-handed, but prospecting continued at a few places as late as 1915. The gold is extremely fine in grain, being known as flour gold, and occurs mostly in placer deposits along the river channel and in terrace gravels. Placer deposits have been prospected at numerous places between the mouth of Chinle Creek and Zahns Camp. The results of work at Zahns Camp are not known, but the richest returns from the rest of the canyon were obtained at the Nephi claim, 4 miles below the Honaker Trail, where $3,000 worth of gold was recovered in 30 days. At Spencer Camp and near the mouth of Copper Creek attempts have been made to extract gold from sandstone debris, which has been derived from the Wingate and Navajo sandstones. Small quantities of gold—20 to 40 cents a ton—are said to occur disseminated through these sandstones.

In 1928 no attempts to recover gold were being made along the San Juan River within the Monument Valley-Navajo Mountain region.

COPPER

Copper in the form of malachite, azurite, and chrysocolla has been observed at a few places as irregular patches impregnating the Shinarump conglomerate and sandstones in the Chinle formation at their outcrops along Copper, Nokai, and Piute Canyons. Numerous pits have been dug in prospecting these deposits, but no deposits of commercial value have been discovered.

WELL RECORDS

The records of the deepest three wells drilled in the area are given on the following pages. The lithologic descriptions are as given by the drillers, but the interpretations of the formations are mine.

Record of the Utah Petroleum Corporation's well on the Halgaito anticline in sec. 36, T. 41 S., R. 17 E.

	Thickness (feet)	Depth (feet)
Rico formation:		
Sandy limestone	43	43
Hard red limestone	66	109
Hard sandy limestone	21	130
Hard sandy red limestone	68	198
Sandy limestone	11	209
Red sandy limestone	81	290
White limestone	20	310
Hard gray limestone	11	321
White limestone	38	359
Hard gray limestone	26	385
White limestone	25	410

[37] Miser, H. D., The San Juan Canyon, southeastern Utah: U. S. Geol. Survey Water-Supply Paper 538, pp. 21–22, 1924.

Record of the Utah Petroleum Corporation's well on the Halgaito anticline in sec. 36, T. 41 S., R. 17 E.—Continued

	Thickness (feet)	Depth (feet)
Hermosa formation:		
White limestone	150	560
Gray limestone	120	680
Hard limestone	22	702
Hard gray limestone	183	885
Black shale	11	896
Hard gray limestone	174	1,070
Dark shale	10	1,080
Gray limestone	20	1,100
Hard white limestone	22	1,122
Limestone	4	1,126
Hard white limestone	24	1,150
Hard gray limestone	28	1,178
Broken limestone	8	1,186
Hard gray limestone	29	1,215
Brown shale and limestone	8	1,223
Blue limestone	5	1,228
Brown shale	2	1,230
Blue limestone	4	1,234
Brown shale	1	1,235
Blue limestone	33	1,268
Blue shale	57	1,325
Blue limestone	10	1,335
Brown and black shale	40	1,375
Hard blue limestone	15	1,390
Brown shale and limestone	40	1,430
Gray limestone	112	1,542
Blue shale	10	1,552
Hard gray limestone	8	1,560
Cavy blue shale	65	1,625
Red shale	15	1,640
Limestone	10	1,650
Red rock	35	1,685
White broken limestone	22	1,707

Record of the Wilson-Cranmer & Co.'s well on the Organ Rock anticline in sec. 35, T. 42 S., R. 14 E.

	Thickness (feet)	Depth (feet)
Cedar Mesa sandstone member of the Cutler formation:		
Pink coarse-grained sandstone	22	22
Brown shale	1	23
Pink coarse-grained sandstone	3	26
Brown shale	6	32
White coarse-grained sandstone	83	115
Brown shale	9	124
Pink coarse-grained sandstone mottled with green	24	148
Brown shale	8	156
Pink coarse-grained sandstone	46	202
Brown shale	5	207
Pink sandstone	146	353
Halgaito tongue of the Cutler formation:		
Brown sandy shale	214	567
Sandstone	10	577
Brown sandy shale with occasional green spots	175	752
Brown sandy shale with pinkish-white spots of irregular shape	45	797
Rico formation:		
Pink sandstone with brown shale partings	100	897
Brown shale	5	902
White sandstone	5	907
Brown sandstone with brown shale partings	25	932
Green shale	4	936
Coarse-grained white sandstone	13	949
White sandstone lightly saturated with oil and showing some gas	14	963
Brown shale	4	967
Pink sandstone	4	971
Brown shale	4	975
Brown sandstone	8	983
Brown shale	2	985
Brown sandstone	20	1,005
Pink sandstone	5	1,010
White sandstone with crevices filled with white salty material	5	1,015

Record of the Wilson-Cranmer & Co.'s well on the Organ Rock anticline in sec. 35, T. 42 S., R. 14 E.—Continued

	Thickness (feet)	Depth (feet)
Rico formation—Continued.		
Brown sandstone with brown shale partings as much as 4 feet thick	150	1,165
Hard fine-grained gray sandstone	2	1,167
Purple shale	5	1,172
Brown sandstone	15	1,187
Brown shale	1	1,188
Hard white sandstone	15	1,203
Grayish sandstone	4	1,207
Brown sandy shale	35	1,242
Hard gray limy sandstone with black spots of irregular shape	25	1,267
Brown fine-grained sandstone	16	1,283
Hermosa formation:		
Gray sandstone	15	1,298
Gray limestone	15	1,313
Speckled limestone containing coarse-grained quartz sand	15	1,328
Brownish-green shaly sandstone	13	1,341
Gray limestone	12	1,353
Brown sandstone	16	1,369
Gray fossiliferous limestone	26	1,395
Purple shale	2	1,397
Brown sandy shale	10	1,407
Brown limy sandstone	15	1,422
White fossiliferous sandy limestone	26	1,448
Brown shaly sandstone	20	1,468
Gray limy sandstone speckled with chert	56	1,524
Brownish fine-grained sandstone	15	1,539
Dark-gray limestone	10	1,549
Greenish limestone	5	1,554
Black fossiliferous limestone	25	1,579
Hard gray limestone with chert	90	1,669
Pink sandstone	15	1,684
Gray limestone	15	1,699
Purplish limestone	5	1,704
Gray fossiliferous cherty limestone	15	1,719
Brown sandy limestone	6	1,725
Hard gray limestone	10	1,735
Brown sandy limestone	5	1,740
Light-gray limestone	20	1,760
Gray limestone	125	1,885
(?)	8	1,893
Gray limestone	13	1,906
Interbedded gray limestone and shale	417	2,323

Record of the Monumental Oil Co.'s well on the Halgaito anticline in sec. 23, T. 42 S., R. 17 E.

	Thickness (feet)	Depth (feet)
Sand	3	3
Rico formation:		
Soft shale	6	9
Broken gray limestone	13	22
Sandstone	80	102
Sandy shale	12	114
Limy shale	1½	115½
Sandy shale	14½	130
Limy shale	8	138
Sandy shale	49	187
Gray limestone	5	192
Sandy shale	28	220
Gray limestone	18	238
Sandy shale	42	280
Gray limestone	11	291
Hard broken limestone	10	301
Fossil limestone	10	311
Gray limestone	3	314
Shale	21	335
Hard gray limestone	18	353
Fossil limestone	14	367
Gray limestone	6	373
Shale	8	381
Hard gray limestone with jasper seams	16	397
Hard gray limestone	14	411
Shale	18	429

Record of the Monumental Oil Co.'s well on the Halgaito anticline in sec. 23, T. 42 S., R. 17 E.—Continued

	Thickness (feet)	Depth (feet)
Hermosa formation:		
Hard gray limestone with jasper seams	16	445
Fossil limestone	5	450
Hard gray limestone	3	453
Shale	38	491
Hard gray limestone	17	508
Fossil limestone	8	516
Hard gray limestone with jasper seams	13	529
Shale	14	543
Sandy limestone	4	547
Sandy shale	10	557
Sandy limestone	15	572
Fossil limestone with jasper	18	590
Hard gray limestone with jasper	5	595
Hard gray limestone	14	609
Fossil limestone	6	615
Hard gray limestone with jasper	51	666
Hard gray limestone	19	685
Dark limestone	9	694
Hard gray limestone	46	740
Sandy limestone	10	750
Hard gray limestone	55	805
Dark shale	2	807
Hard gray limestone	1	808
Oil sand	1	809
Hard gray limestone	46	855
Gray limestone	27	882
Blue limestone	4½	886½
Gray limestone	1	887½
Oil sand	2	889⅓
Hard gray limestone	33½	923
Gray limestone	1	924
Oil sand	2	926
Gray limestone	16	942
Hard limestone	10	952
Broken gray limestone	18	970
Fossil limestone	12	982
Dark shale	⅔	982⅔
Fossil limestone	2	984⅔
Gray limestone	3	987⅔
Dark shale	2⅓	990
Gray limestone	40	1,030
Dark shale	1	1,031
Gray limestone	66	1,097
Shale	7	1,104
Gray limestone	52	1,156
Shale	3	1,159
Gray limestone	29	1,188
Soft shale	8	1,196
Gray limestone	18	1,214
Soft shale	1	1,215
Gray limestone	33	1,248
Very soft shale	12	1,260
Gray limestone	54	1,314
Blue shale	4	1,318
Broken limestone	3	1,321
Gray limestone	37	1,358
Very soft shale	2	1,360
Gray limestone	1	1,361
Very soft shale	2	1,363
Gray limestone	18	1,381
Fossil limestone	5	1,386
Gray limestone	6	1,392
Very soft shale	6	1,398
Gray limestone	16	1,414
Soft shale and fine sandstone	3	1,417
Gray limestone	5	1,422
Soft shale	3	1,425
Gray limestone	7	1,432
Very soft shale	3⅓	1,435⅓
Hard limestone	1⅔	1,437
Soft shale	3	1,440
Hard limestone	1	1,441
White sandy limestone with oil showing	1	1,442
Blue shale and seams of limestone	7	1,449
Very soft shale	10⅓	1,459⅓
Hard limestone	11⅔	1,471
Soft dark shale	18	1,489
Soft gray shale	9	1,498

Record of the Monumental Oil Co.'s well on the Halgaito anticline in sec. 23, T. 42 S., R. 17 E.—Continued

	Thickness (feet)	Depth (feet)
Hermosa formation—Continued.		
Gray limestone with jasper	4	1,502
Gray limestone	4	1,506
Reddish soft shale	22	1,528
Gray limestone	1	1,529
Hard limestone	3	1,532
Soft red sandstone	64	1,596
Gray limestone	4	1,600
Limestone	10	1,610
Red shale	12	1,622

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