UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGY OF AREA BETWEEN GREEN AND COLORADO RIVERS GRAND AND SAN JUAN COUNTIES UTAH

GEOLOGICAL SURVEY BULLETIN 908

UNITED STATES DEPARTMENT OF THE INTERIOR
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BY

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GEOLOGY OF AREA BETWEEN GREEN AND COLORADO RIVERS, GRAND AND SAN JUAN COUNTIES, UTAH

By Edwin T. McKnight

ABSTRACT

The area described in this report comprises about 900 square miles of arid land lying between the Green and Colorado Rivers south of the Denver & Rio Grande Western Railroad and southwest of the Salt Valley anticline. The rocks that crop out or that have been encountered in wells drilled in the area are all sedimentary and range in age from Pennsylvanian to Upper Cretaceous. Mesozoic strata are especially well represented. Including rocks that have been cut by drilling, the maximum thickness of the stratigraphic section is about 2 miles.

The oldest formation described is the Paradox formation, of probable lower Pennsylvanian age. Although it does not crop out within the area, this formation has been penetrated by four deep wells along the Colorado River, and it is exposed in anticlinal folds of closely adjacent areas. Peculiar to this formation are large amounts of salt, gypsum, and anhydrite interbedded with the shales, limestones, and subordinate sandstones. Because of structural complications brought about by the plastic behavior of the salt, gypsum, and anhydrite when subjected to deformation, the thickness of the Paradox formation is not known, but it is believed to exceed 2,000 feet in the deep wells along the Colorado River.

Overlying the Paradox formation is the Hermosa formation, of Pennsylvanian age, comprising about 1,800 feet of marine arkosic sandstones, limestones, and shales. The Rico formation, of Permian age, overlies the Hermosa conformably and consists of red sandstones, arkoses, and shales with minor thicknesses of interbedded marine limestones. It has a maximum thickness of nearly 600 feet. The Rico formation is overlain conformably by the Cutler formation, of Permian age, which also consists of arkosic red beds but differs from the Rico essentially in the absence of fossiliferous limestones. Near the junction of the Green and Colorado Rivers the lower part of the Cutler grades laterally into massive light-colored sandstone that makes up the Cedar Mesa sandstone member of the Cutler. Near or at the top of the formation is the White Rim sandstone member, which is present where the upper Cutler crops out in the Canyon of the Green River and also on the northwest side of the Colorado Canyon below the Shafer dome, but which is absent by reason of nondeposition farther up the Colorado and also on the southeast side of the river. The maximum thickness of the Cutler formation is about 1,000 feet.

The Moenkopi formation, of Lower Triassic age, overlies the Cutler unconformably. It is another "red bed" sequence, composed of thin-bedded chocolate-brown shales and sandstones except locally along the Green River, where the

upper part of the formation is gray. Marine fossils have been found at the base of this gray facies, 220 feet above the base of the formation. The maximum thickness of the Moenkopi is about 525 feet. It is overlain unconformably by the Shinarump conglomerate of probable Upper Triassic age, or where the Shinarump is absent by the Chinle formation, of Upper Triassic age. The Shinarump, considered to be a basal conglomerate of the Chinle formation, occurs only in certain parts of the area, and intermittently in those parts. The Chinle and Shinarump are variegated fluviatile deposits that show a maximum combined thickness of 470 feet.

The formations of the Glen Canyon group, which overlie the Chinle, comprise, in ascending order, the Wingate sandstone, the Kayenta formation, and the Navajo sandstone. These are continental formations that contain no determinative fossils, so their age assignment is uncertain. They are tentatively classed as Jurassic, but some of them may be Upper Triassic. Their stratigraphic relations to each other and to the underlying Chinle have not been settled with unanimous agreement, though the writer believes that the Wingate is conformable on the Chinle, and the Kayenta is unconformable on the Wingate. The aggregate thickness of the three formations of the Glen Canyon group approximates 900 feet.

The formations of the San Rafael group, of Upper Jurassic age, overlie the Glen Canyon group with apparent conformity. They include, in ascending order, the Carmel formation, Entrada sandstone, Curtis formation, and Summerville formation. The Carmel is composed of red and gray muddy sandstones with some shaly material. The Entrada throughout most of the area is a massive pink to white sandstone, but near the Green River the upper part is composed of red muddy sandstone. In the eastern part of the area the Moab tongue of the Entrada is present at the top of the formation; farther west the Moab tongue is separated from the main member of the Entrada by a tongue of the Summerville that increases in thickness westward at the expense of the Moab tongue, finally displacing it completely. The Curtis formation is present only in the western part of the area near the Green River; eastward it grades laterally into the lower part of the Summerville. Both of these formations are alternating thin-bedded sandstones and sandy shales, differing only in that the Curtis is predominantly gray, whereas the Summerville is red. The Curtis shows a slight angular unconformity on the Entrada sandstone, as does also the Summerville formation for a short distance east of the Curtis outcrops. This unconformity, projected eastward, lies between the Entrada sandstone and the Moab tongue, but it is not believed to extend much beyond the limits of the area covered in this report. The San Rafael group shows a total thickness of about 600 feet.

The Morrison formation, of Upper Jurassic age, overlies the San Rafael group unconformably. It is a variegated continental formation consisting predominantly of mudstone but containing zones of thick lenticular sandstones, some of which are conglomeratic, near the base and also near the top. The maximum thickness is about 850 feet.

The Dakota (?) sandstone, of Upper Cretaceous age, overlies the Morrison unconformably. It is a thin conglomeratic sandstone, locally interbedded with shale; its maximum thickness is 60 feet. It is overlain conformably by the gray marine Mancos shale, the lower 1,400 feet of which is exposed within the area treated in this report.

Within the stratigraphic section of rocks exposed in the area are two unconformities both of which locally and regionally truncate considerable thicknesses of the underlying beds. These unconformities are at the base of the Lower Triassic Moenkopi and at the base of the Upper (?) Triassic Shinarump.

Three or four others are known, though not all observers are agreed as to the relative significance of some of them; none of these truncate the underlying strata to any great extent within the area studied.

The dominant structure of the area is a gentle regional dip to the north. Superposed on this regional dip are several more local structural features—broad open folds, normal faults, and grabens—that with few exceptions have a general northwesterly trend. Only in comparison to the regional dip can these features be said to be local, for the length of most of them is measured in tens of miles. Two of the folds were first formed at the end of the Permian epoch and before the deposition of the Lower Triassic sediments. These folds were intensified during the time interval between Lower and Upper (?) Triassic and again in the late Cretaceous. All the other folds of the region apparently date from the late Cretaceous orogeny, coincident with the uplift of the Rocky Mountains. The faulting is largely confined to a relatively narrow belt that includes, from southeast to northwest, three major fault units—the Moab fault, the Tenmile graben, and the Salt Wash graben. The maximum displacement—that on the Moab fault—is 2,400 to 2,600 feet. The faulting of the region appears to be later than the late Cretaceous folding and may date from late Tertiary.

Where the Colorado River has cut deeply into the Paleozoic formations near the junction with the Green River, there is a narrow anticline whose axis follows rather closely the inner canyon of the stream for several miles. This anticline is believed to have been caused by the upward bulge of the plastic salt and gypsum of the underlying Paradox formation as a result of the difference in hydrostatic pressure between the weight of rocks in the canyon walls and the lesser weight of rocks underlying the bed of the canyon. Another structural feature believed to have been produced by plastic movements in the salt series is the Upheaval dome, near the Green River. This steep-sided dome is circular and is surrounded on all sides by a ringlike syncline. The Upheaval dome and several similar structural features have been described by Bucher as "cryptovolcanic structures," but others have recently demonstrated that the structural form of the Upheaval dome closely approximates the theoretical form for salt domes under certain conditions.

During the World War deposits of manganese ore occurring in the Summerville formation were worked in an area near the Green River. Several prospect wells, some of them deep, have been drilled for oil and gas in two different parts of the area, and some of them were located on the most favorable structural features. Although showings of oil and gas have been obtained, the quantities have not been such as to indicate any commercial reserves within the area.

INTRODUCTION

LOCATION, EXTENT, AND POPULATION OF THE AREA

The area described in this report lies in southeastern Utah in the acute angle formed by the Green and Colorado Rivers, which are respectively its southwest and southeast boundaries. The north boundary is arbitrarily placed at the Denver & Rio Grande Western Railroad, and the northeast boundary is an indefinite line on the flank of the Salt Valley anticline, which is treated in a report by Dane.[1] Figure 1 shows the location and general shape of the area

[1] Dane, C. H., Geology of the Salt Valley anticline and adjacent areas, Grand County, Utah: U. S. Geol. Survey Bull. 863, 1936.

mapped. Approximately 900 square miles is included within the boundaries outlined, within which there are only five or six permanent dwellings, chiefly along the Green River and at Valley City, although Courthouse mail station is inhabited intermittently, and

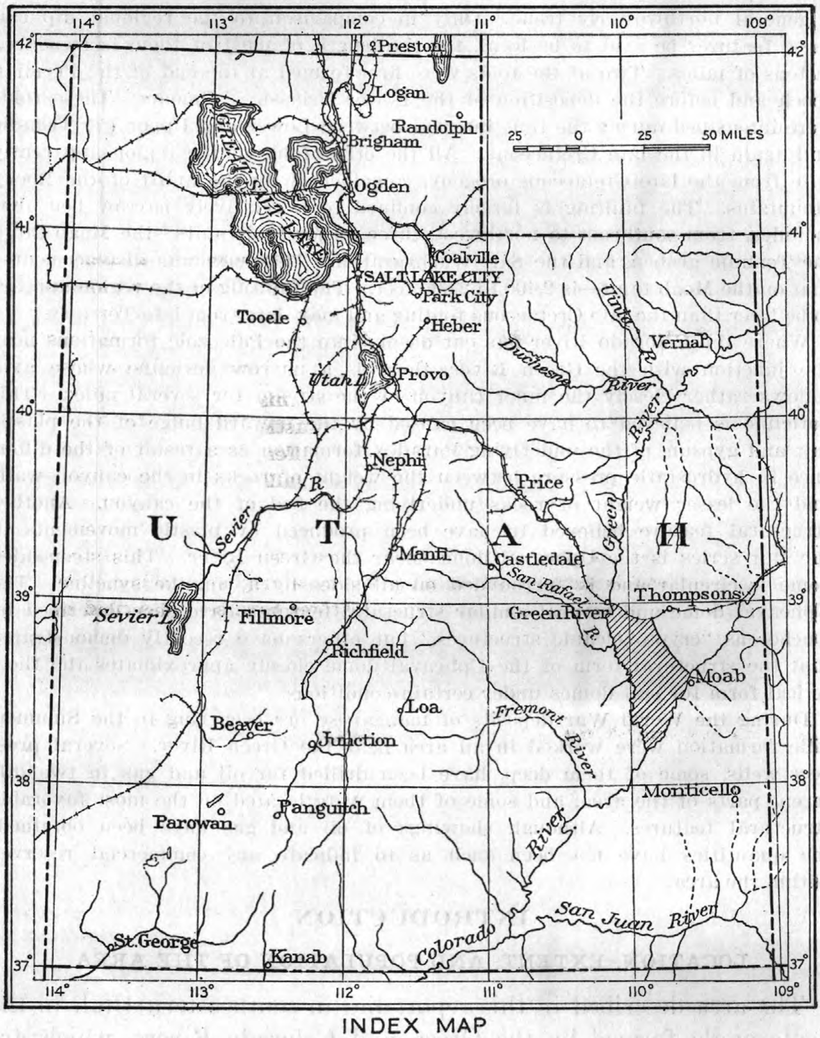

FIGURE 1.—Index map of Utah showing location of the area between the Green and Colorado Rivers.

mining and oil claim locations at numerous places have been temporarily occupied. The permanent population is probably less than 20. Three towns lie just outside the area, however—Green River on the northwest, Thompsons on the northeast, and Moab on the southeast.

FIELD WORK

The field work for the present investigation was done during the summer of 1926 and the spring and early summer of 1927. The report on the area, in preliminary form, was completed shortly afterward, but the necessary revision and final completion of the report has been long delayed by the assignment of the writer to other projects.

During 1926 the writer was assisted by S. S. Nye and during 1927 by J. D. Sears and Otho Murphy. The field work consisted of mapping the rock formations and geologic structure with a plane table and telescopic alidade, combined with a study of the stratigraphy of the area. Each member of the party worked independently, so that the resulting map (pl. 1) is a mosaic, compiled from the work of the individual members. The geology of the Green and Colorado Canyons was mapped on the topographic base maps of these canyons [2] during an 18-day boat trip made by Nye and the writer from Green River to Moab. The topographic map of the Colorado Canyon shows the surface features with considerable detail, but that of the Green Canyon was far more generalized, so the geologic boundary lines at most places could be drawn only approximately, with much loss of detail.

The northern part of the area had been mapped previously by Lupton.[3] From his geologic map the details of certain faults, the outcrop of the Ferron sandstone member of the Mancos, and the locations of prospect wells for petroleum have been taken in part; and observations on strike and dip have been taken in their entirety and incorporated in plates 1 and 3. The formation boundaries below the Ferron sandstone have, however, been completely remapped to correspond with stratigraphic nomenclature that has been developed since the time of Lupton's work.

ACKNOWLEDGMENTS

The writer wishes to acknowledge the hearty cooperation of Mr. H. W. C. Prommel, consulting geologist, of Denver, who not only gave much valuable information in correspondence but also placed at the writer's disposal three detailed unpublished reports dealing with the geology of the Salt Valley anticline, the Colorado Valley structure, and the Green River desert. To J. B. Reeside, Jr., of the Geological Survey, especial acknowledgment is due for aid in the interpretation of the more puzzling stratigraphic sequences

[2] Herron, W. H., Profile surveys in the Colorado River Basin in Wyoming, Utah, Colorado, and New Mexico: U. S. Geol. Survey Water-Supply Paper 396, pls. 13–18, 22–24, 1917.

[3] Lupton, C. T., Oil and gas near Green River, Grand County, Utah: U. S. Geol. Survey Bull. 541, pp. 115–133, pl. 6, 1914.

within the area. Mr. Reeside also furnished numerous stratigraphic descriptions, and the fossil lists are based on collections made chiefly by him and by C. E. Dobbin. Mr. Dobbin was of much assistance in administrative matters that had to do with the organization and equipment of the field parties. G. H. Girty, of the Geological Survey, contributed greatly to the value of the work through his identification of fossils and his age determinations of certain formations. The writer also wishes to express his appreciation to S. S. Nye, J. D. Sears, and Otho Murphy, who assisted in the detailed mapping and to whose ability and energy the successful completion of the work in two field seasons is due.

PREVIOUS LITERATURE

Probably the first geologist to pass through the area was Maj. J. W. Powell, who was in charge of the celebrated exploration of the Green and Colorado Rivers by boat in the summer of 1869. The stretch of Green River along the west side of the area treated in this report was traversed between July 13 and July 17. In the narrative of the expedition, written in diary form,[4] certain of the more striking surface features of the Green River Canyon are described and some of the prominent features are named. In the more technical part of the same report[5] the slight northwesterly regional dip along the lower Green River is pointed out and the geomorphic development of the cliffs and outlying buttes in the same region is described in some detail. Powell's report is probably based in part on information gained on a second boat trip made in the fall of 1871, although this second trip is nowhere specifically mentioned in the report.

Cross,[6] in 1905, made a geologic reconnaissance through a large area southeast of the Colorado River, and at Moab he crossed the river to measure and interpret a stratigraphic section of the formations below the Wingate sandstone. The stratigraphy, structure, and oil possibilities of the northern part of the area covered by the present report have been treated by Lupton,[7] and the occurrence of manganese in the same general area by Pardee.[8] The stratigraphic section in the adjoining region west of the Green River has been described and interpreted by Emery.[9] In 1921 Paige accompanied a surveying party

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[4] Powell, J. W., Exploration of the Colorado River of the West and its tributaries, pp. 3–145, Washington, 1875.

[5] Idem, pp. 167–177.

[6] Cross, Whitman, Stratigraphic results of a reconnaissance in western Colorado and eastern Utah: Jour. Geology, vol. 15, pp. 634–679 but especially pp. 669–671, 1907.

[7] Lupton, C. T., Oil and gas near Green River, Grand County, Utah: U. S. Geol. Survey Bull. 541, pp. 115–133, 1914.

[8] Pardee, J. T., Deposits of manganese ore in Montana, Utah, Oregon, and Washington: U. S. Geol. Survey Bull. 725, pp. 179–206, 1921.

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

down the Green River, and his observations on the stratigraphy of the canyon were combined with the observations of others in a general paper on the rock formations of the Colorado Plateau.[10] The stratigraphy, structure, geologic history, and oil possibilities of the area lying along and partly including the northeast and southeast edges of the area covered in this report have been treated by Prommel,[11] Prommel and Crum,[12] and Harrison.[13] Harrison also describes the Upheaval dome, called by him Christmas Canyon dome, which is near the Green River within the southwest border of the area treated in this report. Moore [14] included the lower part of the Green River in his physiographic study of the Colorado River and its tributaries. Taber [15] has discussed some of the structural features of the area, basing his discussion on Lupton's work.

Studies of the geology, structure, and oil possibilities of several adjacent areas in southeastern Utah and regional stratigraphic correlations over much of the Colorado Plateau, including the area here described, have been made in recent years by several members of the Federal Geological Survey.[16]

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[10] 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–A, pp. 1–22, 1923.

[11] Prommel, H. W. C., Geology and structure of portions of Grand and San Juan Counties, Utah: Am. Assoc. Petroleum Geologists Bull., vol. 7, pp. 384–399, 1923.

[12] Prommel, H. W. C., and Crum, H. E., Structural history of parts of southeastern Utah from interpretation of geologic sections: Am. Assoc. Petroleum Geologists Bull., vol. 11, pp. 809–820, 1927; Salt domes of Permian and Pennsylvanian age in southeastern Utah and their influence on oil accumulation: Idem, pp. 373–393.

[13] Harrison, T. S., Colorado-Utah salt domes: Idem, pp. 111–133.

[14] Moore, R. C., Origin of enclosed meanders on 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.

[15] Taber, Stephen, Fault troughs: Jour. Geology, vol. 35, p. 583, 1927.

[16] 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. 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–D, pp. 61–110, 1928. 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. Gilluly, James, Geology and oil and gas prospects of part of the San Rafael Swell, Utah: U. S. Geol. Survey Bull. 806–C, pp. 69–130, 1929. Gregory, H. E., and Moore, R. C., The Kaiparowits region: U. S. Geol. Survey Prof. Paper 164, 1931. Baker, A. A., Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, 1933. Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., Paradox formation of eastern Utah and western Colorado: Am. Assoc. Petroleum Geologists Bull., vol. 17, pp. 963–980, 1933; Correlation of the Jurassic formations of parts of Utah, Arizona, New Mexico, and Colorado: U. S. Geol. Survey Prof. Paper 183, 1936. Baker, A. A., Geologic structure of southeastern Utah: Am. Assoc. Petroleum Geologists Bull., vol. 19, pp. 1472–1507, 1935. Dane, C. H., Geology of the Salt Valley anticline and adjacent areas, Grand County, Utah: U. S. Geol. Survey Bull. 863, 1936. Baker, A. A., Geology of the Monument Valley-Navajo Mountain region, San Juan County, Utah: U. S. Geol. Survey Bull. 865, 1936; Geology of the Green River Desert-Cataract Canyon region, Utah: U. S. Geol. Survey Bull.—(in preparation). Fisher, D. J., The Book Cliffs coal field in Emery and Grand Counties, Utah: U. S. Geol. Survey Bull. 852, 1936.

GEOGRAPHY

TOPOGRAPHY AND RELIEF

Southeastern Utah lies within the Colorado Plateau province, which in general is characterized by an arid climate, bare rock surfaces, high altitude, and an intricate system of cliff-walled canyons that have been cut into the high tablelands along major streams and many smaller tributaries. According to the degree of dissection, the original upland surface ranges from extensive unbroken plains of slight relief to high isolated butte summits.

These features, characteristic of the province as a whole, are developed in accentuated form in the area treated in this report. Essentially it is an arid upland, low at the north but increasing in altitude toward the south, bounded on two sides by the canyons of two converging perennial streams, the Green and Colorado Rivers, and dissected on the margins by numerous dry canyons tributary to these streams.

The highest altitudes in the area, slightly more than 6,300 feet, are found in three buttes near the south end of Grays Pasture (see pl. 1), but The Knoll, which lies 12 miles to the north, approaches an altitude within 10 feet of the highest of these buttes. The lowest point of the area, 3,875 feet above sea level, is at the junction of the Green and Colorado Rivers.

Because the topographic features of the area are so intimately related to the attitude and lithologic character of the stratified rocks, a brief outline of certain of these geologic features is essential to a visualization of the major topographic units and will be given in advance of a more comprehensive treatment. The rocks of the greater part of the area are nearly horizontal, but there is a slight regional dip to the north so that the Colorado and Green Rivers, in crossing the region from north to south, cut progressively into older formations. In arid regions, where erosion is rapid and where rock disintegration preceding removal by transporting agents is mechanical rather than chemical, the harder formations, such as sandstones, limestones, and conglomerates, are more resistant than the shales, and in areas of essentially horizontal rocks they tend to cap broad benches from which the softer rocks have been removed. The soft formations are in general preserved in relatively narrow belts where, capped and protected by overlying harder formations, they crop out in steep slopes. As these soft beds disintegrate faster on the outcrop than the overlying hard rocks, overhanging cliffs would soon form were it not for the tendency of the overhanging edges of the hard rock to break off as fast as they are undermined, exposing the thickness of the bench-forming member in a steep or vertical cliff, locally called a rim. The mechanical breaking helps to reduce the collapsed rock to a size that can be handled by ordinary sheet-flood and stream erosion. Much of the wearing away of the land in arid regions is accomplished by such a process of cliff recession. A land of alternating hard and soft strata that is being eroded under such conditions appears as a huge uneven stairway of which the benches of hard rock form the treads and the cliffs of hard and soft rock form the risers.[17]

In the area between the Green and Colorado Rivers the Wingate sandstone and the lower 100 feet or so of the overlying Kayenta sandstone form a resistant unit about 400 feet in thickness that dominates the topography of the area (pls. 4, *A*, *B*; 9, *B*; 10, *A*). The cliff formed by this unit is the chief division between two contrasting topographic sections that will be described as the canyon section and the main plateau section. At the north side of the area a thick shale formation crops out near the local baselevel of erosion, and for this reason, as well as because of its great thickness, it has not been stripped from the underlying hard rocks but forms a topographic belt that differs somewhat in aspect from the main plateau section and will be described as the Mancos shale flat.

CANYON SECTION

The canyon section includes everything below the Wingate Rim and in addition certain narrow canyons cut in the overlying sandstone formations, Kayenta and Navajo, wherever these rocks are brought down to river level by structural conditions (pl. 1). It extends up the Green River as far as the mouth of the San Rafael and is also represented throughout the Colorado Valley bordering the area covered by this report. The canyon section attains its broadest development in the region near the junction of the two rivers. Here it extends back about 5 miles from each river into the wedge of land between them. Northward it narrows in each river valley owing to the gradual approach of the Wingate Rim to river level. Above Taylor Canyon on the Green and above the Cane Creek anticline on the Colorado the canyon section includes only the immediate river canyons and several narrow tributary canyons.

The canyon section is typically a land of bare rock, disposed as alternating rims and benches that roughly parallel the main drainage lines, although in detail they follow the contours around the heads of all the minor tributaries. In the vicinity of the junction there are three such rims below the Wingate Rim, each forming the outer edge of a bench. The lowest rim, overlooking the inner gorges of the Colorado and Green Rivers, is not as abrupt a cliff as the one that forms

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[17] For a more complete description of arid-land forms in gently tilted rocks see Powell, J. W., Exploration of the Colorado River of the West and its tributaries, pp. 149–214, Washington, 1875. See especially pp. 167–177.

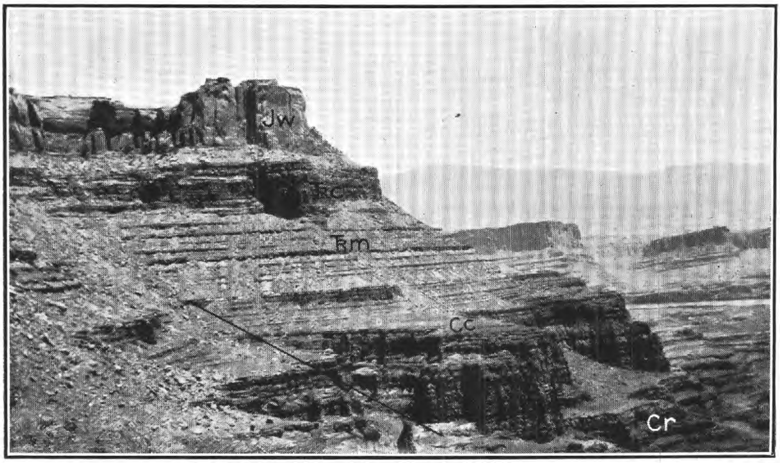
the Wingate Rim, but it is nevertheless just as effective as a barrier (pl. 6, *B*). The bench above it, owing to the lenticularity of the hard rock ledges that hold it up, is a rugged terrane of shallow rock canyons and rounded, horizontally fluted rock ridges and domes, showing an average relief of perhaps 50 feet, with one or two flat limestone benches at the south end. The next overlying rim, called the White Rim, and the bench above it are especially prominent because of their whiteness in a country otherwise characterized by red, buff, and brown outcrops (pl. 5, *A*). This rim is especially abrupt, extending for miles without a break that can be scaled. The upper bench, bordered by a dark-colored (Shinarump) rim, is the least pronounced. At the top the imposing perpendicular Wingate Rim, or Red Rim, as it is called locally, forms the bordering rim for the whole canyon section. Only in the upper and steeper slopes of the canyon country, between the White Rim and the Wingate Rim, are the rock exposures obscured to any considerable extent by talus.

In the narrower canyons, above Taylor Canyon on the Green River and above the Cane Creek anticline on the Colorado River, the bench topography is not well developed, although the rims, where the rocks that make them are present and exposed, still form pronounced breaks in the steep canyon slopes.

The deepest and narrowest canyons are at the south, near the junction of the two rivers. About 19 miles above the junction the Green River goes into a box canyon (lower Stillwater Canyon) whose walls rise gradually southward, attaining a height of about 1,200 feet at the junction (pl. 6, *B*). At very few places in this stretch can the walls be scaled. The increase in the height of the canyon walls southward in Stillwater Canyon is effected not so much by an actual downcutting of the river in that direction relative to sea level as by the southward structural rise of the rocks.

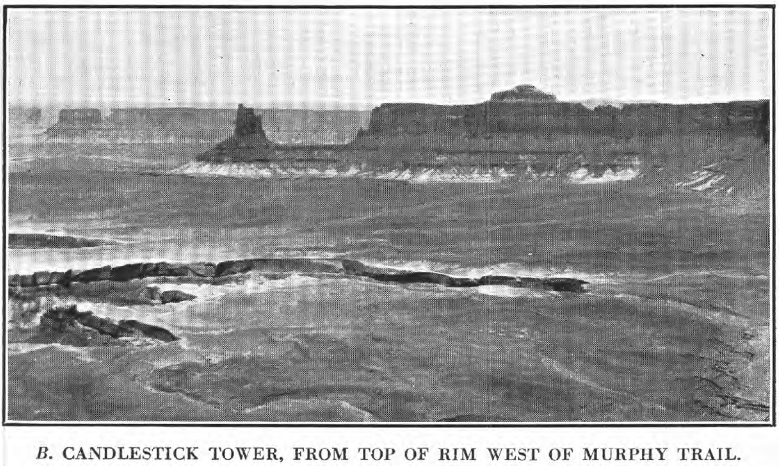
In general, the canyon walls along different sections of the Green River are formed by different rock units, and the tendency toward increase in height to the south by the rise of lower and older rocks into the lower canyon walls is offset by the swing away from the river of the higher and younger rocks in the upper canyon walls. In each section of the canyon that is rimmed by a cliff-making formation different from that of the adjoining section, the depth will be greatest at the downstream end, at that place where the resistant formation that forms the upper part of the canyon walls swings away from the river.

Such simple relations do not prevail throughout on the Colorado River side, owing to the more complicated structure characterized by numerous reversals in dip. Nevertheless, the increase in the depth of the canyon toward the junction is largely due to a structural rise in that direction from a point several miles above the junction.



A. CLIFF ON NORTHEAST FLANK OF CANE CREEK ANTICLINE, LOOKING EAST.

Cr, Rico formation; Cc, Cutler formation (limits indicated by line); Ꞧm, Moenkopi formation; Ꞧc, Chinle formation; Jw, Wingate sandstone.

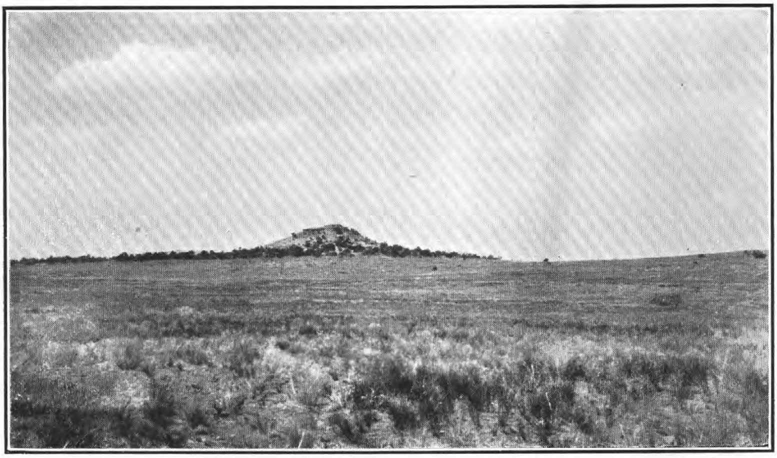


B. CANDLESTICK TOWER, FROM TOP OF RIM WEST OF MURPHY TRAIL.

Shows light phase of upper Moenkopi and threefold division of Chinle. Units pictured are Cutler formation (below White Rim at left), White Rim sandstone member, Moenkopi formation (with possibly some undifferentiated Cutler at base), Shinarump conglomerate (ledge capping the light-colored Moenkopi), Chinle formation, Wingate sandstone (massive vertical cliff), Kayenta formation, and Navajo sandstone (butte on skyline). Photograph by S. S. Nye.

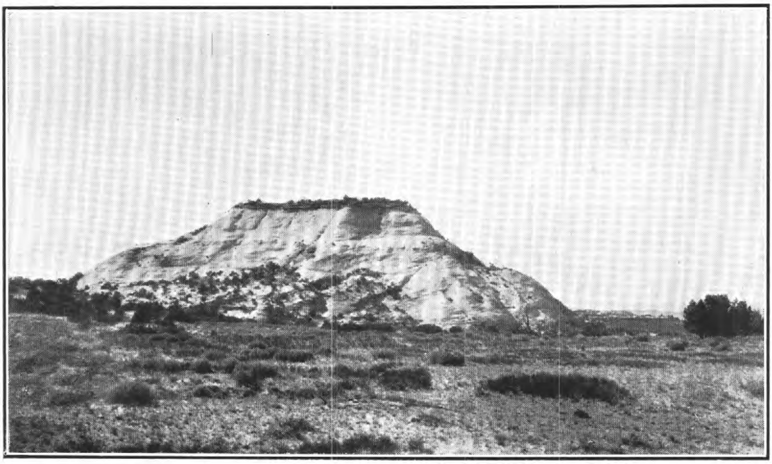
A. GREEN RIVER, LOOKING WEST FROM TOP OF RIM WEST OF MURPHY TRAIL.

Turks Head shows in loop of river at left of center, and White Rim forms the conspicuous bench in the topography, with Cutler formation exposed below it and undifferentiated uppermost Cutler and basal part of Moenkopi formation above it (in foreground). Photograph by S. S. Nye.



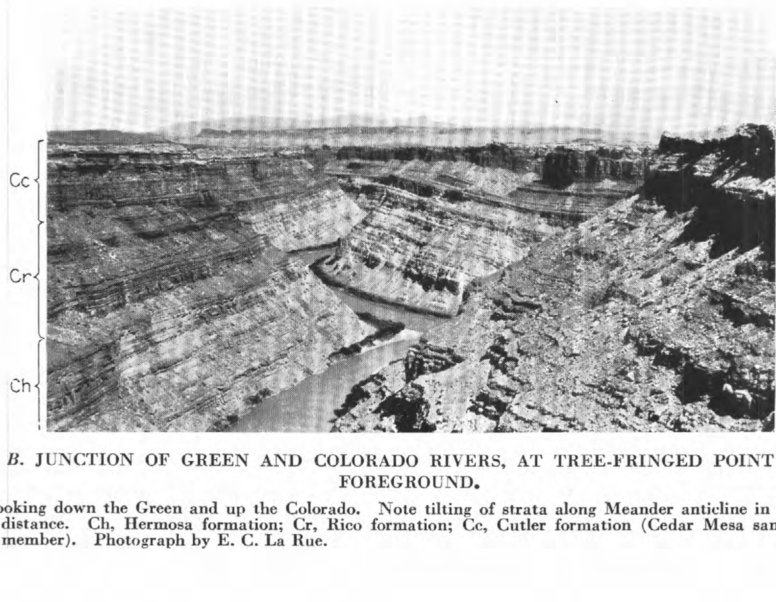
B. THE KNOLL, LOOKING NORTH.

Shows characteristic topography of the Big Flat in foreground. The Knoll is formed of Navajo sandstone, capped by one of the limestones in the Navajo.



A. AZTEC BUTTE, LOOKING NORTH.

Butte formed on Navajo sandstone, capped by a fresh-water limestone in the sandstone. Foreground shows characteristic topography on Grays Pasture.



B. JUNCTION OF GREEN AND COLORADO RIVERS, AT TREE-FRINGED POINT IN FOREGROUND.

Looking down the Green and up the Colorado. Note tilting of strata along Meander anticline in middle distance. Ch, Hermosa formation; Cr, Rico formation; Cc, Cutler formation (Cedar Mesa sandstone member). Photograph by E. C. La Rue.

MAIN PLATEAU SECTION

The main plateau section is not a very sharply defined physiographic unit. In its typical development it is represented by the high land above the Wingate Rim throughout the southern half of the area. The regions of lower altitude to the north and northeast contain indefinite zones transitional to each of the other two physiographic sections here recognized.

The surface of this upland section is in general rather rough and rocky. In the southern half numerous rounded sandstone buttes and ridges rise to heights of 100 to 200 feet above the general surface (pls. 5, *B*; 6, *A*; 11, *A*), and numerous shallow washes have been cut below it. Only on the Big Flat, Arts Pasture, and Grays Pasture are extensive flats developed, so that the section can be called a plateau only in the broadest sense, in comparison with the canyon section. That part of the plateau east of a conspicuous fault between Moab and Courthouse mail station is several hundred feet lower than the region west of the fault, and the two areas are separated by a prominent eastward-facing cliff that extends for several miles, capped by the Wingate Rim. West of the fault the Kings Bottom syncline, a broad, deep structural trough conspicuous in a region of prevailingly flat-lying beds, is strongly reflected in the topography. Erosion on the limbs of this trough has produced an extremely rugged district, which, indeed, may be considered as a transition to the canyon section. From Courthouse west and north the southernmost edges of several of the higher rock formations terminate along very irregular lines in the form of discontinuous southward-facing escarpments, one of which, developed on the Entrada sandstone, appears as vertical pink sandstone cliffs in the region between Courthouse and Tenmile Wash. Certain outliers of this cliff-producing sandstone form picturesque vertical-walled buttes (pl. 12). North and especially northwest of the cliff region sandstone-capped clay hills and cuestas form a transition to the Mancos shale flat.

The Big Flat, Arts Pasture, and Grays Pasture are unique in an otherwise rough country where rock outcrops are the rule in that they are broad flats with a considerable covering of sandy soil (pls. 5, *B*; 6, *A*). In contrast to the scattered growth of piñon and juniper, however sparse it may be, in other parts of the plateau section, the only vegetation that they support is a mantle of grass and low weeds. The general effect from a little distance is that of a pasture, as is recorded in two of the names. They are developed on porous but rather fine grained sandstone formations and apparently owe their development to rather feeble drainage, which has not been able to remove the rock debris as fast as the rocks disintegrate. Gullying has recently become noticeable on parts of the Big Flat; in many places deeply worn horse trails have been intersected by the heads of steep gullies, necessitating continual and ever-lengthening detours. Whether this erosion has been brought about by a climatic change, by overgrazing, or simply by the normal extension of the heads of drainage into the flat, it is impossible to say.

Grassy glades several acres in extent are developed at numerous other places on the plateau where the bedrock is sandstone, but they are much smaller than the three "pastures" above mentioned.

Certain narrow necks connecting adjacent parts of the plateau section in the southern part of the area are of special interest. The Neck is the most striking example, in view of the size of the territory to the south that is thus connected with the main plateau area. Taylor Canyon on the west and Shafer Canyon on the east have cut back into this neck, leaving a high rock bridge only 200 feet wide. South of this connecting bridge the plateau widens out again, including Grays Pasture and extending southward for about 11 miles. The neck connecting Bighorn Mesa with the region to the east is only about 15 feet wide and has vertical cliffs more than 300 feet high on both sides. Bighorn Mesa is bordered by inaccessible cliffs so far as the writer is aware, and when the neck is breached by erosion the mesa will be as isolated and inaccessible as Junction Butte, which is at the southern tip of the main plateau section.

MANCOS SHALE FLAT

The Mancos shale flat is a section of low relief and relatively low altitude lying at the north end of the area between the Book Cliffs on the north and the more rugged country on the south. The average altitude is between 4,500 and 5,000 feet. The underlying rock formation is a monotonous gray shale that weathers into broad clay flats and low clay hills. Concentric with the curving southern margin of the flat but some distance back from it, a thin platy sandstone in the shale forms a low cuesta ridge, which for miles is a conspicuous topographic feature. Remnants of gravel terraces at two or three levels extend down from the Book Cliffs at the north and form benches that are equally conspicuous.

The vegetation is scant and consists chiefly of greasewood along the drainage lines. Some of the region, especially some of the slopes on which the shale is exposed, is almost devoid of vegetation.

Because of its great extent and low relief, the shale belt has served as the main channel for east-west travel through this part of the State since the time of the early explorers.

DRAINAGE

General character.—In the area covered in this report only the two master streams, the Colorado and Green Rivers, which head in the mountains to the north and east beyond the limits of the Colorado Plateau province, are perennial, and even in these the variation in volume between flood and drought periods is great. The local tributary streams are intermittent, becoming raging torrents of water saturated with mud and sand during the thunderstorms that are so characteristic of the region in the summer and reverting within a few days to the dry sandy washes that more nearly represent their normal state.

Incised meanders of major streams.—As shown in plate 1, one of the most conspicuous features of both the Green River and the Colorado River, but especially of the Green, is the intricate meander pattern. From the mouth of the San Rafael River the boatman must wind through 95 miles of canyon before he reaches the Colorado, yet in a straight line the distance is only 40 miles. The upper half of this canyon stretch was named Labyrinth Canyon by Powell [18] because of its excessive winding.

The loop of Bowknot Bend is a striking example of an incised meander. It is almost 7 miles long, yet the two ends of the loop are only 1,200 feet apart (pl. 10, *A*). The depth of the canyon is about 800 feet on the east side of the loop and perhaps 100 feet less at the west side. That the river has maintained essentially its present course during the time required to cut to a depth of 800 feet is attested by the narrowness of the canyon. Because the stream has recently, in terms of geologic time, cut through the hard, resistant formations into weak, easily eroded shales at the neck of the loop, and because the full current of the heavily laden river is thrown directly into this neck, conditions have become ideal for lateral erosion at this point,[19] which in time will breach the neck, leaving the present loop as a canyoned ox bow.

The Loop, on the Colorado River between 5 and 11 miles above the junction, shows an even more striking meander pattern in that it presents a double bow with two necks. The northern neck is 1,600 feet wide and the southern one only 700 feet wide; the distances around the loops, 4 and 3 miles, respectively, are somewhat shorter than at the Bowknot.

Navigability of major streams.—In contrast to the turbulent water in other parts of the Green and Colorado Canyons, quiet water prevails throughout the greater part of this area. Only one riffle occurs in the Green River below the mouth of the San Rafael; this is at the point where the river crosses the White Rim, which separates the Labyrinth and Stillwater Canyons. In the 20-mile stretch between

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[18] Powell, J. W., Exploration of the Colorado River of the West and its tributaries, p. 54, Washington, 1875.

[19] Moore, R. C., Origin of enclosed meanders on streams of the Colorado Plateau: Jour. Geology, vol. 34, pp. 29–57, 1926.

the San Rafael River and the town of Green River numerous riffles make upstream navigation impossible but rowboats can be taken downstream safely with a little care. This stretch is above the canyon section. There are no troublesome riffles in the Colorado River between Moab and the junction, but above Moab swift water and boulders in several stretches make navigation impracticable. The chief obstacle to navigation in the smoother sections of the canyons has been the shallowness of the water and the shifting sand bars at low water.

Tributary drainage.—The dry canyons and washes tributary to the Green River are in general longer than those tributary to the Colorado; the drainage divide, therefore, is generally well to the east of the center line between the two rivers. In the southern half of the area the intermittent streams head back on the plateau section and after flowing in shallow valleys for a few miles plunge over the Wingate Rim, generally in a vertical fall 200 to 300 feet high, and enter canyons that extend to the rivers. The canyons tributary to the Green River between Tenmile Wash on the north and Upheaval Canyon on the south are especially well developed.

CLIMATE

In common with so much of the Southwest, the area treated in this report has an arid climate. The annual rainfall fluctuates from year to year but averages between 6 and 9 inches. Much of it comes in the form of local thunderstorms, especially during the summer. The summers are hot and the winters mild; the highest temperatures are found in the canyons. The whole area lies within the Upper Sonoran faunal zone, with characteristic piñon and juniper on the sandstone uplands, cottonwood along the watered streams, and greasewood, sagebrush, and rabbitbrush on the shaly flats and in the dry canyons.

WATER RESOURCES AND UTILIZATION

Aside from the small amount of manganese mining during the World War in the Little Grand district [20] and the insignificant amount of farming at Valley City and in the bottom land of the Green River opposite the mouth of the San Rafael, the only use made of the area covered in this report has been for grazing. Both plateau and canyon sections constitute cattle and horse range. The scarcity of water in areas away from the rivers, however, is a serious obstacle to full utilization. Areas such as Grays Pasture and the Big Flat, which are otherwise capable of supporting a considerable herd, are completely dry at certain seasons, necessitating the removal of all cattle during such periods.

[20] Pardee, J. T., Deposits of manganese ore in Montana, Utah, Oregon, and Washington: U. S. Geol. Survey Bull. 725–C, pp. 179–206, 1921.

Away from the rivers three types of water holes are found in the area—artificial reservoirs, "tanks" in solid rock, and springs.

ARTIFICIAL RESERVOIRS

Earth dams constructed in a few places near the head of drainage on the flats of the plateau section have impounded water in small reservoirs for short periods after heavy rains. On the whole, however, artificial impounding has not proved practicable in the area covered by this report, although it has been used successfully near Valley City, immediately northeast of this area.

TANKS

The tanks are accumulations of rain water in depressions in sandstone, generally in a series of potholes and rock basins carved in the bottoms of washes but also in rock basins leached in the sandstone of rock benches. Owing to their small volume and general inaccessibility, the tanks are of little importance as a supply of water for stock, but they are of great importance as a source of drinking water for human beings. A single geologic stratum, the lower Kayenta, which caps extensive areas in the southern half of the plateau section, is especially favorable as a tank producer. Some of the deeper tanks in gulches cut in this sandstone contain water throughout the year. Generally such water is chemically rather pure, but it ordinarily teems with organic life, especially in late summer.

SPRINGS

Springs, which commonly occur in groups, are the most constant source of water in areas away from the rivers. Most of the springs are shown on plate 1, and only a few need special mention. An important group is situated along the fault zone between Courthouse Spring and Brink Spring, the two principal springs of the group. Most of these springs appear in the washes just below or north of the points where the washes cross the fault line, but Brink Spring is an exception in that it is right on the fault line on the east bank of a rather small wash. It is believed that the water in this series of springs comes to the surface along the fault zone from an artesian circulation at the horizon of the uppermost Kayenta, which is an important spring horizon elsewhere in the region. The Kayenta crops out at a higher altitude several miles to the south, indicating conditions favorable for the production of considerable hydrostatic head.

Another group of springs is present in Tenmile Wash, about 3 miles north of Tenmile Butte, and also in some of the shallow tributary washes cut in the Navajo sandstone immediately to the south of Tenmile Wash. Tenmile Wash is a flowing stream for about 3 miles through this region. The conditions that account for this group of springs are not obvious.

A third important group of springs is present at the head of Taylor Canyon, southwest of The Neck. The springs of this group are at the horizon of the uppermost Kayenta, at the heads of the several headwater tributaries. The formation crops out at a slightly higher altitude from 1 to 3 miles to the south, but the outcrop appears to be too narrow and too steep to furnish an adequate intake area. It seems probable that the greater part of the water escaping at these springs has seeped through the overlying Navajo sandstone, which caps the upland. The water from these springs is used by a herd of cattle that ranges on Grays Pasture.

A fourth important group comprises perennial springs that issue from the upper part of the Kayenta formation around the Upheaval dome, wherever erosion reentrants from the surrounding canyons cut back to the axis of the syncline surrounding the dome. The intake area of the water-bearing stratum is a comparatively wide belt of the Kayenta cropping out on the flanks of the dome, and the water drains with the dip of the porous rock down the flanks of the dome to the points of escape at the axis of the syncline. Some of these springs are comparatively inaccessible to cattle and are consequently little used.

All the springs that have been mentioned, with the exception of the flowing part of Tenmile Wash, produce excellent drinking water. None of the springs are very large, and many are little more than seeps. Whether improvements would materially increase the total flow of the springs is doubtful, though probably local improvements would tend to conserve and utilize more fully the water available.

STRATIGRAPHY

GENERAL FEATURES

The rocks that crop out or that have been encountered in wells drilled in the area covered by this report range in age from Pennsylvanian to Upper Cretaceous. Mesozoic strata are especially well represented. Including the rocks that have been cut by drilling, the stratigraphic section has a maximum thickness of about 2 miles. Within this section, at the base of the Lower Triassic and at the base of the Upper Triassic, are two unconformities that locally and regionally truncate considerable thicknesses of the underlying beds. Of the three or four other known unconformities, not all observers are agreed as to their relative significance; none of them truncate the underlying strata to any great extent within the area studied. A diagrammatic representation of the stratigraphic section is given in plate 7. As many of the formations grade from one to another in lithology, their exact boundaries as mapped are commonly arbitrary; gross lithologic units, however, are distinct.

Because most of the formations that crop out in the area are of nonmarine origin, the problems of regional correlation are much more difficult than in sedimentary terranes where marine fossils are present to aid the stratigrapher. In the absence of such horizon markers, reliance must be placed on physical tracing of the stratigraphic units in the field, coupled with judicious comparison of stratigraphic sections in adjacent areas.

The application of this method in southeastern Utah is beset with difficulties in spite of the excellence of rock exposures. Many of the formations tend to change laterally, and a lithologic change from one type to another may take place within a relatively small area. Certain formations closely resemble other formations, either in the same area or in adjacent areas. Further complication is produced by unconformities and overlaps. Hence, unless certain critical areas are known, stratigraphic correlations in this region are liable to error. In the past different interpretations and different sets of stratigraphic names have been applied to the stratigraphic section of southeastern Utah by different observers. As the continuity of formations between different areas became known, and as the relative significance of the different stratigraphic breaks became appreciated, stratigraphic names have been dropped or restricted in their application, and new names have been introduced. The stratigraphic nomenclature of the present report is founded on a series of areal and structural geologic studies by different workers in contiguous or closely adjacent areas, supplemented by a study of the literature and by regional correlations based on reconnaissance over much of southern Utah, southwestern Colorado, northwestern New Mexico, and northern Arizona. Because questions of correlation and synonymy have been fully treated in several recent papers by various members of the Geological Survey,[21] especially in certain correlation papers,[22] no attempt will be made in the present report to discuss these matters except so far as they may bear on some special point under discussion.

CARBONIFEROUS SYSTEM

PENNSYLVANIAN SERIES

PARADOX FORMATION

The Paradox formation does not crop out within the area covered by this report, but as it is exposed in closely adjacent areas[23] and is

[21] See list of references, footnote 16, p. 7.

[22] 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. 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, 1936.

[23] Baker, A. A., Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, pp. 13–18, 1933. Dane, C. H., Geology of the Salt Valley anticline and adjacent areas, Grand County, Utah: U. S. Geol. Survey Bull. 863, pp. 25–33, 1936. Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., Paradox formation of eastern Utah and western Colorado: Am. Assoc. Petroleum Geologists Bull., vol. 17, pp. 963–980, 1933.

known to underlie this area, a brief summary of certain features of its geology will be given. The formation has been penetrated in deep wells drilled in a search for oil along the Colorado River Canyon just within this area, also in wells drilled in neighboring areas on the northeast, southeast, and southwest. All that is known of its occurrence in the wells along the Colorado has already been presented and discussed by Baker.[24]

NAME, GENERAL CHARACTER, AND THICKNESS

The Paradox formation was named by Baker [25] from exposures in Paradox Valley in western Colorado. The outstanding characteristic of the formation is the large content of salt, gypsum, and anhydrite, but it also contains much shale and limestone and some sandstone that in the aggregate may locally exceed the chemical sediments in thickness. Owing to the plastic behavior of the chemical sediments under any form of earth stress, the formation is an especially incompetent structural unit. The only known exposures are on the crests of anticlinal uplifts or in strongly faulted zones, and they uniformly show the effects of strong deformation. At the time the anticlines and faults were formed the shales, limestones, and sandstones were greatly folded, faulted, and brecciated, and, contemporaneously, the gypsum, anhydrite, and salt were strongly squeezed and mixed in with the brecciated material and even intruded into overlying formations.[26] Removal of the salt by solution and conversion of the anhydrite to gypsum on the outcrop have still further complicated the structural conditions. As a consequence very little can be learned of the lithologic sequence and nothing of the thickness of the formation from a study of surface exposures. Baker, Dane, and Reeside believe that the thicknesses penetrated in the wells that were drilled along the Colorado River have been greatly augmented by flowage of the plastic material into the crests of the anticlines and domes on which the wells are located, but that probably the original thickness of the formation in this area was in excess of 2,000 feet.

CHARACTER IN WELLS ALONG COLORADO RIVER

Within the area covered by the present report four wells have been drilled into or through the Paradox formation. Drillers' logs of these wells are given on pages 137–142. The Embar-Big Six Oil Co.'s well in sec. 34, T. 25 S., R. 21 E., on the right bank of the Colorado River opposite Moab (see pl. 1), first encountered 3 feet of "salt" at a depth of 408 feet, but as no more salt or gypsum was encountered until a depth of 1,513 feet was reached, and as fossils are reported in the limestones

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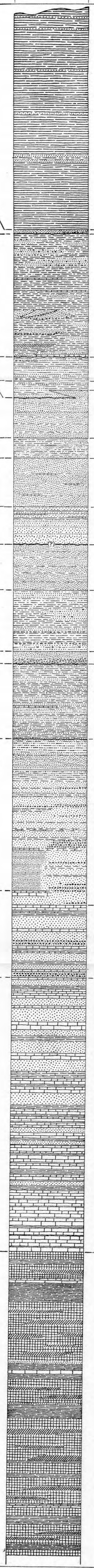
[24] Baker, A. A., op. cit. (Bull. 841), pp. 13–18, 74–76, 80–92, 1933.
[25] Idem, p. 13.
[26] Dane, C. H., op. cit. (Bull. 863), p. 29.



System	Series	Formation and group	Section	Thickness (feet)	Character of rocks
Cretaceous.	Upper.	Mancos shale. (Ferron sandstone member.)		1,400+	Slate-gray marine shale, containing a brown to gray thin-bedded sandy zone (Ferron sandstone member) 440–500 feet above base.
Cretaceous.	Upper.	Dakota(?) sandstone.		0–60	Greenish-gray and yellowish to buff quartzitic sandstone and conglomerate, commonly weathering dark brown or black; locally contains carbonized plant remains.
		— Unconformity —			
Jurassic.	Upper.	Morrison formation. (Salt Wash sandstone member.)		850±	Variegated mudstone containing local thin beds of fresh-water limestone and thicker beds of lenticular cross-bedded channel sandstone; much white to yellow conglomeratic lenticular sandstone in lower 300 feet (Salt Wash member) and much white to gray (weathering dark gray) quartzitic sandstone and conglomerate toward top; near Green River basal part contains some gray limestone and much thick-bedded gypsum.
		— Unconformity —			
Jurassic.	Upper.	San Rafael group. Summerville formation.		77–180	Chocolate-colored shale and mudstone, chocolate-colored to red sandy mudstone and muddy sandstone, and thin ledges of white, greenish-gray and reddish-brown sandstone; local segregations of gray to red chert have apparently replaced impure gray to pale lavender limestone; near Green River considerable thin interbedded gypsum.
Jurassic.	Upper.	San Rafael group. Curtis formation. — UNCONFORMITY —/(Moab tongue)		130	Greenish-gray sandstone, shaly sandstone and sandy shale, with minor shale; grades eastward into Summerville.
Jurassic.	Upper.	San Rafael group. Entrada sandstone.		325±	Massive cross-bedded pinkish- and grayish-white sandstone, cropping out in steep bare slopes and cliffs; near Green River upper part is brownish-red muddy sandstone; Moab sandstone tongue, 0–115 feet thick, lying at top is more massive and whiter and intertongues with overlying Summerville formation to west.
Jurassic.	Upper.	San Rafael group. Carmel formation.		125–150	Pink, red, and reddish-brown muddy sandstone interbedded with reddish sandy mudstone and with thin partings of chocolate-colored to maroon shale; a little white sandstone; bedding irregular, contorted, and shows local unconformities; near Green River upper part of formation is largely gray sandy mudstone.
Jurassic?		Glen Canyon group. Navajo sandstone.		160–330	Pale-buff highly cross-bedded sandstone containing a little reddish sandstone and thin beds of gray to purple cherty fresh-water limestone.
Jurassic?		Glen Canyon group. Kayenta formation.		160–250	Irregularly bedded white, light-gray, buff, pink, red-brown, and lavender sandstone, containing, toward the top, minor lavender to chocolate-colored shale and thin beds of gray fresh-water limestone; contains fresh-water mollusks in limy sandstone beds toward the top.
		— Unconformity? —	(?)		
Jurassic?		Glen Canyon group. Wingate sandstone.		210–340	Massive buff cross-bedded sandstone, cropping out as a vertical brownish-red cliff.
Triassic.	Upper.	Chinle formation.		212–420	Variegated mudstone and sandstone with some conglomerate, all poorly assorted; conglomerate unique in having high percentage of lime pellets in limy mudstone matrix and in containing reptilian bones and teeth.
Triassic.	?	Shinarump conglomerate.		0–50	White to gray cross-bedded conglomeratic sandstone, a varying percentage of the conglomerate pebbles being siliceous (chert and quartzite).
		— Unconformity —			
Triassic.	Lower.	Moenkopi formation.		0–525	Chocolate-brown to red-brown sandy mudstone, muddy sandstone, and shale, with interbedded thin whitish sandstone ledges, the sandier sediments strongly ripple marked; along much of Green River color of upper part changes to greenish gray and at one locality a 1-foot fossiliferous limestone occurs 220 feet above base.
		— Unconformity —			
Carboniferous.	Permian.	(White Rim sandstone member.) Cutler formation.		0–1,000±	Brown to red sandstone and red to purplish arkose, with subordinate red to chocolate-colored shale and local thin beds of cherty unfossiliferous limestone; in southern part of area, white cross-bedded sandstone, 8–135 feet thick (White Rim sandstone member), in upper part of formation; near junction of Green and Colorado Rivers lower 275 feet contains much cross-bedded white to tan sandstone, gradational to Cedar Mesa sandstone member to south.
Carboniferous.	Permian.	Rico formation.		0–585	A redbed formation containing several thin beds of fossiliferous limestone; redbeds include brown to red and purple sandstone, red and purple coarse arkose, and gray, brown, red, and purple shale; limestone where pure is gray, blue-gray, or greenish gray. Upper contact defined as top of highest fossiliferous limestone and is not everywhere at same horizon.
Carboniferous.	Pennsylvanian.	Hermosa formation.		1,800±	Blue, greenish, and gray fossiliferous limestone interbedded with white, gray, and greenish sandstone and gray to green shale; lower half known only from well logs, which indicate a larger amount of limestone than in upper half.
Carboniferous.	Pennsylvanian.	Paradox formation.		2,000±	Salt, anhydrite, and some gypsum, with interbedded gray, black, and brown shale, minor limestone, and a little sandstone; does not crop out but has been penetrated in deep wells.

GENERALIZED SECTION OF ROCKS EXPOSED IN AREA BETWEEN GREEN AND COLORADO RIVERS.

to a depth of 1,010 feet, it is probable that this first seam was a local vein of some material deposited along or near the fault that is known to be concealed in the alluvium somewhere near the well, and that the true sediments of the Paradox formation were not encountered until the greater depth was attained. Below 1,513 feet salt and gypsum are reported in the driller's log at irregular intervals to a depth of 3,985 feet. Because of concealed faults that are known to be present near the well, little stratigraphic significance can be attached to the log.

The other three wells are along the right bank of the Colorado River several miles below Moab, two of them on the Cane Creek anticline and the third on the crest of the Shafer dome (pl. 1). The deeper well (Frank Shafer No. 1, sec. 31, T. 26 S., R. 21 E.) on the Cane Creek anticline is a few feet above river level on the axis of the fold. It first encountered the gypsum of the Paradox formation at a depth of 1,475 feet [27] and penetrated 3,500 feet farther into sedimentary beds referable to this formation, without passing through them. The well on the Shafer dome reached salt at a depth of 1,610 feet, passed through about 3,960 feet of the salt- and gypsum-bearing beds, and cut 300 feet into underlying strata described as limestone, gray sandy shale, and variegated shale containing fresh water. The limestone and gray sandy shale, comprising 120 feet of strata, are classed as basal Paradox, underlying the saliferous part of this formation.

According to the drillers' logs, salt is dominant in the lithology of the Paradox formation in the vicinity of the Cane Creek anticline and Shafer dome. The greatest solid thickness of salt that is recorded amounts to 476 feet, but there are many intervals that exceed 100 feet in thickness. The partings are chiefly gray, black, and brown shale, with minor amounts of limestone and gypsum and still smaller amounts of sandstone. The thickest single parting is shale with a little limestone and amounts to 143 feet, but the average thickness of parting is much less than this. There is no way of telling from the well logs whether these partings in the salt are true bedded deposits such as would be laid down in a sedimentary series, or whether they represent broken blocks or lenses carried in by lateral or vertical movement of the plastic material from an adjacent source, as suggested by Baker,[28] Prommel and Crum,[29] and Harrison.[30] The beds cannot be correlated

[27] The top of the formation is probably at least 50 feet higher than this; see p. 139 (log). The log given by Prommel and Crum (Salt domes of Permian and Pennsylvanian age in southeastern Utah and their influence on oil accumulation: Am. Assoc. Petroleum Geologists Bull., vol. 11, pp. 391–393, 1927) is somewhat different from that given by Baker and records the first bed of gypsum at a depth of 1,380 feet, with showings of gypsum and salt at two higher levels in the well.

[28] Baker, A. A., op. cit. (Bull. 841), pp. 14–15.

[29] Prommel, H. W. C., and Crum, H. E., Salt domes of Permian and Pennsylvanian age in southeastern Utah and their influence on oil accumulation: Am. Assoc. Petroleum Geologists Bull., vol. 11, p. 384, figs. 10, 11, p. 385, 1927.

[30] Harrison, T. S., Colorado-Utah salt domes: Am. Assoc. Petroleum Geologists Bull., vol. 11, pp. 114, 117, 120, 131, fig. 6 p. 118, fig. 11 p. 125, 1927.

across from one well to the other, but as the same holds true for the lower part of the overlying Hermosa formation this fact has no special significance in interpreting the structure. The log of the Embar-Big Six well, on the west bank of the Colorado River opposite Moab, shows a much higher proportion of shale relative to salt than logs of the wells farther down the river, but owing to structural complications already mentioned this log may not even approximate a true picture of the Paradox lithology.

Apparently very little chemical investigation has been made of the material listed in the drillers' logs as "salt." However, potassium is reported in the salt penetrated between depths of 2,412 and 2,508 feet in the Frank Shafer No. 1 well, on the Cane Creek anticline.[31] For adjacent areas some additional information is available on the constitution of this Paradox salt. Prommel[32] states that a qualitative analysis of the "salt" between depths of 1,534 and 2,450 feet in the Western Allies-Big Six well at Moab showed it to be mainly magnesium sulphate, with some calcium sulphate, a small amount of sodium chloride, and a little iron. Mixed chlorides of potassium, magnesium, and calcium were found in the Paradox formation in the Crescent-Eagle well near Thompsons, Utah.[33] Sodium and potassium, undifferentiated, with presumably the sodium largely predominating, are the chief positive radicles in the chloride brine (containing some sulphate) from Stinking Springs, near Richardson, Utah.[34] Some calcium and a little magnesium are also present in the Stinking Springs brine, but their proportion relative to the sodium is distinctly the reverse of that in the sample cited by Prommel. A diamond-drill core of part of the Paradox formation, taken from a test well for potash drilled by the Government in Salt Valley, shows the salt to be chiefly halite, interbedded with a little gypsum and anhydrite, but certain bands of the halite contain blebs of polyhalite ($2CaSO_4.MgSO_4.K_2SO_4.2H_2O$). Selected cores from the King No. 1 well, less than half a mile away, have potash contents as high as 13 percent.[35] It seems probable that the great mass of the material recorded as "rock salt" from the deep wells along the Colorado River is actually sodium chloride.

FOSSILS, AGE, AND STRATIGRAPHIC RELATIONS

A collection of conodonts taken from shale cuttings at depths of 3,250 to 3,340 feet in the Frank Shafer No. 1 well, on the Cane Creek

[31] Baker, A. A., op. cit. (Bull. 841), p. 85, 1933.

[32] Prommel, H. W. C., Geology and structure of portions of Grand and San Juan Counties, Utah: Am. Assoc. Petroleum Geologists Bull., vol. 7, p. 398, 1923.

[33] Lang, W. B., Potash investigations in 1924: U. S. Geol. Survey Bull. 785, pp. 38–39, 1926.

[34] Dane, C. H., Geology of the Salt Valley anticline and adjacent areas, Grand County, Utah: U. S. Geol. Survey Bull. 863, p. 32, 1936.

[35] Idem, p. 175.

anticline, are, according to Roundy,[36] probably of lower Pennsylvanian age, although they could also be upper Pennsylvanian. Poorly preserved plants and marine invertebrates collected by C. H. Dane, H. D. Miser, and J. B. Reeside, Jr., from outcrops in Sinbad Valley, in western Colorado, tend to confirm the lower Pennsylvanian assignment,[37] although further and better-preserved collections may somewhat modify this assignment. Baker, Dane, and Reeside [38] believe that the Paradox formation underlies the Hermosa formation conformably, with probably a transition zone, and in the vicinity of Salt Valley overlies a conglomerate that is equivalent to the Molas formation of the San Juan Mountains.

HERMOSA FORMATION

NAME, DISTRIBUTION, AND THICKNESS

The Hermosa formation, which comprises interbedded sandstone, limestone, and shale, was named by Cross and Spencer [39] from exposures on Hermosa Creek, in La Plata County, southwestern Colorado. It is the lowest stratigraphic unit that crops out in the area covered by this report. The greatest depth to which erosion has cut into it is about 950 feet at the junction of the Green and Colorado Rivers (pl. 6, *B*). Owing to the general northerly dip of the strata, the formation dips below the Green River about 9 miles above its mouth and dips below the Colorado River about 13 miles above its junction with the Green. At only three other places in the area studied does it again come to the surface, roughly 150 feet being exposed where the Colorado River crosses the Shafer dome, 300 feet where it crosses the Cane Creek anticline, and about 300 feet in the upthrown block of the Moab fault on the northwest side of the river at Moab. As the Moab fault crosses the river roughly at right angles to its general course, this last-mentioned exposure is not in the river canyon, like the others, but is at the foot of the cliff on the southwest side of the fault.

The logs of the wells drilled on the Cane Creek anticline and Shafer dome show in depth an alternation of limestones, shales, and sandstones that forms a continuation of the exposed Hermosa sequence and indicates that the complete thickness of the formation is about 1,800 feet, the lower boundary being arbitrarily drawn at or near the top of the uppermost salt bed.

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[36] Roundy, P. V., quoted in Baker, A. A., Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, p. 18, 1933.

[37] Dane, C. H., op. cit. (Bull. 863), pp. 27–29. Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., Paradox formation of eastern Utah and western Colorado: Am. Assoc. Petroleum Geologists Bull., vol. 17, p. 972, 1933.

[38] Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., op. cit., pp. 970–971, 1933.

[39] Cross, Whitman, and Spencer, A. C., Geology of the Rico Mountains, Colorado: U. S. Geol. Survey 21st Ann. Rept., pt. 2, p. 27, 1900.

CHARACTER

The part of the Hermosa formation that crops out is composed of blue, greenish, and gray limestone, sometimes with black, brown or red chert concretions; gray to green and, subordinately, red or purplish shale, commonly calcareous or sandy; white to gray to greenish and sometimes red or purplish sandstone, commonly calcareous or argillaceous; and a minor amount of purplish red arkose. These different types of rock alternate in more or less distinct beds throughout the exposed thickness of the formation, the limestone occurring in beds as much as 40 feet thick, the shale in beds as thick as 20 feet, and the sandstone in beds as thick as 75 feet. At The Slide, near the junction of the Colorado and Green Rivers, limestone makes up 31 percent of the outcrop, shale 20 percent, and sandstone and arkose 49 percent. The limestones may be either thin-bedded or massive, and the sandstones either massive or cross-bedded. The general color tone of the formation considered as a whole is a light to medium gray, in contrast to the prevailing red of the overlying Rico (pl. 6, *B*).

The following section of the upper part of the Hermosa, exposed at The Slide, on the Colorado River about 1½ miles above its junction with the Green, was measured by J. B. Reeside, Jr.:

Section of the Hermosa formation at The Slide

	Feet
Rico formation.	
Hermosa formation:	
1. Shale, calcareous, gray	20
2. Limestone, fine-grained and dense, massive, dove-gray and blue-gray, cliff-forming; contains echinoid spines and crinoid stems	18
3. Mudstone, gray, calcareous	4
4. Limestone, in 2-inch beds separated by streaks of sand, dove-gray, dense	10
5. Limestone, dense, massive, cliff-forming, dove-gray to blue-gray	10
6. Sandstone, massive, calcareous, gray-white when fresh but weathering brown	10
7. Shale, blue-gray	3
8. Limestone, dense, massive, dark gray	5
9. Sandstone, massive, cross-bedded, greenish gray to gray-white on a fresh surface but weathers buff	75
10. Shale, greenish gray, calcareous, interbedded with layers of gray sandy limestone and limestone conglomerate in beds up to 6 feet thick	75
11. Sandstone, massive, calcareous, fine-grained, cliff-forming; contains abundant silicified fossils	10
12. Limestone, dark gray, coarsely crystalline, crinoidal; abundant fossils	5
13. Sandstone, like No. 9	30
14. Limestone, fine-grained, massive, dove-gray, weathering brown; contains scattered fossils and a few masses of brown chert 18 inches long	40

Section of the Hermosa formation at The Slide—Continued

	Feet
Hermosa formation—Continued.	
15. Sandstone, like No. 9	30
16. Limestone, fine-grained, platy, sandy, dark gray	5
17. Sandstone, like No. 9	35
18. Limestone, like No. 16	10
19. Shale, greenish gray, calcareous; scattered fossils	20
20. Limestone, dense in some layers, soft and shaly in others, massive, dark gray; dense layers contain nodules of black chert up to 12 inches long	15
21. Sandstone, like No. 9	15
22. Limestone, like No. 20	25
23. Shale, greenish gray, calcareous, fossiliferous	10
24. Limestone, massive, gray, hard; weathers brown and hackly; contains a few chert nodules	4
25. Sandstone, like No. 9	70
26. Shale, purplish, sandy	7
27. Sandstone, greenish gray, coarse-grained	2
28. Limestone, like No. 24	12
29. Sandstone, gray streaked with red, cross-bedded	25
30. Shale, dark red, sandy	8
31. Sandstone, thin-bedded, calcareous, fine-grained, gray and purple	5
32. Limestone, thin-bedded, gray, interbedded with shale, red chert common	10
33. Limestone, massive, gray, hard; weathers brown and hackly; contains few fossils	18
34. Shale, green	8
35. Limestone, massive, gray, hard	2
36. Sandstone, massive, cross-bedded, medium-grained, greenish gray to light gray, weathering buff	40
37. Limestone, massive, dark gray, much crystalline calcite	2
38. Sandstone, like No. 36	30
39. Shale, light gray, sandy	15
40. Limestone, massive, dark gray, weathering brown	10
41. Shale, like No. 39	15
42. Limestone, fine-grained, light gray, sandy; shale in minor amount, fossils on surface of beds	40
43. Shale, like No. 39	10
44. Sandstone, like No. 36	50
45. Limestone, fine-grained, light gray, sandy, weathers platy	40
46. Sandstone, like No. 36	10
Alluvium to river level, about 20 feet.	
	913

OUTCROP

The Hermosa formation where it is exposed in the canyons of the Colorado and Green Rivers forms narrow, steep-walled canyons. At the Shafer dome and near the junction of the rivers it makes up only the lower part of the canyon walls.

FOSSILS AND AGE

The Hermosa formation is fossiliferous throughout, though the limestones, as might be expected, show by far the greatest abundance and diversity of forms. The fauna is marked by the dominance of brachiopods, but bryozoans, corals, and crinoids form a prominent element. The gastropods and pelecypods are distinctly subordinate. Trilobites are rare, being represented in the collections only by the imperfect remains of a single genus (*Griffithides*). According to G. H. Girty, who has studied and reported upon the fossil collections, the age of the Hermosa is definitely Pennsylvanian. The following table gives his list of species:

Fossils of the Hermosa formation

	5947g	5947f	5947e	5947d	5949	5883	5883a	5883b	5883c	5883d
Foraminifera:										
Fusulina secalica					×					
Porifera:										
Sponges, several		×					×		×	
Tetracoralla:										
Campophyllum torquium						×		×	×	×
Campophyllum kansasense					?			×		×
Campophyllum sp				×				?		
Triplophyllum sp								×		×
Axophyllum rude										?
Clisiophyllum? sp					×					
Lophophyllum profundum	?	?			×				×	
Lithostrotion? sp						×				
Octocoralla:										
Syringopora multattenuata						×				
Crinoidea:										
Echinocrinus coloradoensis						?		×		
Echinocrinus sp					×		×			
Delocrinus aff. D. texanus								×		
Erisocrinus propinquus?		?								
Eupachycrinus? sp		×								
Bryozoa:										
Fistulipora sp					×			×		
Stenopora carbonaria					?			×	×	
Stenopora sp	×	×			×					
Cyclotrypa barberi					×			?	×	
Fenestella sp	×	×	×		×			×	×	
Polypora sp	×	×	×		×	×		×	×	
Pinnatopora sp	×							×		
Thamniscus aff. T. guadalupensis		×								
Chainodictyon sp	×	×								
Rhombopora lepidodendroides					×	×		×	×	
Rhombopora sp	×	×								
Cystodictya sp		×								
Brachiopoda:										
Orbiculoidea sp		×								
Rhipidomella carbonaria	×									
Derbya crassa					×					
Derbya bennetti					×					
Derbya sp	×							?		
Chonetes granulifer					×			×	×	
Chonetes geinitzianus		×								
Productus semireticulatus	×	×			×				×	×
Productus cora		×			×	×	×	×		
Productus pertenuis					×			×		
Productus aff. P. guadalupensis	×	×								

5947g. The Slide, on the west side of the Colorado River about 1½ miles above the mouth of the Green River; 790 feet below top.
5947f. Same as 5947g; 475 feet below top.
5947e. Same as 5947g; 400 feet below top.
5947d. Same as 5947g; 220 feet below top.
5949. West side of the Colorado River at the southwest corner of T. 26 S., R. 21 E., from bed of massive limestone just below thin series of transition beds at top of Hermosa formation.
5883. Near road from Moab to Thompsons, about 5 miles northwest of Moab; 180 feet below top.
5883a. Same as 5883; 120 feet below top.
5883b. Same as 5883; 18 feet below top.
5883c. Same as 5883; 10 feet below top.
5883d. Same as 5883; upper 5 feet.

Fossils of the Hermosa formation—Continued

	5947g	5947f	5947e	5947d	5949	5883	5883a	5883b	5883c	5883d
Brachiopoda—Continued.										
Pustula nebraskensis	×				×			×		
Pustula symmetrica					×			×		
Pustula semipunctata	×				×			×	×	
Pustula aff. P. porrecta	×	×								
Pustula n. sp					×			×		
Marginifera splendens	×	?						×	×	
Marginifera wabashensis					?			×		
Marginifera lasallensis					?			?		
Rhynchopora aff. R. taylori		×								
Rhynchopora illinoisensis					×			×		
Pugnoides osagensis					×			×		
Pugnoides sp							?			
Dielasma sp					×					
Spirifer triplicatus	×	×		×	×			×	×	
Spiriferina kentuckyensis	×	×			×			×		
Spiriferina gonionotus?	?	?								
Squamularia perplexa					×			×		
Squamularia aff. S. guadalupensis		×								
Brachythyris n. sp		×								
Composita subtilita	×	×	×			×		×		×
Hustedia mormoni	×	×	×							
Pelecypoda:										
Edmondia gibbosa								?		
Allerisma terminale?					×					
Pinna peracuta								×		
Acanthopecten carboniferus	?	?	?							
Myalina sp			×							
Gastropoda:										
Schizostoma catilloides					×					
Naticopsis? sp							×			
Euomphalus? sp							×			
Platyceras occidentale	×									
Trilobita:										
Griffithides sp		×								

STRATIGRAPHIC RELATIONS

The Hermosa formation is believed to overlie the Paradox formation conformably, with probably a transition zone.[40] It is conformably overlain by the Rico formation, with lithologic transition from the prevailing gray and greenish beds below to the red beds above; the faunal break between the two formations, however, is sharp, according to Girty.

PERMIAN SERIES

RICO FORMATION

NAME AND DEFINITION

The Rico formation was named by Cross and Spencer[41] from exposures near the town of Rico, in southwestern Colorado. It is defined lithologically as a red-bed formation containing thin beds of fossiliferous limestone, but it is not sharply separable, on the basis of lithology, from either the underlying Hermosa or the overlying Cutler. At the boundary with the Hermosa the red beds are more or less interbedded with gray beds. From the overlying red beds of

[40] Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., Paradox formation of eastern Utah and western Colorado: Am. Assoc. Petroleum Geologists Bull., vol. 17, p. 971, 1933.
[41] Cross, Whitman, and Spencer, A. C., op. cit. (21st Ann. Rept., pt. 2), p. 59.

the Cutler the Rico is differentiated solely by the presence of fossiliferous limestones.

DISTRIBUTION AND THICKNESS

The Rico formation is exposed in the upthrown block of the Moab fault on the northwest side of the Colorado River at Moab; in the canyon of the Colorado River from the Cane Creek anticline to the junction with the Green except for a stretch about 2 miles long below Lockhart Canyon, where the top of the formation dips below the level of the river; and in the lower canyon of the Green for a distance of about 16 miles above the junction. Only the upper beds are exposed over much of the extent along the rivers. The measured thickness at the Cane Creek anticline is 585 feet, according to Prommel and Crum,[42] and at the junction of the rivers 575 feet, according to Reeside (p. 28). Northwest of Moab the Rico was not differentiated from the Cutler during the mapping, but the highest fossiliferous limestone, at which the boundary should be placed according to the original definition of the Rico, lies only 350 feet above the top of the Hermosa. It seems unquestionable, however, that overlying beds are the stratigraphic equivalent of the upper Rico on the Cane Creek anticline.

CHARACTER

The Rico formation is composed of alternating beds of sandstone and arkose, with subordinate limestone and shale. The color of the sandstones ranges from gray (in the zone transitional to the Hermosa) through brown, brownish red, and salmon to red, purple, and maroon; red is the most common color. Some of the red sandstones show streaks of white or greenish gray. The arkoses show a narrower range of color, being commonly either red or purple, but in places drab or brown. Some of the coarser arkoses show fragments of feldspar, quartz, granite, and quartzite of considerable size. Muscovite and to a lesser degree biotite are common in many of the sandstones. The sandstones and arkoses may be either massive or cross-bedded; they are also commonly calcareous or muddy.

The shales are commonly calcareous or sandy and range in color from gray and brown to red, maroon, and purple, the reds again being the most prevalent.

A feature of the Rico formation noticeable at several places around the Cane Creek anticline is the way in which massive sandstones fill depressions in underlying shales and limy shales. In a vertical cliff about 1 mile north-northwest of the Frank Shafer No. 1 well a flat-topped lens of massive maroon sandstone decreases from a maximum

[42] Prommel, H. W. C., and Crum, H. E., Structural history of parts of southeastern Utah from interpretation of geologic sections: Am. Assoc. Petroleum Geologists Bull., vol. 11, p. 810, fig. 1, 1927.

thickness of 35 feet to a thickness of 10 feet in a distance of 200 feet and completely disappears in a distance of 600 feet. What appears to be a cross section of the same channel sand is exposed in a cliff facing this one, about 1,000 feet farther to the southwest. Such evidence of scour and fill, so narrowly limited to certain lines, seems to indicate either that these channels represent actual stream channels, with the corresponding implication that the sandstone part of the series is of subaerial origin, or that they represent the work of sharply defined shore currents such as could originate only in shallow, partly sand-locked tidal bays. The intercalated limestones, however, are certainly of marine origin, as proved by their fossils.

The actual percentage of limestone in the Rico is small, amounting to only 5 percent on the Cane Creek anticline and 10 percent at the junction of the rivers. Eight beds of limestone, ranging in thickness from 1 to 10 feet, are reported by Prommel [43] from the section on the Cane Creek anticline. Seven of them are more or less evenly distributed throughout roughly the lower half of the formation; the eighth, which is a more prominent bed, named the Shafer lime by Prommel, has arbitrarily been mapped as the top of the Rico in this area (pl. 8, *A*).

In the general region of the Cane Creek, Shafer, and Lockhart upwarps, except for a few very thin and discontinuous unfossiliferous limestone beds well up in the Cutler, the Shafer lime of Prommel is the highest limestone in the Paleozoic series. Several miles below Lockhart Canyon, however, a purplish limy sandstone 45 to 55 feet above the Shafer begins to take on a more calcareous composition and in a very short distance southward changes to a limestone that closely resembles the Shafer and indeed was mistaken for that member by the writer at the junction of the rivers. Only after it was carefully watched during the ascent of the Colorado in a boat were the true relations of this bed determined. This is a specific instance of the more general observation that the limestones of the upper Rico, including the Shafer lime of Prommel, increase in prominence toward the southwest. On the northeast the Shafer limestone completely disappears just before its horizon dips under on the east flank of the Cane Creek anticline.

Some of the Rico limestones are massive, others are nodular. Nodules examined by the writer in the Shafer lime of Prommel between the Cane Creek and Shafer anticlines are in general elongate, and are more nearly pure limestone than the surrounding matrix. The color of the nodules is generally a dark gray, blue gray, or greenish gray, in contrast to the purplish, reddish, gray, and white tints of the more sandy and arkosic material that forms the matrix.

[43] Prommel, H. W. C., unpublished report.

It is a general rule applying to all the limestones of the Rico that the purer masses tend to be bluish or greenish gray.

The following section of the Rico formation was measured by J. B. Reeside, Jr., near The Slide, on the Colorado River about 1½ miles above its junction with the Green River:

Section of the Rico formation at The Slide

	Feet
Cutler formation:	
Sandstone, massive, cross-bedded, medium- to coarse-grained, buff to gray; forms rim rock of canyon.	
Rico formation:	
Shale, maroon, interbedded with purple arkosic sandstone	10
Limestone, thin-bedded, gray to purple, sandy; good fossils rare, but crinoid fragments and broken shells abundant	25
Sandstone, calcareous, blue gray	8
Sandstone, massive, cross-bedded, salmon red, medium- to coarse-grained	30
Arkose, coarse-grained, with pebbles of feldspar and quartz as much as half an inch in diameter, interbedded with purple sandy limestone	20
Limestone, massive, gray, sandy, with vermilion jasper in upper part; few cross sections of brachiopods on surface ("Shafer limestone")[44]	30
Mudstone, sandy, purple and maroon, and 2-foot layers of gray sandy limestone interbedded; fossils in limestone	30
Shale, red, calcareous, poorly exposed	25
Sandstone, massive, cross-bedded, deep red, locally mottled with gray white; some parts arkosic; layer of limy nodules 10 feet above base	75
Arkose, thin-bedded, fine-grained	18
Limestone, olive green, coarsely crystalline, fossiliferous	½
Shale and sandstone, deep red; sandstone feldspathic, medium- to coarse-grained, in beds 3 to 8 feet thick; shale in beds 3 to 10 feet thick	55
Arkose, massive, cliff-forming, deep red to purple, medium- to coarse-grained; upper 5 feet limy and contains fragments of fossils	40
Shale, vermilion red, sandy	20
Sandstone, deep red; weathers into bosses	25
Sandstone, shaly, vermilion red to deep maroon	20
Sandstone and shale, brownish red, interbedded	63
Sandstone, hard, brownish red, banded with gray	25
Limestone, greenish gray, coarsely crystalline	1
Shale, light gray, sandy	10
Limestone, sandy, olive green to brown on weathered surface, fossiliferous	4
Arkose, deep red to purple, coarse-grained	40
Hermosa formation.	
	574½

[44] Baker has designated the highest limestone in this Rico section "Shafer" (?), following the suggestion made by Reeside in his field notes. The writer, however, believes that this lower limestone is traceable into the "Shafer" limestone of the Lockhart and Shafer domes. See Baker, A. A., Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, p. 24, 1933.

OUTCROP

Along the lower Green River and the stretch of the Colorado River below the Lockhart dome, the Rico formation is exposed in the walls of the river canyons, the rims of which are formed by the basal sandstone of the Cutler (pl. 6, *B*). In a few places the Shafer limestone of Prommel forms a slight ledge in the canyon walls but at most places the profile is unbroken at this horizon. In the vicinity of the group of anticlines and domes along the Colorado River, however, the overlying Cutler formation recedes for a considerable distance, exposing broad dip slopes capped by the Shafer lime (pl. 8, *A*). This topographic feature is best developed on the Shafer dome and in the region between this dome and the Cane Creek anticline. As a result of its thinning over the Cane Creek anticline, the Shafer lime has been eroded to within a few hundred feet of the Cutler cliffs, although one islandlike outlier is left on the axis of the anticline. No single limestone here forms a continuous dip slope, but three or four of them in the lower part of the formation hold up benches for considerable distances.

FOSSILS AND AGE

The limestones and some of the more limy sands and shales of the Rico are fossiliferous. The general aspect of the fauna, however, is distinctly different from that of the Hermosa. In the Hermosa brachiopods are dominant and pelecypods and gastropods are subordinate; in the Rico the conditions are just reversed. Girty points out that the few brachiopods of the Rico fauna are but survivals from the Hermosa fauna, whereas the scanty fauna of pelecypods and gastropods in the Hermosa also survives but is augmented in the Rico by a large number of species not found in the Hermosa. Corals, nine species of which were recognized in the Hermosa, are rare in the Rico, only one species being represented and that at only one locality. The crinoids have also decreased so far as determinable species are concerned, though the abundance of indeterminable stem fragments in the Rico limestones may mean that this decrease is more apparent than real. The bryozoans have not changed greatly in prominence, although the list of species is largely different. Fossils found in the Rico but not in the collections from the Hermosa include scaphopods, nautiloids, and ostracodes, but these are not common.

In the foregoing discussion of the relative increase and decrease of the different groups the comparisons are made with reference to the number of species present rather than the number of individuals. Although the brachiopods are stated to be decidedly subordinate in the Rico, the few species present are so well represented in individuals that one is rather impressed by the showing made by them, in the Shafer lime of Prommel, for instance. Trilobites, nautiloids, and ostracodes, however, are rare both as species and as individuals.

In the region of the Cane Creek anticline and Shafer dome the Shafer lime is the highest fossiliferous bed, but at the junction of the rivers the lime that has come in above the Shafer is fossiliferous. In a section on the Green River 2½ miles north of the junction a varied fauna composed almost entirely of pelecypods and gastropods, half of which are not included in any of the other collections, is found in a purplish limy arkose whose base is 45 feet above the uppermost limestone at this locality. The arkose bed was not traced around to the junction of the rivers, but from a comparison of the stratigraphic sections at the two localities it is almost certainly correlative with the uppermost lime at the junction.

The following fossils from the Rico formation were identified by G. H. Girty in 1927 and 1928:

Fossils from the Rico formation

[This list includes all of the species and most of the localities given by Baker (U. S. Geol. Survey Bull. 841, pp. 27–28) and also about 20 additional species from 8 new localities in the area between the Green and Colorado Rivers]

	Below Shafer limestone of oil geologists																	Shafer limestone of oil geologists												Above Shafer limestone				
	6013a	5949e	5949a	5949b	5949d	5949c	6011	6012	5947c	5947b	5883e	5950	5951	5883i	5947	5947a	5947h	6035a	6035	5948	5946	6411	6411a	6413	6032	6027	6026	6028	6033	5948a	6029	6036	6415a	6416
Foraminifera:																																		
Fusulinids			X																															
Tetracoralla:																																		
Lophophyllum profundum (Milne-Edwards and Haime)																						X												
Crinoidea:																																		
Echinocrinus sp																										X								
Hydreionocrinus ? sp																							X											
Bryozoa:																																		
Fistulipora sp				X					X		X																							
Meekopora sp																								?		X						X		
Batostomella sp																											X							
Stenopora aff. S. carbonaria (Worthen)															X					X	X													
Stenopora sp					X															X				X		X								
Fenestella sp											X									X														
Polypora sp		X				X					X				?							X			X									
Acanthocladia sp																										X								
Septopora biserialis ? (Swallow)																								X										
Septopora sp																				X														
Rhombopora lepidodendroides Meek						X					X													X										
Rhombopora sp				X											X					X														
Streblotrypa prisca (Gabb and Horn)											X																							
Dichotrypa n. sp																				X														
Brachiopoda:																																		
Orbiculoidea capuliformis (McChesney)									?																	X								
Orbiculoidea sp					X						X																							
Derbya bennetti Hall and Clarke			X		?						X																							
Chonetes granulifer Owen	X																																	
Chonetes sp		X																																
Productus cora (d'Orbigny)	X	X		X	X	X					X				X				X	X	X		X	X	X	X	X							
Productus pertenuis Morgan			X			X					X																							
Marginifera lasallensis ? Worthen					X																													
Pustula nebraskensis Owen		X	X		X	X			X		X				X	X			X	X	X	X		X	X	X	X							
Pustula semipunctata (Shepard)																								X										
Pustula symmetrica McChesney					X																													
Squamularia perplexa McChesney																										X								
Spirifer triplicatus Hall					X	X					X								X	X	X	X		X	X	X	X							
Spiriferina kentuckyensis Shumard										X														?										

Fossils from the Rico formation—Continued

	Below Shafer limestone of oil geologists																	Shafer limestone of oil geologists												Above Shafer limestone				
	6013a	5949e	5949a	5949b	5949d	5949c	6011	6012	5947c	5947b	5883e	5950	5951	5883i	5947	5947a	5947h	6035a	6035	5948	5946	6411	6411a	6413	6032	6027	6026	6028	6033	5948a	6029	6036	6415a	6416
Brachopoda—Continued.																																		
Cliothyridina orbicularis (McChesney)																										×								
Composita subtilita (Hall)	×	×		×			×				×				×	×				×	×	×	×	×	×	×	×							×
Dielasma n. sp.																						×												
Pelecypoda:																																		
Sanguinolites costatus (Meek and Worthen)											?									×														
Sanguinolites n. sp.					×																													
Chaenomya ? sp.											×																							
Edmondia aspinwallensis Meek											×																							
Edmondia gibbosa (McCoy)					×				×		×									×					×		?							
Edmondia glabra ? Meek							×									×																		
Edmondia subtruncata Meek																								×										
Edmondia sp.	?					×					?															?								
Nucula levatiformis Walcott															×					×							?					?		
Nucula sp.		×																	×															
Leda arata (Hall)											×																							
Leda sp.		×									?																							
Yoldia sp.							×								×																			
Parallelodon sp.		?									×		×							×										×				
Pinna peracuta Shumard													×							×														
Pteria longa (Geinitz)						×					×																					×		
Pteria aff. P. ohioensis (Herrick)																																×		
Pteria sp.																	×																	
Monopteria marian White									?																							×		
Monopteria polita (White)																																×		
Monopteria n. sp. ?									×																									
Monopteria sp.																				×														
Pseudomonotis equistriata Beede											×																							
Pseudomonotis kansasensis Beede											×																							
Pseudomonotis sublaevis ? Girty											×																							
Pseudomonotis ? sp.					×																			×										
Myalina aviculoides ? Meek and Hayden													×																					
Myalina kansasensis Shumard											×												?		×	?	?							
Myalina perattenuata Meek and Hayden																						×												
Myalina permiana (Swallow)																				×														
Myalina recurvirostris Meek and Worthen																				×														
Myalina subquadrata Shumard						?			×							?				×														
Myalina swallovi McChesney											×													?										
Myalina wyomingensis (Lea)															×																			
Myalina sp.			×		×					×																								×
Posidoniella ? sp.											×																					×		

Schizodus compressus Beede																×																		
Schizodus curtiformis Walcott						×														×														
Schizodus curtus Meek and Worthen							×				?																							
Schizodus ferrieri ? Girty																																×		
Schizodus aff. S. ferrieri Girty																											×							
Schizodus meekanus ? Girty						×																												
Schizodus wheeleri (Swallow)																				×														
Schizodus sp		?		×										×	×															×				
Aviculipecten aff. A. montpelierensis Girty																																×		
Aviculipecten sp		?			×						×					×				×														
Deltopecten occidentalis (Shumard)	×				×	×					×		×	?	×				×	×				×			×					×		
Acanthopecten carboniferus (Stevens)									×		×																							
Lima retifera Shumard	×																																	
Lima sp											×																							
Limatula fasciculata ? Girty	×																																	
Modiola subelliptica Meek	?																										×							
Allerisma terminale Hall	×	×		×	×	×					×		×							×				×	×	×	×							
Pleurophorus mexicanus Girty																			×															
Pleurophorus aff. P. mexicanus Girty																									×									
Pleurophorus aff. P. oblongus Meek															×																			
Pleurophorus subcostatus ? Meek and Worthen	×							×									×																	
Pleurophorus aff. P. subcostatus Meek and Worthen																													×	×		×		
Pleurophorus aff. P. taffi Girty											×																							
Pleurophorus sp					×								×	×										×			×							
Astartella concentrica ? (Conrad)																				×														
Astartella subquadrata Girty															×							×												
Scaphopoda:																																		
Plagioglypta canna (White)													×							×					×		×							
Plagioglypta ? sp					×																													
Gastropoda:																																		
Bellerophon crassus Meek and Worthen											?	?	×	?																				
Bellerophon aff. B. majusculus ? Walcott																																		×
Bellerophon n. sp. ?																											×							
Bellerophon sp					×									×					×			×			×									
Patellostium sp													×				?																	
Euphemus subpapillosus ? (White)													×																					×
Euphemus sp	×											?															?					?		
Bucanopsis aff. B. bella (Keyes)																				?														
Bucanopsis meekana (Conrad)		×		?							?									×														
Bucanopsis aff. B. modesta Girty		×																																
Bucanopsis sp																					?						×							
Pharkidonotus percarinatus (Conrad)		?											×							×														
Pharkidonotus percarinatus var. tricarinatus (Shumard)						?					×																							
Pharkidonotus ? sp												×		×																				
Worthenia ? sp																									×									
Pleurotomaria sp. a																				×														
Pleurotomaria sp. b																				×														
Pleurotomaria sp	×					×					×		?		×		×		×			×										×		
Goniospira sp																											×			?	×			?
Euconospira excelsa (Newberry)							×		?								×		×			×			×				×	?	×		×	
Euconospira missouriensis (Swallow)																								×										
Euconospira ? sp												×																				×		

Fossils from the Rico formation—Continued

	Below Shafer limestone of oil geologists																	Shafer limestone of oil geologists												Above Shafer limestone				
	6013a	5949e	5949a	5949b	5949d	5949c	6011	6012	5947c	5947b	5883e	5950	5951	5883l	5947	5947a	5947h	6035a	6035	5948	5946	6411	6411a	6413	6032	6027	6026	6028	6033	5948a	6029	6036	6415a	6416
Gastropoda—Continued.																																		
Schizostoma catilloides (Conrad)		?			?						?		?	?	?	×				×				×		?				?				
Schizostoma n. sp																						×												
Straparollus aff. S. spergenensis (Hall)																																×		
Euomphalus sp																																	×	
Omphalotrochus ? sp																																×		
Holopea ? sp							×																									×		
Naticopsis deformis Girty																				?	×													
Naticopsis aff. N. lelia																																×		
Naticopsis n. sp																											×							
Naticopsis sp													×														×			×				
Loxonema ? several sp																																×		
Aclisina sp																	×			×												?	?	
Bulimorpha chrysalis (Meek and Worthen)																				×							?							
Bulimorpha n. sp																																×		
Sphaerodoma aff. S. gracilis (Cox)																																	×	
Sphaerodoma hallana (Geinitz)																				×														
Orthonema sp																											×							
Diaphorostoma remex (White)																	×										?		?				×	?
Cephalopoda:																																		
Orthoceras sp											×						×																	
Pseudorthoceras knoxense (McChesney)											×																							
Nautilus sp							?		×																									
Domatoceras aff. D. simplex Hyatt																												×						
Trilobita:																																		
Phillipsia sp																											×							
Griffithides major ? Shumard																									×									
Griffithides aff. G. major Shumard																		×																
Griffithides sp		×																		×		×		×										
Ostracoda, indeterminate																																×		
Fish remains				×																														

Fossil localities, Rico formation

6013a. Near northwest corner of sec. 31, T. 26 S., R. 21 E.; zone 6 feet thick at base.

5949e. SW¼ sec. 31, T. 26 S., R. 21 E.; 24 feet above base.

5949a. Same as 5949e; 24 feet above base.

5949b. Same as 5949e; 35 feet above base.

5949d. Same as 5949e; 160 feet above base.

5949c. Same as 5949e; 200 feet above base.

6011. SE¼ sec. 31, T. 26 S., R. 21 E.; 525 feet above base.

6012. SW¼ sec. 32, T. 26 S., R. 21 E.; 525 feet above base.

5947c. The Slide, on the west side of the Colorado River about 1½ miles above the mouth of the Green River; 40 feet above base.

5947b. Same as 5947c; 303 feet above base.

5883e. Near road from Moab to Thompsons, about 5 miles northwest of Moab; 18 feet above base.

5950. Same as 5883e; 185 feet above base.

5951. Same as 5883e; 345 feet above base.

5883i. Same as 5883e; 345 feet above base.

5947. The Slide, on the west side of the Colorado River about 1½ miles above the mouth of the Green River; about 15 feet below the Shafer limestone.

5947a. Same as 5947.

5947h. Same as 5947.

6035a. East wall of the Green River 14 miles (by water) above its mouth; loose specimen 30 feet above river, probably derived from Shafer limestone in cliff 200 feet above river.

6035. Same as 6035a; probably Shafer limestone, in steep cliff 200 feet above river.

5948. On the Colorado River near the southwest corner of sec. 19, T. 28 S., R. 20 E.; Shafer limestone.

5946. On the Colorado River in sec. 32, T. 27 S., R. 20 E.; Shafer limestone.

6411. Canyon of Indian Creek in sec. 1, T. 30 S., R. 20 E.; Shafer limestone.

6411a. Same as 6411; top bed of Shafer limestone.

6413. Canyon of Indian Creek in sec. 4, T. 29½ S., R. 20 E.; Shafer limestone.

6032. SW¼ sec. 17, T. 27 S., R. 20 E.; Shafer limestone.

6027. Near center of sec. 10, T. 27 S., R. 20 E.; Shafer limestone.

6026. SE¼ sec. 2, T. 27 S., R. 20 E., where top of Rico is crossed by dry wash; Shafer limestone.

6028. NW¼ sec. 26, T. 26 S., R. 20 E.; Shafer limestone.

6033. NW¼ sec. 24, T. 26 S., R. 20 E.; Shafer limestone.

5948a. On the Colorado River near the southwest corner of sec. 19, T. 28 S., R. 20 E.; a limestone bed above the Shafer limestone.

6029. North side of the Colorado River near center of sec. 13, T. 28 S., R. 19 E.; 40 or 50 feet above Shafer limestone, which here lies below erosion level of river.

6036. East side of the Green River at sharp bend 2½ miles north of junction with the Colorado River; 50 to 60 feet above Shafer limestone.

6415a. Canyon of Salt Creek at the mouth of Butler Canyon; limestone bed 65 feet above Shafer limestone.

6416. Canyon of Salt Creek about 1¼ miles south of the mouth of Horse Canyon; limestone bed 65 feet above Shafer limestone.

Girty considers the Rico fauna to be probably of Permian age and to have closer affinities with the Permian faunas of Kansas and adjacent regions than with those of the Grand Canyon and western Utah.

STRATIGRAPHIC RELATIONS

The Rico formation overlies the Hermosa conformably, with apparent lithologic transition but with a faunal break. It is overlain conformably by the Cutler formation, with lateral transition, from southwest to northeast, of upper Rico beds into lower Cutler beds.

CUTLER FORMATION

NAME AND DEFINITION

The Cutler formation was named by Cross and Howe[45] from exposures on Cutler Creek, near Silverton, Colo. At its type locality the formation is essentially an arkosic red-bed series of fairly uniform character throughout, but to the west, in southeastern Utah and northeastern Arizona, it is made up of red beds alternating and interfingering with massive light-colored cross-bedded sandstone, as many as five different lithologic members or tongues of the Cutler being recognized and named in certain sections.[46] In most of the area covered by the present report the formation is in general very similar to its type occurrence in the San Juan Mountains, but a few miles north of the junction of the Green and Colorado Rivers the lower part of the formation begins to show interbedded whiter and more massive sandstones that, in the vicinity of the junction, have coalesced into the massive gray-white Cedar Mesa sandstone member of the Cutler, which in the area south of the junction has been described by Baker.[47] Near the top of the Cutler red beds in the southern part of the area between the rivers is another massive white sandstone tongue (pls. 5, *A*; 9, *A*), which Baker and Reeside[48] have named the White Rim sandstone member of the Cutler formation. At the time of the field mapping for the present report a brown soft impure sandstone lying above the White Rim and intermediate in its lithologic character between the Cutler red beds and the overlying Moenkopi red beds was classed and mapped as part of the Moenkopi and is thus shown in plate 1. Later work by Baker in the area west of the Green River, however, has indicated that in all probability this sandstone belongs with the Cutler.

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[45] Cross, Whitman, and Howe, Ernest, U. S. Geol. Survey Geol. Atlas, Silverton folio (No. 120), p. 5, 1905.

[46] 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.

[47] Baker, A. A., Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, p. 30, 1933. See also Baker, A. A., Geology of the Green River Desert-Cataract Canyon region, Utah: U. S. Geol. Survey Bull. (in preparation).

[48] Baker, A. A., and Reeside, J. B., Jr., op. cit., p. 1425.

DISTRIBUTION AND THICKNESS

The Cutler formation is exposed in the upthrown block of the Moab fault from a point a little over a mile northwest of the Colorado River to a point near the end of the fault cliff, about 8 miles to the northwest; along the Colorado River from the Cane Creek anticline to the mouth of the Green River; and along the Green for a distance of 35 miles above its mouth. The White Rim sandstone member is present along the Colorado River below the Shafer dome and along the Green River as far upstream as the Cutler outcrops. It also appears as huge broken and tilted blocks in the center of the Upheaval dome. The White Rim tongues out eastward and southeastward and is not present upstream from the Shafer dome nor beyond the Colorado River in the area mapped by Baker.

Near Moab the Cutler formation is cut out by the unconformity at the base of the Moenkopi, but it is 460 feet thick at the north end of the Cane Creek anticline and 840 feet thick west of the Shafer dome. At the last-named locality 40 feet of the total thickness is contained in the White Rim sandstone and 130 feet in the unit lying above the White Rim. Along the lower Green River that part of the Cutler below the White Rim is 825 feet thick and the White Rim is 55 feet thick; the unit above the White Rim was not measured here, but to judge from its thickness elsewhere it probably exceeds 100 feet, making the total thickness for the Cutler formation about 1,000 feet. The White Rim thickens to the northwest up the Green River and near Turks Head is 134 feet thick. In the Phillips Petroleum Co. well west of the Green River, 10 miles northwest of the northernmost outcrop on the river, 320 feet of white sandstone can with considerable confidence be referred to the White Rim.

The thickness of the Cutler increases along the Moab fault northwest of Moab; exact thicknesses were not measured and the Cutler was not distinguished from the Rico in this area, but the two formations, undifferentiated, increase from a feather edge a mile or so from the Colorado River to about 1,000 feet in the cliff south of the head of Little Canyon and may increase still more farther to the northwest.

CHARACTER

In the following description of the Cutler lithology the formation will be treated as comprising three members. The White Rim sandstone forms a well-defined member between the main mass of the Cutler below and a thinner but well-characterized unit above.

Lower member of Cutler.—The Cutler formation below the White Rim is dominantly a red sandstone and arkose series except near the junction of the Green and Colorado Rivers, where the lower half shows a considerable percentage of yellowish-white sandstone, representing a facies gradational into the Cedar Mesa sandstone member to the south. Shales are subordinate and thin limestones exceptional.

The typical red facies as developed at Moab, in the vicinity of the Colorado River upwarps, and in upper Stillwater Canyon on the Green River, is composed of medium to rather thick-bedded sandstones and arkoses which in detail may be either massive, horizontally bedded, or cross-bedded. The details of the bedding, however, are not sharp. The cross-bedding is generally of the low-angle oblique type that is characteristic of deposition in water. The prevailing color of the sandstones is brown to red brown or purplish brown. Some of the beds in this member of the Cutler, especially toward the top, are indistinguishable by color from the uniform brown of the member that lies above the White Rim. Tan is also a common hue, especially of the more massive cross-bedded ledges. Purple is not so common in the true sandstones but is the dominant color in the arkoses. The coarser arkoses are commonly pinkish or flesh-colored, while the finer-grained sandy ones take on a brownish tinge. All the colored sandstones show streaks and blotches of pale greenish white, generally elongated parallel to the bedding and concentrated along certain bedding lines more than along others. Such streaks are believed to be due to some sort of bleaching action on an originally colored sediment, but whether it was contemporaneous with deposition or much later is impossible to say. The gross color effect for the lower member of the Cutler is red, as compared to the brown of the upper member and of the Triassic Moenkopi.

Most of the sandstones are muddy or mealy in texture. In the finer-grained beds both muscovite and biotite are abundant. Many of the coarser sandstones show in detail an interlamination of very fine sand, whose composition cannot be resolved by the naked eye, with very thin zones of quartz and feldspar grains, the scale of the alternation being around half an inch. The quartz grains are subangular to rounded, and the associated feldspar grains, which are decidedly subordinate, are also commonly more or less rounded. This small-scale lamination is most commonly developed in the coarser cross-bedded sandstones and is indeed the physical expression of the cross-bedding. In places it shows deformation in the form of miniature faults, which were apparently contemporaneous with the sedimentation.

A few of the sandstones are calcareous and show transitions to thin limestones. In places the lime that is interstitial to the sand grains is crystalline and shows large cleavage faces upon breaking.

Certain peculiar calcite growths occur in sandstone near the top of the member at the south point of the White Rim. They are crystalline and appear as irregular pocket or pipelike replacement deposits in the sandstone without any regard to the bedding. The largest pipes noted were about 3 feet long and 2 to 3 inches in diameter. The smaller calcite masses are generally composed of a single crystal, but the larger masses are made up of groups of crystals that are generally from half an inch to 1 inch across. The calcite may be accompanied by chert or jasper, with which it is intimately associated. In other places and at other levels the jasper occurs alone, either in irregular pockets in the sandstone or as lenses in the sandstone as much as a foot in thickness. It weathers from red to yellow.

The coarser arkoses of the lower member of the Cutler show angular to rounded fragments of various crystalline rocks, which increase in size and abundance from southwest to northeast, toward the supposed source of the arkosic material.[49] In the north wall of the Colorado River at Richardson, opposite the head of Cache Valley and several miles northeast of the area covered in this report, an arkose near the top of the Cutler shows fairly well rounded pebbles and boulders, some of the most interesting of which are tabulated below.

Composition	Shape	Size
		Inches
Gneiss	Rounded	12
Biotite granite gneiss	do	3
Gray medium-grained muscovite granite		8
Porphyritic pink granite, 1-inch orthoclase phenocryst	Oblong, well rounded	2
Boulder of pegmatite, half of which is a flesh-colored orthoclase crystal at least 2½ inches across, the rest being a pinkish mass of quartz and orthoclase with granular texture.		3
Orthoclase crystal (but most of orthoclase in the arkose is in angular cleavage fragments).	Rounded	1
Quartz pebble		2
Greenstone	Rounded	

In contrast to the very coarse character of this assemblage, a section measured near the junction of the rivers shows a maximum size of half an inch for feldspar fragments and 1 inch for greenstone pebbles. The greenstone is the only rock type that is common to both of these localities. The section at the junction shows on the whole a very much smaller percentage of arkose, chiefly at the top of the member, and the greenstone pebbles are more sparingly distributed in the arkose. Besides the greenstone, however, an arkose near the top contains abundant angular fragments, as much as 2 inches in length, of fine-grained cinnamon and pale brown limy sandstone, weathering olive brown. A 1-inch subangular pebble of purplish chert was collected from the same bed, also several reddish-brown and dark-gray pebbles that appear to represent highly altered porphyries.

[49] Baker, A. A., and Reeside, J. B., Jr., op. cit. (Am. Assoc. Petroleum Geologists Bull., vol. 13), p. 1446.

Between these two extreme localities intermediate composition and coarseness prevail. Besides textural variations of the crystalline rock types already enumerated, muscovite schist was noted as pebbles in this intervening region. Angular sandstone pebbles also occur in the Cane Creek anticline section, but near the base of the member instead of the top. They are very angular, flattened as cleaved parallel to the bedding, and reach 4 inches in greatest dimension but average 1 to 2 inches. The sandstone of which they are composed is fine-grained, brown to gray brown, and in part micaceous.

The upper 10 feet of the lower member of the Cutler, immediately underlying the White Rim sandstone on the south side of Shafer Canyon, contains pellets of soft chocolate-brown shale and muddy sandstone, some of the sandstone pellets 3 feet in length. Smaller shale pellets also occur in sandstones at lower horizons in this section.

The lower Cutler shales, including also mudstones, range in color from red and purplish to chocolate brown. The brown shales are the most common. Many of the shales are micaceous.

Limestones are uncommon, though a few thin ones of slight horizontal extent appear in some sections, especially toward the southwest; none of them are fossiliferous. Two limestones occur near the top of the lowest third of the member north of the junction of the Colorado and Green Rivers. The lower one, followed along the outcrop, is discontinuous and shows abrupt variations in thickness to a maximum of 3 feet. The upper and purer one is about 3 feet thick and is noteworthy for the large amount of jasper it contains; in some places the limestone has been almost completely replaced. A bedded flesh-colored chert occurring as thin lenses in brown muddy sandstone 420 feet above the base of the Cutler in the section west of the Shafer dome is quite similar in general appearance and may possibly have been derived by replacement of a limestone bed. Lenticularly bedded chert in sandstone has already been mentioned as occurring in the upper part of the member at the south point of the White Rim.

Near the junction of the Green and Colorado Rivers a zone of sand crystals was noted at several places in cross-bedded sandstone about 205 feet above the base of the lower Cutler. These crystals are lens-shaped in cross section, and though not perfect enough for identification by crystallographic form they tend in part to be grouped into roughly spherical roselike aggregates that resemble in a general way the sand crystals ("desert roses") of gypsum that have been found in recent sediments in the Sahara Desert.[50] Leaching has removed the crystalline material that originally cemented

[50] Whitlock, H. P., Desert roses: Am. Mus. Nat. History Jour., vol. 30, pp. 421–423, 1930.

the sand, and therefore determination of its composition by chemical analysis or microscopic examination is no longer possible. Because these crystals occur at a definite horizon and because bands of them lie in cross-bedded sandstone along horizontal planes rather than along the bedding planes, which they crosscut, they are believed to be fossil sand crystals that indicate the accumulation of the enclosing sand under subaerial and arid conditions. This conclusion accords with that previously reached by Baker and Reeside as to the physical conditions under which the main mass of the Cutler was deposited.[51]

Gradation to Cedar Mesa sandstone member.—The prominent sandstone that rims the canyons at the junction of the Green and Colorado Rivers (pl. 6, *B*) and that has been named by Baker and Reeside[52] the Cedar Mesa sandstone member is the equivalent of the lower part of the Cutler and is developed by a lateral change from the type of lithology previously described for the regions of Moab and the Cane Creek anticline to a series in which thick cross-bedded yellowish-white sandstones form a prominent percentage of the whole. Upon approaching the junction down either the Green or the Colorado Valley, light-colored bands begin to appear in the red beds of the lower Cutler several miles from the junction; these increase gradually in number and thickness until at the junction they become the dominant facies, although even here they do not entirely replace the red beds. A section of the Cutler examined on the east side of the Green River 2½ miles north of the junction shows that a red sandstone bed may change horizontally into a yellow or white one within a few hundred feet. The contact between a red and a white sandstone is also especially prone to show extensions of one color up or down into the adjacent bed without any regard to the actual plane of stratification.

The cross-bedding of these Cedar Mesa sandstone ledges is generally more conspicuous than that elsewhere in the lower Cutler. Both the tangential and oblique patterns of cross-bedding are well developed, though not in the same beds. The dip of the cross-bedding commonly is as much as 15° or 20°, even in the thick obliquely bedded members; the direction of the dip is dominantly southeast. The high-dip type of cross-bedding is generally found in the yellow to white sandstones, and the low-dip cross-bedding in the red sandstones.

There is no shale in this Cedar Mesa part of the section as exposed near the junction, although in the overlying red beds of the

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[51] 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. 1446–1448, 1929.

[52] Idem.

upper part of the member sandy shales and especially muddy sandstones are not uncommon.

In the following section of the lower Cutler (including also certain overlying and underlying units), measured near the junction of the rivers, sandstones of the Cedar Mesa type are recognizable in the lower part and especially in the lower third. For comparison the section at the north end of the Cane Creek anticline is also given.

Partial section of the Cutler formation at prominent westerly bend of Green River, 2½ miles north of junction with the Colorado

[Upper part of section measured about 2 miles farther north, at south end of White Rim; move from one locality to the other made on a key bed, as shown in the section]

	Feet
Upper member of Cutler probably present but not examined.	
White Rim sandstone member: Sandstone, slightly arkosic, basal 8 feet coarse angular-grained, the rest fine angular-grained; grayish white to pale buff; basal 23 feet horizontally bedded, the rest torrentially cross-bedded in beds averaging 1 to 2 feet thick, maximum 4 feet. Weathered surface shows shotlike calcareous concretions. Base very limy, containing crystalline calcite; also has sporadic subangular quartz grains as much as a quarter of an inch in diameter; contact with lower member of Cutler horizontal and even	55
Lower member of Cutler formation:	
1. Sandstone, muddy, fine-grained, brown with bleached spots along certain zones; massive or obscurely horizontally bedded; weathers to rounded forms. Grades laterally in part to purplish-brown arkose	47
2. Sandstone, conglomeratic, coarse- to medium-grained, red brown; cross-bedded; not sharply separated from No. 3. Several conglomerate lenses, about 1 foot thick, contain pebbles of greenstone (generally more or less rounded), orthoclase (half an inch in diameter), chert (reddish brown, purplish, and dark gray), a little quartz, a little altered porphyry (?, reddish and gray), and much fine limy sandstone (olive brown, cinnamon, pale brown, in angular elongated pebbles as much as 2 inches long)	29
3. Sandstone, muddy, fine-grained, red brown with purplish zones; massive and inconspicuously cross-bedded; grades imperceptibly into No. 4. Calcite segregations abundant in bleached olive-gray zone, 40 feet above base	60
4. Sandstone, generally medium-grained, some bands of coarse rounded quartz grains and minor feldspar grains; red brown, tan, grayish white, minor brownish red and purplish, the colors roughly in beds 5 to 20 feet thick with horizontal and vertical gradations; massive and cross-bedded; calcite segregations occur as single crystals 1 inch or less in size, or as irregular pockets or pipes 2 to 3 feet long and 2 to 3 inches in diameter, composed of many crystals. Discontinuous chocolate-brown muddy sandstone lenses at two or three levels (including base) are 2 to 3 feet thick and weather like shale; rest of member weathers to rounded forms; a few beds with rough slaggy surfaces	215

Partial section of the Cutler formation at prominent westerly bend of Green River, 2½ miles north of junction with the Colorado—Continued

	Feet
Lower member of Cutler formation—Continued.	
5. Sandstone, medium-grained with sporadic larger quartz and feldspar grains; flesh-colored to buff; at 5 feet above base irregular lenses of porous jasper, about 1 foot thick, weather creamy yellow; chert in another zone near top accompanied by coarsely crystalline calcite. Member soft; weathers back on top of bench	12
6. Sandstone, whitish to flesh-colored, massive	1
7. Sandstone, alternating fine- and coarse-grained bands, tan to buff and whitish	18
8. Sandstone, muddy, chocolate-brown to purplish, with several light greenish-gray zones, apparently bleached. At 500 feet to the west, upper 3 feet has increased to 6 feet of cross-bedded muscovitic salmon-buff limy sandstone, capping bench	10
9. Sandstone, finely alternating fine- and coarse-grained; a little feldspar in the coarser material; brownish-tan; poorly cross-bedded; more massive than No. 10	13
10. Alternating brown sandstone and chocolate muddy sandstone; former shows fine alternation of fine-grained material with coarser-grained bands containing rounded quartz grains and some feldspar grains; weathers platy	45
11. Sandstone, medium- to coarse-grained, pale tan to whitish; top 2 feet horizontally bedded, the rest cross-bedded in beds as much as 6 feet thick, bedding shown by alternation of extremely fine-grained material with coarser sand containing rounded quartz and some rounded feldspar grains. Cross-bedded portion shows contemporaneous deformation by intricate faulting in miniature. Member weathers to rounded forms	36
12. Sandstone, muddy, fine-grained, alternating chocolate brown and light tan on very fine scale; thin-bedded horizontally; grades laterally to tan massive cross-bedded sandstone	6½
13. Sandstone, fine-grained, pale tan; alternating horizontal beds and obliquely foreset beds, 1 foot or less thick; weathers to massive cliff	13
14. Lower half sandstone, muddy, brown with bleached lines of light greenish-gray, massive; upper half more sandy, tan; oblique foreset beds in upper 1 foot; top marked locally by chocolate-brown shale parting	15
15. Alternating sandstone, muddy sandstone, and sandy mudstone; the mudstone chocolate brown, others brown to purplish; purplish sandstone with much muscovite and biotite; some of brown sandstone highly calcareous, with calcite cleavage reflections on fresh fractures; thin-bedded; held up in cliff by overlying ledge but weathers with horizontal flutings	29
16. Sandstone, in part limy, tan with bleached whitish bands; massive, roughly horizontally bedded and obliquely cross-bedded in 1- to 5-foot beds; bedding accentuated by fine alternation of very fine sandstone bands with bands showing relatively coarse rounded quartz and feldspar grains; calcite segregations in one or two beds near top. Upper 1 foot light gray to purplish, very limy, grading locally to massive light blue-gray sandy limestone	45±

[Moved south 2 miles on bed No. 19, and rest of section measured there.]

Partial section of the Cutler formation at prominent westerly bend of Green River, 2½ miles north of junction with the Colorado—Continued

Lower member of Cutler formation—Continued.	*Feet*
17. Limestone, gray, extensively replaced by jasper; forms extensive bench toward junction of rivers (in section 2 miles north, where upper part of the Cutler was measured, No. 17 is represented by discontinuous thin lenses of jasper at base of No. 16)	3
18. Sandstone, red-brown, poorly cross-bedded; top is gray and very limy	8
19. Sandy limestone to limy sandstone, gray to purplish gray; some jasper replacement (in area between points where upper and lower parts of section were measured No. 19 is in general a massive purplish muddy sandstone with lighter streaks and with limestone, partly replaced by jasper, forming discontinuous lenses as much as 3 feet thick at base)	5½
20. Sandstone, fine-grained, with some thin films of coarser quartz grains, brownish red; lower part poorly horizontally bedded, upper part cross-bedded in 1-foot beds; has fossil sand crystals of gypsum (?) widely distributed in a zone 5 to 10 feet below top; grades to No. 21	23
21. Sandstone, yellowish white with some reddish laminae, cross-bedded (low southeasterly dip) in beds 1 to 5 feet thick; weathers to rounded ledges	30
22. Sandstone, red brown, poorly horizontally bedded and cross-bedded at low angle; grades to No. 23; some jasper in poorly defined lenses 4 inches in greatest thickness about two-thirds of the way toward the top	39½
23. Sandstone, evenly medium-grained, yellowish white with discontinuous lenses, 200 to 300 feet long, of brownish red in upper one-third; lower two-thirds appears massive, but is in reality poorly cross-bedded tangentially in lenslike beds 3 to 10 feet thick, with 15° dip of foreset beds dominantly to southeast; top third poorly horizontally bedded; unit weathers to massive rounded lenslike ledges	55
24. Sandstone, fine-grained, laminated on fine scale with films of coarser rounded quartz grains, brownish red; poorly cross-bedded at top, poorly horizontally bedded below; upper part weathers to massive rounded ledge overhanging lower part	32
25. Sandstone, fine-grained, yellowish white; cross-bedded throughout, in 1- to 2-foot beds in lower 17 feet, but upper 16 feet is one massive cross-bedded ledge; cross-bedding chiefly oblique, a little tangential; foreset beds dip 15°–20°, chiefly southeast	33
Total lower member of Cutler	823½
Rico formation:	
1. Shale, chocolate brown, thinly laminated	1
2. Sandstone and arkose, very calcareous, biotitic, dark purplish gray; cross-bedded in thin beds below, in thicker beds above where composition is more arkosic, with feldspar grains as large as half an inch and also pebbles of greenstone schist; sparingly fossiliferous throughout (collection 6036); weathers to series of rounded ledges	28

Partial section of the Cutler formation at prominent westerly bend of Green River, 2½ miles north of junction with the Colorado—Continued

	Feet
Rico formation—Continued.	
3. Sandstone, highly calcareous, fine-grained, muscovitic, purplish gray (weathers yellowish white), and dark gray (upper 3 feet)	6½
4. Sandstone, muddy, purplish gray, poorly bedded horizontally	8
5. Sandstone, fine-grained, yellowish white (lower 18 inches) and reddish brown; coarsely cross-bedded in a single bed	13
6. Sandstone, limy, coarse, purplish brown; thin-bedded horizontally	7
7. Arkose; basal 3 feet coarse (feldspar as much as half an inch), drab, horizontally bedded to poorly cross-bedded in thin beds; upper part fine- to medium-grained, purplish, cross-bedded in thin beds; member sparingly fossiliferous	11
8. Limestone, light blue gray, darker toward top; bedding poor, horizontal, gnarly in places; highly fossiliferous at base and top	6
9. Limestone, slightly sandy, blue gray; obliquely cross-bedded in one bed, bedding poor	8
10. Limestone, sandy, gnarly; gnarls blue gray and purer; groundmass greenish gray and sandy	2
11. Limestone, sandy, dark gray; obliquely though poorly cross-bedded in 1- to 2-foot beds; sparingly fossiliferous, crinoidal	10
12. Limestone, gray, poorly horizontally bedded; weathers nodular; sparingly fossiliferous; 2 feet below top is an indefinite zone 4 inches thick marked by rounded and cleaved fragments of feldspar half an inch in maximum diameter and a little rounded glassy quartz, smaller sand grains absent	8
13. Sandstone, fine-grained, horizontally bedded; lower 2 feet massive, greenish white, and forms rounded ledge, grades above to material that is less massive and more generally purplish brown with only streaks of greenish white, and weathers to slope	12
14. Sandstone, muddy, somewhat calcareous, purplish brown; becomes more muddy and grayer toward top; poorly horizontally bedded, in part ripple-marked	4
15. Limestone, somewhat sandy in places, greenish to purplish gray, poorly thin-bedded; highly fossiliferous	9
16. Sandstone, fine-grained, greenish white, with purplish splotches becoming purplish gray at top; bedding approximately horizontal, poor; weathers to rounded forms but would form slope if not held up by limestone; thickness not measured.	
Total Rico formation measured	133½+
Lower beds not examined. Nos. 8 to 12 believed to comprise Shafer lime of petroleum geologists.	

Section of Cutler formation at northwest end of the Cane Creek anticline, sec. 22, T. 26 S., R. 20 E.

	Feet
Moenkopi formation.	
Unconformity.	
Cutler formation:	
1. Sandstone, muddy, fine-grained, in part micaceous, pale chocolate brown with numerous zones of bleached greenish-gray mottlings and a 5-foot bleached zone at top; rounded quartz grains (transparent, pale amber, milky) especially in lower 40	

Section of Cutler formation at northwest end of the Cane Creek anticline, sec. 22, T. 26 S., R. 20 E.—Continued

	Feet
Cutler formation—Continued.	
feet, haphazardly scattered in matrix, or forming little 2- to 3-inch lenslike pockets, or scattered along bedding planes; a very few rounded feldspar grains with the quartz; bedding poorly horizontal to massive, in 1- to 3-foot beds; weathers to slope	109
2. Sandstone, medium-grained, mealy, pale chocolate brown; slightly micaceous; has grains of rounded amber quartz and very little rounded feldspar; cross-bedded. A few hundred feet west is coarsely arkosic with feldspar grains as large as half an inch	6
3. Sandstone, generally fine-grained and micaceous but with a few coarser seams showing rounded quartz and very little rounded feldspar grains; brown, purplish brown, and pale chocolate brown; bedding poor	15
4. Sandstone, micaceous (muscovite and biotite), mealy, purplish, cross-bedded	3
5. Sandstone, fine-grained, but with rather coarse rounded amber quartz and rounded feldspar grains embedded near top; in part micaceous; brown with slightly purplish zones showing a little feldspar in the sand; massive, caps cliff	33
6. Sandstone and arkose, brown with purplish tinge, finer-grained sandstone micaceous; cross-bedded in thin beds, low angle; two or three zones contain angular breccia fragments of olive-brown and olive-gray fine-grained sandstone	34
7. Sandstone, lower three-fourths brown, upper one-fourth buffy brown; detailed composition shows buffy brown, very fine-grained sandstone matrix with beds and thin laminae containing medium-grained amber and dark-gray quartz grains, partly rounded, and white to flesh-colored feldspar grains; cross-bedded, low angle	16
8. Sandstone and arkose, purplish brown, with bleached lines and splotchy zones of pale greenish gray; some of feldspar in arkose as large as half an inch; irregular limy (?) nodules in inaccessible cliff appear to be mud balls	24
9. Sandstone, buffy brown, inclining to salmon, small bleached streaks; detailed composition shows buffy-brown, very fine-grained sandstone with zones and thin lamellar bands containing medium-grained amber and dark-gray subangular to angular quartz grains, and flesh-colored to white subangular feldspar grains; thickly and obliquely cross-bedded at angles of 10° to 15°; lower 25 feet apparently a single cross-bedded unit and most of upper part in one bed; weathers massive	51
10. Arkose and sandstone, brown to purplish brown, with bleached lines and splotchy zones of pale greenish gray; micaceous throughout, but especially in finer-grained bands; poorly horizontally bedded and cross-bedded; weathers to rounded forms. Arkosic conglomerate at base (2 feet) and 10 to 15 feet below top (5 feet) shows feldspar in grains as large as half an inch or more, angular quartz as large as three-fourths inch, angular and subrounded pebbles of greenstone, and many angular flattened	

Section of Cutler formation at northwest end of the Cane Creek anticline, sec. 22, T. 26 S., R. 20 E.—Continued

	Feet
Cutler formation—Continued.	
(along bedding) fragments, the largest 4 inches across, of fine-grained brown to gray-brown, commonly micaceous sandstone; base irregular	91
11. Arkose, coarse, purplish; fragments comprise feldspar (largest half an inch), quartz (largest a quarter of an inch), rounded to angular greenstone (largest more than 1 inch), coarse biotite granite, fine-grained gray granite, a little muscovite schist (largest 1 inch); cross-bedded at low angle; base irregular, with 1-foot relief	11
12. Sandstone, muddy, fine-grained; some sandy shale; coarser-grained toward top; red brown to chocolate brown, some beds in upper part with purplish tinge, certain bands greenish; highly micaceous (muscovite and biotite); bedding obscure, 1- to 2-foot beds in lower part, 5- to 10-foot beds in upper more massive part, certain beds with low-angle cross-bedding; weathers to vertical fluted cliff; 25 feet above base is 2-foot zone marked by irregular more or less rounded limy nodules as much as 2 inches long, apparently representing mud balls contemporaneous with deposition of the sandstone	61
13. Arkose, coarse at base, fine at top; flesh-colored; fragments comprise feldspar (maximum 1 inch, averaging one-quarter inch), angular quartz (maximum half an inch, averaging less than one-quarter inch), coarse granite, fine-grained granite (maximum 1 inch), biotite granite with flesh-colored feldspar, greenstone (maximum one-quarter inch; very little); matrix white, mealy, very limy	5
Total Cutler formation	459
Rico formation:	
1. Sandstone, purplish to purplish brown, with a few light-greenish spots, micaceous (dominantly muscovite); sporadic coarse fragments of quartz and feldspar; massive	4
2. Limestone, sandy, arkosic, mottled purplish and light greenish gray; contains feldspar fragments as large as half an inch (generally less than one-quarter inch), angular quartz as large as one-quarter inch; massive, gnarly (Shafer lime of petroleum geologists)	2
3. Arkose, limy, drab, massive; feldspar fragments as large as half an inch	3
4. Sandstone, micaceous, purplish; thickness not measured.	
Lower beds not examined.	

White Rim sandstone member.—Aside from the grayish-white to pure-white color of the White Rim sandstone, set off by contrast with the overlying and underlying red beds, the most conspicuous feature of the sandstone is its oblique cross-bedding (pl. 8, *B*). The maximum measured angle at which the laminae dip is 23°. As a general rule, foreset beds alternate with horizontal beds in thicknesses of 2 to

5 feet, but the thickness of the individual foreset beds increases northwestward, along with an increase in the thickness of the member as a whole, until in upper Stillwater Canyon beds composed of a single set of foreset laminae not uncommonly reach 20 or 25 feet in thickness. At one locality a certain set of straight laminae was observed to continue at the same dip for 300 feet, though this was not the maximum dip. At the only places where the complete section of the White Rim was studied in detail—namely, at its southernmost point and on the south side of Shafer Canyon—the lower one-third to one-half of the member is horizontally bedded. It is possible that this condition holds everywhere, but as the basal half or two-thirds of the member is generally in a vertical cliff that is inaccessible from above and rather difficult of access from below, the sandstone can be examined only at widely separated places.

The main mass of this sandstone is composed of medium- to fine-grained quartz sand, but in places the sand is coarser and contains a little feldspar. At the base of the member about 3 miles below the point where its outcrop crosses the Green, 1 to 2 feet of buff, very sandy limestone occurs immediately above the basal 1 foot of sandstone. This limestone was carefully searched for fossils but without success. The basal foot or so of the sandstone at the south point of the rim is likewise calcareous, and it is possible that this limy zone is present throughout the intervening region.

The White Rim sandstone thins northeastward up the Colorado River and finally disappears, on the northwest flank of the Shafer dome, by lateral gradation into the basal 7 or 8 feet of the upper brown member of the Cutler.

Upper member of Cutler.—Above the White Rim is a unit consisting of chocolate-brown muddy sandstone that shows a maximum measured thickness, on the west side of the Shafer dome, of about 130 feet. Although it was not mapped separately from the Moenkopi, it is believed to be present everywhere above the White Rim in the area mapped, and it overlaps the White Rim on the northeast nearly as far as the Cane Creek anticline. Along this anticline and along the Moab fault farther to the northeast the upper member of the Cutler and a varying amount of the lower member have been removed by the erosion that produced the unconformity at the base of the Moenkopi.

The brown color of the upper Cutler is indistinguishable from that of the overlying Moenkopi and contrasts with the dominant reddish and purplish browns of the Cutler below the White Rim. On the other hand, the bedding is more of the Cutler type, in massive beds from 1 to 5 feet thick that are inclined to weather in massive "rock baby" forms. The details of the bedding are obscure except on weathered surfaces, where the lamination is seen to be horizontal. A characteristic of this member of the formation is the widespread occurrence of coarse, well-rounded quartz grains, of a translucent milky or amber color, which are embedded in the fine-grained sandy matrix. These grains make up only a small percentage of the rock, and their distribution shows no effects of sorting; locally they are concentrated in pockets that may be elongated parallel to the bedding or at various angles to it.

OUTCROP

The topographic expression of the lower member of the Cutler in its more typical development northwest of Moab and around the Colorado River anticlines and domes (Cane Creek, Shafer, Lockhart) is a horizontally corrugated cliff, whose slope varies in both horizontal and vertical directions (pls. 4, *A*; 8, *A*). The corrugations are due to the slight differences in resistance to weathering offered by the different beds; the result is an erosion form for which Organ Rock, in southeastern Utah, might be taken as the type.[53] The lower Cutler cliff is in general steep but can be scaled at many places. Where it it overlain by the White Rim sandstone, the upper part of the member is more likely to form a vertical cliff (pl. 9, *A*). Near the junction of the Green and the Colorado the Cedar Mesa sandstone member forms a rough bench whose cliffed margins rim the river canyons (pl. 6, *B*). The upper part of the lower Cutler in this region, however, maintains the same general character of outcrop that the whole member assumes northeastward.

The White Rim sandstone crops out as a vertical cliff, unscalable except at a few widely scattered points (pls. 5, *A*; 9, *A*). This cliff is known locally as the White Rim, whence the name that has been applied to the sandstone. The overlying member of the Cutler and the Moenkopi have been stripped off the top for varying distances back from the rim, leaving a white bench, which, together with the precipice at the outer edge, presents a spectacular appearance from the top.

The upper brown sandstone member of the Cutler is in general rather poorly exposed in a debris-covered slope at the base of the Moenkopi outcrop, but on steeper slopes it crops out in rounded corrugated forms like the Cutler below the White Rim.

STRATIGRAPHIC RELATIONS AND AGE

The Cutler formation overlies the Rico conformably. In accordance with the original definition of the Rico formation by Cross and

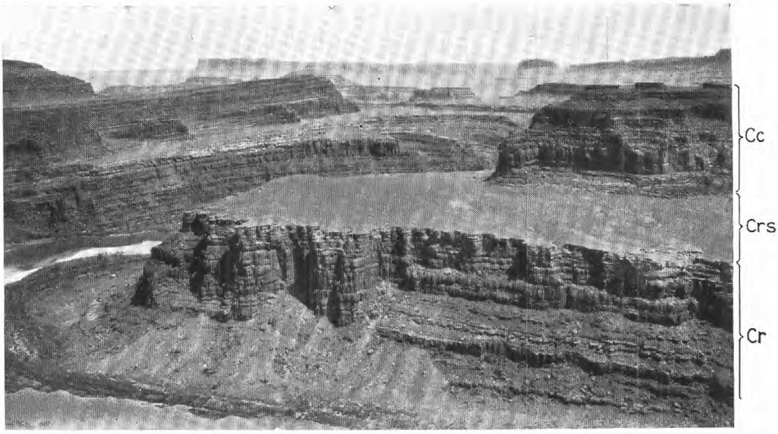
[53] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, pl. 6, 1917.

Spencer[54] the contact has been arbitrarily placed at the top of the uppermost fossiliferous stratum in the Permian red-bed series, which in the vicinity of the Cane Creek anticline and Shafer dome is the Shafer lime of the petroleum geologists, at the junction of the rivers is a limestone above the Shafer, and at a point 2½ miles north of the junction is a purplish limy arkose that without much doubt is correlative with the upper limestone at the junction. Along the Moab fault on the northwest side of the Colorado River at Moab there are only four limestones above the Hermosa, the uppermost lying 350 feet above recognized Hermosa fossils. It is very probable, to judge from the fact that the Shafer lime of the petroleum geologists wedges out northeastward on the east flank of the Cane Creek anticline, that red beds above the upper lime near Moab are to be correlated with the upper Rico of the Cane Creek anticline. The Cutler and Rico have not been differentiated near Moab.

The northwestward thickening of the White Rim sandstone that is manifest within the area mapped continues beyond the area under the cover of later formations, and without much doubt the White Rim merges into and forms the upper part of the Coconino sandstone of the San Rafael Swell. The manner in which this thickening takes place is indicated in the river cliff 3 miles below the place where the base of the White Rim crosses the Green. Here the basal bed of the White Rim wedges out and is overlapped to the southeast by the next overlying bed, which thus becomes the basal bed and in turn wedges out and is overlapped farther southeast by the next higher bed. Several beds that successively form the base of the White Rim are thus cut out southeast within a few hundred feet. The contact between the White Rim and the underlying red beds is even and apparently conformable. To judge from the absence of interfingering between the white sandstone and the red beds below, it would appear that the invasion of sands from the northwest into the region during Cutler time was a relatively rapid process. Possibly the De Chelly sandstone member of the Cutler of southeastern Utah and northeastern Arizona was deposited at the same time as the White Rim, but as these two sandstone members are apparently unconnected except in a very roundabout way through the Coconino sandstone, which covers a larger time interval of the Permian than either of these two sandstone members, direct correlation between them is impracticable. The Cedar Mesa sandstone member of the Cutler is considered by Baker and Reeside[55] to be connected laterally, under the

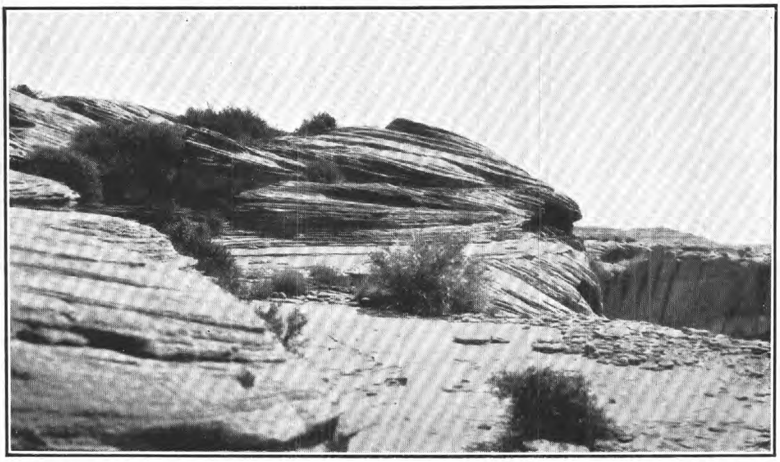
[54] Cross, Whitman, and Spencer, A. C., Geology of the Rico Mountains, Colorado: U. S. Geol. Survey 21st Ann. Rept., pt. 2, p. 60, 1900.

[55] 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.



A. NORTH FLANK OF SHAFER DOME IN MIDDLE DISTANCE, FROM POINT ON WHITE RIM SOUTH OF SHAFER TRAIL.

Bench in foreground and middle distance formed by Shafer limestone. Cr, Rico formation; Crs, Shafer limestone; Cc, Cutler formation. Photograph by J. B. Reeside, Jr.



B. CROSS BEDDING IN WHITE RIM SANDSTONE MEMBER OF CUTLER FORMATION NEAR JUNCTION BUTTE.

Photograph by J. B. Reeside, Jr.

cover of later formations, with the lower part of the Coconino. Red beds between the White Rim and Cedar Mesa sandstones are believed by them to disappear northwestward in the San Rafael Swell by lateral transition into the Cedar Mesa type of sandstone.

Inasmuch as the Cutler is conformable with fossiliferous Permian (Rico) beds below, and as the White Rim sandstone member near its top without much doubt connects northwestward with a sandstone that underlies and grades into fossiliferous Permian (Kaibab) limestone,[56] the Permian age of the Cutler formation is established without much question. The Cutler is overlain unconformably in the area between the Green and Colorado Rivers by the Moenkopi formation.

PRE-TRIASSIC UNCONFORMITY

An angular unconformity at the base of the Lower Triassic Moenkopi formation is very pronounced in exposures along the Moab fault northwest of Moab (fig. 2). Between the head of Little Can-

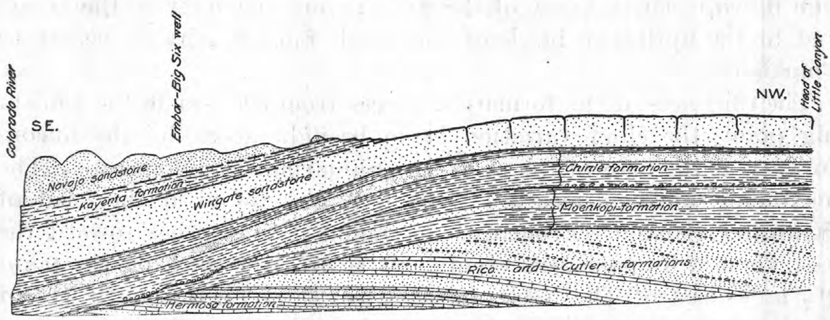


FIGURE 2.—Diagrammatic section showing stratigraphic and structural relations on southwest side of Moab fault northwest of Moab, Utah.

yon and the Embar-Big Six well in a distance of 4 miles the complete Cutler-Rico series, amounting to a minimum of 1,000 feet, has been cut out and in addition the upper 100 feet or so of the Hermosa has been removed, so that at the well the Moenkopi, itself highly attenuated by the erosion recorded in the unconformity at the base of the Shinarump, rests directly on upper Hermosa beds. The angular discordance between the Moenkopi and underlying beds amounts locally to as much as 4°. Pre-Moenkopi erosion also took place on the axis of the Cane Creek anticline. Comparison of the stratigraphic section here exposed with a more nearly complete section measured on the west side of the Shafer dome indicates the

[56] 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-D, pp. 63–64, 1928.

removal of about 300 feet of the Cutler before the Moenkopi was deposited, and this erosion was apparently limited rather sharply to the area involved in the anticlinal folding. In other parts of the area the unconformity at the base of the Moenkopi is not marked, and some difficulty was experienced in determining the contact in the field.

TRIASSIC SYSTEM

LOWER TRIASSIC SERIES

MOENKOPI FORMATION

NAME, DISTRIBUTION, AND THICKNESS

The Moenkopi formation was named by Ward[57] from exposures near the mouth of Moenkopi Wash, in northeastern Arizona. Within the area treated in the present report the formation is widely exposed along the Colorado River below the Kings Bottom syncline and along the Green River below the Bowknot Bend, and in addition it crops out in many of the dry canyons tributary to the Green and in the upthrown block of the Moab fault northwest nearly to Courthouse.

The thickness of the formation ranges from 525 feet to the vanishing point, the chief variation being brought about by the unconformity at the base of the overlying Shinarump conglomerate. The maximum thickness measured, 525 feet, was found at the head of Stillwater Canyon. From this maximum it diminishes toward the east, though by no means evenly. It is 375 feet thick on the point 2½ miles east of The Neck, and 285 feet thick on the north end of the Cane Creek anticline. At the Embar-Big Six well, just west of the river at Moab, the thickness is only 35 feet, and at the point where the Moenkopi horizon reaches the river just south of the well, the formation has possibly been cut out completely, though the talus covering the base of the slope there makes it impossible to determine exactly just where the Moenkopi disappears. At any rate it is absent on the southeast side of the river. Northwestward from the well the thickness increases gradually to a maximum of about 450 feet in the vicinity of The Dugway, beyond which it decreases again until at the northwest end of the Wingate-rimmed cliff along the Moab-Valley City road, only a few feet of Moenkopi remains. It is probable that changes in thickness away from this fault zone are more gradual than those here recorded.

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[57] Ward, L. F., Status of the Mesozoic floras of the United States: U. S. Geol. Survey Mon. 48, pt. 1, pp. 17–19, 1905. In an earlier preliminary paper (Ward, L. F., Geology of the Little Colorado Valley: Am. Jour. Sci., 4th ser., vol. 12, pp. 403–404, 1901) the Moenkopi formation is described as the "Moencopie beds," but the phraseology of the description is otherwise practically identical in the two papers.

CHARACTER

The Moenkopi is everywhere a red-bed series except in a considerable stretch along the valley of Green River, described beyond. The normal red beds resemble in a superficial way those of the Cutler formation, but there is a difference in color and an even more marked difference in bedding (pl. 4, *A*). The general color of the Moenkopi is more brown than red, chocolate brown and reddish brown being the two commonest shades. As pointed out above, the gross color effect of the Cutler, except the upper member, is a distinct red, though there may be several different hues. Although the upper part of the Cutler may contain beds that are typical Moenkopi brown, the Moenkopi does not contain the Cutler purples.[58] The bedding of the Moenkopi is much thinner and varvelike than that in the Cutler, and cross bedding is not nearly so prevalent. Ripple bedding, on the other hand, is one of the most universal and characteristic features of the Moenkopi.

The Moenkopi is composed dominantly of chocolate brown and red brown mudstones, shales, and muddy sandstones showing all degrees of intergradation, interbedded with more resistant partly calcareous sandstones and muddy sandstones that form ledges on the outcrop. These ledges may be only a fraction of an inch or several feet thick; commonly they measure only a few inches. They are discontinuous for any great distance laterally, and they tend to be concentrated in certain zones with relatively ledge-free zones intervening. On a fresh break the sandstone forming these ledges is olive brown, chocolate brown, gray, white, or yellow, and the weathered surface is brown or buff. Most of these ledges show ripple bedding, as do also some of the softer sandstones and shaly sandstones, that, without careful examination, would be passed over as shale or mudstone. Some of the thicker ledges are cross-bedded obliquely on a small scale (1 foot) and at a low dip.

Some of the brown muddy sandstone of the Moenkopi has been irregularly bleached to greenish gray along bedded zones, the degree of bleaching ranging from one extreme where only a few bleached splotches appear along a certain horizon in a colored bed to the other extreme where only a few irregular remnants of the original color remain in a 5- or 6-foot zone of the bleached rock.

Texturally, the Moenkopi sandstones are nearly all fine-grained and mealy, so that the mineral composition in the hand specimen is not evident. The lower Moenkopi that caps Pyramid Butte, between

[58] In regions lying 12 miles or more northeast of the area treated in the present report, purplish arkoses occur not uncommonly in the Moenkopi. See Dane, C. H., Geology of the Salt Valley anticline and adjacent areas, Grand County, Utah: U. S. Geol. Survey Bull. 863, pp. 44–50, 1936.

the Cane Creek anticline and Shafer dome, however, shows a few thin lenses (1 to 2 inches) of coarse- to medium-grained sandstone, composed of well-rounded quartz grains, a little feldspar, and a little gray limestone in fine pebbles that weather to a buffy yellow. A similar 2-inch lens lying 130 feet above the base of the formation, west of the Shafer dome, contains pale olive-greenish shale fragments measuring as much as half an inch. The matrix in one of the lenses on Pyramid Butte is calcite, the cleavage faces of which are very conspicuous. Many of the shales, mudstones, and muddy sandstones of the Moenkopi show fine flakes of muscovite on the cleavage planes. Where the Moenkopi sedimentary materials are coarse enough to be studied mineralogically in the hand specimen, they are seen to be arkosic and are thus similar in composition to the underlying Cutler.

Less common and peculiar sedimentary rocks noted in the lower red beds of the Green River section at the head of Stillwater Canyon include a 1-inch resistant seam of limy mudstone of a tile-red color; other similar thin bands of orange red; one or two thin beds of fine limestone conglomerate, 200 feet above the base, purplish gray when fresh but weathering to a deep buff; and, 140 feet above the base, a cross-bedded sandstone containing isolated hard, rounded shale pebbles as much as an inch in diameter that are brilliantly colored yellow, buff, orange red, scarlet, and maroon.

A 4-inch band of oolite occurs 130 feet above the base in the section on the Cane Creek anticline. The oolite grains, embedded in a greenish-gray very calcareous mudstone, are brown, generally hollow, and lined with a shiny black hydrocarbon.

A local unconformity covering several square miles is present at a horizon 120 feet above the base of the Moenkopi on the Green River southwest of Bighorn Mesa. The strata below the horizontal sandstone that tops the unconformity dip to the east at a maximum angle of about 10°. These tilted beds, made up of alternating well-bedded sandstones and shales, occupy a vertical zone about 30 feet thick, below which they flatten out tangentially to the horizontal beds below. They are believed to represent the foreset beds of a delta.

Along a considerable stretch of the Green River the upper part of the Moenkopi, with the exception of the upper 40 feet, is greenish gray instead of the normal brown color (see pls. 4, *B*, and 9, *B*). Down the river the change from red brown to greenish gray takes place rather abruptly 2 miles above the mouth of Taylor Canyon; the reverse change from greenish gray to red beds occurs near Muffin Butte. The weathered surface of the gray facies is of a rich cream color. Just below this surficial crust the material is deep buff, apparently representing the initial oxidation of the iron, which has been later toned down by leaching at the very surface. The gray-green beds are composed largely of sandy shale, with some thin ledges of ripple-marked sandstone. A thin impure fossiliferous limestone occurs in transition beds at the base of the zone. Gypsum is common in this gray phase, occurring both as selenite plates lying on the porous outcrop of the shale and as thin veinlets ramifying through the shale. The top 3 feet of the Moenkopi is olive-green mudstone and is full of gypsum veinlets; the 36 feet immediately beneath is reddish-brown mudstone and has no gypsum. The very top of the Moenkopi, which is here olive green, assumes in many places in Taylor Canyon a bright-yellow color.

The following section, measured at the head of Stillwater Canyon, is typical of the Moenkopi where the gray phase is present along the Green River. For comparison a thinner red-bed section, measured at the north end of the Cane Creek anticline, is also given.

Section of Moenkopi formation on east side of Green River where White Rim crosses at head of Stillwater Canyon

Shinarump conglomerate.
Unconformity.
Moenkopi formation:

	Feet
1. Shale and mudstone, olive green, slightly micaceous; many gypsum veinlets crosscutting and parallel to beds	3
2. Shale and mudstone, brownish red and reddish brown; a few olive-yellow streaks; basal 6 inches purple; slightly micaceous; top 16 feet held up in cliff by Shinarump	36
3. Dominantly shale, sandy, greenish gray, weathering just below surface to deep buff but right at surface to deep cream; intercalated thin discontinuous seams of ripple-bedded brownish-gray to grayish-brown sandstone (weathering buffy and tan) are especially massed along certain zones; gypsum common throughout as selenite plates on the weathered surface, also locally as crosscutting veinlets; weathers to slope	198
4. Alternating greenish-gray sandy shale (similar to No. 3) and brownish-gray (weathering yellowish brown) shaly sandstone; sandstone strongly ripple-marked, forms very thin seams in the shale, becomes dominant in upper 10 feet, which is chiefly thin-bedded ripple-bedded creamy sandstone with locally a lavender tinge	38
5. Chiefly sandstone, fine-grained, thin-bedded, ripple-marked, tan to reddish brown; certain parts (basal 3 feet and 7- to 8-foot zone 10 feet above base) cropping out as massive tan ledges; a little chocolate-brown mudstone and greenish sandy mudstone alternating with the thinner-bedded sandstone	29
6. Limestone, muddy, carbonaceous, dark gray, weathering buffy yellow (in places with a lavender tinge); fossiliferous; mud-cracked at top; contains nodular concretions of limonite	1⅓

Section of Moenkopi formation on east side of Green River where White Rim crosses at head of Stillwater Canyon—Continued

Moenkopi formation—Continued.	*Feet*
7. Shaly sandstone and sandy shale, limy toward top, thin-bedded, buffy, with a little orange red in indistinct bands at top; gypsiferous muddy sandstone band at very top	10
8. Dominantly sandstone, shaly, thin-bedded, in large part ripple-bedded, red brown, becoming more buffy at top; a few thin beds of grayish-white sandstone (weathering yellowish), in part ripple-bedded, in part horizontally bedded; a little red-brown shale; 10 feet below top, one or two thin beds of fine conglomerate containing pebbles of creamy to buff limy shale	55
9. Dominantly sandstone, gray to white (weathering buffy), highly cross-bedded; some red-brown shale and ripple-marked shaly sandstone. Above middle, 5-foot sandstone that is obliquely cross-bedded, low dip in 1-foot beds, contains hard rounded pellets of limy shale (maximum 1 inch in diameter) of brilliant colors—yellow, buff, orange red, scarlet, maroon; member coalesces laterally to one massive bed	33
10. Alternating sandstone, muddy sandstone (dominant), sandy shale, and mudstone, general color dark chocolate brown; basal 2 feet gray sandstone; another 2-foot sandstone 5 feet above base is white (weathering buffy brown) and cross-bedded; muddy sandstone is reddish brown (some approaching tile red) to purplish brown and grayish, generally ripple-marked; some of the sandy shale is greenish. Upper 30 feet shows marked local unconformity, foreset beds (alternating well-bedded sandstone and shale) dipping 10° E. and joining underlying horizontal beds tangentially	49
11. Mudstone and shale, dark chocolate brown, with thin (1 to 2 inches or less) seams of olive-brown to olive-gray, highly calcareous sandy mudstone or muddy sandstone forming little discontinuous ledges especially concentrated at certain horizons; sandier of these seams ripple-marked; one seam of slightly sandy calcareous mudstone of tile-red color	72
Total Moenkopi formation	524
Unconformity not evident.	
Upper member of Cutler formation:	
1. Sandstone, muddy, fine- to medium-grained, chocolate brown with some bleached spots; finely muscovitic; rounded quartz grains in medium-grained material; massive (poorly horizontally bedded); weathers to rounded forms	69
2. Sandstone, gray white, massive, soft and friable, possibly coarser-grained than White Rim sandstone member; top irregular; poorly exposed	33
Total upper member of Cutler	102
White Rim sandstone member of Cutler formation, fine-grained, grayish white, nearly all quartz; top cross-bedded on large scale, dip 23°; forms cliff.	

Section of Moenkopi formation at northwest end of the Cane Creek anticline, sec. 22, T. 26 S., R. 20 E.

Chinle formation: Basal 8 feet massive sandy mudstone, mottled whitish, purple, and lavender, interpreted as reworked Moenkopi.

Unconformity.

Moenkopi formation:	Feet
1. Alternating chocolate-brown sandy shale and muddy sandstone, with some pale greenish-gray muddy sandstone, in zones 5 to 15 feet thick; finely micaceous; sandstone ripple-marked, weathers to rounded ledges; top 5 feet shale, bleached along bedding and crosscutting lines to pale greenish white	94
2. Sandstone, muddy, fine-grained, finely micaceous, chocolate-brown, massive; weathers to rounded forms on talus slope	33
3. Sandstone, fine-grained, in part very calcareous, light olive gray and chocolate brown (weathering brown); roughly horizontally bedded; weathers to massive rounded ledge	16
4. Interbedded chocolate-brown, sandy, finely micaceous shale and greenish-white (weathers yellowish) and (toward top) chocolate-brown, fine-grained muddy sandstone, in part calcareous; sandstone in beds as much as 6 inches thick, averaging 1 to 2 inches, and occurs every 2 or 3 feet (or closer toward top) in the shale; sandstone commonly ripple-marked asymmetrically; 83 feet above base, at the top of an 8-foot massive ledge of horizontally bedded chocolate-brown muddy sandstone, are pockets containing rounded to subangular quartz grains (1/16 to 1/32 inch in diameter) and a few rounded to subangular feldspar grains; 10 feet below top, oolitic bed shows brown hollow oolites lined with black shiny hydrocarbon (?) in a greenish-gray (weathering yellowish brown), very calcareous mudstone matrix; top 10 feet bleached to greenish gray; member weathers to talus slope with harder bands forming subdued ledges	142
Total Moenkopi formation	285

Unconformity.

Cutler formation.

OUTCROP

The Moenkopi crops out typically as a steep slope broken by sandstone ledges (pls. 4, *A*; 9, *B*).

FOSSILS AND AGE

Fossils are uncommon in the Moenkopi. A small collection was obtained from an impure limestone, 15 inches in thickness, that lies near the base of the greenish-gray shale series on the Green River 220 feet above the base of the formation. This limestone is muddy and also carbonaceous. It is gray in color, though it weathers to a buffy yellow, sometimes with a lavender tinge. The upper surface is extensively mud-cracked. None of the fossils collected could be determined exactly, owing to their poor state of preservation, yet according to Girty they have a distinctly Lower Triassic aspect. He lists the forms *Lingula* sp., *Monotis?* aff. *M. thaynesiana*, viviparoid gastropods, and *Meekoceras?* sp. The gastropod fauna is varied, and all the species are probably new; though undoubtedly marine, many of them show a marked superficial resemblance to the fresh-water genus *Viviparus*. It is probable that this fossiliferous limestone is to be correlated with the Sinbad limestone member of the Moenkopi formation in the San Rafael Swell, as its interval above the base of the Moenkopi is within 10 feet of that of the highest Sinbad reported in the Swell.[59]

CONDITIONS OF DEPOSITION

Most observers have agreed that the Moenkopi red beds of southeastern Utah are of continental origin and probably accumulated, in part at least, under arid climatic conditions. Evidences of subaerial deposition are abundant, though not everywhere confined to the red portion of the formation. Raindrop imprints are recorded from the Moenkopi on the Colorado River near the mouth of Crescent Wash.[60] Casts of salt crystals are recorded from the Moenkopi in the San Rafael Swell,[61] in the Kaiparowits region,[62] and in the Little Colorado Valley [63] and have beeen found by the writer in Moenkopi red beds northeast of the area covered in the present report, in Cache Valley, near Richardson, Utah. Fossil mud cracks occur in the formation on the Green River near the head of Stillwater Canyon (see p. 55), and at several other localities in southeastern Utah.[64] Gypsum is widely distributed at or near the base of the formation on the west side of the Uncompahgre Plateau and well into Utah,[65] also in the San Rafael Swell,[66] and at higher horizons of the Moen-

[59] 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–D, pp. 96–97, 1928.

[60] 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–A, p. 18, 1923.

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

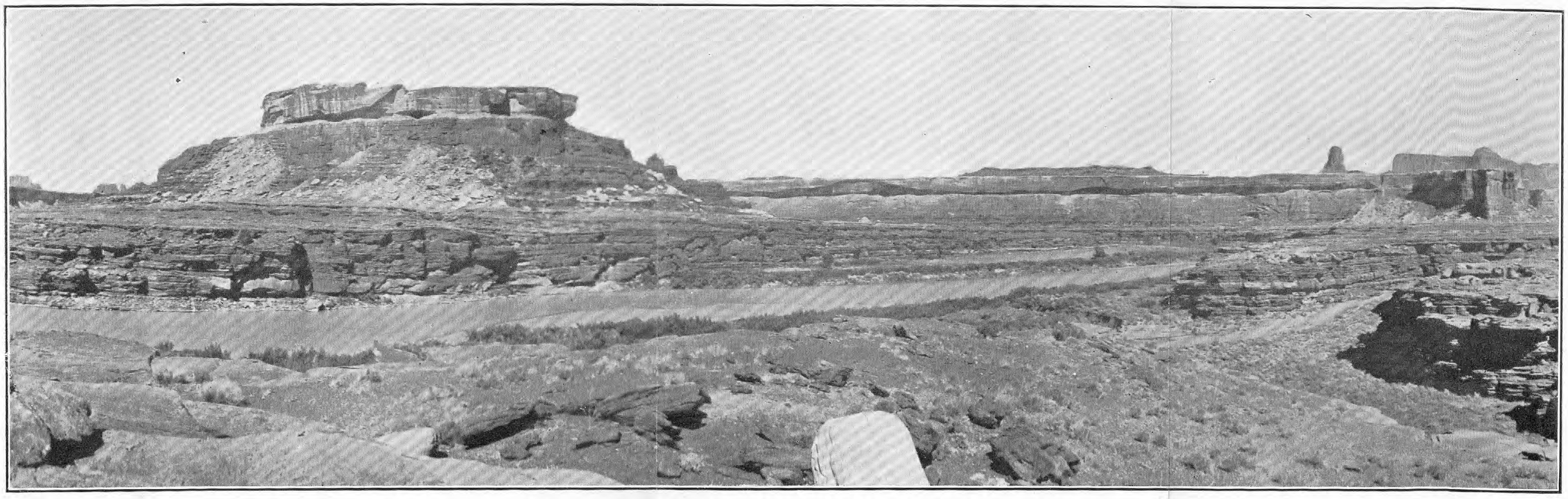
[62] Gregory, H. E., and Moore, R. C., The Kaiparowits region: U. S. Geol. Survey Prof. Paper 164, p. 48, 1931.

[63] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, p. 27, 1917.

[64] 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–D, p. 65, 1928. Gregory, H. E., and Moore, R. C., op. cit. (Prof. Paper 164), p. 48. Baker, A. A., Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, p. 36, 1933. Dane, C. H., Geology of the Salt Valley anticline and adjacent areas, Grand County, Utah: U. S. Geol. Survey Bull. 863, p. 52, 1936.

[65] Dane, C. H., op. cit. (Bull. 863), p. 44.

[66] Gilluly, James, op. cit. (Bull. 806–C), p. 86.



A. GREEN RIVER NEAR HEAD OF STILLWATER CANYON, LOOKING NORTH.

Turks Head at left, Candlestick Tower at right. Red-bed phase of Cutler formation forms foreground and basal part of cliff in middle distance, White Rim sandstone member of Cutler formation caps Turks Head and the vertical cliff in middle distance, Wingate sandstone forms vertical part of Candlestick Tower and the cliff in right distance. Navajo sandstone forms butte on right skyline. Photograph by E. C. La Rue.

B. BIGHORN MESA WITH STEER MESA IN RIGHT CENTER BACKGROUND, LOOKING EAST FROM FORT BOTTOM.

Shows light-colored phase of upper Moenkopi. T̶Rm, Moenkopi formation; T̶Rs, Shinarump conglomerate; T̶Rc, Chinle formation; Jw, Wingate sandstone; Jk, Kayenta formation. Photograph by E. C. La Rue.

kopi in the Moab district,[67] at Lees Ferry,[68] and in southwestern Utah.[69]

Gilluly [70] has advanced the idea that the red-bed part of the Moenkopi, as developed in the San Rafael Swell, represents broad deltaic conditions where the sediments were deposited under low gradient, presumably along the borders of the Lower Triassic sea that is known to have covered much of western Utah, Nevada, and Idaho, extending at one stage as far east as the San Rafael Swell, the head of Stillwater Canyon, and possibly Salt Valley.[71] An elaboration of this same general idea is presented by Dane,[72] who believes that the sea advanced initially as far east as the Uncompahgre Plateau, cutting the sub-Moenkopi erosion surface by a process of marine planation; gradually the land that had been invaded was reclaimed from the sea by the deposition of fine-grained sediments from the northeast. Baker [73] pictures a broad flood plain sloping gently toward the sea from higher lands in western Colorado, and Gregory [74] pictures a combination of flood-plain, deltaic, lacustrine, and playa deposition under arid climate, with one or two incursions of the sea.

The concept of flood-plain conditions passing locally toward the west into deltaic conditions can perhaps be applied to the Moenkopi red beds in the region between the Green and Colorado Rivers and probably in other more widely separated regions to the east and south, where conditions of sedimentation seem to have been essentially the same. These red sediments were evidently deposited over a wide area by running water but apparently under very low gradient for, although ripple bedding is widespread and very characteristic, cross bedding and lenticular scouring such as would be expected of swift currents are uncommon. The foreset beds observed on the Green River were evidently formed by deposition of the red sediments in a body of standing water, which may or may not have been marine. The thin fossiliferous limestone in the same general locality records a temporary incursion of the sea from the west, but immediately after it was deposited slight crustal or more probably tidal

[67] Baker, A. A., op. cit. (Bull. 841), p. 35.

[68] Longwell, C. R., Miser, H. D., Moore, R. C., Bryan, Kirk, and Paige, Sidney, op. cit. (Prof. Paper 132–A), p. 10.

[69] Reeside, J. B., Jr., and Bassler, Harvey, Stratigraphic sections in southwestern Utah and northwestern Arizona: U. S. Geol. Survey Prof. Paper 129–D, pp. 59, 60, 1922.

[70] Gilluly, James, op. cit. (Bull. 806–C), p. 86.

[71] Dane, C. H., op. cit. (Bull. 863), p. 43.

[72] Idem, pp. 52–54.

[73] Baker, A. A., op. cit. (Bull. 841), p. 36. See also Longwell, C. R., Miser, H. D., Moore, R. C., Bryan, Kirk, and Paige, Sidney, op. cit. (Prof. Paper 132–A), p. 10.

[74] Gregory, H. E., op. cit. (Prof. Paper 93), p. 34.

movement placed it above water so that its upper surface became mud-cracked.

The gray facies of the Moenkopi along the Green River is similar in color and composition to certain parts of the Moenkopi in the San Rafael Swell for which Gilluly and Reeside [75] have postulated in part submarine accumulation near the border of the red-bed delta, and in part delta-pool accumulation in stagnant ponds on the surface of the delta, where abundant organic material produced a reducing environment similar to that more usually characteristic of marine conditions. The apparent large area covered by the gray facies on the Green River, combined with its thickness of 200 feet or more, would seem to preclude any such local conditions as demanded by the second interpretation; on the other hand, there is no evidence other than the gray color that would suggest marine conditions. It is not known whether the fossiliferous limestone is coextensive with the gray facies, but if this relation should be disclosed by later work, some significance may be attached to it.

Dane [76] has presented ample evidence to show that much of the material making up the Moenkopi red beds that border the Uncompahgre Plateau on the southwest was derived from this upland, which in Lower Triassic time possibly continued for some distance to the northeast beyond its present defined limits. Because the Moenkopi sedimentary material becomes coarser and more arkosic toward the top, he concludes that the invasion of the Moenkopi sea on the west may have instituted a climatic change, so that the later part of the Moenkopi may have accumulated under less arid conditions, with consequently greater volumes of water available for moving sedimentary material. Other writers have not generally discussed the source of the Moenkopi sediments, and further observation is needed on the direction of dip of the cross-bedding and ripple bedding in the formation. Inasmuch as the ripple marks are generally described as current rather than oscillation ripples, a study of them may throw light on the direction or dominant direction of water-current movement during Moenkopi time. The writer's observations on eastward-dipping foreset beds within the lower Moenkopi near the head of Stillwater Canyon (see p. 56) indicate that, locally at least, the sediments may have been moving eastward, and this seems incompatible with a derivation of these sediments from the east. Derivation from the west or northwest seems equally improbable, because marine conditions existed in these directions in much

[75] Gilluly, James, and Reeside, J. B., Jr., op. cit. (Prof. Paper 150–D), p. 65. Gilluly, James, op. cit. (Bull. 806–C), p. 86.

[76] Dane, C. H., op. cit. (Bull. 863), pp. 43–52.

of early Moenkopi time. The most probable source would seem to be the north or northeast, with local distributary conditions leading to eastward-dipping foreset beds. The coarser and more lenticular character of the Moenkopi red beds in the San Rafael Swell as compared to Moenkopi deposits over much of the region to the south and east at first thought suggests a derivation from the northwest but is not incompatible with a derivation from the north or northeast.

STRATIGRAPHIC RELATIONS

The unconformity between the Moenkopi and the underlying Cutler formation is not apparent throughout the greater part of the area, but on the Cane Creek anticline there was obvious erosion of the Cutler before the Moenkopi was laid down, and along the Moab fault northwest of Moab an even more pronounced unconformity is present. There the base of the Moenkopi transgresses the beveled edges of the undifferentiated Cutler and Rico formations and part of the Hermosa formation. The Moenkopi is overlain unconformably by the Shinarump conglomerate or, where that formation is absent, by the Chinle formation.

MID-TRIASSIC UNCONFORMITY

Throughout most of the Colorado Plateau, where Triassic rocks are exposed, the lower Triassic Moenkopi formation is followed unconformably by the Upper (?) Triassic Shinarump conglomerate or by the Upper Triassic Chinle formation. On the east and southeast these formations overlap the Moenkopi regionally and rest on older rocks.[77] In a few other places the Moenkopi was completely eroded from the crests of structural upwarps before the overlying rocks were deposited, so that the later Shinarump and Chinle formations rest locally on pre-Moenkopi rocks. One of these upwarps lay along the general axis of the Moab anticline, whose faulted north end extends into the area covered by this report. The local area adjacent to this structural arch had been a zone of pronounced uplift in post-Permian pre-Triassic time, and although the renewed warping within the Triassic was intense enough to raise the complete thickness of the Moenkopi above the base level of erosion, it was apparently not as intense as the earlier deformation. This conclusion is based on a study of the angular discordance of the Moenkopi with the underlying Paleozoic formations, on the one hand, and with the overlying Shinarump and Chinle formations, on the other (fig. 2).

[77] 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, figs. 2, 4, 5, 6, 1929.

The Moenkopi is about 450 feet thick at The Dugway, 2½ miles northwest of the Colorado River at Moab, but it is truncated southeastward so that only a vanishing wedge remains at the river, beyond which the formation has been completely removed. To judge alone from stratigraphic relations on the southeast side of the river, where the Chinle rests on Hermosa beds, it might be supposed that a single large unconformity existed at the base of the Chinle, accounting for the absence, by erosion, of the Moenkopi, Cutler, Rico, and part of the Hermosa beds, yet it is known from a study of relations on the northwest side of the river that this unconformity is really the summation of two separate ones, and that the one at the base of the Chinle is really subordinate to the one that would show at the base of the Moenkopi had this formation not been removed.

Marked thinning of the Moenkopi beneath the overlying Chinle has also been observed on the crest of the Cane Creek anticline,[78] but here the formation was not entirely removed. Elsewhere in the area between the Green and Colorado Rivers evidence of the unconformity is not conspicuous. The base of the Shinarump, or of the Chinle where the Shinarump is missing, is not especially irregular. Reeside[79] reports that at several places along the cliff between the Colorado River and The Dugway, near Moab, thin and discontinuous lenses of grit and conglomerate that probably represent the Shinarump are massed chiefly in the shallow hollows that are cut in the top of the Moenkopi, showing a relief of as much as 40 feet, but the amount of this relief is believed to be exceptional within the area. The upper 12 feet of the Moenkopi in Hell Roaring Canyon differs from the underlying chocolate-brown mudstones in the assumption of peculiar colors in addition to the original brownish red, irregular splotches and masses of which remain unaltered. The new colors are lavender, blue, purple, olive, and white, commonly mottled, the most prevalent mottle-pattern being white with one of the other colors. The dominant color, however, is an unmottled lavender. This uppermost member of the Moenkopi also contains considerable gypsum, which was not observed in any of the underlying sedimentary beds. The writer is inclined to interpret the peculiar coloration of this extreme top of the Moenkopi as the product of some sort of process that took place at the old erosion surface, no attempt being made to explain the chemistry and physics of the resulting colors. Bleaching to olive green and to yellow has been noted at the very top of the Moenkopi elsewhere within the area (see p. 55) and is likewise believed to be related to the unconformity.

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[78] Baker, A. A., Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, pp. 35, 36, 1933.

[79] Reeside, J. B., Jr., unpublished notes.

UPPER (?) TRIASSIC SERIES

SHINARUMP CONGLOMERATE

NAME AND DEFINITION

The Shinarump Cliffs, in southern Utah north of the Grand Canyon, are formed by a resistant conglomerate which Powell[80] named the Shinarump conglomerate. In his usage of the name "Shinarump" in the Colorado Plateau, however, he extended it to include the stratigraphic series comprising, as now recognized, the Moenkopi, Shinarump, and Chinle formations; the conglomerate in the middle of these shales, because of its unique lithologic features, was used as the marker for the shale series. As more was learned about the stratigraphic interrelations of the different units previously grouped together under the one term, the Moenkopi and Chinle formations were split off by later workers, the name "Shinarump" being left to apply to the conglomeratic unit.

Over much of the Colorado Plateau where the Shinarump crops out, it shows unique lithologic features that distinguish it readily from the enclosing formations. It is a hard, resistant conglomeratic sandstone unit in the midst of strata that are essentially shaly, and it is widely distributed with a fairly uniform thickness. But its most distinctive feature is the character of the pebbles that enter into its composition.[81] These are well rounded, are generally not more than 2 inches in diameter, and, as described, are largely quartz, quartzite, chalcedony, and chert of various colors, including white, yellow, red, greenish, bluish, and black. Silicified wood is common in the conglomerate but is not distinctive, as it is also found in the overlying Chinle. Locally no pebbles are present and the Shinarump is composed entirely of sandstone.

Where the Chinle is dominantly sandy and conglomeratic, as in parts of the area between the Green and Colorado Rivers, the distinction between Shinarump and Chinle may become difficult. Gregory,[82] facing this same problem in parts of the Navajo country, has suggested that the term "Shinarump" be confined to the basal conglomeratic portion that contains siliceous pebbles, and that the higher conglomerates be classed as Chinle. This is the solution adopted in the present report, but it is not entirely satisfactory. Thus, in the basal conglomeratic member the pebbles may be siliceous to the extent of only 1 or 2 percent and pebbles of other types may make up the bulk of the conglomeratic material; such a conglomer-

[80] Powell, J. W., Report on the geology of the eastern portion of the Uinta Mountains and a region of country adjacent thereto, pp. 41, 68–69, U. S. Geol. and Geog. Survey Terr., 1876.

[81] Gregory, H. E., The Shinarump conglomerate: Am. Jour. Sci., 4th ser., vol. 35, pp. 426–430, 1913.

[82] Idem, p. 429.

ate is nevertheless classed as Shinarump. On the other hand, where the basal conglomerate has no siliceous pebbles of the type that normally characterize the Shinarump it is classed as Chinle. Locally the distinction between the two formations thus becomes insignificant and artificial, and it may lead to inconsistencies. However, the parts of the basal ledge mapped as Shinarump according to the criterion indicated are in general topographically prominent and continuous, and the parts classed as Chinle are in general inconspicuous and lenticular.

DISTRIBUTION AND THICKNESS

The thick conglomerate at the base of the Chinle in the Upheaval dome is highly quartzose and thus fits the definition of the Shinarump in every sense of the term. The thick conglomerate (estimated 40 feet) at the base of the Chinle where it is crossed by the Shafer trail east of The Neck contains siliceous pebbles in the proportion of about 2 out of every 100 pebbles, and after some hesitation it was mapped as Shinarump, especially as this thick ledge-forming conglomerate extends only a comparatively short distance farther east, not quite to the axis of the Cane Creek anticline. As this basal unit of the post-Moenkopi Triassic, when followed on its outcrop between the Upheaval dome and the Shafer trail, is everywhere a prominent ledge and as it was called Shinarump in these two end points, it was consequently mapped as Shinarump in the intervening distance. Along the Green River upstream from the Upheaval dome a thick variably quartzose ledge continues as far as Horsethief Point, where it wedges out. Farther up the Green lenses of conglomerate may appear for short distances at the horizon of the Shinarump but they are of slight extent. Although a few quartzose pebbles were noted in one of the lenses at one place, such pebbles are not at all common, and no Shinarump has been mapped north of Horsethief Point.

Along the Moab-Valley City road the relations of the Shinarump are especially confusing. At the northwest end of the fault cliff the conglomerate at the base of the Chinle shows no siliceous pebbles, and it was therefore mapped as Chinle. In the vicinity of the Embar-Big Six well, near the Colorado River, thin, disconnected lenses of quartz pebbles, poorly consolidated, lie in depressions on the surface of the Moenkopi. Although these lenses meet the definition of Shinarump, they are too small and inconspicuous to map. The only Shinarump mapped along this cliff occurs around the head of Little Canyon.

The thickness of the ledge commonly assignable to the Shinarump ranges from that of a thin wedge up to 50 feet.

CHARACTER

The siliceous pebbles in the Shinarump within the area mapped are well rounded and rather small, averaging less than 1 inch in diameter, though a few 2-inch pebbles were found. Rock types represented in these pebbles include argillite, quartzite, and chert. The colors are varied, including white, yellow, caramel, gray brown, olive brown, orange red, dark blue gray, and black. Besides the siliceous pebbles, many other rock types are represented in the pebbles of the conglomerates. All gradations in the series from limestone to limy sandstone are present. Mudstone and shale are also well represented; the base of the Shinarump at the head of Stillwater Canyon shows green shale pellets as much as 4 inches in diameter. The siliceous conglomerate in this section contains bone fragments that are more characteristic of the limestone conglomerates of the Chinle.

Commonly the siliceous conglomerate is present only as thin and ill-defined lenses within the Shinarump ledge, which may consist largely of other materials. The greater bulk of the ledge is gray to whitish sandstone, which may be either thin-bedded horizontally or else cross-bedded on a small scale with low dips. Besides the included conglomerate, lenses of green mudstone, more or less sandy, are common.

At several places in the region of the Cane Creek anticline and Shafer dome the Shinarump outcrop shows a thin green crust of the copper carbonate, malachite.

OUTCROP

The Shinarump normally crops out in a nearly vertical cliff, unscalable except in a few places (pl. 9, *B*).

STRATIGRAPHIC RELATIONS, FOSSILS, AND AGE

As pointed out in preceding pages, the base of the Shinarump marks one of the more pronounced unconformities in the stratigraphic section of the Colorado Plateau. At its top the Shinarump grades into the conformably overlying Chinle beds. It is probable that the Shinarump is, in part at least, equivalent to the basal part of the Chinle formation where the Shinarump is absent, especially where the basal Chinle is a thick conglomeratic sand that is indistinguishable from the Shinarump except for the absence of siliceous pebbles. Although none of the bone fragments that have been found in the Shinarump at the head of Stillwater Canyon and elsewhere in southeastern Utah have been well enough preserved for age determination, their occurrence is very similar to that of less broken up material in the Chinle from which several forms of amphibians and crocodilian reptiles have been identified and assigned to the Upper Triassic. The Shinarump seems best interpreted as the basal conglomerate of the Chinle, into which it grades imperceptibly, and there is probably no essential difference in age.[83]

UPPER TRIASSIC SERIES

CHINLE FORMATION

NAME AND DEFINITION

The Chinle formation was named by Gregory [84] from exposures in Chinle Valley, in the Navajo Reservation, northeastern Arizona. It is essentially a series of continental "red beds" and "variegated beds" characterized, throughout most of the Colorado Plateau, by peculiar intraformational lime-mud conglomerates, by conspicuous fragments and logs of petrified wood, and by the fragmental remains of a reptilian fauna that only locally is well enough preserved for identification. The persistence of these features has made the Chinle a valuable unit in correlating strata between widely separated districts.

DISTRIBUTION AND THICKNESS

The Chinle formation is exposed in canyons of the Green River and its tributaries almost as far north as Tenmile Canyon and in the canyons of the Colorado River and its tributaries along the entire border of the area mapped except for short stretches where the Colorado is crossed by the Kings Bottom and Courthouse synclines. There are also isolated exposures on the steep southwest flank of the Kings Bottom syncline, where canyons draining down the structural slope have cut into it, and there is a continuous exposure along the upthrown side of the Moab fault, from the Colorado River northwestward almost to Courthouse mail station.

The Chinle is variable in thickness. At the head of Stillwater Canyon on the Green River it is 420 feet thick and underlain by 50 feet of Shinarump. In Hell Roaring Canyon, where no Shinarump is present, the thickness is 375 feet, and at The Dugway on the Moab-Thompsons road it is only 212 feet.[85] Throughout the greater part of the region the combined thickness of the Chinle and Shinarump is about 400 feet.

CHARACTER

Lithologically, the Chinle is composed of mudstones, sandy mudstones, shales, sandstones, and conglomerates. These materials are not well assorted, and there are all gradations between the various types.

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[83] This same conclusion has been expressed by Camp, C. L., A study of the phytosaurs: California Univ. Mem., vol. 10, p. 1, 1930.

[84] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, pp. 42–43, 1917.

[85] Reeside, J. B., Jr., unpublished stratigraphic section.

In color the mudstones and shales range from gray green through lavender and purple (which, however, are quite subordinate) to chocolate brown. The different colors of the mudstones are inclined to be splotchy, showing in detail no relation to the bedding. In the gross, however, there is a correspondence between color and bedding. A lower mudstone member of the Chinle that occurs widely in the Green and Colorado Valleys contains at its top, where examined near the head of Stillwater Canyon, several discontinuous green concretionary layers, 1 to 2 feet thick, that approach in character a muddy limestone. These layers contain segregated masses of crystalline calcite, and one of them shows local small segregated masses of gray to whitish chert near its top.

The sandstones are generally grayish white to greenish gray in the lower part of the formation but become predominantly brownish red at the top; in addition a little purplish-brown sandstone may appear at random horizons. The gray sandstones commonly weather to a darker color, olive brown or reddish brown. The bulk of the sandstones, especially the greenish-gray ones, tend to be more or less mealy and friable and, unlike those of the Moenkopi, are not sharply set off from the adjoining argillaceous beds. Nor is the sharp interlamination of sandstones with shales so marked a feature as in the Moenkopi; instead a sandy zone with only a few minor lenses of green shale may make up a considerable thickness, followed by mudstone with very little sandstone. The few thin sandstone beds that form ledges in the mudstones are generally of small horizontal extent. Many of the sandstones, as well as some of the shales, are finely muscovitic. Chocolate-brown shale pellets as much as 4 inches in length are commonly found along certain zones in the sandstone.

The sandstones may be thinly and horizontally bedded or they may be cross-bedded with lop dip, or they may be massive. The stratification of the reddish muddy sandstones near the top is especially prone to be obscure, though commonly it becomes evident on a slightly weathered surface. Ripple marks are common in both the red and the gray sandstones.

The conglomerate presents two distinct types—a normal one, composed of impure sandstone and mudstone pebbles and boulders, more or less limy, with a sandy matrix, and a peculiar limestone-pellet type, with a limy mudstone matrix. The normal type is rather coarse; the basal conglomerate of the Chinle in Hell Roaring Canyon shows rounded and more or less disk-shaped boulders of gray limy sandstone as much as 2 feet in diameter. The usual colors of these sandstone boulders are gray, green, and purplish; they weather to hues of brown, olive, and gray. The muddy matrix of a conglomerate of this type in lower Salt Valley, northeast of the area mapped, contains angular fragments of quartz and feldspar as large as a quarter of an inch. This is the only occurrence known to the writer of detrital feldspar in the Chinle.

The pellets in the peculiar limestone conglomerates are usually flattened parallel to the bedding and are in general less than 1 inch in their greatest dimension. They are composed largely of limestone and muddy limestone, ranging in color through various hues of gray, green, purple, reddish, olive, buff, and brown. The unweathered pebbles are commonly gray, and the weathered ones commonly yellowish brown, olive brown, or olive gray. In addition a few pebbles of limy sandstone and limy mudstone in hues of gray and brown are present in these limestone conglomerates. The matrix at a few places contains a little clear glassy quartz in angular fragments.

In Hell Roaring Canyon the conglomerates are irregularly distributed in lenses 10 feet in greatest thickness throughout the lower sandy part of the section. From Taylor Canyon to the Cane Creek anticline the conglomerate is chiefly massed within a central dark-colored ledge, from 10 to 40 feet in thickness, leading to a pronounced threefold division of the Chinle throughout this region (pls. 4, *B*; 9, *B*). The lower division consists chiefly of gray-green, purple, and purplish-brown sandy mudstone giving at a little distance a uniform effect of bluish gray; the central division is the dark brownish-gray conglomeratic ledge; the upper division is chiefly mudstone, more or less sandy, becoming sandstone at the top, and shows a corresponding change in color from red brown below to brownish red above, the whole member giving at a little distance a general effect of brownish red. It is probable that the so-called Black Ledge in the Moab district is the same as the unit that lies in the middle of the Chinle section to the west, though it cannot be traced across the intervening synclinal region because of concealment by younger rocks. The beds, both below and above the Black Ledge at Moab, however, do not resemble very closely those at the corresponding horizons farther west.

In the bluff at the north end of the Cane Creek dome the Chinle changes in places almost entirely to sandstone. This facies forms a much steeper bluff than is usual for the formation, one that is unscalable for long distances (pl. 4, *A*).

Commonly the Chinle shows some form of red beds at the top. There are stretches, however, mostly of very small extent, where the red beds at the top grade horizontally for short distances into the greens and grays of the beds at lower horizons. The variability that is shown in the stratigraphic character of the Chinle from place to place is especially noticeable in Hell Roaring Canyon, where the lower part of the formation is in some places composed almost completely of whitish sandstone, in others in large part of green shale and mudstone.

The Chinle beds in Hell Roaring Canyon show several local unconformities in the basal half. The inclined strata are interbedded greenish sandstone and shale, with the shale greatly predominating in places. The dip of these inclined beds is commonly 30° but locally may be nearly vertical. The more nearly vertical beds are commonly sharply curved and may even be sinuous in section, as if deformed by pressure from the ends, and the individual sandstone beds in such sequences are rarely parallel. The strata both above and below the inclined beds are roughly horizontal. The truncating beds at the top are commonly sandstone with minor amounts of shale, but locally they may be largely shale. The truncation at the unconformity is not sharp, and in places the basal sandy bed of the upper horizontal series is continuous with one of the dipping sandy beds. The relations of the dipping beds to the underlying horizontal beds are everywhere obscured by talus. The thickness of the zone of dipping beds may be 20 or 30 feet.

These local unconformities have points of similarity with the delta bedding in the Chinle, described by Dane,[86] and are believed to be of the same origin—namely, produced by stream deposition in a body of standing water. They differ from the features described by Dane in being on a smaller scale, in occurring at several horizons rather than at a single one, in the muddier character of the sedimentary material involved, and in the deformed nature of the bedding. This deformation is believed to have been contemporary with the sedimentation and to have been caused by subaqueous slumpage and sliding in the rapidly accumulated, unconsolidated, and water-saturated material of the delta deposit.

OUTCROP

The Chinle crops out normally in a steep slope, more or less talus-covered, at the foot of the vertical Wingate cliff (pls. 9, *B*; 10, *A*).

FOSSILS AND AGE

Organic remains found in the Chinle in this region are typical of the formation throughout its known occurrence. They consist of fragments of bone and teeth of crocodilian reptiles and possibly large amphibians; also of fresh-water mollusks and of silicified wood. The bones and teeth were noted only in the limestone-pellet conglomerates. Fresh-water mussel shells embedded in a Chinle type of matrix were picked up in the inner "crater" of the Upheaval dome,

[86] Dane, C. H., Geology of the Salt Valley anticline and adjacent areas, Grand County, Utah: U. S. Geol. Survey Bull. 863, pp. 56, 64–65, 1936.

and similar shells, collected from the Chinle in the Moab region, have been identified by J. B. Reeside, Jr., as species of *Unio* of long-ranging types.[87] Gastropods were found in limestone conglomerate at the top of the formation in upper Salt Valley, northeast of the area mapped, and near the middle of the formation in the cliff at the northwest end of the Cane Creek anticline. The fossil wood, which in its present form is generally chert, may be gray, yellow, or black.

Studies of the Chinle vertebrate fauna from the Colorado Plateau as a whole have placed its age as most probably Upper Triassic, though a few investigators believe that part or all of it may be Middle Triassic.[88]

CONDITIONS OF DEPOSITION

The fluviatile character of the Chinle fauna and the presence of much fossil wood, which in some localities is piled together in fossil log jams,[89] are in accordance with more purely physical evidence presented by the strata themselves to indicate that they accumulated under flood-plain conditions. This physical evidence includes the poor assortment and rapid lateral and vertical variation of materials, the occurrence of shale pellets in the sandstones, and the local presence of pronounced delta bedding. The origin of the peculiar limestone-pellet conglomerates is not known, but the writer agrees with most other workers who have described them in believing that the pellets are not fragments of preexisting limestone formations, but are products of the Chinle sedimentation, formed only a short while before they were embedded in the limy matrix in which they occur. From the coarser nature and poorer assortment of the sedimentary material in the Chinle and the more massive character of its bedding, it is believed that the rivers depositing the Chinle had somewhat higher gradients than those that deposited the Moenkopi sediments, and that the climate was probably somewhat more humid. Baker, Dane, and Reeside [90] believe that most of the material

[87] Baker, A. A., Geology and oil possibilities of the Moab region, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, p. 41, 1933.

[88] Case, E. C., Indications of a cotylosaur and of a new form of fish from the Triassic beds of Texas, with remarks on the Shinarump conglomerate: Michigan Univ., Mus. Paleontology, Contr., vol. 3, no. 1, pp. 7–12, 1928. Camp, C. L., A study of the phytosaurs: California Univ. Mem., vol. 10, pp. 2–13, 1930. Von Heune, F. R., Notes on the age of the continental Triassic beds in North America, with remarks on some fossil vertebrates: U. S. Nat. Mus. Proc., vol. 69, art. 18, pp. 1–5, 1926. Branson, E. B., Triassic-Jurassic "red beds" of the Rocky Mountain region: Jour. Geology, vol. 35, pp. 610, 614–618, 1927. Branson, E. B., and Mehl, M. G., Triassic amphibians from the Rocky Mountain region: Missouri Univ. Studies in Geology, vol. 4, pp. 17–20, 1929.

[89] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, p. 50, 1917.

[90] 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, p. 50, 1936.

making up the Chinle deposits came from the southwest and west, rather than from the east.

STRATIGRAPHIC RELATIONS

As the transition from the Shinarump to the overlying Chinle is generally gradational, the boundary is arbitrarily placed at the horizon where the upper beds begin to weather back from the basal ledge into slopes that are characteristic of the shale type of outcrop, though this change may be simply from hard to soft sandstone. Where the Shinarump is absent in the area covered by this report the Chinle is unconformable on the Moenkopi.

The Chinle is overlain by the Wingate sandstone. In the opinion of the writer, the contact between them is conformable, but other observers describe an unconformity at this horizon.

JURASSIC (?) SYSTEM

GLEN CANYON GROUP

The group of sandstones comprising the Wingate, Kayenta, and Navajo was long thought to be equivalent, in whole or in part, to the La Plata sandstone in southwestern Colorado, and the term "La Plata group" was extended by some writers to include these units. Later work, however, has shown the sandstones in Utah to be older than their supposed equivalent in Colorado,[91] and hence a new group name was needed for them. Gregory and Moore [92] have supplied the name "Glen Canyon group," from Glen Canyon of the Colorado in southern Utah and northern Arizona, which has been cut in these sandstones.

The three formations of the Glen Canyon group have several features in common: they are composed dominantly of cross-bedded sandstone; their mutual boundaries are indefinite and, in part at least, gradational; they are all of continental origin; the few fossils that have been found in them have left their respective ages in doubt; and they form striking topographic features wherever they crop out.

A regional study of the Glen Canyon group and later Jurassic formations of the Colorado Plateau has recently been published,[93] and the reader is referred to that study for a discussion of such questions as regional correlation and nomenclature within the Jurassic.

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[91] 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, p. 3, 1936.

[92] Gregory, H. E., and Moore, R. C., The Kaiparowits region: U. S. Geol. Survey Prof. Paper 164, p. 61, 1931.

[93] 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, 1936.

WINGATE SANDSTONE

NAME AND DISTRIBUTION

The name "Wingate sandstone" was applied by Dutton [94] to exposures near Fort Wingate, in northwestern New Mexico. In the area covered by the present report the Wingate crops out along the Green River and its tributaries below a point near the head of Labyrinth Canyon, along the Colorado River and its tributaries except for short stretches where the river is crossed by the Kings Bottom and Courthouse synclines, and along the upthrown side of the Moab fault from the Colorado River nearly to Courthouse mail station.

OUTCROP

The Wingate sandstone forms the most spectacular topographic feature in the whole region. For scores of miles it runs as a reddish-brown vertical cliff, 300 feet or more in height, forming an impassable barrier that separates the canyon areas from the relatively flat plateau above (pls. 4; 9, *B*; 10, *A*). The cliff is generally capped by the lower beds of the Kayenta formation, which form a continuation of the Wingate cliff and add about 100 feet to its height.

From a distance the Wingate part of the cliff appears to be a single massive bed, cut by vertical fracture systems. The face of the cliff is generally determined by these fractures, which extend with remarkably smooth or perhaps conchoidal surfaces through the complete thickness of the sandstone, irrespective of bedding. In a few places, especially along the points of divides, the recession of the cliffs on opposite sides has left slender isolated columns of the standstone extending upward for the complete thickness of the Wingate and perhaps part of the Kayenta (pl. 4, *B*). The Wingate outcrop is characterized by relatively straight lines combined with sharp angles. There are alcoves and amphitheaters, the walls of which commonly join the main face of the cliff at sharp angles. The point of the Wingate cliff along a divide is commonly acute-angled.

Drainage lines across the Wingate in general have only a slight effect on the character of the outcrop. An unimpressive flat-valleyed wash on the plateau above, developed entirely on the Kayenta, plunges over the vertical Wingate cliff in a sheer fall of 300 feet or more and continues as a sinuous thread through a deep canyon. On the flanks of the Kings Bottom syncline where the beds are tilted at angles of 5° to 15°, the outcrop of the Wingate may form a long slope, in contrast to the type of outcrop in flat-lying beds.

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[94] Dutton, C. E., Mount Taylor and the Zuñi Plateau: U. S. Geol. Survey 6th Ann. Rept., pp. 136–137, 1885.

THICKNESS

The thickness of the formation is 290 feet at the mouth of Hell Roaring Canyon, 305 feet in Taylor Canyon, 340 feet near Candlestick Tower, and 295 feet in the upper end of Salt Valley, northeast of the area mapped. Gilluly and Reeside[95] report a thickness of only 210 feet along the Moab fault, 2¾ miles south of Courthouse mail station.

CHARACTER

The color of the freshly broken sandstone is buff brown (locally pinkish brown), very similar to that of the Navajo sandstone, but the exposed cliff soon takes on a characteristic reddish-brown color. Long-continued exposure produces a black "desert varnish" that is typical of the Wingate, although it is far less abundant than the prevailing red-brown color. The sandstone is uniformly fine-grained. It is made up of cross-bedded layers alternating with thinner horizontally bedded layers. The average thickness of the beds is in most places 1 to 4 feet. The cross-bedding may be tangential, but far more commonly it is oblique; the dip of the foreset laminae is generally less than 15°. On the Murphy trail, however, well above the base of the sandstone, a bed 25 feet thick is made up of a single set of tangential cross-bedding laminae, dipping steeply, and undoubtedly beds of this type are present elsewhere in the Wingate of the area but were not observed owing to the inaccessible position of most parts of the formation in the Wingate outcrops. On the whole the general aspect of the Wingate, in the area covered by the present report, indicates prevailing deposition by water, but the thick tangentially cross-bedded layers can, without much doubt, be attributed to wind deposition.

In the walls of the lower part of Upheaval Canyon a light-gray to purplish-gray slabby limestone, 2½ feet thick, appears in the Wingate about 100 feet above the base. It contains a little bluish to pinkish chert. Although examined carefully for fossils, none were found. What is apparently the same limestone was observed in the south wall of the Wingate butte west of Steer Mesa, 2 miles to the south. A similar limestone, but somewhat thinner (maximum 1 foot) and discontinuous, occurs at the same height above the base of the formation in Salt Valley, northeast of the area mapped. It likewise contains irregular segregations of chert, which are white to blood red.

A 10-foot bed of chocolate-brown micaceous shale observed in the south wall of Hell Roaring Canyon about 6 miles above its mouth

[95] 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–D, p. 108, 1928.

is interpreted as the top of the Wingate, from its similarity to thinner shale beds in the upper 15 feet of this sandstone at the same locality and from the apparently unconformable relation that it bears to the overlying Kayenta sandstones. Gilluly and Reeside[96] also report discontinuous lenses of red-brown shale in the Wingate near Courthouse mail station.

CONDITIONS OF DEPOSITION

The physical conditions that prevailed during Wingate time are not well understood, but the writer pictures a flat basin region into which many small streams from the west and northwest carried and deposited sand derived almost entirely from the erosion of an earlier sandstone terrane. Absence of any considerable amount of shaly material in the deposits and of depositional features that could be interpreted as stream channels of a fluviatile deposit would be explainable by the uniformly sandy nature of the source material and also perhaps in part by a supposed seasonal limitation of the rainfall to periods of torrential downpour. The region was probably arid, and it contained a certain amount of drifting sand during at least part of Wingate time, perhaps during cycles of increased aridity. Local and ephemeral playa lakes in the basin allowed the accumulation of thin beds of fresh-water limestone, but there were probably many of these lakes formed and destroyed without leaving any sedimentary record. The presence of more shaly material in the Wingate near the east and south margins of the basin of deposition[97] precludes the possibility that the waters depositing the more sandy phase of the Wingate could have come from the east or south, though if judged solely by the character of the marginal sediments they could possibly have come from the southeast. A much more probable source, however, was the low, flat upland on the west which first developed in Upper Triassic time and which Crickmay[98] has called the Sonoran geanticline.

STRATIGRAPHIC RELATIONS

From a distance the contact between the Wingate and Chinle appears to be sharp, but when examined in detail the actual contact is rather difficult to determine. The upper sandstones of the Chinle are practically identical in composition, texture, and character of bedding with the lower part of the Wingate, though they are possibly a little redder. The Chinle sandstones weather back step-

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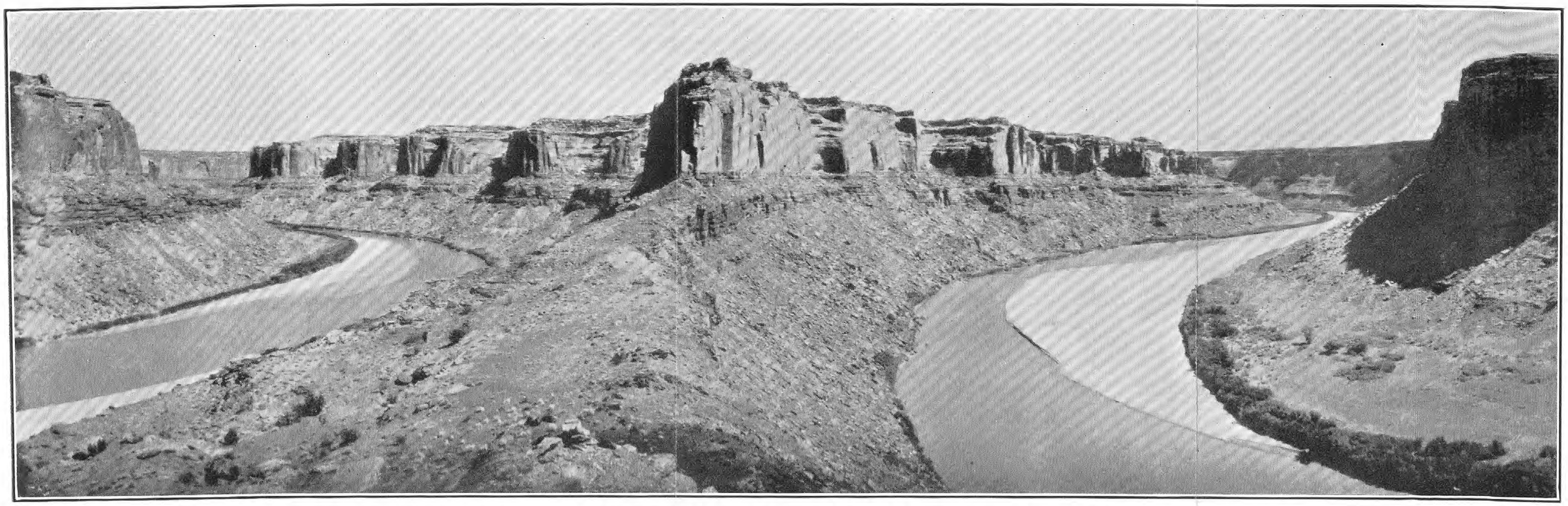
[96] Gilluly, James, and Reeside, J. B., Jr., Sedimentary rocks of the San Rafael Swell and some adjacent areas in eastern Utah: U. S. Geol. Survey Prof. Paper 150–D, p. 108, 1928.

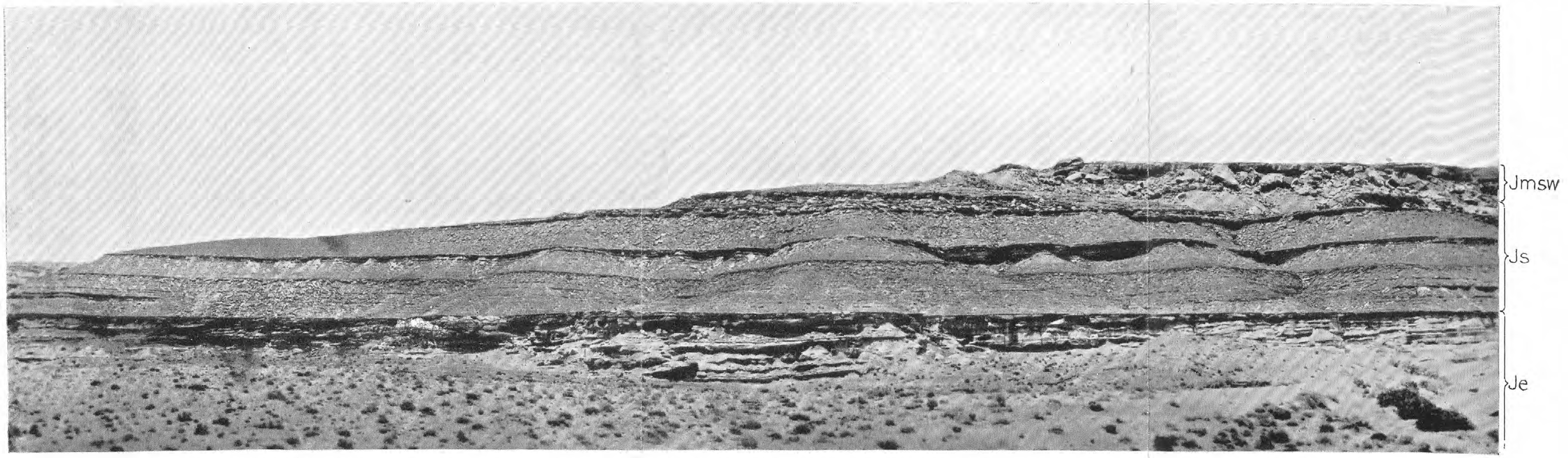
[97] Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., op. cit. (Prof. Paper 183), p. 53.

[98] Crickmay, C. H., Jurassic history of North America; its bearing on the development of continental structure: Am. Philos. Soc. Proc., vol. 70, No. 1, pp. 20, 38–39, 1931.



A. NECK OF BOWKNOT BEND ON GREEN RIVER, LOOKING EAST TOWARD THE LOOP.

Moenkopi formation exposed just above water level. Chinle formation forms slope and Wingate sandstone forms massive cliff capped by basal part of Kayenta formation. Photograph by E. C. La Rue.



B. UNCONFORMITY AT BASE OF SUMMERVILLE FORMATION A FEW HUNDRED FEET WEST OF THE NORTHEAST TRIBUTARY OF WHITE WASH, LOOKING NORTHWEST.

Je, Entrada sandstone; Js, Summerville formation; Jmsw, lower part of Salt Wash sandstone member of Morrison formation. Photograph by J. D. Sears.

like at the top and form a molding ledge at the base of the Wingate. The top of this ledge is not everywhere at the same horizon, and beds that in one place make up the top of the Chinle ledge in other places form the base of the vertical Wingate cliff. The zone of fluctuation may amount to several feet. The Chinle sandstone along this molding ledge contains numerous thin lenticular beds (maximum 8 inches thick) carrying chocolate-brown and more rarely green shale pellets. This occurrence at first thought suggests that these sandstones are Wingate containing shale pellets of the Chinle, but as they grade almost insensibly into the underlying mudstones that are definitely Chinle, the logical stratigraphic break comes at the top of the ledge; the shale pellets are best interpreted as contemporaneous with the Chinle deposition. The writer believes that the Wingate is essentially conformable on the Chinle with a zone of lithologic transition between them.

Chert in the form of very angular chips of detrital origin occurs in several places at the top of the Chinle, or else at the very base of the Wingate. It ranges from white to salmon red in color, and the fragments may be as much as 3 inches across, though they are commonly much less. More varied types of fragmental material along the Wingate-Chinle contact, which some writers have interpreted as an indication of significant unconformity, have been observed rather widely in southeastern Utah and northeastern Arizona.[99] Mud cracks at the same horizon have also been commonly reported [1] and have been suggested as evidence of emergence and erosion. But, as Dane has pointed out,[2] the fact that such evanescent features as mud cracks have been preserved is direct evidence against any prolonged erosion; they indicate simply subaerial conditions. The type of unconformity commonly described as occurring at the base of the Wingate, in which this sandstone fills scoured channels in the Chinle shales, is also a feature to be expected of continental deposits and to which no significance as a geologic time break can be attached. Pronounced variations in the thickness of the upper Chinle beneath the Wingate rim along the Moab fault northwest of the Colorado River were formerly interpreted to be evidence of unconformity accom-

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[99] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, p. 48, 1917. 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–A, pp. 12, 17, 1923. Gregory, H. E., and Moore, R. C., The Kaiparowits region: U. S. Geol. Survey Prof. Paper 164, p. 58, 1931.

[1] Gilbert, G. K., Report on the geology of the Henry Mountains, p. 9, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1880. Gregory, H. E., op. cit. (Prof. Paper 93), p. 48. 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–D, p. 108, 1928. Gregory, H. E., and Moore, R. C., op. cit. (Prof. Paper 164), p. 58. Dane, C. H., Geology of the Salt Valley anticline and adjacent areas, Grand County, Utah: U. S. Geol. Survey Bull. 863, pp. 58, 59, 61, 72, 1936.

[2] Dane, C. H., op. cit. (Bull. 863), pp. 72–73.

panied by erosional truncation at the base of the Wingate,[3] but later observation by the writer has shown that the increase in Chinle thickness to the southeast, amounting to 150 feet within 3 miles, takes place by internal thickening within the upper Chinle rather than at the base of the Wingate.

On the whole, the writer believes that there is no significant hiatus between the Wingate and Chinle. This belief is in harmony with the observations of Cross [4] in the San Juan country of southwestern Colorado, where what are believed to be the stratigraphic equivalents of the Wingate and Chinle are grouped together as the **Dolores formation**, within which no hiatus is recognized.

The Wingate sandstone is overlain by the Kayenta formation, whose basal 100 feet or so is composed of sandstone that does not differ markedly from that of the Wingate. The contact between them is placed at the horizon where the massive-appearing sandstone below is followed by the more obviously bedded sandstones above. This change in any given section is commonly sharp, yet when followed laterally it may disappear, so that the beds immediately above may blend with those below in a smooth face. The relation has usually been interpreted as one of conformity, with gradational contact, but Longwell and others [5] believe that at many localities along the Colorado River in southeastern Utah an erosional unconformity occurs at this horizon.

A local erosional unconformity along which, within a distance of 200 feet, the Kayenta cuts 15 or 20 feet into sandstone and subordinate chocolate-brown shale assigned to the Wingate is exposed on the south side of Hell Roaring Canyon 6 miles above its mouth. No great significance can be attached to an unconformity of this type, as it is a characteristic feature of fluviatile deposits such as make up the basal beds of the Kayenta. The writer believes, however, that the stratigraphic break at the top of the Wingate may possibly represent a greater hiatus than the break at the base of the Wingate, which has been described by different writers. Features in addition to the local unconformity mentioned that suggest an unconformity between the Wingate and Kayenta are, first, the conspicuous bleached zone in the upper 10 or 15 feet of the Wingate, which may run for considerable distances along the cliff, and second, the abundant occurrence throughout the Kayenta of small detrital pebbles of sandstone, some of which resemble the sandstone of the Wingate.

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[3] 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. 801, 1927.

[4] Cross, Whitman, Stratigraphic results of a reconnaissance in western Colorado and Utah: Jour. Geology, vol. 15, pp. 650, 656, 1907.

[5] Longwell, C. R., Miser, H. D., Moore, R. C., Bryan, Kirk, and Paige, Sidney, op. cit., pp. 13, 19, 1923.

It is at least conceivable that the bleached zone at the top of the Wingate might be related in some way to fairly recent movements of ground water. Under the climatic conditions existing today, however, there is no indication of any water movement at this level. What the conditions were in the past we cannot say, but even though there were a free circulation at this level it is difficult to see just how such circulation could bleach a sandstone—an effect that would require a reducing property of the water—and it is even more questionable that the bleached zone would be sharply defined above by the contact of the Wingate with the Kayenta. The more logical deduction would seem to be either that the bleached zone is primary or that the bleaching took place in the interval between the deposition of the Wingate and that of the Kayenta. The bleaching is not confined to a stratigraphic unit, as would be expected under the first hypothesis; on the other hand, it does show the limitation to the very top of the formation regardless of bedding and the gradation into the normal rock below that would be expected under the second hypothesis. This suggests at least that there may have been a period of erosion before the Kayenta was laid down.

The writer believes that in those sections where there is no apparent break between the well-bedded Keyenta and the more massive Wingate the actual stratigraphic break may, nevertheless, be present, but that conditions have not been such that it has been brought out by weathering. The difference in lithology between the Wingate sand and the basal sands of the Kayenta is small; the latter are slightly coarser and perhaps more porous. It would not be surprising, therefore, if the break between the two should in places be obscure, just as the numerous breaks between the individual beds of the Wingate are.

AGE

No fossils that are diagnostic of age have yet been found in the Wingate, though tracks of dinosaurs that are indeterminate have been reported from the sandstone in the San Rafael Swell[6] and from the lower part of the sandstone near the mouth of the San Juan River.[7] Dating of the Wingate is therefore dependent on its relations to other formations of known age. It is underlain by the Chinle, of Upper Triassic age, and overlain successively by the Kayenta and Navajo, undated, and the Carmel, of Upper Jurassic age. The three formations of the Glen Canyon group may therefore represent all or any part of the interval from Upper Triassic to

[6] 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–D, p. 70, 1928.

[7] 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–A, p. 13, 1923.

Upper Jurassic inclusive. Because most observers have believed that the mutual formational boundaries within the Glen Canyon group are gradational and that an unconformity occurs at the base of the group (base of the Wingate), as well as a probable unconformity at the top, the general tendency has been to consider all three formations as Jurassic, and more probably Lower or Middle Jurassic. As discussed above, the writer believes that the stratigraphic break at the top of the Wingate is greater than the one at its base, with the implication that the Wingate may be Upper Triassic and the Kayenta and Navajo Lower or Middle Jurassic. In the absence of more definite evidence, however, the prevailing classification of the Glen Canyon group as Jurassic (?) will be followed, more exact dating being left to await the discovery of fossil evidence that will surely be forthcoming in time. Baker, Dane, and Reeside [8] class the Glen Canyon group as Jurassic (?), with the stated possibility that later information may prove the Wingate and Kayenta to be Upper Triassic.

KAYENTA FORMATION

NAME AND DEFINITION

The Kayenta formation is named for the town of Kayenta, Ariz., near which it is well exposed. The term was first used by Baker [9] to replace the name Todilto, which he and others [10] believed to have been incorrectly applied in southeastern Utah. The Kayenta is a continental and probably fluviatile formation, composed largely of cross-bedded sandstone with minor amounts of shale and fresh-water limestone.

DISTRIBUTION AND OUTCROP

The Kayenta formation crops out characteristically in the form of a bench between the Wingate and Navajo sandstones. This bench is held up largely by a resistant sandy zone some 60 feet in thickness that begins about 100 feet or less above the base of the formation; the lower Kayenta, as mentioned previously, forms a continuation of the Wingate cliff, and the soft upper Kayenta weathers back and forms a slope below cliffs of the Navajo sandstone. The Kayenta bench forms the greater part of the plateau above the Wingate cliffs, extending from the south point of the plateau near Junction Butte northward as a widening wedge to an irregular east-west line con-

[8] 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, p. 58, 1936.

[9] Baker, A. A., Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, pp. 45–46, 1933.

[10] Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., op. cit. (Prof. Paper 183), p. 5.

necting Monitor and Merrimac Buttes with the mouth of Tenmile Canyon. This bench is well wooded by juniper and piñon except for extensive grassy flats, such as the Big Flat and parts of Grays Pasture, that are developed largely on the upper beds of the Kayenta. It is traversed by numerous shallow washes whose wooded slopes show widespread exposures of the sandstone in the form of low discontinuous rounded ledges. A large part of the water that is of importance in the economy of the area between the two rivers is stored in sandstone "tanks" or reservoirs in the Kayenta, not only in the drainage channels but also on the benches developed on the harder sandstones. A horse can traverse the greater part of the Kayenta outcrop without any great difficulty, although some of the washes in their lower and more deeply cut courses require considerable search before a satisfactory crossing can be found. By following the higher divides and grassy flats the field party under the direction of the writer was able to drive a car from the north across the plateau to The Neck, a large part of the line traveled being on the Kayenta.

THICKNESS

The formation is 250 feet thick on Hell Roaring Canyon 6 miles from its mouth, 205 feet thick in upper Salt Valley, northeast of the area mapped, and, according to Gilluly and Reeside,[11] 160 feet thick along the Moab fault near Courthouse mail station.

CHARACTER

The Kayenta formation is composed largely of sandstone, with minor amounts of shale and limestone, chiefly at the top. The lower beds are very similar to the sands of the Wingate except that they are not broken by vertical joints and their cross-bedded character stands out on the weathered surface. In color they are buffy brown. On the south side of Hell Roaring Canyon 6 miles above its mouth one or two thin (1 to 2 feet) lenses of chocolate-brown sandy shale are present about 50 feet above the base, and it is probable that similar shale lenses occur elsewhere in the lower part of the Kayenta. These lower beds grade up imperceptibly into the overlying resistant zone. The hard sandstone that holds up the Kayenta bench is in general white to light gray, with commonly a pinkish tinge; some thin lenses, however, are deep brown to deep purplish brown, and certain lenses weather to yellowish and reddish brown. This resistant member is composed of medium-sized quartz grains, with a little muscovite, and has a calcareous cement. It is distinctly coarser than the sandstones of the Wingate.

[11] Gilluly, James, and Reeside, J. B., Jr., op. cit. (Prof. Paper 150–D), p. 108.

These lower sandstones are rather coarsely cross-bedded on the whole, but locally they may show rather thin-bedded cross-bedding of the "torrential" type. The angle of foreset is low, and the cross-bedded laminae are obliquely truncated below. The beds are manifestly water-laid. They are peculiar in that they contain numerous lenses in which pebbles of older sandstones are concentrated, forming a sort of sandstone conglomerate in which the texture of the enclosing sand does not differ in any way from that of the normal unconglomeratic sandstone. These sandstone pebbles are commonly a very small fraction of an inch in diameter but boulders 4 feet in diameter were observed in the Upheaval dome. These larger ones are angular to subrounded in shape. The pebbles are generally brown or red brown but may also be gray, yellowish, olive brown, purplish, or brownish red. Many of them are distinctly calcareous, and a few are best described as olive-yellow limestones. As previously noted, some of them may have been derived from the Wingate sandstone, but it is doubtful if any of the larger ones could have had that origin. Besides the sandy pebbles, all the Kayenta sandstones show pellets of chocolate-brown shale, generally concentrated in certain zones from 1 to 5 feet thick. One particular shale slab noted in sandstone, 25 feet above the base of the Kayenta in Hell Roaring Canyon, was 2 feet across.

The upper Kayenta differs from the lower part in showing more shaly beds, more thin-bedded material, and a more varied assortment of colors. The shales appear as thin lenses in certain sections only. Part of the sandstones are muddy, thin-bedded horizontally, and ripple-marked and show abundant muscovite on the cleavage planes; sandstone of this type is generally red brown, less commonly lavender. Other colors noted were white, yellow, buff, and reddish buff (sandstone) and chocolate brown, lavender, and gray (shale). Certain beds of buff sandstone at the top show angular, thin platy, or lenticular fragments of white opaque chert. When these fragments are broken the center is seen to be brown or flesh-colored and more translucent than the surface.

Certain of the muddy sandstones at the top of the Kayenta on the northeast side of Salt Valley, northeast of the area mapped, show excellent mud cracks.

Gray slabby limestone at the top of the Kayenta caps two or three benches in the general region of the Upheaval dome, more specifically on Bighorn Mesa and on Grays Pasture, west of The Seep. It is everywhere thin (2 to 8 feet) and of slight areal extent. No fossils were found in it.

FOSSILS, AGE, AND STRATIGRAPHIC RELATIONS

The only fossils found by the writer in the Kayenta were taken from a massive limy sandstone near the top of the formation, in Salt Valley, northeast of the area mapped and about 13 miles southeast of U. S. Highway 450. The sandstone is medium- to fine-grained, white, with lavender and brown splotchings, and contains numerous green, chocolate-brown, and lavender shale pellets as much as 1 inch in diameter but averaging a quarter of an inch. It is about 2 feet thick and lies at the top of a thin series of interbedded sandstones of the same general type and chocolate-brown shale. The 20-foot interval between the fossil ledge and the overlying basal sandstone of the Navajo is composed largely of a dirty-whitish sandstone that weathers buffy to brown and shows a little oblique cross-bedding, but there are also minor bands of chocolate-brown shale and at the top a platy zone of lavender-gray limy sandstone.

The fossils have been studied by J. B. Reeside, Jr. They are well-preserved shells belonging to two or possibly three undescribed species of *Unio* and are apparently the same as the forms that were collected by Baker at the same horizon on the southeast side of the Colorado.[12] They are of no value as age determinants but give some clue as to the conditions of sedimentation. A small unidentifiable pelecypod is also reported from the Kayenta formation in the San Rafael Swell.[13]

Dinosaur tracks in the Kayenta have been reported from two localities in northeastern Arizona[14] and from the Green River Desert, west of the area treated in this report.[15] Lull[16] has studied photographs and measurements of the tracks found at one of the Arizona localities and has reported them to be not older than the latest Triassic. The only other fossils found in the Kayenta have been indeterminable stems of plants.

In the absence of diagnostic fossils, opinions as to the age of the formation have to be based on stratigraphic relations. As pointed out in the discussion of the age of the Wingate, the formations of the Glen Canyon group embrace part or all of the time interval between Upper Triassic and Upper Jurassic inclusive and the Kayenta is believed to be Jurassic rather than Triassic. Baker, Dane, and Reeside[17] class it as Jurassic (?), with the stated possibility that later information may prove it to be Upper Triassic.

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[12] Baker, A. A., op. cit. (Bull. 841), pp. 45, 46.

[13] Gilluly, James, and Reeside, J. B., Jr., op. cit. (Prof. Paper 150–D), p. 71.

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

[15] Baker, A. A., op. cit. (Bull. 841), p. 46, 1933.

[16] Lull, R. S., quoted in Gregory, op. cit. (Prof. Paper 93), p. 56.

[17] Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., op. cit. (Prof. Paper 183), p. 58.

The Kayenta formation overlies the Wingate sandstone with local erosional unconformity, and the writer believes that this erosional unconformity is rather widespread, though most other observers believe that the contact is essentially gradational. The Kayenta is overlain conformably, with gradational boundary, by the Navajo sandstone.

NAVAJO SANDSTONE

NAME AND DEFINITION

Gregory[18] applied the name "Navajo sandstone" to a prominent light-colored, highly cross-bedded sandstone that is widely exposed in the northern part of the Navajo Reservation, in northeastern Arizona. The sandstone also crops out widely through southern Utah, northern Arizona, and southeastern Nevada and probably connects beneath younger formations with the Nugget sandstone of northern Utah, western Wyoming, and southeastern Idaho.[19] It is the upper of the three formations comprised in the Glen Canyon group.

DISTRIBUTION AND THICKNESS

In the area treated in this report the Navajo sandstone crops out along the divides on the higher part of the plateau between the Green and Colorado Rivers, and it is the surface rock over most of Grays Pasture. In addition, it crops out in the ringlike syncline surrounding the Upheaval dome, in the northeast limb of the Kings Bottom syncline near the Colorado River, in the Courthouse syncline and Moab anticline near the Colorado River, and in a broad belt from the head of Labyrinth Canyon eastward to the Moab fault 2 miles or so south of Courthouse mail station.

The thickness of the Navajo near the head of Spring Canyon is about 330 feet, though this figure may be subject to some error, as it was calculated from strike and dip measurements taken at the base, combined with altitudes on the top and bottom of the formation, which are here over a mile apart. Near Courthouse mail station the Navajo is reported to be only 158 feet thick,[20] but in two localities a short distance northeast of the area mapped, one in upper Salt Valley and the other southwest of Elephant Butte, the thickness is reported to be 250 and 300 feet, respectively.[21] In the Green River Desert, 8 miles west of Fort Bottom on the Green River, the thickness is 500 feet.[22] Because the Navajo sandstone is generally the

[18] Gregory, H. E., op. cit. (Prof. Paper 93), pp. 52, 57.
[19] Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., op. cit. (Prof. Paper 183), p. 5.
[20] Gilluly, James, and Reeside, J. B., Jr., op. cit. (Prof. Paper 150–D), p. 108.
[21] Dane, C. H., Geology of the Salt Valley anticline and adjacent areas, Grand County, Utah: U. S. Geol. Survey Bull. 863, p. 86, 1936.
[22] Baker, A. A., Geology of the Green River Desert-Cataract Canyon region, Utah: U. S. Geol. Survey Bull. — (in preparation).

highest formation exposed along drainage divides in the area covered by this report, or else because the width of its outcrop is generally so great, satisfactory determinations of its thickness cannot commonly be made.

CHARACTER

The Navajo is composed largely of sandstone but contains a few thin beds of limestone. The sandstone is medium- to fine-grained and dominantly yellowish white, pale buff, or buffy brown, tarnishing brown or black. It is tangentially cross-bedded on a magnificent scale. The lamination of the foreset beds is generally very perfect, down to a fraction of an inch in thickness. Some individual laminae, which at the top have the maximum dip of 25°, may show a length of 100 feet before they finally disappear by blending tangentially into the basal beds of the unit. Individual beds that in detail show foreset laminae may reach 20 or 30 feet in thickness. Among geologists who have studied the cross-bedding of the Navajo there has been general though not unanimous agreement that the sand was deposited largely by wind under widespread desert conditions. Dreikanter, or wind-faceted pebbles, have been reported from the Navajo sandstone of the San Rafael Swell [23] and the Green River Desert.[24] A small percentage of the Navajo sandstone is brownish red. The only red color noted in the area mapped, at one locality near the head of Spring Canyon, occurs in a lens about 500 feet long and 10 feet thick, which differs from the rest of the Navajo in the neighborhood by being horizontally bedded instead of cross-bedded, showing deposition by water. It is probable that such lenses represent an accumulation of sand in temporary ponds among areas of dunes during comparatively wet periods.

The limestones that appear in the Navajo occur as isolated thin beds of small areal extent (estimated less than 1 square mile). The maximum observed thickness is 15 feet, on the top of The Knoll, though most of them do not exceed 3 or 4 feet. The color of the limestone is generally blue gray, but shades of purple are not uncommon. Pinkish and salmon to opaque red (jasper) chert nodules are of common occurrence in the limestone, and blue-gray chert lenses were noted in the limestone on top of The Knoll. Although a careful search for fossils was made, none were found. These limestones are interpreted as of fresh-water origin. They are not confined to any particular horizon in the Navajo.

The upper part of the Navajo sandstone in the region south of Courthouse Spring shows a considerable amount of angular chert, chiefly concentrated along certain beds.

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[23] Gilluly, James, and Reeside, J. B., Jr., op. cit. (Prof. Paper 150–D), p. 72.

[24] Baker, A. A., op. cit. (Bull. —, in preparation).

OUTCROP

The lower part of the Navajo crops out as a rounded cliff in which there is a tendency for alcoves to develop (pl. 11, *B*). The upper part, except where limestones are present, or where the formation is overlain by higher formations, tends to weather into picturesque rounded domelike forms (pl. 11, *A*), or else into tree-covered, brushy, or grassy flats (pls. 6, *A*; 11, *A*). Some of the rocks stand out like huge cathedrals or mosques (Whitbeck Rock) surrounded by relatively flat tree- or grass-covered areas in which no outcrops are found. Where limestones are present in the section they form the protecting cap rock on flat-topped mesas and buttes. The Knoll (pl. 5, *B*) and Aztec Butte (pl. 6, *A*), two of the most conspicuous land marks of the region, are capped by limestone in the Navajo formation.

STRATIGRAPHIC RELATIONS

The boundary between the Kayenta and Navajo is arbitrary, as there is a complete gradation from the dominantly water-laid material below to the dominantly wind-laid material above through a series that may be as much as 40 feet thick, in which the two types of bedding alternate in thicknesses of 10 feet or less. This transition series consists of thick beds with the cross-bedding laminae tangential below, zones made up of thinner beds with the cross-bedding laminae obliquely truncated below, and zones showing horizontal though generally poor bedding. The first is interpreted as eolian, the other two as water-laid. As this transition series commonly forms the base of the topographic features developed in the Navajo, it has generally been mapped with that formation. Most of the better springs of the region appear at the base of this transition zone or else along faults that cut this zone, from which presumably the water ascends.

At the base of the Navajo in Salt Valley, northeast of the area mapped and about 6 miles from U. S. Highway 450, an excellent system of mud cracks is developed in a thin shale layer on top of a limy sand. This sand is about 1½ feet thick and lies on top of Kayenta chocolate-brown shale. The mud cracks have a maximum width of 2 inches and separate the mud surface into blocks that may be a foot across. This occurrence of mud cracks in the base of the Navajo recalls similar occurrences in the same general transition zone at the top of the Kayenta in this region.

The Navajo is overlain by the Carmel formation. There is an abrupt change in lithology across the contact, but the plane of the contact is apparently smooth, and no evidence of an erosional break has been found in the area covered by the present report.

AGE

No fossils that are diagnostic of geologic age have yet been found in the Navajo sandstone, but in 1934 there was unearthed from the upper Navajo in northeastern Arizona the skeleton of a small theropod dinosaur that is reported to show Upper Triassic affinities.[25] However, because the species represented in this find is apparently new and belongs to a little-known group, and because a complete study has not yet been made of it, final weight cannot at present be attached to this tentative age assignment. The only other vertebrate remains known from the Navajo consist of another skeleton of a small theropodlike dinosaur found in northeastern Arizona in 1933, but this form is so entirely different from any dinosaur yet discovered that it has no value in geologic age correlation.[26] Indeterminate tracks of dinosaurs are reported from the lower part of the Navajo on the east flank of the San Rafael Swell.[27]

As pointed out in the discussion of the age of the Wingate sandstone, the formations of the Glen Canyon group embrace part or all of the time interval between Upper Triassic and Upper Jurassic, inclusive, and heretofore the Navajo has been considered to be more probably Jurassic than Triassic. Baker, Dane, and Reeside[28] class the formations of the Glen Canyon group as Jurassic (?), with the stated belief that later work may prove the Navajo to be definitely Jurassic. They correlate it with the Nugget sandstone of northern Utah, from which a single marine shell (*Trigonia*), indicative of Jurassic age, has recently been reported.[29] They also believe, considering the occurrence of this shell and the known distribution of Jurassic seas, that the Middle Jurassic is a more probable age assignment for the Nugget sandstone than the Lower Jurassic.

JURASSIC SYSTEM

SAN RAFAEL GROUP

A varicolored series comprising sandstones, shales, some gypsum, and some limestone and containing, in the limestone, marine invertebrates of Upper Jurassic age, has been known for many years in

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[25] Brady, L. F., Preliminary note on the occurrence of a primitive theropod in the Navajo: Am. Jour. Sci., 5th ser., vol. 30, pp. 210–215, 1935; A note concerning the fragmentary remains of a small theropod recovered from the Navajo sandstone in northern Arizona: Idem, vol. 31, p. 150, 1936.

[26] Camp, C. L., and Vander Hoof, V. L., Small bipedal dinosaur from the Jurassic of northern Arizona: Geol. Soc. America Proc. 1934, p. 384, 1934. Camp, C. L., quoted in Brady, L. F., op. cit. (1935), p. 215.

[27] Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., op. cit. (Prof. Paper 183), p. 6.

[28] Idem, p. 58.

[29] Mathews, A. A. L., Mesozoic stratigraphy of the central Wasatch Mountains: Oberlin Coll. Lab. Bull., new ser., No. 1, p. 42, 1931.

southern Utah. The classification of this series into its component formations is of comparatively recent date, however, largely because the area in which it is best developed and in which the interrelations of its component units are most clearly shown—namely, the San Rafael Swell—was long neglected by geologists. The term "San Rafael group" was introduced by Gilluly and Reeside [30] in 1928 to include four formations whose names and stratigraphic characteristics were presented in the same paper for the first time. The San Rafael group, in its type area, includes in ascending order the Carmel, Entrada, Curtis, and Summerville formations.

Along the Green River near the mouth of the San Rafael River all four formations of the group are present, but they have changed considerably from the characters that they show in the San Rafael Swell and the group as a whole has thinned perceptibly. A short distance east of the Green River the Curtis formation loses its identity by merging into the Summerville, but the other three formations are distinct and mappable units across the area treated in this report and into adjacent areas on the northeast and southeast. The Carmel and Curtis formations are not fossiliferous, but they can be traced almost continuously across the Green River Desert into their fossiliferous facies in the San Rafael Swell.

Questions of correlation and nomenclature involving all the Jurassic formations of the Colorado Plateau have been thoroughly treated in a recent paper,[31] and no attempt will be made in the present report to repeat these phases of the stratigraphy.

CARMEL FORMATION

NAME, DISTRIBUTION, AND THICKNESS

The term "Carmel formation" first appears in the paper by Gilluly and Reeside,[32] but they state that the name was taken from a manuscript report by Gregory and Moore,[33] which was printed some time later. The formation is named for the village of Mount Carmel, in southwestern Utah, where Gilbert first described the rocks that make up the formation. In the area between the Green and Colorado Rivers the Carmel is exposed along an irregular belt from the Green River near the mouth of the San Rafael roughly eastward to the Moab fault at Courthouse Spring, and in another belt running from the Moab fault at The Dugway northeastward across the Moab anti-

[30] Gilluly, James, and Reeside, J. B., Jr., op. cit. (Prof. Paper 150–D), p. 73.
[31] Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., op. cit. (Prof. Paper 183).
[32] Gilluly, James, and Reeside, J. B., Jr., op. cit. (Prof. Paper 150–D), p. 73.
[33] Gregory, H. E., and Moore, R. C., The Kaiparowits region: U. S. Geol. Survey Prof. Paper 164, p. 72, 1931.

cline and Courthouse syncline. Its thickness is 125 feet at the north end of Tenmile Butte and 152 feet near Courthouse Spring.[34]

CHARACTER

In contrast to its lithology in the San Rafael Swell and other parts of southern Utah, the Carmel contains no limestone in the area treated in this report. It is composed chiefly of pink to red to reddish-brown muddy sandstone with, locally, considerable gray to reddish sandy mudstone. The mudstone occurs in the upper part of the formation near the Green River, but eastward it grades into the reddish-brown muddy sandstone that forms the top of the Carmel in Courthouse Rock. This gradation takes place chiefly in the 2 or 3 miles west of Tenmile Wash. In the eastern part of the area light-colored beds are subordinate to the red facies of the Carmel and appear chiefly in the basal part of the formation, which toward the Green River is entirely red. These light-colored beds toward the east are largely sandstone, in part limy, and are white, yellowish white, and dirty grayish. They are interbedded with red muddy sandstones, are discontinuous along the outcrop, and commonly show unaccountable lenslike thickenings and thinnings. They may be massive, thin-bedded, ripple-bedded, or cross-bedded at a low angle. Many of the Carmel sections show thin partings of chocolate-brown or maroon shale that weathers to a purplish color. The top of the Carmel in Tenmile Butte is formed by 4 inches of purplish-brown shale, and in the Courthouse Rock section by 2½ feet of maroon shale.

The Carmel formation contains a noticeable amount of chert showing two types of occurrence. In one type the chert occurs as angular fragments of detrital origin, a quarter to half an inch in maximum diameter, embedded in the sandstone of the basal 10 feet of the formation in Tenmile Butte; the color may be dull white to flesh-colored. In the other and more conspicuous type the chert is of replacement origin and occurs as thin lenses and nodules embedded in the red beds. This chert is white, flesh-colored, pink, purplish, or red. Characteristically, the color occurs in the center of the nodule and grades out into opaque white at the surface, which may show a pitted "bony" texture.

The bedding of the Carmel, except in certain of the whitish sandstone lenses previously described, is chiefly horizontal, though uniformly poor. Throughout the greater part of the area studied the bedding is irregular and contorted. The upper sandstones east of

[34] The last figure is obtained from reinterpretation of the Carmel section given by Gilluly and Reeside (op. cit. (Prof. Paper 150–D), pp. 107–108) to include the lower 105 feet there assigned to the Entrada. Baker and Dane, however, in the respective reports on the areas described by them (Bull. 841, p. 48; Bull. 863, pp. 90–91, 99–100), apparently follow Gilluly and Reeside in placing strata equivalent to these in the Entrada.

Tenmile Wash show rather widespread and large-scale angular discordances both among themselves and with the beds of the overlying Entrada sandstone. The line of this discordance with the Entrada is irregular in detail and is in many places marked by a thin shale bed. These discordances near and at the top of the Carmel are not distinct in every section but appear to die out and come in again laterally. As the interval below the plane of discordance increases, the beds of the Carmel become flatter and flatter, so that at the base they are horizontal. In this respect the discordances at the top of the Carmel resemble the intraformational one in the Moenkopi described on page 54.

OUTCROP

Except in the region between Tenmile Wash and the Green River and in the vicinity of Du Binky Spring, the upper Carmel forms the base of the cliff made by the Entrada sandstone, and the lower Carmel beds weather into slopes characteristic of the shale type of weathering (pl. 12). Where not protected by the overlying Entrada, the Carmel has in general been swept from the hummocky flat formed on the upper Navajo. West of Tenmile Wash, where the upper Carmel is shaly and the lower Carmel sandy, the upper part weathers into broad soil-covered flats and the lower part weathers into the rounded forms that are commonly called "rock babies." In the vicinity of Du Binky Spring the stratigraphic series from Navajo to Morrison has been tilted northward and its surface truncated by a Tertiary (?) peneplain (p. 114).

STRATIGRAPHIC RELATIONS AND AGE

No evidence was found in the area covered by this report to show that the Carmel is other than conformable on the underlying Navajo, although the fairly sharp lithologic boundary between the two suggests a stratigraphic break. The Carmel is overlain by the Entrada sandstone with apparent conformity. Although in many sections the discordant bedding in the top part of the Carmel may strongly resemble an angular unconformity beneath the Entrada, this discordance does not extend to the lower beds of the Carmel, which are essentially parallel to the bedding of the Entrada. Eastward the Carmel becomes thinner and more sandy and finally, in an area beyond that described in this report, disappears from the section.[35] Westward it becomes thicker and grades into the partially marine Carmel of the San Rafael Swell. No Carmel fossils have been found in the

[35] Dane, C. H., Geology of the Salt Valley anticline and adjacent areas, Grand County, Utah: U. S. Geol. Survey Bull. 863, pp. 90–91, 1936.

area between the Green and Colorado Rivers, but limestones in the Carmel of the San Rafael Swell contain numerous marine invertebrates of early Upper Jurassic age.[36]

CONDITIONS OF DEPOSITION

The conditions under which the Carmel was deposited in this area are not clear. The long sweeping bedding laminae that show discordances among themselves and with overlying strata resemble foreset beds of a delta, and their contortion suggests deformation, under slight loading, of unconsolidated material heavily saturated with water—just such conditions as might be expected along the submerged seaward border of a delta. It is known that marine conditions prevailed only a short distance to the west during at least part and possibly all of Carmel time, so that the geographic position of these strata is in accordance with the conception of them as delta deposits, or marginal deposits of a sea. The lower light-colored sandstones in the Courthouse region may well represent marine deposits antedating the invasion of the overlying deltaic material.

ENTRADA SANDSTONE

NAME AND DEFINITION

The Entrada sandstone was named by Gilluly and Reeside [37] from outcrops of the formation at Entrada Point, in the northern part of the San Rafael Swell. Throughout the Swell it is essentially an earthy red-brown sandstone that crops out in a steep horizontally corrugated slope, but in the general area east of the Green River the sandstone is purer, lighter-colored, and more massive and crops out as a smooth, steep, or vertical cliff (pl. 12). At its top, separated from the main body of sandstone by a soft zone of red shaly material, is another sandstone unit to which the name "Moab tongue of the Entrada sandstone" has been applied.[38] The Moab tongue decreases in thickness toward the west, and correspondingly the shaly beds under it increase in thickness. In the western part of the area treated in this report the Moab tongue finally loses its identity, and the underlying shaly beds merge into the overlying Summerville formation, with which they are lithologically identical (fig. 3). East and southeast of the area treated in this report the shaly beds decrease in thickness and finally disappear, so that the Moab tongue becomes inseparable from the main mass of the Entrada. Over large areas

[36] Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., op. cit. (Prof. Paper 183), p. 58.
[37] Gilluly, James, and Reeside, J. B., Jr., op. cit. (Prof. Paper 150–D), p. 76.
[38] 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. 804, 1927.

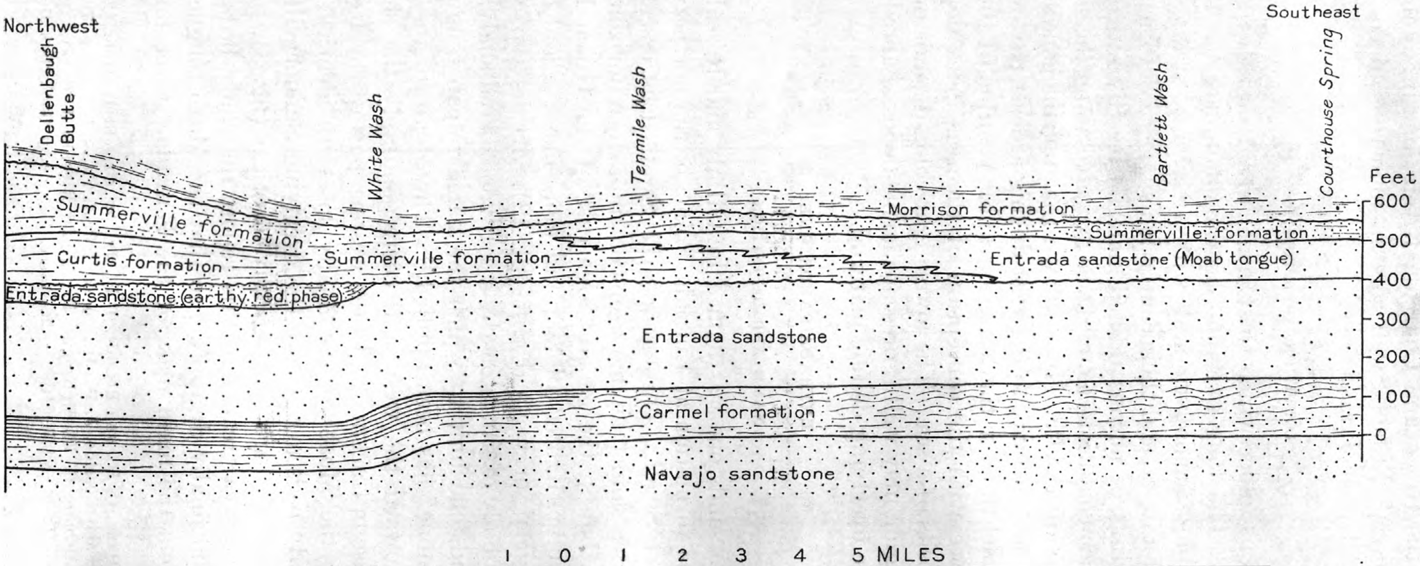
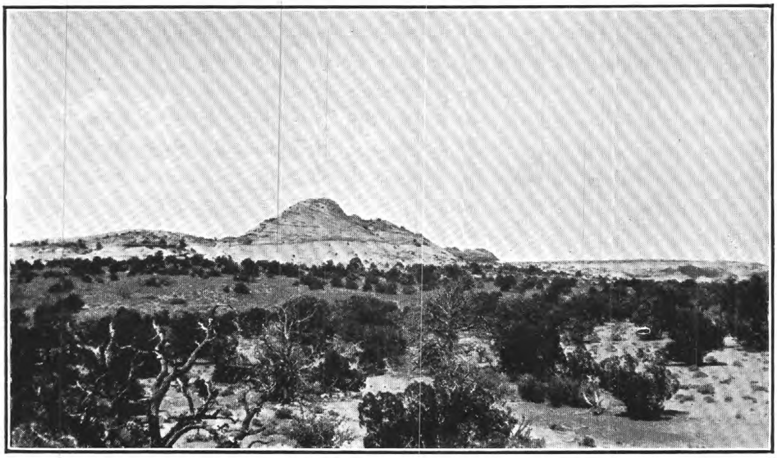
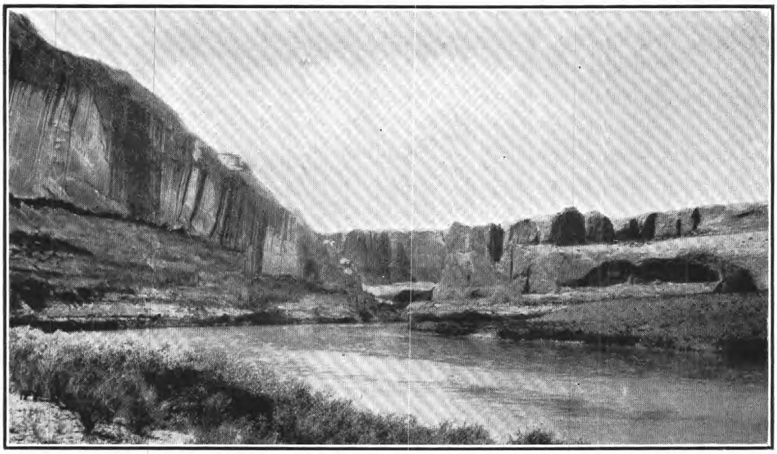


FIGURE 3.—Diagram showing stratigraphic relations of San Rafael group between Dellenbaugh Butte and Courthouse Spring.



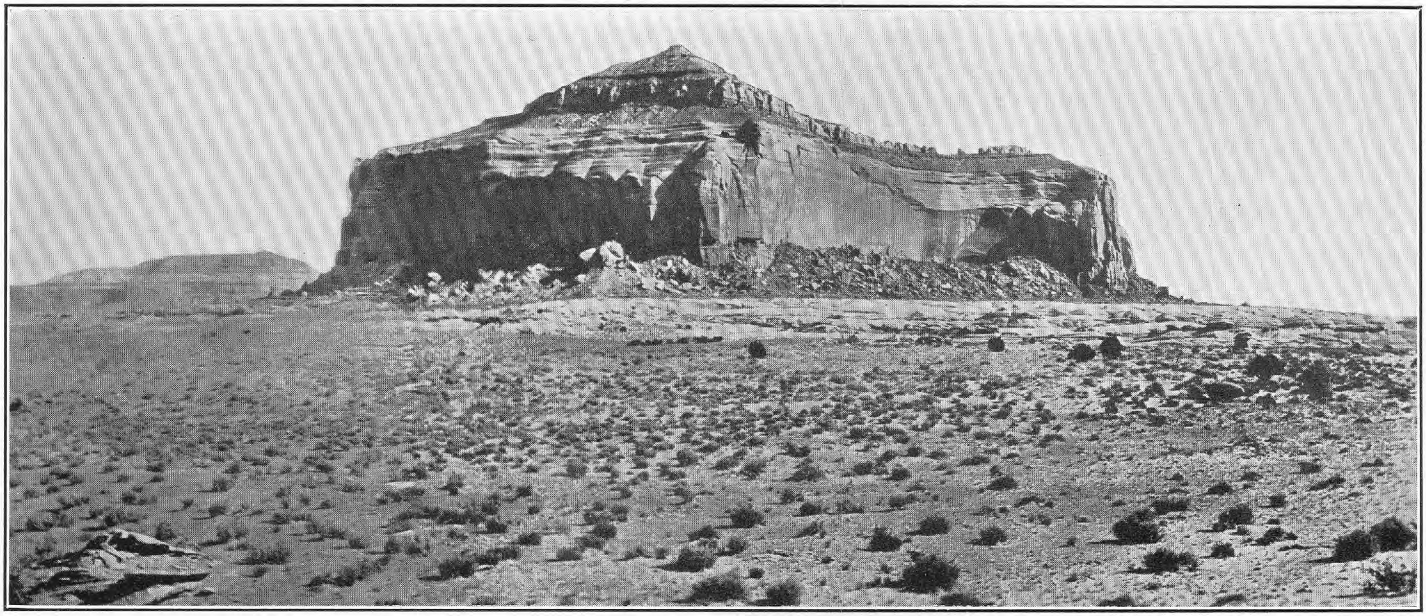
A. MUFFIN BUTTE, LOOKING NORTH.

Shows characteristic dome topography developed on Navajo sandstone.



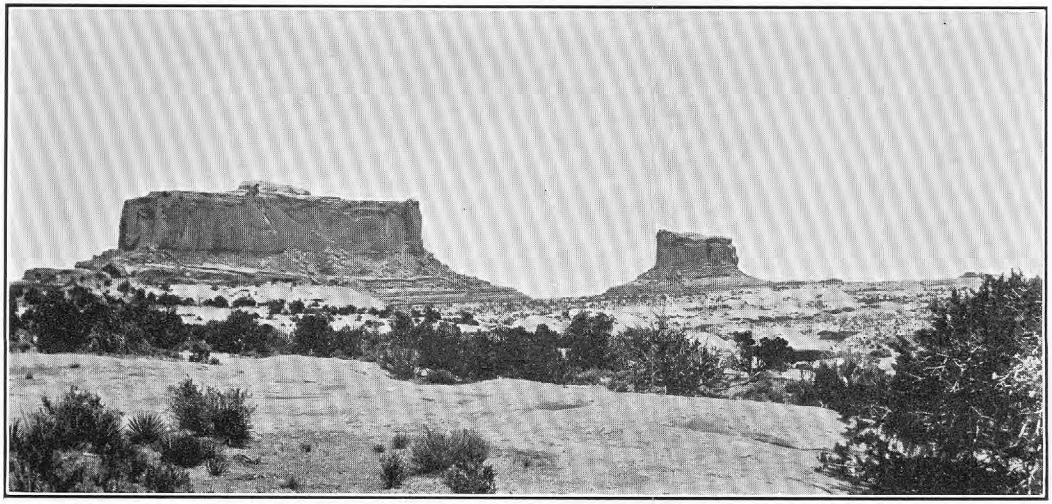
B. CLIFFS BORDERING COLORADO RIVER ABOUT 3 MILES ABOVE MOAB VALLEY, LOOKING DOWNSTREAM.

Shows characteristic outcrop of Navajo sandstone along drainage lines, stained by desert varnish.



A. TENMILE BUTTE, LOOKING SOUTH.

Butte capped by Morrison formation; sandstone of Moab tongue forms serrated skyline on right side of butte; a tongue of Summerville formation below Moab tongue; Carmel formation largely talus-covered at base of cliff formed of Entrada sandstone; Navajo sandstone forms platform below the talus and also the foreground. Photograph by Otho Murphy.



B. MONITOR BUTTE AT RIGHT AND MERRIMAC BUTTE AT LEFT, LOOKING NORTHEAST.

Navajo sandstone forms white platform, Carmel formation forms slope at base of the vertical cliff, which is formed by the Entrada sandstone, and remnant of Moab sandstone member caps Merrimac Butte. Photograph by S. S. Nye.

where the shale no longer exists, however, the Moab tongue preserves its identity as a single massive bed forming the top of the Entrada.

DISTRIBUTION AND THICKNESS

The Entrada sandstone crops out in four areas or belts: (1) In a broad area extending from the Moab fault near The Dugway north across the basin of Courthouse Wash onto the southwest flank of the Salt Valley anticline; (2) in a general northwesterly zone from the Moab fault near Courthouse Rock to the Green River at the mouth of the San Rafael River; (3) in another northwesterly belt on the upthrown side of the fault north of Salt Wash; and (4) in a small area along the Green River on the upthrown side of the Little Grand fault. The Moab tongue forms part of the outcrop in areas southeast of Tenmile Wash, but a short distance northwest of this drainage line it is no longer recognizable.

Exclusive of the Moab tongue, the Entrada sandstone is about 250 feet thick in the general vicinity of Courthouse Spring and is 270 feet thick at the north end of Tenmile Butte. The Moab tongue is at least 50 feet thick near Courthouse Spring, where it is essentially in contact with the main Entrada ledge, but the original thickness may have been somewhat greater, for the overlying strata and possibly part of the Moab tongue have been eroded away. The Moab tongue is 115 feet thick on the west side of the head of Bartlett Wash, where it is underlain by 33 feet of chocolate-brown shales, and 56 feet thick just east of Tenmile Wash, where it is separated from the underlying Entrada by 72 feet of red shaly beds.

CHARACTER OF MAIN ENTRADA

The main member of the Entrada sandstone is generally light reddish brown or light brownish red, more or less banded with grayish white or yellowish. This banding is not very well defined; it may show abrupt or gradual transitions to the solid red facies, both horizontally and vertically. The general effect is pink or light red, in contrast with the darker red brown of the Wingate. A dark red-brown to black surface tarnish is not so common as in the Wingate. On the west flank of the Salt Valley anticline, as viewed from the vicinity of Courthouse mail station, the color of the Entrada is a full red.

The sandstone is made up of alternating cross-bedded and horizontally bedded layers, of which the former constitute the greater percentage. There are a few thin chocolate-brown shale partings, but they are not conspicuous. The cross-bedded layers reach 10 feet in maximum thickness though they are commonly only 6 to 12 inches thick; usually they have well-defined parallel boundaries. In general the foreset laminae show dips of 10° or less and may be obliquely or less commonly tangentially truncated below. In many places torrential cross-bedding is shown in textbook perfection. The character of the bedding indicates prevailing deposition by running water. The thicker beds, however, show the steeper dips (as much as 25° at the top) and the tangential blending with the horizontal beds below that are commonly attributed to an eolian origin.

Texturally the Entrada sandstone is medium- to fine-grained, the two grain sizes commonly alternating on a very fine scale. The lamination of the cross-bedding is expressed chiefly in this manner rather than by the presence of any distinct parting planes. The medium-grained material is composed of well-rounded quartz grains, with in places a little opaque white chert in the form of small subangular grains. The top part of the sandstone near Tenmile Wash contains small calcareous concretions, about half an inch in diameter.

The Entrada commonly shows a concentration of hematite cement—enough to impart the hematite color and streak—in irregular pipelike bodies that cut more or less vertically across the bedding of the sandstone. Such bodies can as a general rule be traced only a short distance before they die out, possibly by withdrawal from the plane of the outcrop. Similar concentrations of hematite cement are commonly found in the Moab tongue, and less commonly in the Carmel formation and Navajo sandstone.

From the Green River eastward almost to the point where the outcrop of the Entrada crosses White Wash, and also on the north side of the Salt Wash graben block, the top of the Entrada is a brownish-red muddy sandstone that weathers into rounded "rock baby" surfaces. The bedding is poor but appears to be largely horizontal (pl. 10, *B*). This facies of the Entrada resembles the typical Entrada of the San Rafael Swell and is unlike anything developed to the east. The maximum thickness measured was about 70 feet, southeast of the Colorado Fuel & Iron Co.'s manganese camp. Eastward, within half a mile, this facies is cut out by an unconformity at the base of the Summerville (pl. 10, *B*), but probably it was never deposited much east of its present easternmost occurrence. A short distance west of the Green River this earthy facies of the Entrada is 142 feet thick.[39]

The facies of the Entrada occurring in the San Rafael Swell is possibly of marine origin,[40] whereas the more massive sandier facies of the formation as developed throughout most of the area treated in this report is believed to be of continental origin.

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[39] Gilluly, James, and Reeside, J. B., Jr., op. city. (Prof. Paper 150–D), p. 107.
[40] Idem, p. 78.

CHARACTER OF MOAB TONGUE

In the area covered by this report the sandstone of the Moab tongue is typically white, but on a part of the southwest flank of the Salt Valley anticline opposite Courthouse mail station it is pink. Much of the same features of bedding structure are shown as were described for the main Entrada mass, including the alternation of cross-bedded with horizontally bedded layers, the low dip—10° or less—of the foreset laminae, and their generally oblique truncation below. No cross-bedding was observed that could be ascribed to an eolian origin. The Moab tongue differs in detail from the main Entrada by containing, in addition to the dominant quartz sand, reddish grains of chert and also rust spots that record some iron-bearing mineral, probably pyrite, that has been completely altered. The sandstone commonly contains small calcareous concretions, about half an inch in diameter, and some of the bedding laminae are cemented by calcite, causing them to stand out in relief on the weathered surface.

OUTCROP

The main Entrada crops out typically as a smooth-walled vertical or steeply sloping cliff (pl. 12). The vertical cliffs resemble those formed on the Wingate except for the difference in color, the absence of conspicuous jointing, and the common rounding of the top of the cliff into a shoulder. Where the Moab tongue has been removed or where, as near the Green River, it was never present, the Entrada weathers into rounded bare-rock buttes somewhat similar to those developed on the Navajo sandstone, but the presence of horizontal bedding in the Entrada leads to profiles made up of irregularly changing slopes.

A conspicuous erosion feature of the Entrada is the occurrence of rather closely spaced solution cavities, a few inches to a foot in diameter, that develop in the bases of many of the cross-bedded layers (especially the red ones) wherever the Entrada has weathered back into a steeply sloping surface. At a little distance these cavities resemble a miniature colony of cliff dwellings arranged in a pattern of horizontal lines at different levels.

The Moab tongue crops out as a perpendicular ledge that is essentially continuous with the underlying Entrada cliff where there are no intervening shales, or that is separated from the Entrada cliff by a steep, narrow slope where shales are present. The soft deposits of the overlying Summerville formation are commonly stripped from the top of the Moab tongue, leaving it exposed as an extensive cliff-bordered bench. White benches and dip slopes on top of the Moab tongue are especially conspicuous along the middle course of Courthouse Wash and in the region between Courthouse and Brink's Springs.

FOSSILS

The only relics of animal life in Entrada time appear in the form of tracks in the very top of the Moab sandstone tongue just below Courthouse Spring. The tracks have been preserved on a bedding plane that was either horizontal or else foreset at a very low angle. The extent of the slab that is at present exposed in the bottom of the wash is only about 10 feet. The trails of two or three animals are shown, the most perfectly preserved one of which records a bipedal creature with three functional toes, a 2½-inch foot, and an 8-inch stride. Photographs and a sketch of these tracks were submitted to Charles W. Gilmore, of the United States National Museum, who reports that the animal making the tracks was probably an ornithopod dinosaur but that nothing further can be determined from the available material.

STRATIGRAPHIC RELATIONS AND AGE

The base of the Entrada sandstone is conformable on the Carmel formation. East of the area mapped, however, the Entrada overlaps all the older formations, locally down to the pre-Cambrian, and is widely extended through central and northern Colorado, where it is unconformable on the underlying formations.[41] At the top of the Entrada the Moab tongue intertongues conformably with the overlying Summerville formation but near the Green River, where the Moab tongue is absent, the Summerville or the Curtis formation rests with angular unconformity upon the main member of the Entrada.

The sandstone of the Moab tongue is almost or quite in contact with the underlying Entrada in the area between Courthouse Spring and Brink's Spring. Eastward from Courthouse Spring the shaly zone at its base is either entirely wanting or else is represented by beds that, although not typical, can logically be classed as a part of the Moab tongue. South and west from the Courthouse-Brink's Spring area a thin red shale parting at the base of the Moab tongue begins to thicken at the expense of the sandstone. Southward the change cannot be followed far owing to the removal of the beds by erosion; westward, however, the exposures are continuous and the stratigraphic relations are clearly shown (fig. 3). On the west side of Bartlett Wash near its head the Moab tongue is 115 feet thick and the underlying chocolate-brown shales 33 feet; just southeast of

[41] Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., op. cit. (Prof. Paper 183), pp. 7, 17–18, 27, 28.

Tenmile Wash the sandstone is 56 feet thick and the underlying red beds, typically Summerville in lithology and topographic expression, 72 feet; 2 miles or less northwest of Tenmile Wash the Moab is gone entirely, and beds characteristic of the Summerville formation extend down to the massive member of the Entrada. The thin wedge of the Moab tongue where it finally disappears is the time equivalent of only the uppermost beds of the Moab tongue in the Courthouse Spring region, and the lower Moab near Courthouse Spring is the equivalent of Summerville beds farther west. The gradation from sandstone typical of the Moab to more shaly red beds typical of the Summerville at the base of the Moab ledge was observed on the southeast side of Tenmile Wash, near the place where the ledge swings across the wash.

Five miles northwest of the last exposures of the Moab tongue, in the general locality west of the head of White Wash, a perceptible angular unconformity appears at the top of the Entrada, between this formation and the Summerville-Curtis (the lower part of the Summerville grading laterally into the Curtis on the west). Between the Colorado Fuel & Iron Co.'s manganese camp and a point on the north side of White Wash half a mile to the east, 70 feet of red muddy sandstone of the facies characteristic of the San Rafael Swell, which forms the top of the Entrada in this area, is cut out (pl. 10, *B*, fig. 3). This unconformity also shows along the north side of the Salt Wash graben, where 40 feet of the red muddy sandstone is cut out within a distance of 1¼ miles east of the road that leads north from the manganese camp to the spring west of Levi well No. 2. West of these localities in which the unconformity is noticeable the thickness of the muddy sandstone facies at the top of the Entrada does not increase very much, at least in the area east of the Green River, and it appears that the bedding of the Entrada is about parallel to that of the Curtis. An unconformity with a basal conglomerate at the base of the Curtis is present in the San Rafael Swell, however, several miles farther west.[42]

The horizon of this unconformity, when extended eastward, lies between the Moab tongue and the main ledge of the Entrada. No unconformity has been observed by the writer between these sandstones. Dane[43] describes the Moab tongue in the country northeast of the area treated in this report as essentially conformable on the Entrada with an indefinite gradational contact, and Baker[44] states that in the southern part of the Moab district the Moab tongue

[42] Gilluly, James, and Reeside, J. B., Jr., op. cit. (Prof. Paper 150–D), pp. 78, 79.

[43] Dane, C. H., Geology of the Salt Valley anticline and adjacent areas, Grand County, Utah: U. S. Geol. Survey Bull. 863, p. 94, 1936.

[44] Baker, A. A., Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, p. 50, 1933.

cannot be sharply separated from the rest of the Entrada. Prommel,[45] however, reports a slight unconformity at this horizon along the Courthouse syncline and Salt Valley anticline. In view of the erosional unconformity present in localities which during Upper Jurassic time lay supposedly seaward from the localities in which the Moab tongue is present,[46] and also in view of the definite truncation to the east that can be observed a short distance from the Green River, it seems probable that this unconformity is somewhat more significant than heretofore suspected. Crickmay [47] has called attention to widespread uplift and erosion at this horizon in British Columbia, southern Alaska, and California. It is questionable, however, whether a moderate uplift that might initiate erosion in an area that was previously near or at sea level would be great enough to produce erosion any considerable distance back from the sea in a bordering land area that was undergoing continental sedimentation. At most it might do no more than produce a temporary halt in sedimentation, such as might be recorded in the obscure break at the base of the Moab sandstone tongue in areas where this sandstone is separable with difficulty from the main Entrada.

No fossils that are diagnostic of age have been found in the Entrada, but in the San Rafael Swell the underlying Carmel contains marine fossils of early Upper Jurassic age, and the overlying Curtis has fossils of middle Upper Jurassic age.

CONDITIONS OF DEPOSITION

During the greater part of Upper Jurassic time marine conditions prevailed in northern Utah, eastern Idaho, and western Wyoming. The margins of the sea fluctuated widely, and at two different epochs marine waters extended into southeastern Utah, as recorded in the deposits of the Carmel and Curtis formations. In the San Rafael Swell the red earthy sandstone facies of the Entrada sandstone, lying between these two unquestionably marine formations, is believed by Gilluly and Reeside [48] to be probably also of marine origin, and Baker and others [49] refer to the San Rafael Entrada as a marginal facies of marine rocks to the north. All these authors consider the more sandy facies of the Entrada, as developed east of the Green River, to be a continental phase of the Entrada, in part,[50] or even largely,[51] of eolian origin.

[45] Prommel, H. W. C., Geology and structure of portions of Grand and San Juan Counties Utah: Am. Assoc. Petroleum Geologists Bull., vol. 7, p. 392, 1923.

[46] Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., op. cit. (Prof. Paper 183), pp. 54–55.

[47] Crickmay, C. H., Jurassic history of North America; its bearing on the development of continental structure: Am. Philos. Soc. Proc., vol. 70, No. 1, pp. 45–47, 1931.

[48] Gilluly, James, and Reeside, J. B., Jr., op. cit. (Prof. Paper 150–D), p. 78.

[49] Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., op. cit. (Prof. Paper 183), p. 54.

[50] Gilluly, James, and Reeside, J. B., Jr., op. cit. (Prof. Paper 150–D), p. 78.

[51] Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., op. cit. (Prof. Paper 183), p. 54.

In the writer's opinion, which is based on the character of the bedding, the main Entrada sandstone in the region covered by this report was deposited by water except for a few beds that are probably of eolian origin. The conditions of deposition seem to have been most comparable with those that prevailed during the deposition of the Wingate sandstone, but what these conditions were is rather hard to visualize. If the Entrada and Wingate represent widespread stream deposits, as seems most probable to the writer, the source of sediments must have been some preexisting sandstone from which shaly material had been largely segregated in an earlier cycle of sedimentation. During Entrada time, because of the presence of an open sea to the north and probably to the west, the source of the Entrada sands is believed to have been to the east or south.[52] The facies of the Entrada in the San Rafael Swell supposedly represents a marine deposit, and the shaly constituent of this facies probably came from a different source. The occurrence of these earthy sandstones in only the upper part of the Entrada for a short distance east of the Green River would seemingly indicate a lowering of the land relative to sea level toward the end of Entrada time.

The western fringe of the Moab tongue was undoubtedly deposited by water, as was also much of this sandstone in areas to the east where the Moab is thicker and in contact with the main Entrada.[53] The tracks at Courthouse Spring prove that the sand in which they are imprinted was deposited by water. They could not have been preserved in dry wind-blown sand unless its surface had been recently wetted by rain, and such a surface would present a different appearance from the smooth, even bedding plane that is shown. Deposition by water, however, does not necessarily mean that the surface was under water at the time the tracks were made; indeed it would seem that chances for preservation would be best on a surface that was originally formed under water but that was later exposed to the air. Such conditions would certainly prevail in fluviatile or delta deposits. Whatever were the actual conditions of sedimentation under which the track-bearing sand was deposited, they cannot be assumed positively for the Entrada or Moab sandstone as a whole, because of the stratigraphic position of these tracks, at the top of the massive sandstones and beneath a red-bed series that is unquestionably of water deposition.

The thinning and disappearance of the Moab sandstone tongue to the west and northwest indicates that its source was to the east

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[52] Dane, C. H. (op. cit. (Bull. 863), p. 102), suggests an eastern source and points out certain differences of composition that suggest a different source from that of the sandstones of the Glen Canyon group.

[53] Dane, C. H., op. cit. (Bull. 863), p. 102.

or southeast and probably the same as that of the main mass of the Entrada.

CURTIS FORMATION

NAME, DISTRIBUTION, AND THICKNESS

The Curtis formation was named by Gilluly and Reeside[54] for exposures on Curtis Point, in the northern part of the San Rafael Swell. The formation extends only a short distance into the area covered by the present report. It is restricted to a belt with a maximum width of about 5 miles that lies along the east side of the Green River above the mouth of the San Rafael. Within this belt it crops out in three separate subparallel lines, separated by faults. Its thickness is 130 feet in Dellenbaugh Butte (pl. 13, *A*), but only 34 feet just west of the Green River at the Little Grand fault.[55]

CHARACTER

In the San Rafael Swell the Curtis is a well-defined unit, differing from the Summerville not only in its light greenish-gray to whitish color but also in its constitution, being more nearly a true sandstone as compared with the muddy sandstones and shales of the Summerville. In the area covered by this report, however, the distinction between the two is rather artificial and would never have been made had this area alone been considered. The Curtis here has about the same physical constitution as the Summerville, from which it differs in showing a general greenish-gray rather than reddish tone. All the Curtis sections east of the Green River show some red coloration, which gradually increases in amount to the east until the red color predominates, whereupon the Curtis loses its identity and becomes lower Summerville.

The Curtis in this area is composed of sandstone, shaly sandstone, and sandy shale, with a minor amount of true shale. In the lower half the more sandy beds predominate over the more shaly ones; in the upper half the reverse is true. The dominant color is greenish gray, but some of the sandstones, especially those in the lower 13 feet, show pink and less commonly lavender and maroon tints; the shale, which generally is present as thin (1- to 4-inch) partings, is chocolate brown in the lower part of the formation, as is also some of the sandy shale. Commonly the colors are more or less streaky, with ill-defined boundaries. The formation is thin-bedded, except for the basal 1 foot, and shows ripple marks near the base.

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[54] Gilluly, James, and Reeside, J. B., Jr., op. cit. (Prof. Paper 150–D), p. 78.

[55] Baker, A. A., Geology and oil possibilities of the Green River Desert-Cataract Canyon region, Utah: U. S. Geol. Survey Bull. — (in preparation).

The basal 1 foot at Dellenbaugh Butte is a very resistant gray quartzitic sandstone that differs in texture from the rest of the formation in being medium- to coarse-grained. It is more or less cross-bedded, in contrast to the thin-bedded character of the rest of the Curtis. It contains a few mud inclusions the size of a pea. The base of this sandstone is slightly wavy, and over considerable areas this waviness is the only expression of the unconformity that exists at this horizon.

OUTCROP

The outcrop of the lower sandy facies of the Curtis generally shows a jagged profile owing to the alternation of soft and hard sandstones. The upper, more shaly half weathers back into gentler debris-covered slopes with a few projecting sandstone ledges here and there.

AGE AND STRATIGRAPHIC RELATIONS

No fossils have been found in the Curtis formation east of the Green River, but in the San Rafael Swell marine fossils of middle Upper Jurassic age are reported.[56] The Curtis overlies the Entrada unconformably and is overlain conformably, with gradational lithology, by the Summerville formation, into the basal part of which it also grades laterally within a short distance east of the Green River (fig. 3).

SUMMERVILLE FORMATION

NAME, DISTRIBUTION, AND THICKNESS

The Summerville formation was named by Gilluly and Reeside[57] for exposures on Summerville Point, in the northern part of the San Rafael Swell. In the area between the Green and Colorado Rivers it shows roughly the same distribution as the Entrada: (1) A narrow outcrop band runs from the Moab fault near The Dugway northward across the Courthouse syncline to the southwest flank of the Salt Valley anticline; (2) a broad zone, through which more or less continuous outcrops wind irregularly, extends from the mesa east of the head of Bartlett Wash northwestward to the Green River between Dellenbaugh Butte and the mouth of Salt Wash; (3) a more sharply defined belt lies along the upthrown side of the fault north of Salt Wash; and (4) a narrow outcrop band is exposed over a small area on the north side of the Little Grand fault.

The thickness of the Summerville is variable. On the northeast flank of Salt Valley, northeast of the area mapped, it is 45 feet. On the west side of Bartlett Wash the thickness below the Moab tongue of the Entrada is 33 feet and that above the Moab 44 feet, a total

[56] Gilluly, James, and Reeside, J. B., Jr., op. cit. (Prof. Paper 150–D), p. 79. Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., op. cit. (Prof. Paper 183), p. 58.

[57] Gilluly, James, and Reeside, J. B., Jr., op. cit. (Prof. Paper 150–D), p. 80.

of 77 feet. On Tenmile Wash the thickness below the Moab is 72 feet, that above the Moab 48 feet, and the total 120 feet. At the Colorado Fuel & Iron Co.'s manganese camp the formation is 150 feet thick. At Dellenbaugh Butte (pl. 13, *A*) the Summerville is 180 feet in thickness and overlies 130 feet of Curtis, which was not separated from the Summerville in sections to the east. The section exposed in Dellenbaugh Butte apparently represents local maximum thicknesses of both the Summerville and Curtis formations, for a short distance west of the Green River the Summerville is only 96 feet thick and the Curtis 103 feet.[58]

CHARACTER

The Summerville is composed of chocolate brown shales and mudstones (rarely purplish brown or lavender in very thin beds) that weather brownish red; chocolate-brown to brownish-red and dull-red sandy mudstones and muddy sandstones; brownish-red soft sandstones; and thin (1 inch to 2 feet) ledges of sandstone, commonly somewhat calcareous, that are white, yellow, greenish gray, brownish gray, purplish, or reddish brown. The shales and mudstones, as well as the cleaner sandstones that form the ledges, are quantitatively subordinate to the less well assorted sediments, the muddy sandstones and sandy mudstones. Some sections also contain a little more or less impure limestone, but it is not common. The limestone is gray, greenish gray or brownish, locally with a lavender tinge. The weathered surface of the lavender-brown limestone assumes an olive-brown shade. Some of the more structureless mudstones, especially toward the top, show numerous calcareous nodules and lenses concentrated along certain bands; when broken these nodules commonly show spots and streaks of crystalline calcite.

In the territory between the Colorado Fuel & Iron Co.'s manganese camp and the Green River the upper part of the Summerville contains a considerable amount of interbedded gypsum. The individual gypsum seams are about 1 inch thick and alternate with the normal clastic deposits on a fine scale. Certain anomalous variations in thickness that take place within very short distances are possibly to be explained by variations in gypsum content, the clastic materials remaining practically constant in the different sections. In the SW¼ sec. 8, T. 23 S., R. 17 E., the thickness of a certain section of beds increases within 100 feet from 7 to 14 feet. This is accomplished by a divergence of the bedding laminae in the direction of thickening. The divergence between any two adjacent laminae is imperceptible, but the summation of all the minute divergences is considerable.

[58] Baker, A. A., Geology of the Green River Desert-Cataract Canyon region, Utah: U. S. Geol. Survey Bull. — (in preparation).

The red or brown color of many of the sandstone ledges seems to be produced by the weathering of whitish ledges. These ledges commonly show an abundance of shale pellets that are green in the greenish-gray ledges and brown in the red-brown ones. Practically all the sandstones are so fine-grained that in general the mineral composition is not evident from the hand specimen. Some of the coarser greenish-gray ledges show, in addition to the more or less rounded quartz grains, a few scattered grains of reddish chert. Muscovite was noted in some of the sandstones.

The Summerville taken as a whole is rather thin bedded (pls. 10, *B*; 13, *A*), and many of the sandstones are platy. However, a few muddy sandstones near the middle of the formation in the region between Tenmile Wash and the Green River are massive, reaching 4 feet in thickness. Ripple marks are common in the thinner-bedded sandstones.

The Summerville in adjoining areas on the northeast and southeast is marked by a conspicuous amount of contained chert. In this area chert is of very irregular distribution. It was noted on the west side of Bartlett Wash near the Moab fault, on the southeast side of Tenmile Wash, and in Dellenbaugh Butte. The chert is whitish, pinkish, orange red, and blue gray and is translucent. It commonly appears as irregular spots and masses in limestone, the boundary between the two being so completely gradational that it is practically impossible to tell where the one leaves off and the other begins. The occurrence on Bartlett Wash is in the form of a lenslike mass, 10 feet across and 3 feet thick, within about 20 feet of the top of the formation. The cherty limestone in the Tenmile section is only 2 or 3 inches thick and is broken up into a series of small lenses only a few feet across at the maximum. It is within 5 feet of what was considered the base of the Morrison, the lower beds of which contain similar limy zones but without the chert. The chert at Dellenbaugh Butte appears at the base of the formation.

OUTCROP

The Summerville generally weathers into steep detritus-covered slopes that are broken by thin, massive, or platy ledges formed by the harder sandstones (pl. 10, *B*). From the character of the outcrop the formation would seem to contain more shale and mudstone than it really does. In the Green River region, where the formation is thickest, horizontally corrugated cliffs are common, formed especially by the upper part of the formation. The most imposing exposure is at Dellenbaugh Butte, in whose sides practically the whole thickness of the Summerville is exposed in a vertical thin-banded cliff (pl. 13, *A*).

STRATIGRAPHIC RELATIONS AND AGE

The Summerville formation is conformable on the Curtis formation, into which its lower part grades laterally (fig. 3). It is also conformable on the Moab tongue of the Entrada sandstone and intertongues conformably under the Moab from the west. It is unconformable on the main mass of the Entrada sandstone, possibly throughout the area covered in this report, though only in a small area near the Green River can angular divergence between the two formations be demonstrated (pl. 10, *B*). The Summerville is overlain unconformably by the Morrison formation, with local angular divergence between the beds above and below the contact.

No fossils have been found in the Summerville formation, but its age is closely defined by its position between the Curtis and Morrison formations. The Curtis in the San Rafael Swell contains marine invertebrates of middle Upper Jurassic age, and the Morrison contains a widespread vertebrate fauna of still later Jurassic age.

CONDITIONS OF DEPOSITION

The Summerville formation in the area between the Green and Colorado Rivers is believed to have been deposited largely as a continental formation. The poor sorting of materials, the numerous ripple marks, the abundant shale pellets in the sandstone, and the dinosaur tracks in the closely associated Moab tongue of the Entrada sandstone are all in keeping with this interpretation. On the other hand, westward gradation of the lower part of the formation into the marine Curtis and the occurrence to the west of bedded gypsum in the upper part of the formation point to the close proximity of the sea. The Summerville thus seems best interpreted as a delta deposit. On the outer westward fringe of the delta lagoonal invasions of the sea were common, each invasion followed by the evaporation of much of the water and precipitation of the gypsum. The absence of foreset delta beds is perhaps a result of the shallowness of the sea, which gave the waves a chance to rework and redistribute the sedimentary material in relatively flat beds.

MORRISON FORMATION

NAME, DISTRIBUTION, AND THICKNESS

The Morrison formation was named by Cross [59] for exposures near the town of Morrison, in the eastern foothills of the Front Range, a short distance southwest of Denver, Colo. Although exposures cannot be traced directly, the lithologic and stratigraphic characters of the formation and its unique vertebrate fauna have been the basis

[59] Cross, Whitman, U. S. Geol. Survey Geol. Atlas, Pikes Peak folio (No. 7), p. 2, 1894.

for widespread recognition of its outcrops throughout the Rocky Mountain and Colorado Plateau regions.

In the area covered by this report Morrison outcrops occupy a broad belt extending from the valley of Courthouse Wash near Courthouse mail station northwestward to the Green River between Dellenbaugh Butte and the town of Green River. The outcrop pattern of the Morrison is complicated by faults, but there are broad areas in this belt where no other formation is exposed.

The total thickness of the Morrison was not measured at any one locality, but the most nearly complete section, north of Tenmile Wash near the center of T. 23 S., R. 18 E., contains all but the upper 75 or 100 feet of the formation. The total thickness before erosion of the upper beds was here close to 850 feet, which is greater than the thickness reported in any of the closely adjacent areas. Baker [60] reports a thickness of 620 feet just west of the Green River at the Little Grand fault, and 760 feet on the San Rafael River 10 miles west of the Green. Of the 850 feet in the section north of Tenmile Wash 330 feet is contained in the Salt Wash sandstone member and 260 feet in the variegated mudstone member, as defined in the following paragraph.

CHARACTER

The Morrison is made up of three divisions which in their typical development are well-defined units but which show very indefinite mutual boundaries. In general, the Morrison may be described as a mudstone formation containing two zones in which lenticular sandstone and conglomerate beds are massed, one near the top and one near the bottom. The three resulting divisions are the Salt Wash sandstone member below, the variegated mudstones in the center, and the sandy and conglomeratic beds at the top.

The Salt Wash sandstone member was named by Lupton [61] for exposures along Salt Wash, within the area treated in this report. It is characterized by the dominance of thick whitish to flesh-colored, locally pale-yellow sandstones (pl. 10, *B*). They range from fine to coarse in texture and grade into grits or fine conglomerates. The pebbles in the conglomeratic layers are more or less rounded and average a quarter of an inch or less in diameter, though they may reach 1 or even 2 inches. They are composed of white (most common), gray, gray-green, yellow, brown, black, and reddish cherts and quartzites; white and light-gray translucent quartz; a little transparent colorless quartz in rather small grains; and a small

[60] Baker, A. A., Geology of the Green River Desert-Cataract Canyon region, Utah: U. S. Geol. Survey Bull. — (in preparation).

[61] Lupton, C. T., Oil and gas near Green River, Grand County, Utah: U. S. Geol. Survey Bull. 541, p. 127, 1914.

amount of gray limestone. Shale pellet zones are also common in the Salt Wash member. At the north end of the Salt Valley anticline, on the west flank, two small, well-rounded gray chert pebbles were found that had originally been fossil brachiopods.

Most of the Salt Wash sandstones are obliquely cross-bedded at a low angle, though some are massive, and a few of the muddy ones are thin-bedded. Ripple marks are present but not abundant. The individual beds reach 50 feet or more in thickness, but they are not continuous along the outcrop for distances much greater than 2 miles and generally can be traced only a few hundred feet before they die out. The contact with the overlying variegated beds is thus not at a definite horizon but in any particular section is arbitrarily placed at the top of the uppermost sandstone lens that is present. Sparse thin sandstone lenses appear in the overlying variegated beds, but these are not considered a part of the Salt Wash member, which breaks off rather abruptly above.

Interbedded with the sandstones of the Salt Wash member are gray, green, lavender, purple, chocolate-brown, and maroon shales and mudstones, in part sandy, and in part containing calcareous nodules or nodular limestone bands, especially at the base of the formation. These limestones are blue gray, greenish gray, or lavender and commonly weather to olive brown.

The base of the formation between the Colorado Fuel & Iron Co.'s manganese camp and the Green River is formed either by a thin platy blue-gray limestone or else by a bed of gypsum. That part of the Salt Wash member lying below the main mass of Salt Wash sandstones in this same region contains a large amount of bedded gypsum, some of the beds fairly pure and reaching 30 feet in thickness. Fragments of opaque yellow and red chert lie on the weathered surface of the basal bed of gypsum where it caps certain benches in this district and were apparently derived from a higher part of the gypsiferous series. The basal bed of gypsum is also present along the north side of the Salt Wash graben, where it extends about as far east of the Green River as in the vicinity of the manganese camp. A third band of outcrop of this basal gypsum lies along the north side of the Little Grand fault, but here the basal part of the Morrison is exposed only near the river.

Except in the vicinity of the Green River, where gypsum is so conspicuous, the lower part of the Salt Wash in most sections consists dominantly of shale and mudstone, containing many thin sandstone lenses 6 inches to 2 feet or more thick. The sandstone increases upward in the section until near the top of the Salt Wash member it makes up by far the greater percentage of the material and occurs in the thickest beds. At one place on the south side of Tenmile Wash the thick sandstones of the upper Salt Wash extend down to the Summerville-Morrison contact.

The variegated mudstone member of the Morrison consists largely of green-gray, chocolate-brown, and maroon mudstone that weathers into rounded slopes, generally steep owing to the resistance of the overlying beds (pl. 13, *B*). A dark greenish-gray zone near the base of the variegated beds northwest of Tenmile Wash is peculiar in that it weathers to olive yellow instead of the normal Morrison hues. Lenses of muddy sandstone as much as several feet in thickness are present in nearly every section, but they are of minor importance in actual bulk, and many of them have no distinct expression on the erosion surface. A dark-gray (weathering brown) limestone, 1 foot thick, is present near the top of the variegated beds in the region north of Tenmile Wash. In the same locality chert occurs at the top of these beds; hues of red, yellow brown, brownish gray, bluish gray, and black appear and are in part interbanded, frequently forming the shells of geodes, the centers of which show crystals of quartz as much as half an inch in diameter.

The upper part of the Morrison is sandy and conglomeratic but not to so marked an extent as the Salt Wash member. The character of many of the sandstones is also entirely different in that they approach quartzites. The change from normal sandstone to quartzite may be gradational within a few feet or it may be abrupt; it may take place vertically between different beds or horizontally between different parts of the same bed. The quartzite shows a very haphazard distribution and was apparently formed by the cementing action of underground waters, the greater part of whose circulation was confined to certain channels. Most of the quartzitic conglomerates and grits are so strongly indurated that they break across the pebbles instead of around them.

The gross color of these upper Morrison quartzites is generally white on fresh surfaces, but the weathered outcrop is generally dark brown or dark gray, approaching black. These beds are dominantly cross-bedded, on a low dip. Silicified wood is a common constituent; one tree trunk that was between 25 and 40 feet long and 1 foot or more in diameter was noted on the east side of Bartlett Wash, north of the Moab fault.

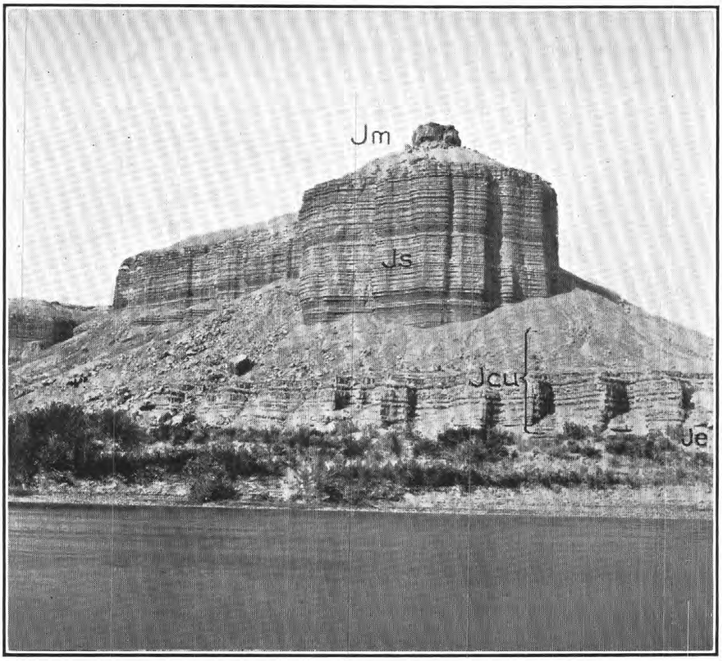
An entirely different and peculiar type of quartzite occurs in a 4½-foot bed in this upper division of the Morrison where it was measured north of Tenmile Wash. This quartzite is bright green and contains segregated masses of white, blue-gray, and reddish chert, though some of the reddish masses may be pebbles. In places the solidification to quartzite has been incomplete. The original rock appears to have been a mudstone.

Besides the quartzitic sandstones there are in the upper division other sandstones that are similar to the sandstones of the lower members except that they are, perhaps, more friable and are on the average finer-grained. They may be cross-bedded or thinly horizontal-bedded, white or yellow or yellowish-brown. Some of the yellow sandstones at the top show red stains.

The conglomerate of the upper division appears both as a coarsening of material along certain thin zones in beds that are dominantly sandstone or quartzite, and as more pronouncedly conglomeratic ledges. The pebbles of the conglomerates are not essentially different from those of the Salt Wash member already described except that considerable gray to drab limestone and some sandstone and mudstone occur as pebbles. Gray quartzite or chert pebbles are more abundant than the white ones. Some limestone boulders reach 6 inches in diameter and some of the mudstone slabs are as much as 1 foot in length. The siliceous pebbles are more rounded and average less than 1 inch in diameter; the maximum diameter noted was 4 inches, which, however, was exceptional. One of the upper Morrison conglomerates noted north of Tenmile Wash has, instead of a sandstone matrix, one of white silica that resembles milky chalcedony.

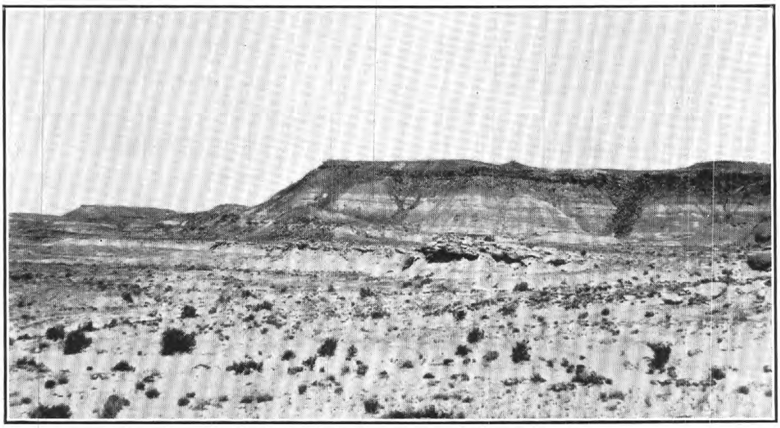
The maximum thickness of the upper Morrison ledges of sandstone and conglomeratic sandstone is about 75 feet, though the usual thickness is from 15 to 30 feet.

In spite of the prominence of sandstones and conglomerates, the greater part of the upper Morrison division is mudstone, more or less sandy. The common colors are light gray or green, with lavender less common. This is in marked contrast with the dominance of "red beds" in the variegated beds that make up the middle of the formation. Blackish flaky carbonaceous shale appears near the base of this upper Morrison division on the highway a short distance south of Courthouse mail station, but was not observed elsewhere in the area. At certain horizons there is a development of calcareous nodules, and in a few places thin concretionary muddy limestone bands that weather to a rich brown are formed by a more complete cementation of the mudstone. A little thin platy limestone appears at the very top of the formation north of Courthouse Spring. Near Brink's Spring a gray limestone near this same horizon shows extensive silicification. The base of the limestone ledge has been fractured in all directions, but especially parallel to the bedding, and the fractures have been filled by blue-gray chert. The limestone is preserved as angular (frequently rectangular in section) fragments in the chert. At 6 inches above the base the chert begins to increase in amount and the limestone remnants become more and more rounded.



A. DELLENBAUGH BUTTE, LOOKING NORTHEAST.

Jm, Morrison formation; Js, Summerville formation; Jcu, Curtis formation; Je, Entrada sandstone. Photograph by J. K. Hillers.



B. VARIEGATED BEDS OF MORRISON FORMATION.

From a point near spring that lies 1 mile northwest of Levi well No. 2, looking northwest. Upper sandstones and conglomerates of Morrison formation cap the slope.

A little higher the bed is practically all blue-gray to white chert with only a few limestone inclusions. At its upper surface this silicified limestone shows a more or less gradational contact with a peculiar white to drab novaculitic rock that appears to be a silicified silt. This "novaculite" is about 4 feet thick and contains a few minute segregations and stringers of chert throughout its mass as well as at the very base.

The feature that is most characteristic of the Morrison is the rapid lateral variation of the sediments in all its members. No two sections more than 1,000 feet apart are alike other than in general distribution of the kinds of sediments. The chief change takes place in the sandstone and conglomerate beds; the argillaceous beds act as a sort of a matrix for the coarser clastic materials.

OUTCROP

Topographically the Salt Wash sandstone member tends to form wide tree-covered benches or dip slopes, but as the individual sandstone beds are not at the same horizon, the result is a number of benches at different levels. In some places a drainage system may be developed on one sandstone, forming a broad, flat-bottomed basin that is rimmed by the heavy sandstone of a higher level; the south head of Tenmile Wash is an example. The benches developed on the dip slope of the Salt Wash west of Bartlett Wash show numerous pedestals formed by the sandstone of overlying lenses. Wherever the edge of the Salt Wash crops out in a steep slope, the slope characteristically shows huge blocks of sandstone covering the surface so thickly that very few exposures are available for examination.

The variegated beds of the Morrison are expressed topographically as steep clay slopes, held up by the resistance of the sandstones and conglomerates of the upper division of the formation (pl. 13, *B*). Were it not for this protecting layer at the top, these Morrison mudstones would no doubt be carved into badland forms.

The sandstones and conglomerates of the upper Morrison commonly cap buttes, mesas, and dip slopes that, owing to the lenticularity of the beds, are usually of no great area.

FOSSILS AND AGE

The Morrison throughout the Rocky Mountain region is noted for its fossil-bone beds. In the area treated in this report fragments of large bones were found at one place near the center of T. 23 S., R. 18 E., at a horizon near the top of the variegated mudstones, but they were too fragmentary to be of any value. No other relics of vertebrate life were found in the Morrison in this area. A silicified lime-

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stone at the very top of the formation near Brink's Spring contains a few poorly preserved casts of gastropods, the only invertebrate fossils found. The age of the Morrison, as based on a comprehensive study of its vertebrate fauna, is now considered to be uppermost Jurassic, though it was long classed by the United States Geological Survey as Lower Cretaceous (?).[62]

CONDITIONS OF DEPOSITION

Most geologists who have studied the Morrison, taking into account its lithologic constitution and its terrestrial and fresh-water fauna, have agreed that it was deposited by rivers sweeping over an extensive flood plain on which lakes and ponds of varying sizes and shapes were of common occurrence. The fresh-water limestones that are found in the Morrison are believed to have accumulated in these small bodies of standing water.

STRATIGRAPHIC RELATIONS

Between the Green River and the Colorado Fuel & Iron Co.'s manganese camp a local unconformity shows in several places at the base of either a thin light-gray limestone or a bed of gypsum, one of which forms the basal unit of the Morrison in this region. The unconformity is apparently of minor importance, for at no place is more than 10 feet or so of the underlying Summerville cut out before the two formations resume the structural parallelism that prevails everywhere to the east. Unconformity of the same type appears at this horizon in the San Rafael Swell, to the west,[63] but has not been observed east of the manganese camp. Over the greater part of the area mapped the Morrison appears to be conformable on the Summerville, though the relation is more probably one of disconformity. The contact between the two formations has been drawn where the argillaceous beds grade from some shade of red or reddish brown below to gray and lavender above. In many places the narrow gradational zone is marked by thin seams and lenses of fresh-water limestone. It is the horizon down to which the Salt Wash sandstones of the Morrison extend in a few places but below which they do not extend.

The Morrison is overlain unconformably by the Dakota (?) sandstone.

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[62] 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, pp. 58–63, 1936.

[63] 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–D, p. 81, 1928.

STRATIGRAPHIC FACIES OF UPPER JURASSIC IN AREA NEAR THE GREEN RIVER

The general characteristics of the whole Upper Jurassic for a few miles east of the Green River tend to link this part of the area more intimately with the San Rafael Swell than with the rest of the area mapped to the southeast, which is more typical of the southeastern Utah facies. The occurrence of shale in the Carmel, the occurrence of the San Rafael type of Entrada at the top of this formation, the angular unconformity at the top of the Entrada, the presence of the Curtis formation, the thickness of the Summerville formation, the unconformity at the base of the Morrison, and the large amount of gypsum in the upper Summerville and lower Morrison are all points of similarity with the San Rafael Swell and of contrast with the region to the southeast.

CRETACEOUS SYSTEM

UPPER CRETACEOUS SERIES

DAKOTA (?) SANDSTONE

NAME AND DEFINITION

The Dakota sandstone was named by Meek and Hayden[64] for exposures near the town of Dakota City, Nebr. In that region it lies at the base of the Upper Cretaceous. Sandstone at approximately the same stratigraphic horizon is widely distributed through the Rocky Mountain and Colorado Plateau regions, but because exposures cannot be directly traced and because absolute equivalence in age has not been established the name is properly used with a query when applied in regions remote from the type area, and it is so used in the present report.

On account of its similarity to the upper conglomeratic sandstones of the Morrison, coupled with its nonpersistent character, the Dakota (?) is a difficult unit to map. As interpreted and mapped in the present report it is the basal sandstone or conglomerate of the Mancos shale (Upper Cretaceous), and is unconformable, though not markedly so, on the Morrison. It may be a single bed of variable thickness, or it may be made up of two or three beds which are separated by dark-gray shales of the Mancos type, but not by the pale-greenish mudstones and sandy mudstones of the Morrison type, at least not by more than 3 or 4 feet of them. Any sandstones lying below the latter type of sedimentary beds are classed as Morrison.

[64] Meek, F. B., and Hayden, F. V., Descriptions of new Lower Silurian (Primordial), Jurassic, Cretaceous, and Tertiary fossils, collected in Nebraska Terr., * * * with some remarks on the rocks from which they were obtained: Acad. Nat. Sci. Philadelphia Proc., vol. 13, pp. 419–420, 1862.

The present interpretation of the Dakota is the most restricted one that has been applied in the region. Certain sandstones mapped as Dakota by Lupton [65] are here classed as Morrison and have been remapped accordingly, although in places, especially near the Green River, the two interpretations of the Dakota have been in agreement. Much of Prommel's Dakota-Lakota unit [66] has also been assigned to the Morrison.

As practically all the sandstone and conglomerate lenses in the upper Morrison show erosional unconformities at their bases, significance can be attached only to those unconformities that show an angular discordance as well. This angularity, which is present in places at the base of the Dakota (?), is nowhere great enough to be perceptible in any one outcrop, but when the contact is followed for some distance along the outcrop it becomes evident by the cutting out of certain beds in the underlying series.

DISTRIBUTION AND THICKNESS

The Dakota (?) sandstone crops out discontinuously along a broadly curving line near the north side of the area included in this report. The generalized line of outcrop runs southeast from the town of Green River to the vicinity of Courthouse Spring, thence west of north to Valley City.

The thickness of the sandstone varies from 60 feet to the vanishing point. In the graben block that is transversed by Salt Wash and in some of the region to the north the Mancos gray shale rests directly on the Morrison greenish-white mudstone without any suggestion of a sandstone along the boundary. The usual thickness of the formation is from 5 to 25 feet, the smaller thicknesses prevailing to the west (west of Tenmile Wash) and the greater thicknesses to the east (on the flanks of the Salt Valley anticline). The only section examined that exceeded 40 feet in thickness contained a thick bed of shale.

CHARACTER

The general lithologic aspect of the Dakota (?) is quite similar to that of the upper Morrison conglomerates. It is made up of sandstone and conglomerate, the latter occurring as lenses in the former and nearly everywhere forming the base of the formation. Locally the Dakota (?) also contains a high percentage of shale.

The pebbles of the conglomerate are subangular to well-rounded and attain 6 inches in size, although the extreme sizes are not present

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[65] Lupton, C. T., Oil and gas near Green River, Grand County, Utah: U. S. Geol. Survey Bull. 541, pl. 6, 1914.

[66] Prommel, H. W. C., Geology and structure of portions of Grand and San Juan Counties, Utah: Am. Assoc. Petroleum Geologists Bull., vol. 7, pp. 387, 393, 1923.

in every section. The pebbles are composed dominantly of opaque gray and black chert, gray translucent chert, and translucent gray quartzite; less common types are white and reddish quartzite and chert, white quartz, hard brown sandstone, and buff mudstone. There seem to be some differences in size of material according to the composition of the pebbles. Thus the watery translucent quartzite cobbles are commonly larger than the cherts, many or all of which could have been derived from the underlying Morrison. These particular quartzites were derived from some extraneous source, for they do not commonly occur in the Morrison.

The matrix in which the pebbles and cobbles are embedded is made up of medium- to coarse-grained quartz and chert sand, not very well rounded, and commonly more or less muddy. The general colors are gray, greenish, yellow, and rarely whitish, but greenish and yellow are the most characteristic. In many places the sands are streaked and spotted with brick red, brownish red, brown, buff, or lavender. Certain of the sandstones weather to a dark brown, almost black.

Both sandstone and conglomerate beds may be either horizontally bedded or obliquely cross-bedded on a medium-sized scale. Some of the sandstone is thin-bedded and shows ripple marks.

The Dakota (?) sandstone just east of the Thompsons-Moab highway, half a mile north of Courthouse mail station, is made up of two sandstones separated by 27 feet of shale. The lower sandstone unit, 26 feet thick, consists of several beds and is normal Dakota, with conglomeratic base. A 6-inch parting of green mudstone that weathers yellow is bedded in this sandstone near the base and carries a considerable amount of gypsum as small selenite plates. The upper sand is 7 feet thick, medium- to fine-grained, and buffy with in part a greenish tinge. It weathers on the surface to brownish black. This upper sandstone contains a few dark rock grains, similar to the lower sands of the Dakota. It is obliquely cross-bedded, and the individual beds average about 1 foot in thickness. The shale between the two sandstones is in its lower part laminated, slate gray (weathering blue gray), and similar to the Mancos shale that overlies the Dakota (?). The middle and upper parts of this shale unit are yellow sandy shale with one or two lenses of greenish-yellow muddy sandstone.

OUTCROP

The Dakota (?) generally forms a low inconspicuous cuesta ridge, facing the rough hills and badlands developed on the Morrison. Where the Dakota (?) is thin its presence may be indicated by loose pebbles that lie scattered over a shaly soil mantle.

FOSSILS

Many of the sandstone beds of the Dakota (?), especially the more muddy ones, show carbonized plant fragments, and in places fossil leaves are well preserved. Leaves collected near Elgin are reported by Richardson to be of Dakota types.[67] The only other fossils found within the area mapped are small woody-appearing cups resembling pieces of small cherry pits and identified by Reeside as pycnodont fish teeth. Single teeth were found at several widely separated localities.

STRATIGRAPHIC RELATIONS AND AGE

The Dakota (?) is unconformable on the Morrison, its base locally truncating the upper Morrison beds at low angles. In general, the contact between the two formations must be traced for some distance along the outcrop before the truncation becomes apparent. In one locality between Bartlett Wash and the Thompson-Moab highway 15 feet of Morrison has been cut out within a little over a quarter of a mile. Similar cut-outs apparently occur on the southwest flank of the Salt Valley anticline and in the region west of Tenmile Wash. The Dakota (?) is overlain by the Mancos shale with apparent conformity, and locally shale of the Mancos type is bedded in the Dakota. At present the age of the sandstone seems best indicated by this intimate stratigraphic association with the basal Mancos, suggesting essential contemporaneity of the two. Present knowledge of the Dakota (?) flora and fauna in the area covered by this report is not in itself detailed enough for exact age assignment of the formation, though future work on the flora may furnish the basis for closer correlation.

CONDITIONS OF DEPOSITION

The carbonized wood and fossil leaves found in the Dakota (?) suggest fluviatile rather than marine conditions of deposition. On the other hand, the general thinness and discontinuity of the sandstone, the local inclusion of the marine Mancos type of shale within the sandstone, the presence of *Halymenites* below a similar thick shale in the Dakota (?) near the north end of the Salt Valley anticline,[68] and the stratigraphic position of the Dakota (?) immediately above a widespread plane of unconformity and below a conformable marine unit all suggest a marine origin. Possibly the true picture

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

[68] 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–D, p. 108, 1928. According to Reeside (personal communication), *Halymenites*, so far as known at present, is indicative of marine conditions.

is a combination of both of these conditions, but it is believed that on the whole marine accumulation prevailed over any type of continental accumulation within the area treated in this report. The fish teeth, according to Reeside, are not diagnostic as between marine and fresh-water deposits. In adjacent regions it is possible that the Dakota (?) includes a higher proportion of fresh- or brackish-water deposits.[69] As pointed out by Lee,[70] very slight differences in altitude or in rate of sedimentation at the beginning of Upper Cretaceous time might account for contemporaneous deposition of marine and fresh-water beds in closely adjacent areas or even interfingering at different times in the same area. On the other hand, the Dakota (?) of some of these adjacent areas may include older continental deposits that are not represented in the Dakota (?) of the area covered in the present report.[71]

MANCOS SHALE

NAME, DISTRIBUTION, AND THICKNESS

The Mancos shale was named by Cross[72] for exposures near the town of Mancos, in southwestern Colorado. It crops out across the north side of the area covered in this report, forming an extensive area of low relief and relatively low altitude as compared to the upland farther south. The thickness of the shale ranges between 3,450 and 4,120 feet,[73] but only the lower 1,400 feet of the formation is exposed within the area treated in this report.[74]

CHARACTER AND OUTCROP

The Mancos is a slate-gray shale that weathers commonly to a dove color, although certain zones produce cream-colored bands on the weathered surface. A little sand is present, either as a constituent of some of the shales or as thin sandstone zones interbedded in the shale. The brown to gray thin-bedded Ferron sandstone member, between 440 and 500 feet above the base of the formation, is the thickest of these and is the only one that forms an escarpment. It is generally best developed in two zones at the top and bottom of the interval

[69] Baker, A. A., Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, pp. 54–55, 1933. Dane, C. H., Geology of the Salt Valley anticline and adjacent areas, Grand County, Utah: U. S. Geol. Survey Bull. 863, pp. 113–117, 1936. Lupton, C. T., Geology and coal resources of Castle Valley in Carbon, Emery, and Sevier Counties, Utah: U. S. Geol. Survey Bull. 628, pp. 26–30, 74–76, 1916.

[70] Lee, W. T., Relation of the Cretaceous formations to the Rocky Mountains in Colorado and New Mexico: U. S. Geol. Survey Prof. Paper 95, pp. 27–38, 1915.

[71] Erdmann, C. E., The Book Cliffs coal field in Garfield and Mesa Counties, Colo.: U. S. Geol. Survey Bull. 851, pp. 27–28, 1934.

[72] Cross, Whitman, U. S. Geol. Survey Geol. Atlas, Telluride folio (No. 57), p. 4, 1899.

[73] Fisher, D. J., The Book Cliffs coal field in Emery and Grand Counties, Utah: U. S. Geol. Survey Bull. 852, p. 11, 1936.

[74] Lupton, C. T., Oil and gas near Green River, Grand County, Utah: U. S. Geol. Survey Bull. 541, p. 128, 1914.

stated above, with shaly beds between, so that the escarpment produced has a double crest. A noticeable amount of gypsum in the form of scattered selenite plates 1 or 2 inches across occurs on the weathered surface of the basal Mancos near Brink's Spring.

Except for the weak Ferron cuesta ridge, the Mancos shale is expressed topographically as a broad barren flat, supporting little or no vegetation except for a little greasewood along the washes. Locally the shale is capped by remnants of gravel terraces which extend from the Book Cliffs on the north.

FOSSILS, AGE, AND STRATIGRAPHIC RELATIONS

The Mancos shale contains a lower Upper Cretaceous marine fauna, that of the Ferron sandstone being correlated with that of the Carlile shale of Montana, Wyoming, and Colorado.[75] The shale overlies the Dakota (?) sandstone conformably and is conformably overlain, in the Book Cliffs north of the area mapped, by the sandstones of the Mesaverde group.

TERTIARY (?) SYSTEM

A thin veneer of caliche that caps remnants of an old erosion surface on the upland plateau in the vicinity of DuBinky Spring is considerably older than the alluvial deposits along the present-day streams and may be of late Tertiary age. This deposit is a pinkish to light-gray calcareous crust without bedding structure. It was nowhere observed to be more than a few inches thick and hence is stratigraphically insignificant, though geomorphically it is of considerable interest. Remnants of the erosion surface on which it occurs are preserved over an area of 6 or 7 square miles and are confined to the upland north of Hell Roaring Canyon. Before dissection by southward-flowing tributaries of Hell Roaring Canyon this surface had a gentle, probably irregular southerly dip and truncated the Jurassic strata from Navajo to Morrison, which have a gentle northerly dip in this area. Details of the surface were not worked out, and the surface was not mapped, but a few scattered determinations of altitude indicate that as reconstructed its average altitude is perhaps 5,300 feet. South of Hell Roaring Canyon the ridge that forms the present divide rises a few hundred feet above the level of the old erosion surface, which thus slopes toward higher ground. It is believed that this surface as formed was somewhat rolling and probably rose gently on the south side of Hell Roaring Canyon, but has there been removed by erosion during the present

[75] Reeside, J. B., Jr., in Clark, F. R., Economic geology of the Castlegate, Wellington, and Sunnyside quadrangles, Carbon County, Utah: U. S. Geol. Survey Bull. 793, p. 14, 1928.

cycle of denudation, whereas less vigorous erosion on the north side of this canyon has allowed certain remnants to be preserved. To explain its absence south of Hell Roaring Canyon as due to warping of an originally plane surface combined with later erosion requires more differential deformation since the development of this surface than is indicated by the existing bedrock structure, which represents the summation of structural movements dating from a much earlier time.

The terrace gravel that caps isolated ridges in the Mancos shale flat in the northern part of the area mapped has not been studied in connection with the present report. These ridges show a graded profile into the Book Cliffs on the north and are but the remnants of extensive erosion surfaces that were developed at several levels.[76] Some of these surfaces may be correlative with the erosion surface at DuBinky Spring, or all of them may be younger.

STRUCTURE

GENERAL FEATURES

The dominant structure of the area treated in this report is a gentle regional dip to the north that drops the strata about 7,400 feet in a distance of 52 miles across the area. Superposed on this regional dip are local structural features—open folds, faults, and grabens—that, with few exceptions, have a general northwesterly trend. Only in comparison to the regional dip can these features be said to be local, for the length of most of them is measured in tens of miles. They are believed to have formed in response to regional stresses, largely compressive stresses. A radically different type of superposed structure is presented in the Meander anticline and the Upheaval dome. These structural features represent very local disturbances that are entirely unrelated, either in form or in origin, to the other features controlled by regional trends. They probably were formed by plastic movement in deeply buried salt of the Paradox formation.

Details of the areal structure are shown by structural contours on plate 3. Because two pronounced unconformities intervene between the Paleozoic and Jurassic (?) strata the contours are drawn on the Shafer lime of drillers (top of Rico formation) in the area along the Colorado River, where post-Paleozoic formations have been eroded, and on the base of the Wingate sandstone in the rest of the area, where Paleozoic sediments are for the most part deeply buried. In the following pages only the outstanding characters of the better-

[76] Fisher, D. J., The Book Cliffs coal field in Emery and Grand Counties, Utah: U. S. Geol. Survey Bull. 852, p. 21, 1936. Rich, J. L., Origin and evolution of rock fans and pediments: Geol. Soc. America Bull., vol. 46, pp. 999–1017, 1935.

defined structural features will be pointed out. A regional treatment of geologic structure in southeastern Utah, including the area discussed in this report, has been published recently.[77]

FOLDS FORMED BY REGIONAL STRESSES

The folds in the area are broad and open, the better-defined ones commonly showing dips of 5° to 10° on their flanks and exceptional dips as great as 16°. Most of the folds are unbroken, but two of the anticlines are cut near their crests by faults that run parallel or essentially parallel to the axes of the folds. The part played by the thick plastic salt series of the Paradox formation in the development of the folds is believed to have been one of passive yielding to regional forces that were in no way connected with movements within the salt mass.[78] Southeast of the area treated in this report the Moab anticline is believed to have undergone certain modifications due to recent movements in the salt,[79] but this effect is apparently lacking northwest of the Colorado river.

COURTHOUSE SYNCLINE

The Courthouse syncline is a prominent structural trough that borders the Salt Valley anticline on the southwest. It trends N. 45°–50° W. along the northeast boundary of the area mapped for a distance of perhaps 30 miles, although details of its position and character have not been worked out in the Mancos shale area at the northwest end. The axis follows the general course of Courthouse Wash from its mouth to Courthouse mail station, continues northwest near the Klondike well, and is believed to extend to the north boundary of the area near the Floy station on the Denver & Rio Grande Western Railroad. In the opposite direction it extends about 5 miles southeast of the Colorado River.[80] The axis plunges at a low angle to the northwest. The northeast flank of the syncline at its highest point, near Courthouse mail station, shows a structural rise of 2,500 feet in a distance of 4½ miles. In general the northeast flank has an average dip of 5°–10°, but locally dips of 15° were observed. The southwest flank is flatter; near the Colorado River the structural rise is 600 feet in a distance of 1½ miles to the crest of the Moab anticline, but northwest of Courthouse mail station this anticline has flattened out and disappeared, so that the southwest flank of the syncline merges into the regional northward dip.

[77] Baker, A. A., Geologic structure of southeastern Utah: Am. Assoc. Petroleum Geologists Bull., vol. 19, pp. 1472–1507, 1935.

[78] Baker, A. A., Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, pp. 74–76, 1933.

[79] Idem. pp. 64–66, 75–76.

[80] Idem, pl. 2.

MOAB ANTICLINE

The axis of the Moab anticline trends about N. 45°–50° W. and extends for about 9 miles northwest of the Colorado River from Moab Valley. Throughout this length the anticline is broken a short distance southwest of its crest by the Moab fault, which drops the crest of the anticline, at one place about 2,600 feet. There is also a short fault at one place almost along the axis. On the unbroken northeast flank of the anticline near the place where it is crossed by the Colorado River the structural drop to the axis of the Courthouse syncline amounts to 600 feet in a distance of 1½ miles, and the maximum dip is about 9°. On the southwest flank near The Dugway, the structural drop to the Moab fault is about 700 feet in a distance of 1 mile, with local dips as high as 37°, and the structural drop from the Moab fault to the axis of the Kings Bottom syncline is 1,500 feet in a distance of 2 to 2½ miles, with dips between 6° and 16°.

The area of more complex deformation along the Moab anticline adjacent to and southeast of the Colorado River [81] has had a very complex geologic history, involving strong anticlinal folding and erosion in pre-Triassic and Triassic time and deep erosion in Quaternary time. The net result has been to bring the saliferous and gypsiferous Paradox formation much closer to the present surface than in areas northwest of the Colorado River. Much of the structural complication found along the Moab anticline near and southeast of the Colorado River may thus be attributable to plastic deformation of the Paradox formation under relatively light load, and much of it may be of more recent date than the development of the simpler elements of structure along the Moab anticline and Moab fault in the area that is treated in the present report, northwest of the river.[82]

Baker [83] has shown that the Moab anticline a few miles southeast of the Colorado was a general axis of anticlinal folding in pre-Moenkopi time and also in pre-Chinle time. A study of the area in which the upper Paleozoic formations were removed by the erosion that produced these unconformities indicates that the pre-Triassic and mid-Triassic uplift along the Moab anticlinal axis was somewhat broader than the present structural crest of the anticline. Furthermore, the rate at which these unconformities decrease northwest of the Colorado, in the cliff along the Moab fault (pl. 1), suggests that in the pre-Moenkopi and pre-Chinle folding the axis of the anticline did not extend as far to the northwest as the present axis. Thinning and weakening of the Paleozoic strata above the Paradox formation by erosion that produced these early Mesozoic unconformities led to

[81] Baker, A. A., op. cit. (Bull. 841), pp. 63–66, pl. 2.
[82] Idem, pp. 64, 65.
[83] Idem, pp. 65–66.

more intensified and more sharply delimited deformation and to narrower structural features when the region was next folded in late Cretaceous or post-Cretaceous time.

KINGS BOTTOM SYNCLINE

The Kings Bottom syncline reaches its greatest structural depth where it is crossed by the Colorado River. Into this structural sump the synclinal axis plunges from both the northwest and the southeast. On the northwest side of the river the syncline has a length of about 11 miles, with an average axial trend of about N. 55° W. The northeast flank of the syncline shows a structural relief of 1,500 feet in a distance of 2 to 2½ miles to the Moab fault, with a maximum dip of about 16°. The southwest flank rises 2,500 feet in a distance of 5 miles and shows dips as steep as 11°. The syncline has a comparatively broad, flat bottom, so that the steeper dips occur at a considerable distance from the axis.

CANE CREEK ANTICLINE

The Cane Creek anticline apexes where it is crossed by the Colorado River; from the river its axis plunges both to the northwest and southeast. The flank that connects with the Kings Bottom syncline shows a structural drop of about 2,500 feet in 5 miles, with an average dip of 7° to 10° and a maximum dip of about 11°. The average dip of the southwest flank is 3° to 5° and the maximum about 7°. The structural saddle connecting with the Shafer dome lies about 2 miles from the apex of the anticline and is 650 feet lower. The apex is broken by a small vertical normal fault that, to the northwest, diverges slightly from the anticlinal axis onto the northeast flank; the maximum displacement is about 30 feet down on the northeast.

Like the Moab anticline, the Cane Creek anticline was formed early in the geologic history of the region and has been accentuated by folding at several subsequent times. The earliest folding of which we have record occurred between the Cutler and Moenkopi epochs of deposition. Another warping occurred between the Moenkopi and Chinle epochs. Many of the details of still later folding have been removed by erosion over the main part of the anticline, but both on the southeast and on the northwest the ends of the anticline are recognizable in the Wingate and later formations. Northwest from the Colorado River the axis of the anticline trends about N. 45° W. for perhaps 7 miles and then swings to the west. Its southwest flank in the Wingate and later formations is very much flattened as compared to the dip in the Paleozoic formations, showing that the dip in this flank is largely of pre-Wingate and probably pre-Moenkopi date. Actually the earth block containing the Cane Creek anticline and Shafer dome apparently acted as a rigid structural unit during post-Wingate deformation, and the downwarping occured on the northeast and southwest borders of this block, leaving it as a broad, flat, ill-defined anticlinal area swinging off westward toward Bowknot Bend on the Green River. There appears to be a local flat dome with a closure of perhaps 200 feet on this anticlinal block in the vicinity of The Knoll; contours on this dome are only approximate, owing to the absence of beds at recognizable stratigraphic horizons on which altitudes could be determined.

SHAFER DOME

The Shafer dome is elongated about N. 65° E., hence it does not conform with the regional trend shown by most of the other structural features. It is developed in Carboniferous rocks in an area along the Colorado River where later formations have been almost entirely removed by erosion (pl. 8, *A*). Its steepest dips are 15° on the northwest flank and 8° on the west end; the southeast flank dips from 3° to 6°, and the east end at a somewhat lower angle. The structural saddle separating the Shafer dome from the Cane Creek anticline is about 400 feet lower than the apex of the dome; that separating the Shafer dome from the Lockhart anticline is a little more than 500 feet lower than the apex of the dome. The area occupied by the dome is at least 6 miles long and 4 miles wide. It is possible that the Shafer dome may have been formed, in part at least, by plastic movements of salt in the Paradox formation in response to lightened load brought about by erosion of the stratigraphic overburden along the Colorado River. (See pp. 123–124.)

LOCKHART ANTICLINE

Only the northwest end of the Lockhart anticline extends into the area northwest of the Colorado River. There the dip off of the dome is northwest and amounts to 450 feet in a little more than 2 miles. The following summary of the essential features of the anticline is abstracted from Baker's report.[84] The axis of the anticline trends about N. 65° W., and its apex is about 300 feet higher than the saddle separating it from the Shafer dome on the north. The closure of the anticline is about 100 feet, as it is separated from the Rustler dome on the southwest by a low saddle. An area of about 6 square miles is included within the lowest closing contour.

[84] Baker, A. A., op. cit. (Bull. 841), p. 69.

RUSTLER DOME

The Rustler dome is another structural feature lying largely southeast of the Colorado River, only its northwest end extending into the area treated in the present report. The dome is about 3 miles long and 2 miles wide and is elongated about N. 50° W. A closure of only 50 feet or so separates it from the Lockhart anticline on the north and the Gibson dome on the south, both of which are larger folds.[85]

FAULTS

As compared with adjacent regions, there are few faults in the area treated in the present report. Most of the faulting is limited to a line or relatively narrow belt extending from Moab Valley northwestward to the Green River near the mouth of Salt Wash. The three major units along this line of break are the Moab fault, the Tenmile graben, and the Salt Wash graben. Another major break lying north of this group is the Little Grand fault. Elsewhere in the area the few faults that occur are relatively insignificant. Except for a minor thrust fault that is described in the discussion of the Meander anticline, with which it is genetically connected, all the faults of the area are normal faults with moderate to steep dips.

MOAB FAULT

As mapped by Baker,[86] the southwest wall of Moab and Spanish Valleys in the area southeast of the Colorado River is marked by a zone of faulting that extends for about 12 miles to the southeast from the river. None of the faults show a displacement of more than 300 feet. Most of them effect a structural drop on the northeast, but the fault segments for a mile or two adjacent to the river show an upthrow on the northeast, probably as a result of geologically recent upward movements of massive salt along the Moab anticline. Owing to lack of exposures, the nature of the faulting where it crosses the Colorado is not clear, but 1 mile northwest of the river there is again a perceptible downthrow on the northeast. The throw increases at a rapid rate to the northwest, and at the same time a more eastward-trending prong of the fault converges with the main prong at The Dugway so that all of the movement becomes concentrated on one break, the Moab fault. This fault can be traced for 29 miles northwestward from the Colorado River. The general trend is N. 40°–50° W. over most of this distance, but at the northwest end the fault swings gradually to N. 70° W. and becomes the south fault

[85] Idem, pp. 69, 70.
[86] Baker, A. A., op. cit. (Bull. 841), pl. 2.

of the Tenmile graben. At three places between Courthouse Spring and Brink's Spring the fault branches to the northwest. In each place the prong that is the direct continuation of the main stem of the fault dies out within a mile or two, whereas the prong that branches off to the west, first at an obtuse angle but later bending around more nearly parallel to the original course, becomes the main stem of the fault. The maximum displacement on the fault, amounting to 2,400 to 2,600 feet, is found along the 5-mile stretch between The Dugway and Sevenmile Wash. The dip of the fault surface is about 50° NE. near The Dugway and 62° NE. near Brink's Spring.

TENMILE GRABEN

The Tenmile graben is so named because its east end is drained by Tenmile Wash. Its trend is N. 75° W., its length about 7 miles, and its width 800 feet at the west end and 3,600 feet at the east end. The maximum displacement on the north fault is about 800 feet, and on the south fault, which is the northwestern extension of the Moab fault, about 700 feet. As the Moab fault swings away from Tenmile graben its displacement is somewhat greater than that shown on the south side of the graben. To offset this excess displacement a fault with a reversed displacement diverges from the Moab fault at its bend away from the graben and continues to the southeast more nearly in line with the south wall of the graben. Throughout most of its course the Moab fault drops a large earth block on the northeast, but where the simple fault is replaced at its northwest end by the Tenmile graben the block on the northeast side of the broken zone is raised relative to the block on the southwest side. This uplift of the northeast block is carried still farther in the net displacement shown across the Salt Wash graben, which is the next structural unit to the northwest along the same general zone of faulting.

SALT WASH GRABEN

The Salt Wash graben is closely followed over most of its length by the stream bed of Salt Wash. It has a trend of N. 70° W., a length of 10 miles within the area mapped, and an average width of 2,400 feet. A short distance above the mouth of Salt Wash it crosses Green River and continues, after a minor offset, for 4 miles into the Green River Desert on the west.[87] The maximum displacement on the north fault is about 1,050 feet and on the south fault 800 feet. At its southeast end the Salt Wash graben overlaps on the south side of the Tenmile graben for a mile or so, its north fault lying only 1,200 feet from the south fault of that graben. The floor

[87] Baker, A. A., Geology of the Green River Desert-Cataract Canyon region, Utah: U. S. Geol. Survey Bull. — (in preparation).

of each graben plunges away from this area of overlap, that of the Tenmile graben plunging to the southeast and that of the Salt Wash graben to the northwest. The plunge within or close to the area of overlap is steep, and the displacement along the bounding faults of the grabens increases rapidly, but away from the overlap the floor of each graben flattens and correspondingly the displacement along the bounding faults gradually decreases.

LITTLE GRAND FAULT

The Little Grand fault lies along the north edge of the drainage basin of Little Grand Wash and crosses the Green River about 3½ miles below the Denver & Rio Grande Western Railroad crossing at Elgin. It has been traced for a distance of about 5 miles east of the river, to a point where it runs into the area underlain by Mancos shale. Here tracing is no longer feasible, but what is apparently the same fault is mapped by Fisher[88] in the Book Cliffs, 7 miles beyond the traced extent along Little Grand Wash. West of the Green River the fault has been traced for about 16½ miles by Baker.[89] Near the river the strike of the fault is approximately east, but farther east it swings gradually to N. 70° E. The north side of the fault has moved up relative to the south side. The throw, totaling 950 feet as a maximum in the area shown on plate 1, is accomplished near the river on two parallel breaks that are nowhere more than 400 feet apart and that merge eastward. The southern of these breaks is the greater, showing about 700 feet of the total displacement.

LITTLE GRAND GRABEN

Near the mouth of Little Grand Wash the strata on the downthrown side of the Little Grand fault dip northward at a low angle into the fault. The rocks for about 2 miles from the fault are broken by two nearly parallel minor faults that strike nearly with the dip of the strata and hence at wide angles to the major fault. The strata between these two minor faults dip somewhat more steeply into the major fault than the adjoining strata. The resulting structural feature is a shallow graben 2 miles long, trending about N. 30° W. and having a width of 1,800 feet at the northwest end and 4,000 feet at the southeast end. It is bounded on the north end by the Little Grand fault. The maximum displacement on the east side is about 100 feet and on the west side about 50 feet.

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[88] Fisher, D. J., The Book Cliffs coal field in Emery and Grand Counties, Utah: U. S. Geol. Survey Bull. 852, pl. 9, 1936.

[89] Baker, A. A., op. cit.

STRUCTURAL FEATURES FORMED BY PLASTIC MOVEMENT OF BURIED SALT

MEANDER ANTICLINE

The Meander anticline was first described and named by Harrison.[90] Its axis follows the meander of the Colorado River for several miles above the junction with the Green—in particular, through that part of the canyon that is cut to or into the Hermosa formation. The axis follows the inner canyon except that the trend is more generalized and may cut across spurs produced by local deviations in the course of the river. Thus, at The Loop, where the river goes through a double bend in the form of a bowknot, the anticlinal axis cuts across the low divides in the knot area without changing its general course appreciably. The width of the anticline is between 1,000 and 2,000 feet, so that the strata affected are practically confined to the immediate walls of the canyon, and the beds are undisturbed a short distance beyond the canyon rims (pl. 6, *B*). Dips away from the river reach a maximum of 30° but are generally between 10° and 20°. Although the fold has been mapped and described as a continuous anticline, it shows several constrictions due to minor synclines that are too insignificant to map. The amount of closure is probably everywhere less than 100 feet. Where the anticline cuts across one of the divides at The Loop its crest is broken by a small thrust fault of low dip showing a displacement of about 30 feet.

The relation of this fold to the present topography suggests very strongly that the anticline is due to a bulging of the bed of the canyon under the pressure of the weight of rocks forming the canyon walls. Except for the larger scale and apparently deeper-seated mechanism, the situation is very similar to that formerly prevailing along a part of the Culebra Cut in the Panama Canal.[91] In order to produce such a result it is necessary that the material in or underlying the bed of the canyon or excavation should have a relatively high degree of plasticity. At the Culebra Cut argillaceous beds, and especially chloritic volcanic clays, heavily saturated with water, possess the requisite degree of plasticity. In the Colorado Canyon several hundred feet of salt of the Paradox formation undoubtedly serves as the plastic medium. It is not necessary to assume that the salt has migrated from some remote distance, profoundly rupturing the inter-

[90] Harrison, T. S., Colorado-Utah salt domes: Am. Assoc. Petroleum Geologists Bull., vol. 11, pp. 125–127, 1927.

[91] This similarity was first pointed out by Harrison, T. S., op. cit., p. 127. See also Sibert, W. L., and Stevens, J. F., The construction of the Panama Canal, pp. 277–280, New York, D. Appleton & Co., 1915. Goethals, G. W., The Panama Canal, an engineering treatise, vol. 1, pp. 372–374, New York, McGraw-Hill, 1916. MacDonald, D. F., Outline of Canal Zone geology, in Goethals, G. W., op. cit., pp. 71–72, fig. 1, pp. 78–80.

vening strata like some igneous body; the present conditions were more probably produced simply by an increase in the amount of the salt underneath the Meander anticline and a decrease in its amount under the adjoining cliffs. Only where erosion has cut deeply into the rocks overlying the salt has the difference in pressure between the loaded and unloaded areas exceeded the strength of these rocks. The total Hermosa formation, amounting to about 1,800 feet of strata, is the maximum thickness of rock that has failed on the Meander anticline. Although the lower canyon of the Green River has cut through about half of the Hermosa formation, there has been no doming along this stream. The explanation for this difference in structural behavior between the two canyons is to be found in the straightness of the weakened zone along several miles of the Colorado and its corresponding crookedness along the lower Green. With a comparable amount of weakening by erosion channeling, the rocks that overlie the salt would be more likely to fail if the channeling were in a straight line than if it showed a winding pattern.

The explanation here presented to account for the Meander anticline is essentially that offered by Harrison [92] except that the salt is not believed by the writer to have broken into the Hermosa formation very far above its original stratigraphic position. Because of the local nature of the fold no attempt has been made to contour it on plate 3.

UPHEAVAL DOME

The Upheaval dome is the most peculiar structural feature that has yet been found in southeastern Utah. It lies about 4 miles east of the Green River at the head of a short canyon (Upheaval Canyon) that cuts through the Wingate cliff. It is circular in ground plan and consists of a conical dome surrounded by a ringlike syncline (pl. 3). The diameter of the dome, measured through its center from the axis of the syncline on one side to the axis on the other, is 2 miles. The outer flank of the syncline is uniformly half a mile wide, making the complete diameter of the affected area 3 miles. Outside of the very sharply defined line along which the strata dip in abruptly toward the syncline, the regional low dip to the north has been undisturbed. The inward dip on the outer flank of the syncline is generally between 15° and 30°; the outward dip on the central dome ranges between 30° and 90°, though generally between 40° and 60°. The general shape of the dome and surrounding syncline is depicted with fair accuracy on plate 3, but because the information on which this part of the map is based was not detailed enough for mathematical representation of such features as the exact

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[92] Harrison, T. S., op. cit., pp. 126–127, fig. 13.

structural depth and configuration of the syncline and the exact closure on the central dome, the structure contours within the involved area have been dotted.

The strata that crop out in the area affected by the deformation range from the White Rim sandstone member of the Cutler formation to the Navajo sandstone. The White Rim member does not occur in place but appears as huge up-ended blocks the size of a house in the highly disturbed area of jagged pinnacles at the center of the dome. Surrounding this is the Moenkopi, very much crumpled and dissected by numerous gullies. The Shinarump forms a jagged fringe to the Moenkopi, its huge tilted triangular blocks sticking up like the teeth of a saw. The Chinle forms a relatively low "inner lowland" at the foot of the Wingate escarpment, though it is not at the same altitude all the way round the dome. The Wingate forms a steep, though not vertical escarpment, encircling the central area everywhere except on the west, where it is breached by Upheaval Canyon. The overlying Kayenta has been stripped off the encircling rim of Wingate in a large number of places, exposing the Wingate for short distances as steep dip slopes. The center of the dome as seen from some point on the cuesta ridge formed by the inner edge of the Wingate is spectacular and resembles a huge crater, a mile or so across, but formed in bright-colored sedimentary rocks rather than in more somber igneous rocks. The Kayenta, cropping out on the back slope of the Wingate rim, is a relatively unresistant unit and hence forms a wooded lowland, concentrically placed between the Wingate on the inside and the Navajo cliff on the outside. Falling between two structurally competent members, it has been decidedly crumpled, so that its dip is highly variable and may even show reversals. The numerous sawtooth hogbacks that have been produced by erosion on the tilted sandstones of the Kayenta make difficult any travel across the strike of the beds. The Navajo sandstone, which occupies the axis of the syncline, encircles the north, east, and south sides of the dome but has been removed on the west except for an isolated butte just south of Upheaval Canyon. The sandstone is cut through on the north by a steep, narrow gorge that drains the greater part of the lowland developed on the Kayenta. The Navajo weathers into picturesque rounded, steep-sided forms and can be crossed by horse in only one place.

The less competent beds involved in the folding have been considerably crumpled, but there is a conspicuous lack of faulting. The only fault noted is a small normal fault of low dip on the east side where the beds first bend in, which apparently represents a horizontal slip due to local stretching beyond the limit of deformation. The thickness of the Wingate on the axis of the syncline on the east side of the dome is only 30 or 40 feet. The formation does not seem to be shattered to any excessive degree. It hardly seems conceivable that a massive sandstone such as the Wingate could be plastically deformed to the extent indicated, and it may be that part of the thinning was produced by some slippage along horizontal faults that were not observed in the short time available for examination.

In a discussion of the fluid mechanics of salt domes Nettleton[93] has shown by theoretical analysis and by experiment that the deformation produced in stratified materials by focal intrusion of a plastic material of lower specific gravity through an overlying material of higher specific gravity leads to a structural form that is circular in plan and that is characterized by a steep central dome surrounded by a "peripheral sink" or syncline. The force of gravity, acting differentially on the lighter and heavier material, is sufficient to produce the intrusion provided that some local disturbance ever upsets the unstable equilibrium. The peripheral syncline is formed by the migration of the plastic material underlying it into the dormal area, where it is intruded upward. In applying the results of his work, Nettleton points out that the structure produced in the overlying rocks by the intrusion of a salt plug from a deeply buried stratum of salt should approximate the shape derived in these theoretical calculations and experiments. The structure-contour surface of the Upheaval dome is practically identical with the curved surface expressing the theoretical structural shape of a salt dome; this fact, together with the known existence of a thick salt series at moderate depth in the Paradox formation would seem strong presumptive evidence that the Upheaval dome is the structural expression at the present surface of a salt dome that has not yet been exposed by erosion.

Bucher,[94] on the other hand, has shown that the structure of the Upheavel dome is that of a widely distributed type to which he has called attention under the name "cryptovolcanic structure." Five of the six or seven known examples in the United States lie in regions where, according to Bucher, no salt or gypsum beds are known in the formations underlying the disturbed areas. He attributes the origin of these unique features to the upward explosion of volcanic gases from some hidden source, such as a lava plug, that has penetrated so close to the surface that the expansive force of the gases liberated when it crystallizes is greater than the weight of the superincumbent rock. The mechanics of the development of the ringlike syncline is not discussed by Bucher, but as he has shown, this feature is present in at least three other examples of

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[93] Nettleton, L. L., Fluid mechanics of salt domes: Am. Assoc. Petroleum Geologists Bull., vol. 18, pp. 1175–1204, 1934.

[94] Bucher, W. H., Cryptovolcanic structures in the United States: 16th Internat. Geol. Cong. Rept., vol. 2, pp. 1055–1084, 1936.

the structural type in the eastern United States. Among the examples known, the Upheaval dome is one of the most symmetrical and is the least faulted, owing perhaps in part to the structural competency of the sandstone formations that predominate in the stratigraphic section of the area. The writer has examined the crater of the Upheaval dome in some detail but found no trace of igneous rock nor evidence of igneous metamorphism. Their absence is, however, common to the other examples of the structural type. The dome lies about 35 miles west of the La Sal Mountains, 45 miles north-northwest of the Abajo Mountains, 55 miles northeast of the Henry Mountains, and 60 miles east of the nearest dikes and sills in the San Rafael Swell.

Nettleton's explanation of the peripheral sink as due to migration into the dome of plastic material originally underlying the sink seems to be the most reasonable explanation of this feature, but it is possible that other materials than salt may be subject to this movement. Thus, the rise of a magmatic plug from a thick sill of liquid or viscous magma might lead to an identical type of structure. The fact that the overburden drops in the synclinal area indicates that no excess pressure was transmitted to the plastic medium from regions outside the disturbed area, hence the propelling mechanism must have been the local gravity differential between the synclinal area and the dome area. In salt domes, if a level topographic surface above the affected area is maintained, either by erosion or by sedimentation, the difference in specific gravity between the salt and the overburden in adjacent columns of equal height, once the salt is displaced at a focal point by some tectonic accident, furnishes a gravity differential sufficient to cause the dome and associated syncline to grow slowly. Where an igneous magma is involved instead of salt, though there is still a difference in specific gravity between the magma and the overburden,[95] this difference is not nearly so great, and there is some doubt as to whether it alone would be adequate to produce the gravity differential necessary for the deformation shown in the "cryptovolcanic" structural type. However, if there is a topographic depression over the dome area, it would not be necessary to have a difference in specific gravity between the buried plastic material and the overburden. Thus, in the Meander anticline (pp. 123–124) the doming would still have occurred regardless, within certain limits, of the relative specific gravities of the salt and the overburden. As the examples of cryptovolcanic structure that show a peripheral syncline are all markedly circular in plan and symmetrical to a central point rather than to a line, the topographic

[95] Daly, R. A., Igneous rocks and the depth of the earth, pp. 276–280, New York, McGraw-Hill, 1933.

depressions produced by drainage lines would apparently be eliminated as playing any essential part in the mechanism. On the other hand, if the explosion of volcanic gases postulated by Bucher were powerful enough to blow out an explosion crater, the depression so formed would be an ideal focal point for the rise of viscous partly consolidated magma in depth, forced up by the hydrostatic pressure of the overburden sinking in the peripheral syncline.

It would therefore seem possible that at least two rather dissimilar modes of origin can give rise to very similar structural features that constitute the "cryptovolcanic" type. Because of the known occurrence of thick salt under the Upheaval dome, the writer prefers to consider this feature a salt dome. The rock in the center of the dome is greatly broken, mashed, and squeezed, as if it had been plastically kneaded, but it shows no voids or cavities and can in no way be described as a breccia. The massive sandstones on the axis of the peripheral syncline also appear to have been deformed plastically and do not show the breaking and shattering that would be expected had they been deformed rapidly and near the surface. The topographic relief shown in the deformed area amounts to about 1,600 feet, and as the structure is in no way modified by the existing topography it must have developed before any of the present relief was formed. Every indication points to slow deformation under thick cover, which is the hypothetical situation considered by Nettleton to be most favorable for producing the gravity differential necessary to propel a salt plug toward the surface.

The Upheaval dome is figured and briefly described by Harrison [96] as a salt dome under the name "Christmas Canyon dome."

AGE OF DEFORMATION

Although most of the essential facts relating to different ages of deformation are given indirectly in the discussion of unconformities in the stratigraphic section and in the descriptions of the individual structural features, this information is here collected together for more coherent treatment.

The earliest deformation recorded in the rocks exposed at the surface occurred at the end of the Permian and before the Triassic. At least two of the structural features lying within the area treated in this report came into existence at that time—namely, the Moab and Cane Creek anticlines. The erosion that followed this earliest folding removed at least 1,000 feet of the Cutler and Rico and in addition at least 100 feet of the Hermosa from the flank of the ancient Moab anticline in the area that now lies northwest of the Colorado

[96] Harrison, T. S., Colorado-Utah salt domes: Am. Assoc. Petroleum Geologists Bull., vol. 11, p. 128, 1927.

River, and it is probable that an additional thickness of Hermosa strata was removed from the apex of the fold lying, it is believed, in the area that is now southeast of the river. The fold was thus comparable in size to many of the later folds of the region that are developed in the Wingate sandstone. On the Cane Creek anticline pre-Triassic erosion removed about 300 feet of the upper Cutler beds. Baker [97] has shown that the Castle Valley anticline, lying east of the area covered in this report, was also an area of uplift and erosion at the end of the Permian epoch.

Accentuation of the earlier folding took place on the Moab and Cane Creek anticlines in mid-Triassic time, between the deposition of the Moenkopi and that of the Chinle formation. Erosion along the upfolded axis of the Moab anticline in this period removed the complete thickness of the Moenkopi, amounting to about 450 feet, and an unknown additional thickness of the Hermosa. At the same time about 200 feet of upper Moenkopi beds was eroded from the crest of the rejuvenated Cane Creek anticline in the area of maximum uplift, which now lies a short distance southeast of the Colorado River.

Not until after the deposition of the great thickness of Jurassic and Cretaceous rocks was the region again deformed to any great degree. That part of plate 3 in which the contours are drawn on the base of the Wingate sandstone records this late Cretaceous and post-Cretaceous deformation, which, probably at different times, included faulting as well as folding. Folding took place along the Moab and Cane Creek anticlinal axes for a third time, but the other structural features that are apparently attributable to regional diastrophic forces were evidently formed for the first time. In the area mapped there are no late Cretaceous or post-Cretaceous formations by means of which the deformation can be dated more closely, but observations in adjoining parts of the Colorado Plateau [98] show that large-scale regional deformation antedated the deposition of a conglomerate which was formerly believed to be the basal part of the Wasatch (Eocene) formation but which recent discoveries may prove to be late Cretaceous.[99] A later orogenic disturbance of lesser intensity may also fall within the Cretaceous.[99] It seems highly probable that the regional folding after Mancos time in the area between the Green

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

[98] Gregory, H. E., and Moore, R. C., The Kaiparowits region: U. S. Geol. Survey Prof. Paper 164, pp. 116, 120–121, 1931. Spieker, E. M., and Reeside, J. B., Jr., Cretaceous and Tertiary formations of the Wasatch Plateau, Utah: Geol. Soc. America Bull., vol. 36, pp. 445–453, 1925. Spieker, E. M., Stratigraphic relations of the Wasatch formation, central Utah: Geol. Soc. America Proc., 1933, pp. 108–109, 1934. Erdmann, C. E., The Book Cliffs coal field in Garfield and Mesa Counties, Colo.: U. S. Geol. Survey Bull. 851, pp. 22, 48, 53, 64, 1934.

[99] Spieker, E. M., The orogenic history of central Utah: Science, new ser., vol. 83, pp. 62–63, 1936.

and Colorado Rivers is to be correlated with this known deformation of adjacent regions, which is probably of the same age as the folding and elevation of the Rocky Mountains during the Laramide revolution. The faulting appears to be later than the folding. Thus, the Moab fault on the flank of the Moab anticline is normal and apparently records a tensional stress later than the compressional stress that produced the anticline. According to Spieker and Reeside [1] the normal faulting of the Wasatch Plateau is later than the pre-Eocene folding and is possibly late Tertiary.

The latest deformation in the area here considered is that due to plastic movements within the underlying salt mass in response to differential unloading by erosion along the canyon of the Colorado, as exemplified in the Meander anticline. The doming that shows along this axis is believed to have taken place in geologically recent time and to be still continuing. Graben faulting that resulted from this plastic movement in the salt has led to recent drainage changes in the area just south of the junction of the Colorado and Green Rivers.[2] The Upheaval dome, on the other hand, is somewhat older than the present topography. If the interpretation of this feature as a salt dome is correct, the deformation was probably produced by very slow movements of the salt that may have extended over several geologic periods.[3]

ECONOMIC GEOLOGY

MANGANESE

Deposits of manganese ore in the Summerville formation within this area were of some economic interest during the World War.[4] All of them lie in the western part of the area, near the Green River, in what is known as the Little Grand district. The most productive deposit occurs in the top of the formation about a mile northwest of White Wash. This deposit was worked by the Colorado Fuel & Iron Co. and yielded the greater part of the 8,000 tons of ore produced by the Little Grand district during the years 1915–18. Other camps of lesser output are strung along the Summerville escarpment between this locality and Tenmile Wash. An isolated deposit appears east of Tenmile Wash, about 2 miles northeast of Tombstone Butte, but it appears to have been less productive than those lying west of the wash.

[1] Spieker, E. M., and Reeside, J. B., Jr., op. cit., p. 453.

[2] Baker, A. A., Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, p. 74, 1933.

[3] Nettleton, L. L., Fluid mechanics of salt domes: Am. Assoc. Petroleum Geologists Bull., vol. 18, pp. 1175–1204, 1934.

[4] Pardee, J. T., Deposits of manganese ore in Montana, Utah, Oregon, and Washington: U. S. Geol. Survey Bull. 725–C, pp. 245–309, 1922.

These manganese deposits occur at several horizons in the Summerville, both above and below the Moab sandstone, or its stratigraphic horizon where it is absent to the west. According to Pardee, three types of deposits are represented—(1) a "blanket vein" deposit that has replaced thin limestone lenses (this, the Colorado Fuel & Iron type, is the most important as a source of ore); (2) a replacement deposit of impure sandstone, both along bedding planes and along cross-cutting veins and pipes, generally beneath the "blanket veins" in limestone; (3) a residual concentration of nodular ore derived from the two preceding types. The commercial deposits are thin (4 inches to 3 feet thick) and of moderate extent, averaging 100 feet across, but in most camps there are several deposits at the same horizon. The ores are reached by stripping the thin overburden. The ore minerals are pyrolusite and manganite; the gangue minerals are calcite, gypsum, and barite.

OIL AND GAS

HISTORY OF DRILLING

Wells drilled within the area in a search for oil and gas are confined to two general districts—(1) the area of Morrison, Dakota (?), and Mancos outcrops along a general northwesterly belt from Courthouse mail station to the town of Green River and (2) the area of Hermosa outcrops along the Colorado River on the Moab and Cane Creek anticlines and Shafer dome. The history of drilling in these two districts has been given by Lupton [5] and Baker,[6] respectively, in their more comprehensive treatments of broader areas. The information given in the following pages is taken largely from the reports of these two authors, as very little development work has been done in the area since their reports were published.

COURTHOUSE-GREEN RIVER DISTRICT

The earliest well in the Courthouse-Green River district, known as the Elgin well, was drilled in about 1891 to a depth of 1,000 feet, in the SW¼SE¼ sec. 15, T. 21 S., R. 16 E., near the town of Elgin. The surface at this well is 100 feet above the base of the Mancos shale, and the bottom of the well is probably in the Summerville formation. The location is on the northward-dipping monoclinal slope, 3 miles north of the Little Grand fault. No oil was found, but a little carbon dioxide escaped at one or more levels during the drilling. A little water, probably containing lime, issues from the well and has built up a small deposit around it.

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[5] Lupton, C. T., Oil and gas near Green River, Grand County, Utah: U. S. Geol. Survey Bull. 541, pp. 117–120, 132–133, 1914.

[6] Baker, A. A., Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, pp. 81–82, 1933.

Levi well No. 1, in sec. 25, T. 23 S., R. 18 E., was drilled to a depth of 530 feet in the spring and early summer of 1912. It begins in the Morrison formation and may have reached the Moab tongue of the Entrada sandstone. The location is on a northeastward-dipping monoclinal slope perhaps a quarter of a mile south of a spur of the Moab fault. A fairly strong flow of water was hit at 350 feet and still rises to or nearly to the surface. A little gas and a small quantity of oil are reported to have been encountered near the bottom of the well.

Levi well No. 2, in the NE¼NW¼ sec. 35, T. 22 S., R. 17 E., was drilled to a depth of 1,500 feet, probably in 1912. It begins in the Morrison formation and is located on a northeasterly monoclinal slope, 1¼ miles northeast of the Salt Wash graben. No oil or gas was encountered, and the hole was clogged by "shooting" in an attempt to pull the casing. Another hole, drilled by the same company in the SE¼SE¼ sec. 26 of the same township, was drilled to a depth of 425 feet in an attempt to cut one of the Salt Wash sandstones of the Morrison, which is partly saturated with petroleum at its outcrop in the cliff 1,700 feet southwest of the well. The horizon of this sandstone should have been reached at about 140 feet in the well, but no oil-bearing sand was found, possibly owing to the lenticular nature of the outcropping sandstone followed under cover.

The Klondike well of the Moab Oil Co., drilled some time between 1910 and 1913, is in the NW¼SW¼ sec. 26, T. 23 S., R. 19 E. It is about 700 feet deep and is believed to be entirely in the Mancos shale. The location is close to the plunging axis of the Courthouse syncline. No oil or water was encountered in the well, but pockets of gas were found at depths of 75, 265, and 500 feet. The middle pocket showed the strongest flow, and the lower pocket the weakest. The intermediate flow from the upper pocket, when conducted through a ¾-inch pipe and ignited, is reported to have made a flame 1½ to 2 feet long. All three gas pockets were cased off in further drilling.

The Queen well, in the SE¼SE¼ sec. 18, T. 23 S., R. 19 E., was drilled to a depth of 920 feet at some time between 1910 and 1913. The upper 410 feet of the well is believed by Lupton to be in the Mancos shale, and the hole would thus bottom in the Morrison. Detailed mapping by the writer in the vicinity of the well indicates that the location is probably just south of a concealed fault showing a downthrow of about 150 feet on the south. If this interpretation is correct, the well begins 100 to 150 feet above the Ferron sandstone, but it may pass through the fault and into the footwall block, where it would reach the base of the Mancos at approximately the depth given by Lupton. The well is reported to have yielded fresh water from a white sandstone at a depth of 425 feet, salt water at 600 feet and again at 870 feet, and a showing of oil at 910 feet.

Since Lupton's work in the area the Marland Oil Co., between June 25, 1925, and September 14, 1926, drilled a well to a depth of 3,820 feet in the NW¼SE¼ sec. 35, T. 21 S., R. 16 E. The location is on the northward-dipping monoclinal slope 1,600 feet north of the Little Grand fault, where the fault shows a displacement of about 900 feet. The well begins in the Morrison formation and is believed to bottom in the Cutler or the Rico. (See pp. 142–143 for log.) Slight shows of oil were reported in sandstone, probably Morrison, at a depth of 400 feet, and in sandstone, probably Shinarump, at a depth of 2,396 feet, and showings of gas and oil were reported in "red shale," probably Moenkopi, at a depth of 2,630 to 2,645 feet. From 3,060 to 3,400 feet the hole passed through a massive white sandstone, believed to be the Coconino of the San Rafael Swell, that showed a slight amount of oil at the top and a little gas 110 feet or so below the top. Oil and gas in commercial quantity, however, were not found in the well. Lupton [7] reports that an oil seep called "Goin's seep" occurs on the Little Grand fault just south of the site of the well, and it is probable that this showing of oil influenced the location of the well. The fault has apparently acted as an avenue of escape for petroliferous material rather than as a seal across the ends of the broken and tilted beds as the drilling company had hoped.

Between November 27, 1935, and July 1936 a prospect well, known as the No. 1–X State well, was drilled by Glen Ruby and others to a depth of 2,627 feet in the SE¼SE¼ sec. 34, T. 21 S., R. 16 E., on the east bank of the Green River a short distance north of the Little Grand fault. Showings of oil and gas were reported at numerous levels to a depth of 536 feet. The log of this well has been obtained only to a depth of 2,417 feet; it shows the base of the Wingate sandstone at a depth of 1,610 feet. According to contemporary reports in the files of the Conservation Branch of the Geological Survey, the bottom 5 feet of the hole was in dense cherty limestone, which was correlated with the Kaibab limestone. Although the Kaibab was not recognized in the well drilled by the Marland Oil Co., only three-fourths of a mile away, the interval between the top of the Coconino (where the Kaibab should occur were it present) and the base of the Wingate is 1,005 feet, which compares favorably with a correlative interval of 1,017 feet in the Glen Ruby well.

COLORADO RIVER DISTRICT

In 1920 the Big Six Oil Co. started a well on the northwest bank of the Colorado River at Moab, in sec. 34, T. 25 S., R. 21 E. The location is on the southwest flank of the Moab anticline and very near the Moab fault. It is not certain where the fault lies with respect

[7] Lupton, C. T., op. cit. (Bull. 541), p. 120.

to the well, as the exposures are poor along the edge of the flat on which the well is located; it is possible that the well may cross the fault in depth. The well was drilled to a depth of 2,870 feet with no encouraging results, and drilling was suspended. After small quantities of oil had been found in later wells drilled in the district, however, the drilling was extended by the Embar Oil Co. in 1926–28 to a depth of 5,345 feet. The well starts in the Hermosa formation and passes into the Paradox formation, probably somewhere between depths of 1,245 and 1,513 feet. (See p. 141.) The deepest salt of the Paradox formation is cut at or near 3,985 feet, but it is probable that shale and limestone facies of this formation extend to 4,170 feet, below which an unidentified section is encountered. Showings of gas and oil are reported to have been found at 17 horizons in the well, beginning at a depth of 104 feet and extending to the bottom, chiefly in limestone and shale though subordinately in thin sandstone beds. No accumulation of commercial value was found, however.

In 1924 the Frank Shafer No. 1 well was begun by the Utah Southern Oil Co. and the Utah Oil Refining Co. on the crest of the Cane Creek anticline where it is crossed by the Colorado River, in sec. 31, T. 26 S., R. 21 E. Later taken over by the Midwest Co., under an agreement with the original companies, the hole was sunk to a depth of 5,000 feet before drilling was finally discontinued late in 1926. The hole begins in the Hermosa formation, 300 feet below its top, and passes into the Paradox formation at a depth of about 1,425 feet, remaining in this formation to the bottom. (See pp. 138–139.) Beginning in the limestone that has been tentatively assigned to the base of the Hermosa and recurring at several levels in the underlying Paradox formation, showings of oil and gas are reported in the driller's log. They occur in material logged as limestone, shale, or salt. From a limestone encountered at a depth of 2,028 feet gas and oil gushed to the surface and caught fire, burning the rig. The well was soon brought under control, but after an unsuccessful attempt was made to shut off water from a higher level the oil-bearing bed was cased off and the drilling resumed. This oil is reported to have been a green paraffin-base oil with a gravity of 36° Baumé. At a depth of 3,628 feet another showing of oil was obtained and the oil is reported to have risen 800 feet in the well. This bed was also cased off during further drilling. After the well was completed attempts were made, in 1927, to recover the oil from the levels that had been cased off, but without success.

In 1926 the same companies that had drilled the well on the Cane Creek anticline started a well on the apex of the Shafer dome where it is crossed by the Colorado River, in sec. 16, T. 27 S., R. 20 E. This well, known as the J. H. Shafer No. 1, was drilled to a depth of 5,863 feet before it was finally abandoned. It begins about 150 feet below the top of the Hermosa formation and cuts into the Paradox formation at a depth of 1,610 feet and into unknown strata underlying the Paradox at a depth of 5,690 feet. (See pp. 137–138.) A showing of oil was encountered in sandstone of the Hermosa formation at a depth of 764 feet, but the quantity was negligible.

In 1928–29 another well, known as the J. L. Shafer No. 1A, was drilled by the Utah Southern Oil Co. on the north flank of the Cane Creek anticline in sec. 25, T. 26 S., R. 20 E., near the Colorado River. The hole begins apparently in the Rico formation but soon cuts into the Hermosa. (See pp. 140–141.) It reached the Paradox formation at a depth of 2,048 feet and continued in this formation to the bottom of the well at a depth of 4,107 feet. A show of gas was reported in the top of the Paradox formation at a depth of 2,055 feet, but no commercial yield was found.

POSSIBILITY OF OIL AND GAS PRODUCTION

That some oil is present in the prospected area between Courthouse mail station and the town of Green River is shown by the occurrence of petroleum and the residual products of petroleum in surface seeps and outcrops at several localities. In the Tenmile Wash region the Moab tongue and the upper part of the Entrada are saturated to a varying degree with the residual products of oil. The saturation is not continuous but appears in lenses from 5 to 10 feet thick and a few hundred feet long. The greatest amount of saturation occurs in the NE¼ sec. 35, T. 23 S., R. 18 E., where the normally white sandstone of the Moab tongue is colored black by the large amount of bituminous material. Usually, however, the oil sands are of varying shades of gray, denoting only partial saturation. "Goin's seep," on the Little Grand fault, is mentioned in the discussion of the Marland well (p. 133), and another seep is mentioned in the discussion of the Levi wells (p. 132). None of the present seeps or asphaltic residues are more than a few miles from faulted zones, and the petroleum may have been derived from Pennsylvanian rocks and reached the present surface by migration along the faults. There are few places in the northern part of the area where structural conditions are favorable for the accumulation of petroleum in large reservoirs. The general structure is that of a monoclinal dip toward the north, broken by faults. In some oil fields where the gouge along a fault plane is impervious and where the strata contain impervious layers of shale that may confine the oil, a favorable location is at the upper end of dipping strata where they have been broken and sealed by the fault. In this area, however, the faults have apparently acted as porous zones of escape rather than as seals. The Marland and Glen Ruby wells prospected the top of a monoclinal slope on the down-dip side of a major fault and found it barren, though apparently the most favorable formation—namely, the Hermosa with its numerous limestone beds—was not reached, or had just been reached in the Marland well, when the drilling was abandoned. Other wells in the district have yielded few showings to encourage further prospecting, though none of them were located with any consideration of the geologic principles of oil accumulation.

Two localities in the district that appear to be structurally favorable for the accumulation of oil or gas have not yet been tested. One is the structurally high area just north of the Salt Wash graben, where the structural situation is much the same as that on which the Marland well was drilled. (See pl. 3.) It is believed that the negative results obtained at the Marland well indicate that a test well in that area would probably be barren. The other locality is in the area of rather ill-defined dip reversals in the northwestern part of T. 23 S., R. 17 E. If any structural closure exists in this area, however, it is too small to be indicated clearly on a structural map with a contour interval of 100 feet (see pl. 3),[8] and any closed dome that may be present is too small to be of any great prospective value, especially as the structure may be modified in depth. The area has one advantage, however, in that it is favorably placed to trap, below any of the impervious shales present in the stratigraphic section, any oil that might escape out into strata adjoining the south Salt Wash fault.

The district along the Colorado River that has been prospected for oil would appear to be structurally the most promising part of the area, yet the wells that have been drilled to date have not been successful. That some oil is present in the Paradox formation was proved by the Frank Shafer No. 1 well on the Cane Creek dome, by the showings of oil and gas obtained in other wells in the district, and by wells drilled in Salt Valley and near Crescent,[9] both northeast of the area treated in this report. All the more promising anticlines and domes along both sides of the Colorado River have been drilled, however, with negative results so far as commercial yield is concerned. It is possible that flowage in the Paradox formation has so broken the strata along the anticlinal axes that the normal movement of oil and gas into the crests of the domes and anticlines has been inhibited. Thus, by way of analogy, in Louisiana and Texas, where salt plugs have been intruded into overlying sedimentary rocks, the

[8] Details of dip reversals in this general area are given by Lupton (op. cit. (Bull. 541), p. 130), who believes that there may be three or four small and poorly defined domes present in this township and adjacent parts of the townships on the west and northwest.

[9] Dane, C. H., Geology of the Salt Valley anticline and adjacent areas, Grand County, Utah: U. S. Geol. Survey Bull. 863, pp. 158, 161–164, 1936.

upturned and punctured strata bordering the salt cores have proved highly productive, whereas the cores themselves are barren. With this principle in mind, the J. L. Shafer No. 1A well was drilled for the purpose of testing the flank of the Cane Creek anticline, but it failed to find oil. Other wells drilled on the flanks of the Moab anticline have been similarly unproductive, though it is possible that these wells were drilled too close to the broken and squeezed zone along the crest of the anticline. The absence of favorable reservoir sediments, such as sandstone, in the Paradox formation may also be a contributing cause to the barrenness of the wells that have been drilled to date. On the whole, however, the major factor contributing to this barrenness appears to be an insufficiency of source beds of petroleum. The possibility of escape of the oil and gas under such structural conditions as prevail in the Moab anticline is not to be minimized, but this possibility could hardly have existed in the Cane Creek anticline and Shafer dome, and there is furthermore no evidence of seepage.

There is, of course, a possibility that, owing to the peculiar structural and stratigraphic conditions brought about by the presence and flowage of the salt, the oil that occurs in the Paradox formation may have accumulated in discontinuous blocks or lenses irrespective of anticlinal folding. Finding such an accumulation, however, would be a difficult and haphazard undertaking. The small amounts of oil that have been found on the Cane Creek anticline and near Crescent have been so closely associated with salt water as to present major problems of recovery.

RECORDS OF WELLS

The records of six deep wells drilled in the area are given on the following pages. The records of the shallow wells are not shown. The lithologic descriptions are those given by the drillers, and the writer has interpreted the formation boundaries.

Record of J. H. Shafer No. 1 well in sec. 16, T. 27 S., R. 20 E. (*Shafer dome*)

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Hermosa formation:			Hermosa formation—Continued.		
Blue limestone	25	25	Gray limestone	39	414
Red sandstone; water-bearing	38	63	Black shaly limestone	11	425
Limestone	10	73	Gray sandy limestone	15	440
Sandstone; water-bearing	8	81	Muddy gray sandstone	25	465
Red shale	19	100	Hard gray sandy limestone	20	485
Hard brown limestone	10	110	Dark sandstone	10	495
Blue shale and hard shell	21	131	Sandy brown shale	30	525
Gray limestone	14	145	Gray limestone	45	570
Shale	63	208	Brown shale	20	590
Gray limestone	74	282	Brown limestone	6	596
Shale	3	285	Gray shale	3	599
Gray limestone	65	350	Brown limestone	6	605
Black slate	15	365	Interbedded shale and limestone	21	626
Black limestone	10	375			

Record of J. H. Shafer No. 1 well in sec. 16, T. 27 S., R. 20 E. (Shafer dome)—Continued

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Hermosa formation—Continued.			Paradox formation—Continued.		
Gray limestone	29	655	Salt	10	2,050
Blue shale and gray limestone	5	660	Limestone	25	2,075
Gray limestone	10	670	Gray shale	19	2,094
Blue shale	10	680	Limestone	6	2,100
Sandstone	5	685	Sandstone, shale, and salt	25	2,125
Gray limestone	11	696	Salt	130	2,255
Gray shale	5	701	Limestone	15	2,270
Gray limestone	17	718	Gray shale	95	2,365
Sandstone; water-bearing	6	724	Salt	18	2,383
Gray limestone	29	753	Gray shale	107	2,490
Blue shale	11	764	Salt	100	2,590
Sandstone; salt water and show of oil	18	782	Shale and gypsum	10	2,600
Gray limestone and gray shale	323	1,105	Salt	190	2,790
Black limestone	70	1,175	Shale and gypsum	35	2,825
Black shale	5	1,180	Salt	165	2,990
Gray limestone	6	1,186	Limestone	50	3,040
Gray shale	104	1,290	Salt	200	3,240
Gray limestone	19	1,309	Sandy shale	30	3,270
Gray sandy shale	11	1,320	Black shale	35	3,305
Gray limestone	13	1,333	Salt	43	3,348
Black limestone	29	1,362	Gray shale and gypsum	62	3,410
Gray limestone	138	1,500	Salt	130	3,540
Limy shale	25	1,525	Gray shale	55	3,595
Black limestone and black shale	40	1,565	Salt	65	3,660
Gray limestone	45	1,610	Gray shale	36	3,696
Paradox formation:			Salt	264	3,960
Limestone and salt	10	1,620	Black shale	5	3,965
Salt	13	1,633	Salt	360	4,325
Shell	2	1,635	Gray shale and gypsum	55	4,380
Salt	100	1,735	Salt	476	4,856
Limestone	10	1,745	Brown shale	41	4,897
Brown sandstone	10	1,755	Gray shale and gypsum	118	5,015
Black slate	15	1,770	Salt	265	5,280
Black shale	18	1,788	Black shale	40	5,320
Black limestone	8	1,796	Gray sandy shale	70	5,390
Salt	4	1,800	Salt	125	5,515
Limestone and salt	23	1,823	Black shale and gypsum	55	5,570
Salt	76	1,899	Gray sandy shale	20	5,590
Gray limestone	39	1,938	Black limestone	25	5,615
Black shale	102	2,040	Gray sandy shale	65	5,680
			Limestone	10	5,690
			Molas formation (?):		
			Variegated shale, fresh water	173	5,863

Record of Frank Shafer No. 1 well in sec. 31, T. 26 S., R. 21 E. (Cane Creek anticline)

	Thickness (feet)	Depth (feet)		Thickness (feet)	Depth (feet)
Alluvium: Sand and gravel	55	55	Hermosa formation—Continued.		
Hermosa formation:			Gray limestone	9	365
Gray shale	8	63	Gray shale	3	368
Hard gray limestone	7	70	Gray limestone	5	373
Gray sandstone, water bearing	12	82	Gray sandy shale	17	390
Gray shale	3	85	Brown sandy limestone	30	420
Gray sandstone	10	95	Gray sandy limestone	30	450
Gray shale	30	125	Gray shale	2	452
Brown limestone	5	130	Hard gray limestone	15	467
Brown sandy shale	10	140	Brown sandy limestone	7	474
Brown sandstone	10	150	Gray shale	21	495
Brown shale	12	162	Hard gray limestone	105	600
Hard brown limestone	38	200	Blue limestone	100	700
Gray limestone	17	217	Brown limestone	100	800
Brown sandstone	2	219	Gray to black limestone	87	887
Brown shale	18	237	Gray limy shale	4	891
Gray shale	3	240	Hard gray limestone	4	895
Gray limestone	92	332	Black limestone	7	902
Gray limy shale	4	336	Gray limestone	7	909
Gray limestone	16	352	Blue shale	2	911
Gray limy shale	4	356	White limestone	8	919
			Gray limestone	3	922

Record of Frank Shafer No. 1 well in sec. 31, T. 26 S., R. 21 E. (Cane Creek anticline)—Continued

	Thickness (feet)	Depth (feet)
Hermosa formation—Continued.		
Gray and black limestone	23	945
Gray shale	15	960
Gray limestone	15	975
Brown limestone	50	1,025
Blue shale	2	1,027
Gray limestone	31	1,058
Black limy shale	40	1,098
Black limestone	19	1,117
Gray limestone	170	1,287
Brown shale	22	1,309
Brown shale, sticky with tar	2	1,311
Black limestone	7	1,318
Blue shale	3	1,321
Dark-gray limestone	5	1,326
Gray shale	19	1,345
Gray shale, sticky	9	1,354
Light-gray shale	6	1,360
Blue shale	12	1,372
Gray limestone	8	1,380
Gray shale	17	1,397
Gray limestone	11	1,408
Gray to brown limestone; gas	17	1,425
Paradox formation:		
Brown shale	26	1,451
Hard shell	1	1,452
Black shale	13	1,465
Gray shale	10	1,475
Gray limestone with some gypsum	21	1,496
Gray shale, sticky	2	1,498
Gray limestone with some salt	5	1,503
Salt	42	1,545
Salt, limestone, and shale	18	1,563
Gray limestone	2	1,565
Brown shale	67	1,632
Gray limestone	23	1,655
Salt	178	1,833
Limestone	2	1,835
Gray shale	30	1,865
Salt; showing of oil	125	1,990
Gray sandy limestone	20	2,010
Gray sandy shale with salt	15	2,025
Dark sandy limestone; gas and oil	33	2,058
Black shale	5	2,063
Limestone	3	2,066
Salt	79	2,145
Limestone	2	2,147
Salt	41	2,188
Limestone	1	2,189
Salt and gypsum	4	2,193
Limestone	1	2,194
Salt with thin shale beds	59	2,253
Limestone	2	2,255
Salt with thin shale beds	8	2,263
Limestone	2	2,265
Salt and gypsum	28	2,293
Black shale	3	2,296
Salt and gypsum	46	2,342
Limestone	3	2,345
Salt	30	2,375
Black shale	3	2,378
Salt	31	2,409
Black shale	3	2,412
Salt showing some potash	96	2,508
Limestone	3	2,511
Salt with some gypsum	71	2,582
Black shale	2	2,584
Gray shale	20	2,604
Salt	122	2,726
Limestone	1	2,727
Paradox formation—Continued.		
Gray shale	2	2,729
Salt with thin beds of shale	21	2,750
Limestone	3	2,753
Salt	62	2,815
Limestone	1	2,816
Gray shale and limestone	36	2,852
Limestone	5	2,857
Salt	113	2,970
Limestone	2	2,972
Salt	35	3,007
Limestone	1	3,008
Black shale	19	3,027
Gray shale with some sandstone	10	3,037
Salt	221	3,258
Black shale	87	3,345
Salt	38	3,383
Limestone	2	3,385
Gray sandy shale	6	3,391
Salt	31	3,422
Black shale	92	3,514
Salt	108	3,622
Black shale	6	3,628
Sandy limestone and shale	5	3,633
Black shale; show of oil	17	3,650
Black shale with gypsum	20	3,670
Gray sandy shale	3	3,673
Salt	6	3,679
Black sandy shale	9	3,688
Salt	165	3,853
Fine-grained sandstone and shale	6	3,859
Sandstone, shale, and gypsum	6	3,865
Black shale	22	3,887
Black shale, salt, and gypsum	5	3,892
Salt	163	4,055
Black shale	11	4,066
Limestone	1	4,067
Shale and gypsum	58	4,125
Salt	71	4,196
Limestone	2	4,198
Salt	30	4,228
Limestone	2	4,230
Salt	42	4,272
Sandy shale and gypsum	28	4,300
Limestone	1	4,301
Shale	34	4,335
Salt	10	4,345
Black shale	15	4,360
Salt	15	4,375
Black shale	21	4,396
Salt	54	4,450
Shale	15	4,465
Gray sandy shale and salt	43	4,508
Salt	12	4,520
Gray sandy shale	10	4,530
Salt and gypsum	9	4,539
Salt	13	4,552
Limestone and shale	13	4,565
Shale	23	4,588
Salt	102	4,690
Gray shale	10	4,700
Salt and shale	35	4,735
Salt	30	4,765
Gray shale	15	4,780
Salt	70	4,850
Black sandy shale	66	4,916
Salt	16	4,932
Salt and shale	16	4,948
Limestone	1	4,949
Salt and gypsum; gas	27	4,976
Salt	24	5,000

Record of J. L. Shafer No. 1A well in sec. 25, T. 26 S., R. 20 E. (north flank, Cane Creek anticline)

	Thickness (feet)	Depth (feet)
Alluvium: Surface wash	30	30
Rico formation:		
Red sandstone	8	38
Limestone	4	42
Blue limestone	6	48
Brown sandstone	3	51
Gray limestone	3	54
Red clay	11	65
Red sandstone	5	70
Hermosa formation:		
Broken limestone	40	110
Gray limestone; sulphur water	5	115
Hard gray limestone	10	125
Blue limestone	10	135
Gray limestone	50	185
Blue limestone	10	195
Gray limestone	30	225
Blue shale	5	230
White limestone	89	319
Brown shale and clay	11	330
Gray limestone	10	340
Brown limestone	5	345
Gray limestone	115	460
Interbedded gray limestone and shale	24	484
Gray limestone	35	519
Black limestone	6	525
Gray limestone	25	550
Blue sandy limestone	4	554
Blue limestone	11	565
Gray limestone	23	588
Shale	3	591
Black limestone	4	595
Gray limestone and shale	4	599
Gray limestone	5	604
Blue clay	4	608
Gray limestone	6	614
Coarse gray sandstone	6	620
White sandy limestone	31	651
Red limestone	9	660
Red clay	2	662
Red limestone	11	673
Brown limestone	11	684
Red clay	1	685
Brown limestone	42	727
Gray limestone	38	765
Blue limestone	3	768
Gray limestone	25	793
Brown clay	1	794
Brown limestone	15	809
White limestone	8	817
Brown limestone	5	822
White limestone	33	855
Blue limestone	12	867
Gray limestone	7	874
Blue limestone	6	880
Gray limestone	18	898
Gray sandstone	7	905
Gray limestone	34	939
Brown coarse-grained sandstone; water	11	950
Brown sandy limestone	10	960
Gray limestone	116	1,076
Blue limestone	26	1,102
Black limestone	17	1,119
Gray limestone	174	1,293
Black limestone	12	1,305
Gray limestone	11	1,316
Brown shale	6	1,322
Gray limestone	56	1,378
Blue limestone	9	1,387
Gray limestone	59	1,446
Blue limestone	22	1,468
Gray limestone	3	1,471
Blue limestone	5	1,476
Black limestone	2	1,478
Gray limestone	63	1,541
Blue limestone	4	1,545
Gray limestone	5	1,550
Hermosa formation—Continued.		
Blue limestone	5	1,555
Gray limestone	40	1,595
Black limestone	16	1,611
Gray limestone	29	1,640
Blue shaly limestone	5	1,645
Blue limestone	5	1,650
Gray limestone	28	1,678
Brown limestone	23	1,701
Dark-gray limestone	3	1,704
Brown shale	6	1,710
Brown limestone	10	1,720
Gray limestone	78	1,798
Black limestone with a little shale	46	1,844
Gray limestone	7	1,851
Gray limy shale	6	1,857
Gray sandy limestone	2	1,859
White limestone	23	1,882
Brown limestone and shale	11	1,893
Gray limestone	92	1,985
Brown limestone	43	2,028
Gray limestone	20	2,048
Paradox formation:		
Blue shale	20	2,068
Brown shale	8	2,076
Black shale and anhydrite	6	2,082
Black shale	4	2,086
Gray limestone	37	2,123
Gray shale	2	2,125
Gray limestone	9	2,134
White sandstone	2	2,136
Salt with thin beds of shale and limestone	234	2,370
Sandy limestone; water	36	2,406
Black shale	25	2,431
Sandy limestone	9	2,440
Anhydrite	3	2,443
Sandy limestone	32	2,475
Blue clay	2	2,477
Limestone	2	2,479
Salt	15	2,494
Shale	2	2,496
Salt	5	2,501
Black shale	30	2,531
Salt with thin beds of black shale	39	2,570
Gray limestone	42	2,612
Soft black shale	8	2,620
Limestone	1	2,621
Black shale	26	2,647
Gray sandy limestone	25	2,672
Salt	34	2,706
Gray shale	11	2,717
Salt	34	2,751
Gray shale	4	2,755
Salt	38	2,793
Limestone	2	2,795
Salt	48	2,843
Gray sandy limestone	17	2,860
Anhydrite	8	2,868
Black shale	17	2,885
Salt	143	3,028
Anhydrite	7	3,035
Anhydrite and limestone	5	3,040
Gray and black shale	6	3,046
Shale and anhydrite	6	3,052
Gray limestone	8	3,060
Shale, limestone, and gypsum	4	3,064
Gray shale	30	3,094
Gray shale and sandy limestone	1	3,095
Gray sandy shale	4	3,099
Gray shale and gypsum	3	3,102
Anhydrite	3	3,105
Salt and gray shale	1	3,106
Salt	4	3,110
Salt and anhydrite	10	3,120
Salt and black shale	55	3,175

Record of J. L. Shafer No. 1A well in sec. 25, T. 26 S., R. 20 E. (north flank, Cane Creek anticline)—Continued

	Thickness (feet)	Depth (feet)
Paradox formation—Continued.		
Salt	257	3,432
Anhydrite, gray shale, and gypsum	11	3,443
Limestone	2	3,445
Gray shale	9	3,454
Salt and black shale	6	3,460
Salt	120	3,580
Paradox formation—Continued.		
Black shale	10	3,590
Salt streaked with black shale	25	3,615
Salt	73	3,688
Black shale	52	3,740
Salt and shale streaks	10	3,750
Salt	357	4,107

Record of well drilled by Embar-Big Six Oil Cos. in sec. 34, T. 25 S., R. 21 E.

[The strata penetrated by this well have undoubtedly been faulted, and it is not possible to make a satisfactory interpretation of the well record]

	Thickness (feet)	Depth (feet)
Alluvium	56	56
Hermosa and Paradox formations:		
Blue limestone; show of oil and gas at 104 feet	171	227
Brown fossiliferous limestone	20	247
Hard blue limestone	27	274
Red shale	11	285
Brown shale	27	312
Hard gray fossiliferous limestone	6	318
Hard blue limestone and conglomerate	55	373
Black shale; show of oil and gas	6	379
Blue shale and limestone	26	405
Salt	3	408
Blue shaly limestone	12	420
Shale	2	422
Black fossiliferous limestone	19	441
Brown limestone	10	451
Blue limestone	11	462
Red shale	2	464
Gray and brown fossiliferous limestone	48	512
Black shaly limestone	13	525
Gray limestone	21	546
Black shaly limestone	4	550
Black fossiliferous limestone	15	565
Chocolate-brown shale	1	566
Red shale	14	580
Blue shale; sulphur water	30	610
Hard sandy limestone	20	630
Sandy shale	10	640
Black limy shale	54	694
Sandy shale; show of oil and gas	41	735
Gray limestone	30	765
Black limestone	15	780
Gray limestone	120	900
Variegated shale	26	926
Fossiliferous limestone	3	929
Blue shale	3	932
Blue limestone	34	966
Gray shale	17	983
Salmon shale	25	1,008
Blue fossiliferous limestone	3	1,011
Blue shale	6	1,017
Black limestone; show of oil and gas	35	1,052
Blue shale	60	1,112
Red shale	34	1,146
Brown limestone	3	1,149
Sandstone; show of oil	2	1,151
Hard black limestone	12	1,163
Blue clay; show of gas and salt water	49	1,212
Grayish-brown limestone	11	1,223
Brown shale	14	1,237
Hermosa and Paradox formations—Continued.		
Blue sandy limestone	8	1,245
Blue shale; show of gas	45	1,290
Brown shale	20	1,310
Gray shale, sulphur water	30	1,340
Brown shale	173	1,513
Gypsum	27	1,540
Brown shale	30	1,570
Black shale	10	1,580
Brown shale	10	1,590
Black shale	320	1,910
Black shale and salt	50	1,960
Gray shale	36	1,996
Sandy brown shale; show of oil and gas	19	2,015
Chocolate-brown shale	45	2,060
Brown sandy shale; show of gas	105	2,165
Black shale; show of oil; water	30	2,195
Salt	40	2,235
Black shale	48	2,283
Fine-grained sandstone; show of gas	2	2,285
Salt	25	2,310
Gray shale	40	2,350
Black shale; show of oil and gas	68	2,418
Gray shale	27	2,445
Salt with thin beds of black shale	300	2,745
Gray shale	10	2,755
Gray sandstone	55	2,810
Black shale; show of oil and gas	60	2,870
Blue shale	54	2,924
Dark-gray shale	136	3,060
Brown shale	65	3,125
Light-gray sandstone and gypsum	57	3,182
Gray sandstone	18	3,200
Light-brown shaly limestone	12	3,212
Light-brown sandy shale	6	3,218
Light-gray shale	7	3,225
Gray and blue shale	39	3,264
Gray shale	37	3,301
Blue shale	46	3,347
Gray shale	14	3,361
Gray sandy shale	37	3,398
Black shale	110	3,508
Black shale and gypsum	17	3,525
Gray shale	325	3,850
Black shale, sandstone, and limestone; show of oil and gas	35	3,885
Gray sandy shale	68	3,953
Gray sandy shale with salt beds	32	3,985
Dark shale	40	4,025

Record of well drilled by Embar-Big Six Oil Cos. in sec. 34, T. 25 S., R. 21 E.—Continued

	Thickness (feet)	Depth (feet)
Hermosa and Paradox formations—Continued.		
Sandy shale and limestone	15	4,040
Gray sandy shale	45	4,085
Sandy limestone; show of oil	10	4,095
Gray and black sandstone, limestone and shale	25	4,120
Black shale	20	4,140
Brown shale	30	4,170
Conglomerate	190	4,360
Gray limestone	15	4,375
Hermosa and Paradox formations—Continued.		
Hard sandy limestone; show of gas	35	4,410
Sandy shale with thin limestone beds	565	4,975
Sandy shale with thin limestone beds and thick beds of hard sandstone; show of oil and gas	370	5,345

Record of well drilled by Marland Oil Co. in sec. 35, T. 21 S., R. 16 E.

	Thickness (feet)	Depth (feet)
Alluvium: Surface wash	5	5
Morrison, Summerville, Curtis, and Entrada formations:		
Green shale	3	8
Gray sandstone	7	15
Brown sandstone	30	45
Gray sandstone	5	50
Red rock	5	55
Shelly gray shale	15	70
Brown sandstone	15	85
Gray sandstone	5	90
Gray shale	5	95
Gray sandstone	15	110
Blue shale	10	120
Pink shale	5	125
Blue shale	5	130
Red rock	5	135
Blue shale	5	140
Gray sandstone	5	145
Pink shale	5	150
Gray sandstone	5	155
Blue shale	5	160
Gray sandstone	25	185
Brown shale	10	195
Gray sandstone	5	200
Blue shale	5	205
Brown shale	30	235
Brown sandstone	15	250
Brown sandy shale	105	355
Gray shale	25	380
Brown shale	5	385
Brown sandstone; slight show of oil and water at 385 to 400 feet	35	420
Brown shale	80	500
Blue shale	5	505
Gray shale	55	560
Gray sandstone	10	570
Gray shale	25	595
Gray sandstone	5	600
Gypsum and brown sandstone	20	620
Gray shale	5	625
White sandstone	20	645
Brown sandstone	15	660
Gray sandstone	10	670
Brown sandy shale	25	695
White sandstone	15	710
Gray sandstone	20	730
Brown sandstone	5	735
Gray sandstone	15	750
Brown sandstone	10	760
Brown shale	10	770
Brown sandstone	5	775
Morrison, Summerville, Curtis, and Entrada formations—Con.		
Brown sandy shale	20	795
White sandstone	155	950
Carmel formation:		
Brown sandstone	10	960
Brown shale	18	978
Brown sandstone	17	995
Gray sandy shale	7	1,002
Brown sandstone	13	1,015
Gray shale	5	1,020
Gray sandstone	10	1,030
Brown sandstone	40	1,070
Brown shale	10	1,080
Brown sandstone	10	1,090
Gray sandstone	15	1,105
Brown sandstone with sulphur water	25	1,130
Navajo sandstone:		
Gray sandstone	80	1,210
Hard white sandstone	75	1,285
Brown sandstone	10	1,295
Gray sandstone	15	1,310
Hard white sandstone	70	1,380
Brown sandstone	10	1,390
Hard white sandstone	10	1,400
Brown and gray sandstone	15	1,415
Brown sandstone	45	1,460
Hard white sandstone	40	1,500
Kayenta formation and Wingate sandstone:		
Brown sandstone; show of gas	30	1,530
Brown shale	15	1,545
Brown sandstone	15	1,560
White sandstone	45	1,605
Brown sandstone	10	1,615
Brown sandy shale	20	1,635
Brown sandstone	35	1,670
White sandstone	45	1,715
Brown sandstone	340	2,055
Chinle formation:		
Green shale	5	2,060
White sandstone	5	2,065
Red shale	35	2,100
Chocolate-brown sandstone	30	2,130
Purple sandstone; show of water	5	2,135
Brown sandstone	5	2,140
Purple and brown shale	30	2,170
Red shale	70	2,240
Brown shale	15	2,255
Brown sandstone	45	2,300
Brown shale	30	2,330

Record of well drilled by Marland Oil Co. in sec. 35, T. 21 S., R. 16 E.—Continued

	Thickness (feet)	Depth (feet)
Chinle formation—Continued.		
Brown and yellow shale	15	2,345
Brown shale	11	2,356
Gray shale	29	2,385
Purple sandstone	5	2,390
Shinarump conglomerate:		
Gray sandstone; slight show of oil at 2,396 feet	15	2,405
Quartz sandstone	10	2,415
Moenkopi formation:		
Brown shale and sandstone	10	2,425
Shelly brown shale	25	2,450
Cream sandstone	5	2,455
Brown sandy shale	65	2,520
Red and gray sandstone	5	2,525
Red shale	55	2,580
Gray sandstone	5	2,585
Red shale; slight show of gas at 2,630 feet, slight show of oil at 2,630 to 2,645 feet	90	2,675
Gray limestone	5	2,680
Red shale	185	2,865
White sandstone	20	2,885
Red sandstone and shale	10	2,895
Red sandy shale	40	2,935
Red shale	120	3.055
Green shale	5	3,060
Coconino sandstone:		
Gray and black sandstone; slight show of oil	10	3,070
Gray sandstone	17	3,087
White sandstone	33	3,120
Hard sandstone	50	3,170
Sandstone; slight show of gas	10	3,180
Hard sandstone	135	3,315
White sandstone	65	3,380
Hard sandstone	20	3,400
Cutler or Rico formation ?:		
Red rock	5	3,405
Sandy limestone	20	3,425
Red shale	75	3,500
Hard red sandstone	10	3,510
Red shale	60	3,570
Red limestone	25	3,595
Red shale	5	3,600
Sandy limestone	5	3,605
Red shale	15	3,620
Red sandy limestone	15	3,635
Red shale	10	3,645
Limestone	15	3,660
Hard gypsiferous limestone	20	3,680
Red shale	5	3,685
Hard limestone	135	3.820

Partial record of No. 1–X (State) well drilled by Glen Ruby and others in sec. 34, T. 21 S., R. 16 E.

	Thickness (feet)	Depth (feet)
Entrada and possibly younger formations:		
Porous rock	15	15
White rock, red clay, sticky	12	27
Hard calcite	2	29
White calcite, streaks of red shale and red sandstone; showing of gas	9	38
Calcite and red sandstone; showing of gas	9	47
Calcite and red shale; showing of gas	6	53
Calcite and red sandstone	4	57
Calcite; showing of gas	2	59
Hard sand; showing of oil	3	62
White soapstone, streaks of red shale; oil and gas	11	73
Red sandstone	15	88
Hard sand	3	91
Sand with streaks of shale	4	95
Hard red sand	3	98
Lime shell	½	98½
Red sandstone	8½	107
White calcite	4	111
Sandstone	1	112
Water sand	4	116
Hard sand	9	125
Hard white sand, oil and gas	3	128
Hard sand, streaks of blue shale	5	133
Sandy blue shale; showing of light-green oil at 134 feet	4	137
Hard sand, streaks of shale	14	151
Hard white sand; showing of light-green oil	20	171
Hard white sand	8	179
Gray sandstone	6	185
Shell	3	188
Red sandstone; showing of light oil	9	197
Entrada and possibly younger formations—Continued.		
Red sandstone, streaks of gray sand	4	201
Hard red sand	4	205
Red sand; showing of light oil	4	209
White fine sand	13	222
Hard white sand	48	270
Hard red sandstone, showing of water and gas	10	280
Hard red and white sandstone, streaked; water and gas	5	285
Hard sand; water and gas	5	290
Red and white sandstone; heavy oil	18	308
White sandstone	12	320
White sandstone, streaks of red sand	2	322
No record	1	323
Hard sand	11	334
Hard white sand	17	351
Gray limestone shell; much gas	4	355
Hard white sand; showing of heavy oil at 364 feet	12	367
Hard white sand, showings of oil and gas	111	478
Hard white sand with red streaks; oil	9	487
Carmel formation:		
Hard red sand; gas at 487 to 490 feet	11	498
Brown sand; light-green oil and gas	2	500
Red sandstone	19	519
Hard brown sand; oil	17	536
Hard gray sand	6	542
Hard red sand	7	549
Hard gray sand	10	559

Partial record of No. 1–X (State) well drilled by Glen Ruby and others in sec. 34, T. 21 S., R. 16 E.—Continued

	Thickness (feet)	Depth (feet)
Carmel formation—Continued.		
Hard reddish-brown sand	2	561
Hard gray sand	6	567
Hard reddish-brown sand	14	581
Hard brown and gray sand	9	590
Brown shale	6	596
Sand	1	597
Shale	1	598
Sticky brown shale	4	602
Shale and brown sand	6	608
Hard brown sand	9	617
Hard sand	9	626
Sand and shale	7	633
Hard sand	13	646
Hard sand and shale	5	651
Hard sand	14	665
Sand	7	672
Gray sand	13	685
Gray and white hard sand	5	690
Shale and sand	5	695
Navajo, Kayenta, and Wingate formations:		
Gray sand	52	747
Gray sand with harder zones	24	771
Gray sand with calcite and gypsum	2	773
Gray sand	7	780
White sand	2	782
Gray sand	4	786
Brown sand	3	789
Gray sand	4	793
Brown sand	16	809
White sand	4	813
Brown sand	14	827
White sand	15	842
Gray sand	5	847
Light-brown sand	17	864
White sand	7	871
Brown sand	25	896
No record	151	1,047
Brown sand	16	1,063
White sand	10	1,073
Brown sand	5	1,078
Reddish-brown sandy shale	41	1,119
Brown sand	40	1,159
Gray-brown sandstone, thin lime shells	7	1,166
Hard red-brown sand	14	1,180
Brown sand	7	1,187
Brown sandy shale	8	1,195
Brown sand	415	1,610

	Thickness (fee)	Depth (feet)
Chinle and Moenkopi formations:		
Brown sandy shale	4	1,614
Brown sand	3	1,617
Reddish-brown sandy shale; very slight show of oil at 1,659 to 1,681 feet	64	1,681
Red shale	16	1,697
Red sandy shale	15	1,712
Red shale	18	1,730
Purple sand	20	1,750
Brown sand	25	1,775
Red sandy shale	53	1,828
Red shale	3	1,831
Red sandy shale	19	1,850
Hard red-brown shaly sand	7	1,857
Same as above, but more shale	6	1,863
Red sandy shale	17	1,880
Yellow sandy shale	6	1,886
Brown shale	1	1,887
Yellow and brown shale, sticky; decreasing amount of yellow	8	1,895
Brown sticky shale	10	1,905
Shale and sand	2	1,907
Purple sandy shale; streaks of calcite at 1,920 to 1,922 feet	24	1,931
Brown sandy shale with green streaks	19	1,950
Red and brown shale	7	1,957
Brown shale with green streaks	4	1,961
Brown shale	47	2,008
Brown shale with green streaks	10	2,018
Brown shale	12	2,030
Brown sandy shale	14	2,044
Brown shale and green sand	33	2,077
Reddish brown shale	31	2,108
Brown sandy shale	266	2,374
Gray sandy shale	12	2,386
Red sandy shale	10	2,396
Gray sandy shale	8	2,404
Red sandy shale	10	2,414
Brown sandy shale	3	2,417
No record	205	2,622
Kaibab limestone ?: Dense cherty limestone	5	2,627

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