Geology of the Lees Ferry Area Coconino County, Arizona

GEOLOGICAL SURVEY BULLETIN 1137

Prepared on behalf of the U.S. Atomic Energy Commission and published with permission of the Commission

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By DAVID A. PHOENIX

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UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1963

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

The U.S. Geological Survey Library has cataloged this publication as follows:

Phoenix, David Allen, 1916–
Geology of the Lees Ferry area, Coconino County, Arizona. Washington, U.S. Govt. Print. Off., 1963.

v, 86 p. illus., maps (part col.) diagrs., tables. 24 cm. (U.S. Geological Survey. Bulletin 1137)

Part of illustrative matter folded in pocket.

Prepared on behalf of the U.S. Atomic Energy Commission and published with permission of the Commission.

Bibliography: p. 83–86.

(Continued on next card)

Phoenix, David Allen, 1916–
Geology of the Lees Ferry area, Coconino County, Arizona. 1963. (Card 2)

1. Geology—Arizona—Coconino Co. I. Title: Lees Ferry area, Coconino County, Arizona. (Series)

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C., 20402.

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[Plates are in pocket]

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Note.—Since the completion of this bulletin, revised age determinations for the formations of the Glen Canyon group have been published by G. E. Lewis, J. H. Irwin, and R. F. Wilson in "Age of the Glen Canyon Group (Triassic and Jurassic) on the Colorado Plateau" (Geol. Soc. America Bull., v. 72, no. 9, p. 1437–1440, 1961). The revised ages, which could not be incorporated practicably on the maps for this report, are:

Glen Canyon group, Triassic and Jurassic;
Navajo sandstone, Late Triassic (?) and Jurassic;
Kayenta formation, Late Triassic (?) and Jurassic;
Moenave formation, Late Triassic (?); and
Wingate sandstone, Late Triassic.

The Kayenta was changed from Jurassic (?) to Triassic (?) after reevaluating its fossil fauna, which includes both a new genus of tritylodont reptile and the crocodilian *Protosuchus richardsoni.* The uppermost part of the Navajo was assigned to the Jurassic because it intertongues with the Jurassic Carmel formation.

GEOLOGY OF THE LEES FERRY AREA, COCONINO COUNTY, ARIZONA

By DAVID A. PHOENIX

ABSTRACT

The Lees Ferry area includes about 270 square miles of sparsely populated semiarid canyon and plateau country in Coconino County, Ariz. The historic crossing of the Colorado River at Lees Ferry is situated in the geographic center of the area above the confluence of the Paria and Colorado Rivers. At Lees Ferry the altitude is about 3,100 feet; the surrounding high plateaus are from 4,500 to 7,000 feet above sea level.

The rocks exposed in the area are all sedimentary formations that were deposited under marine or continental conditions; their aggregate thickness is about 6,500 feet and they range in age from Pennsylvanian to Late Cretaceous. The Supai formation, of Pennsylvanian and Permian age, consists of a ledge-forming buff crossbedded sandstone and limestone interbedded with red sandy shale. Rocks of Permian age are, from oldest to youngest, the Hermit shale, Coconino sandstone, Toroweap formation, and Kaibab limestone. The Kaibab limestone forms a widespread resistant surface that is trenched by Marble Canyon, and the older formations form cliffs or steep slopes on the inner walls of Marble Canyon. Rocks of Triassic age are the Moenkopi formation, resting unconformably upon the Kaibab limestone, and the Chinle formation. The Moenkopi consists of two units, a thick lower unit of light red-brown thin-bedded silty shale and a thin upper unit of chocolate-brown limy shale and dark-brown sandstone; the formation is between 320 and 550 feet thick. The Chinle formation rests unconformably on the Moenkopi formation and is divided into the conglomeratic Shinarump member at the base, an unnamed sandstone and mudstone unit above the Shinarump member, and a thick unit of mostly varicolored mudstone that comprises the upper one-half to two-thirds of the formation. The thick mudstone unit has been subdivided into members in other parts of the Colorado Plateau, but for various practical reasons these units were not distinguished in the Lees Ferry area. The Chinle formation is between 1,000 and 1,150 feet thick in the Lees Ferry area. The cliff-forming Glen Canyon group of Triassic and Jurassic age overlies the Chinle formation and comprises rocks of the Moenave, Kayenta, and Navajo formations. The Moenave formation, unconformable upon the Chinle formation, consists of two members, a lower brick-red silty sandstone unit called the Dinosaur Canyon sandstone member, and an upper thicker purple-red massive sandstone unit, the Springdale sandstone member.

The Kayenta formation consists of horizontal beds of red-brown sandstone and orange-red siltstone about 200 feet thick. It underlies the crossbedded Navajo sandstone, and the two formations intertongue. The Navajo sandstone of Triassic (?) and Jurassic age forms spectacular cliffs, is a massive, crossbedded orange, yellow-brown, and pale-yellow or nearly white sandstone, and is

about 1,700 feet thick. Beds of red and brown limy siltstone within the upper part of the Navajo sandstone intertongue with the overlying Carmel formation. In the Lees Ferry area these intertonguing units are assigned names; the beds of Carmel-like lithology are herein named the Judd Hollow tongue of the Carmel formation, beds of Navajo-like lithology are called the Thousand Pockets tongue of the Navajo sandstone.

The Carmel formation consists of about 430 feet of red, brown, and yellow-brown sandstone, silt, and mudstone that is fully exposed only in the northern part of the area on the Echo monocline. Above the Carmel formation are the Entrada sandstone of Late Jurassic age and the Dakota sandstone of Late Cretaceous age. Unconsolidated deposits of windblown sand, stream gravel, and landslide and talus debris of Quaternary age mantle the bedrock formations in many places.

The formations in the Lees Ferry area have been uplifted and broadly tilted during several periods of deformation, but they were not severely folded until Late Cretaceous or Tertiary time. The most conspicuous fold in the area is the Echo monocline, a northward trending fold at least 30 miles long that drops sedimentary strata about 2,000 feet to the east. The fold plunges about 2° N. and the regional dip of the strata on both sides of the fold is also 2° to 3° N. Breccia zones and reefs of calcareous and silicified sandstone in the Navajo sandstone trend northward along the anticlinal bend of the fold; joints in the Navajo form an arcuate pattern eastward from the anticlinal bend. Small folds and faults in the Kaibab limestone are localized en echelon along the crest of the Echo monocline, but displacement along these and other structures is partly absorbed by the overlying Moenkopi formation.

Several mines and prospects in the area explore the Chinle formation for uranium deposits; but although uranium and associated copper minerals have been found in several stratigraphic horizons in this formation, the only commercial production has been from the Shinarump member; this production has been small. Uranium minerals are usually associated with organic debris, and they are localized in and at the bottom of channels scoured in the top of the Moenkopi formation. Deposits of other minerals have been prospected in the area, but to date none has been productive. Reportedly gold and mercury have been found in the Chinle formation; the Kaibab limestone has been studied as a source for cement; and the Chinle formation, for clay minerals of various types.

INTRODUCTION

LOCATION AND EXTENT OF AREA

The map area, which is in the northern part of Coconino County, Ariz. (fig. 1), includes an area of about 270 square miles (pl. 1). The approximate center of this area is at Lees Ferry, the historic and now abandoned ferry station on the Colorado River. Glen Canyon dam across the Colorado River is at the eastern edge of the region.

PURPOSE OF INVESTIGATION

The geologic study of the Lees Ferry area was undertaken by the U.S. Geological Survey on behalf of the Division of Raw Materials of the U.S. Atomic Energy Commission as a part of the Colorado Plateau program of uranium investigation. The uranium-bearing

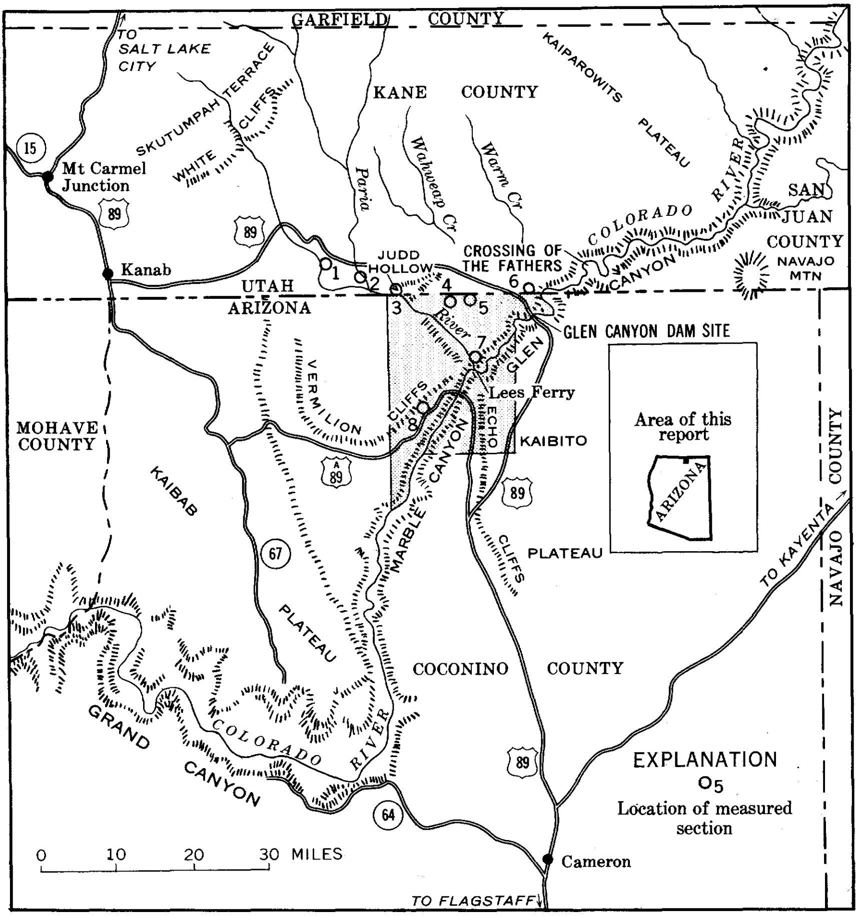

FIGURE 1.—Index map showing location of the Lees Ferry area and of measured stratigraphic sections described in text.

Shinarump member of the Chinle formation was mapped in order to provide a basis for projecting its occurrence into areas mantled by younger rocks, and uranium deposits in the area were studied to provide a background for the estimation of uranium reserves.

ACKNOWLEDGMENTS

The geologic study of the Lees Ferry area is a part of a larger study of the East Vermilion Cliffs carried out under the supervision of R. G. Petersen. Mapping of the East Vermilion Cliffs started in 1955, and in 1956 the writer was assigned the eastern or Lees Ferry portion. Fieldwork was begun in June 1956 and completed in October 1956.

The investigation was carried out under the supervision of A. L. Brokaw and D. G. Wyant, who have made many helpful suggestions

during the field and office work. Larry Schluchtner and Charles Steele acted as geologic field assistants. D. W. Petersen was assigned to the project in September, and the writer expresses appreciation for his able and conscientious help.

PREVIOUS INVESTIGATIONS

The trails of many famous expeditions into southern Utah and northern Arizona are now faint in the Lees Ferry area, but American literature is permanently enriched by the records of these early scientific and exploratory undertakings; they are chronologically summarized by Gregory (1945). Gregory and Moore (1931) also described the geography and geology of the Kaiparowits region, thus presenting a description of the geologic framework that underlies the map area.

Other published geologic data from the area relate to general stratigraphic problems and to the regional correlation of formations. The studies of McKee (1938, 1954) on the Toroweap, Kaibab, and Moenkopi formations are partly based on data from the Lees Ferry area, as are similar studies of the Chinle formation and the Glen Canyon group by Callahan (1951), Wanek and Stephens (1953), Averitt and others (1955), Harshbarger, Repenning, and Irwin (1957), and R. F. Wilson (written communication). Much of this information has been summarized on paleotectonic maps of the Jurassic system (McKee and others, 1956). The structure of the Colorado Plateau region, including brief mention of the Echo monocline, has been described by Luedke and Shoemaker (1953) and Kelley (1955b). Geomorphic studies of the effects of wind erosion (Bryan, 1923), of landslides on the Vermilion and Echo Cliffs (Strahler, 1940), and geomorphic studies of the Kaibab and Grand Canyon region and Little Colorado River (Babenroth and Strahler, 1945; Childs, 1948; Hunt, 1956) contribute data on the development of landscape in the area. La Rue (1925) describes briefly the engineering geology of a proposed damsite at Lees Ferry. Lawson (1913) reported small quantities of gold in the Chinle formation near Lees Ferry, and Lausen (1936) presented analytical data to demonstrate the occurrence of mercury in the Chinle formation, also near Lees Ferry.

GEOGRAPHY

ROADS

The map area is in the southwestern part of the Colorado Plateau about 75 miles north of Cameron, Ariz., and about 85 miles southeast of Kanab, Utah, via U.S. Highway 89-A. Lees Ferry is in the geographic center of the area and U.S. Highway 89-A enters the

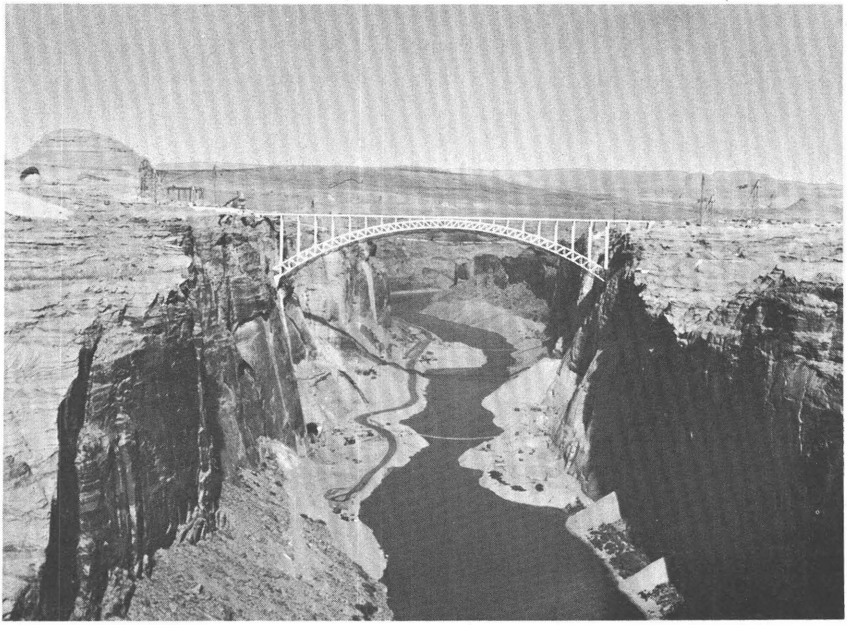

FIGURE 2.—Site of the Glen Canyon dam; northeastward view, upstream along the Colorado River.

southern part of the area and crosses the Colorado River at Navajo Bridge about 5 miles downstream from Lees Ferry. U.S. Highway 89 from Kanab provides access to the site of the Glen Canyon dam in the eastern part of the map area (fig. 2), and this road again connects with U.S. Highway 89-A about 15 miles south of Navajo Bridge. Other parts of the region are accessible by dirt roads or trails that are occasionally maintained by stockmen or prospectors.

Until U.S. Highway 89 spanned the Colorado River at Navajo Bridge, and until the bridge spanned Glen Canyon at the Glen Canyon dam, Lees Ferry was the only accessible crossing of the Colorado River for many miles. Trails and abandoned roads radiating in all directions from this crossing recall that both historic and prehistoric communication from a large part of the desert southwest was funneled to this spot.

PHYSIOGRAPHY

The region is characterized by high plateaus and deep, steep-walled canyons. The Colorado River, entrenched in Glen Canyon in the eastern part of the area and in Marble Canyon in the southwestern part of the area, transects the region from northeast to southwest. The southerly flowing Paria River joins the Colorado River at Lees Ferry and the canyons of the Colorado and Paria Rivers divide the area into three high plateaus of almost equal area.

West of Lees Ferry is the Paria Plateau, where altitudes of the upland surface are between 5,800 and 7,000 feet. The surface of the plateau slopes gently northward, and runoff follows this direction in poorly defined sand-filled valleys to the canyon of the Paria River. Vertical walls of the canyon of the Paria River border the plateau on the north and east and the Vermilion Cliffs border it on the south.

North of Lees Ferry and on the north side of the Colorado River is a dissected sandy highland that extends as a broadening bench below the Kaiparowits Plateau from the vicinity of the Crossing of the Fathers (fig. 1) west to the Paria River. The boundaries of this broad bench are largely out of the mapped area, but prominent parts of the bench are shown on the maps that accompany this report; the highest point is Cedar Mountain. Wahweap Creek, a tributary to the north side of the Colorado River, flows in a deep narrow canyon in the northeast corner of the map area, and much of the drainage from the bench area is towards this creek. Other notable landmarks in this remote area include Ferry Swale—a part of an abandoned meander of the Colorado River—and Thousand Pockets, Willow Tanks and Water Pockets—all areas of shallow windblown depressions or "tanks" in the Navajo sandstone that retain runoff from occasional rains. Beehive Rock is a dome-shaped butte of Navajo sandstone that overlooks the west end of the dam across Glen Canyon. Rawhide cave, about 3 miles west of the damsite, is an alcove in the Navajo sandstone that has been a temporary dwelling for prehistoric Indians and later cattlemen.

The third major highland subdivision is the northwest part of the extensive Kaibito Plateau, south of the Colorado River. In the southeastern corner of the map area the upland surface of this plateau is at an altitude of about 5,600 feet, but it slopes northward to the Colorado River and at the lip of Glen Canyon it is about 4,200 feet above sea level. The western edge of the Kaibito Plateau is thoroughly dissected and drops off abruptly, forming the Echo Cliffs.

Near Lees Ferry, the Echo Cliffs to the south and the Vermilion Cliffs to the west are only about 3 miles apart and talus slopes below the cliffs encroach upon both sides of the Colorado River. At the south edge of the map area however the cliffs are farther apart, and the lower country between forms a broad resistant platform that is deeply entrenched by the Colorado River (fig. 3).

CLIMATE AND WATER SUPPLY

The climate in the vicinity of Lees Ferry is arid; summer temperatures are high, and plant growth is sparse. Locally, however, the tops of the plateaus receive sufficient moisture to support cedar and hardy desert shrubs. Prehistoric man was attracted by the rainfall, and his ruined dwellings and utensils are found in the high places.

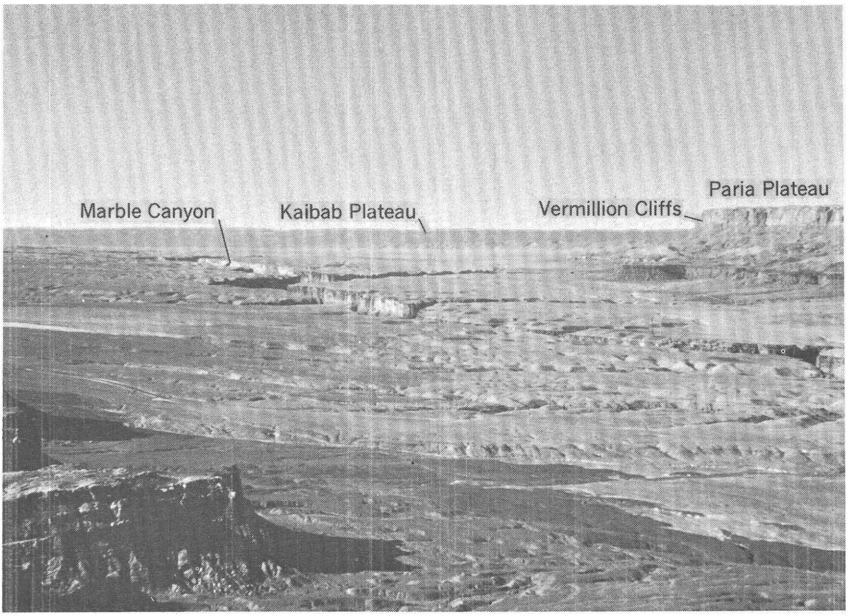

FIGURE 3.—View of Marble Canyon looking west to the East Kaibab monocline; Vermilion Cliffs and Paria Plateau on north edge of photograph.

On the high plateaus water for stock and wildlife periodically accumulates in the natural "tanks" in the Navajo sandstone, but the replenishment of this supply is not dependable.

The base flow of both the Paria River and Wahweap Creek is maintained by springs that discharge from the Navajo sandstone; springs near the mouth of Wahweap Creek contribute an estimated 1 cubic foot per second to the Colorado River. The contribution of between 5 and 7 cubic feet per second from springs discharging from the Navajo sandstone in Paria Canyon is sufficient to suggest that deep wells might augment the sparse natural water supply on Paria Plateau.

Water suitable for drinking is scarce in most of the map area. During most of the year the Paria River is turbid with large quantities of suspended sediment, and the same is generally true for water in the Colorado River, although the latter supply contains considerably less dissolved minerals. At present most of the drinking water is drawn from several springs at the base of the Vermilion and Echo Cliffs or from a few deep wells near Wahweap Creek. The springs discharge from the Moenave, Kayenta and Navajo formations and although the water supply is limited, it is of excellent chemical quality. Several deep wells penetrate the Navajo in the vicinity of Wahweap Canyon and the Glen Canyon damsite, and

TABLE 1.—*Chemical analyses of well and spring water in the Lees Ferry area*

[In parts per million. Analyses 1-3 by O. Hattori; analyses 4, 5 by Arizona State Health Laboratory]

Source and aquifer	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium plus potassium (Na+K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (sum)	Total hardness
1 Navajo Spring, Moenavi formation	15	32	11	42	172	43	19	0.3	1.8	249	124
2 Lowery Spring, Moenavi formation	11	18	9.7	23	116	14	14	.3	5.4	152	84
3 Wahweap Lodge well, Carmel formation	16	142	51	276	444	544	164	.5	1.1	1,410	564
4 Bureau of Reclamation well 3, Navajo sandstone	------	97	48	97	------	260	88	.3	3.6	789	442
5 Bureau of Reclamation well 1, Navajo sandstone	------	39	18	20	------	70	7	.2	5.0	232	176

water from these wells has been used for domestic purposes. Unfortunately the water table in the area is several hundred feet below the land surface and hence the supply is expensive to pump. Filling of the Glen Canyon reservoir will probably raise the water table in parts of the area where it is now below the proposed reservoir level. But the reservoir will not greatly influence the recovery of ground water in most of the map area. Chemical analyses of well and spring water in the area are shown in table 1.

STRATIGRAPHY

The consolidated rocks in the Lees Ferry area form a succession of 13 sedimentary formations of Paleozoic and Mesozoic age that are about 6,500 feet thick (pl. 2). Although the characteristics of each formation are distinct and in the following discussion of the stratigraphy they are described separately, in the sections of this report dealing with structure and geomorphology the formations are divided among three main components, each with distinctive characteristics. These components are, from oldest to youngest, about 1,600 feet of quartzite, limestone, and shale of Permian and Pennsylvanian age—the Aubrey group; about 1,600 feet of clay and mudstone with subordinate but resistant strata of sandstone and conglomerate of Triassic age—the Moenkopi and Chinle formations; and about 3,500 feet of sandstone of Triassic and Jurassic age—the Glen Canyon and locally the San Rafael groups. The resistant rocks underlie the Marble Platform and form the sides of Marble Canyon and the Vermilion and Echo Cliffs; the intermediate slopes between Marble Platform and the cliffs are composed of the nonresistant rocks of the Chinle and Moenkopi formations. In the northern part of the map area these three major components are overlain by the San Rafael group of Jurassic age and by the Dakota sandstone of Late Cretaceous age.

FIGURE 4.—View east toward Echo Cliffs at junction of Rider Canyon with the Colorado River showing the Aubrey group (Supai formation, PPs; Hermit shale, Ph; Coconino sandstone, Pc; Toroweap formation, Pt; and Kaibab limestone, Pk).

Unconsolidated alluvial debris covers the consolidated rocks in many places, and the distribution and character of these deposits indicate that the climate and position of streams and rivers have changed considerably in the relatively recent geologic past.

PERMIAN AND PENNSYLVANIAN SYSTEMS

AUBREY GROUP

The walls of Marble Canyon in the vicinity of Lees Ferry and for about 17 miles to the west edge of the map area comprise five formations (fig. 4) that make up the Aubrey group (Gilbert, 1875, p. 176–177, 184–185, 187). From the oldest to the youngest they are the Supai formation (Noble, 1923, p. 59–64), the Hermit shale (Noble, 1923, p. 63–66), Coconino sandstone (Darton, 1910, p. 27–28), Toroweap formation (McKee, 1938), and the Kaibab limestone (Darton, 1910, p. 21, 28–30). The latter three formations form the vertical lip of Marble Canyon. The Hermit shale crops out in Marble Canyon about 1 mile downstream from the Navajo Bridge, and from this point to the south edge of the map area it forms a conspicuous and smooth inclined slope below the lip of the canyon. The Supai formation, of which only the upper part crops out in the map area, forms cliffs or steep slopes in the bottom of Marble Canyon near the south edge of the map area. Sedimentary rocks within the exposed portion of the Aubrey group are about 1,500 feet thick. The group is Permian in age, except possibly some beds in the lower part of the Supai formation that may be Pennsylvanian (Noble, 1923, p. 63) but that probably do not crop out in the map area.

The lower two-thirds of the Aubrey group, including the upper part of the Supai formation, the Hermit shale, the Coconino sandstone, and parts of the Toroweap formation, consists of shale and crossbedded sandstone of continental origin; the upper one-third of the group, including part of the Toroweap formation and the Kaibab limestone, is marine. Regional studies of the continental deposits—that is, the Supai formation and the Hermit shale (McKee, 1951; Baker and Reeside, 1929)—suggest that they accumulated on low-lying terrain marginal to the Cordilleran geosyncline to the west, and that they were probably derived from source areas to the east. The Coconino sandstone is believed to have a northwesterly source, possibly as windblown sand from the shoreline of the Cordilleran geosyncline; the Toroweap formation is composed largely of shallow-water near-shore deposits; and the Kaibab limestone was deposited from quiescent seas of the Cordilleran geosyncline that finally encroached as far southeastward as northwestern Arizona during Permian time.

SUPAI FORMATION

The Supai formation of Permian and Pennsylvanian age, the oldest exposed rocks in the area, forms the innermost wall of Marble Canyon in the southeast corner of the map area. The most accessible part of the formation is at the mouth of Rider Canyon. Here, about 500 feet of the Supai formation is exposed above the river; the lower 350 feet forms a vertical cliff, and the upper 150 feet crops out in ledges. This upper part consists of light-colored medium- to fine-grained sandstone in strata 2 to 10 feet thick that are separated by ripple-laminated red-brown siltstone and shale. About 130 feet below the top of the formation the rocks are interbedded cliff-forming sandstone and limestone, for the most part inaccessible for study. In the map area the top of the Supai formation was placed at the top of the uppermost resistant stratum of sandstone.

Lithologic and sedimentary structural studies of the Supai formation sediments by McKee (1940) and by McNair (1951) show that the sandstone is probably of deltaic origin and was probably deposited from currents that moved southeastward over a large part of northern Arizona.

HERMIT SHALE

Beginning about 1 mile downstream from Navajo Bridge and continuing to the south edge of the map area, the Hermit shale of Permian age forms a smooth inclined slope along the inner walls of Marble Canyon. Access to the formation is difficult because rocks above and below the Hermit shale form sheer cliffs in Marble Canyon and waterfalls in the tributary canyons; however, the upper part of the formation was examined in Jackass Canyon and the entire formation was examined in lower Soap Creek Canyon and downstream along the Colorado River. In these places the formation is about 500 feet thick and consists mostly of thin-bedded deep brownish-red siltstone and shale. The siltstone is interbedded with thin discontinuous beds of lighter colored fine-grained sandstone. Where the formation is sheltered from the sun the siltstone crops out on poorly defined ledges, but in most places the formation weathers easily and is covered with conchoidal chips and fragments of shale.

Near the mouth of Soap Creek the formation rests conformably upon the underlying Supai formation, although in places along the walls of Marble Canyon the Hermit shale appears to truncate beds in the Supai. According to Noble (1923, p. 63–64), the Hermit shale rests unconformably upon the Supai formation in Bass Canyon, and the eroded surface exhibits in places irregularities with relief of 50 feet or more.

Veinlets of calcite transect the formation in many places and are conspicuous because they are edged with siltstone that is altered light gray. Gray spots one-half inch in diameter are distributed at random in some of the beds of siltstone, and locally the formation is also light colored adjacent to faults. Locally, bedding surfaces in the shale show polygonal sun cracks, casts of salt crystals, rain prints, and ripple marks. These features, together with fragmentary remains of several species of ferns and tracks of fresh-water amphibians, indicate that the formation was deposited on a broad flood plain and in arid climate (Noble, 1923, p. 65–66; White, 1929, p. 13–25); the tracks and plant remains are adequate to indicate that the formation is Permian in age.

COCONINO SANDSTONE

In the Lees Ferry area the Coconino sandstone, of Permian age, is the lowermost of three formations that form the lip of Marble Canyon. At Navajo Bridge the Coconino sandstone is well exposed although inaccessible, but at Jackass Canyon and Badger Canyon the formation was examined in detail. At these places the unit is about 60 feet thick, and rests conformably upon the Hermit shale. It consists of light yellow-gray, medium- to fine-grained tangentially cross-bedded sandstone. The sweeping crossbeds locally transgress nearly the entire formation. Although the beds are inclined in many directions the prevailing dip direction in this area is southerly (Reiche, 1938). Tracks of vertebrates, raindrop imprints and burrowlike trails are preserved on these bedding surfaces.

Regional studies of the Coconino sandstone by McKee (1934, 1945) show that the formation is of aeolian origin and that it is present as a wedge-shaped deposit over much of northern Arizona. Because the size of the sand grains and the thickness of the formation increase southward, a southerly source area is suggested by McKee for the formation. However, as pointed out by McNair (1951), the widespread southerly dip direction of foreset bedding in the sandstones may indicate that the source area is to the north. Regional studies of the stratigraphy indicate that the Coconino sandstone is continuous with the De Chelly sandstone member of the Cutler formation in Monument Valley, Ariz. (Baker, 1933, p. 33; 1946, p. 49–50; Hunt and others, 1953, p. 46).

TOROWEAP FORMATION

The Toroweap formation, of Permian age, is not a conspicuous unit in the Lees Ferry area. Exposures of the Toroweap formation that are typical of those throughout Marble Canyon are at the base of the southeast abutment of Navajo Bridge. The formation can barely be distinguished from the cliff-forming Kaibab limestone and Coconino sandstone above and below by having closer spaced somewhat wavy bedding, by the general absence of chert nodules in the beds, and by the lack of large-scale crossbedding. On the northwest side of the Colorado River, about 200 yards downstream from Navajo Bridge, the Toroweap forms a steep rubble-covered slope. This slope starts at a bed of soft red siltstone just below the Kaibab limestone and continues to the base of the formation, where it breaks to a vertical cliff at resistant crossbedded sandstone of the Coconino formation; at this place the Toroweap formation is about 120 feet thick.

In Jackass Canyon, sediments in the upper part of the Toroweap formation are white and light grayish-yellow, fine-grained crossbedded sandstone, dark-red silty mudstone and siltstone, and light-gray cherty limestone. The sandstone is in beds 3 inches to 1½ feet thick, and the limestone is in beds 6 inches to 2 feet thick. A bed of mudstone 2 feet thick occurs at the top of the formation, but mudstone is not common in the formation. Sediments in the lower part of the formation are medium- to fine-grained sandstone in beds 1 to 5 feet thick, and the thicker more massive beds are crossbedded. Throughout the formation the sandstone is well cemented with calcite and locally the beds are cemented with silica and are quartzitic.

The Toroweap formation rests upon a planar surface that truncates broadly sweeping crossbeds in the underlying Coconino sandstone. Locally, crossbedded sandstone of the Toroweap formation rests upon crossbedded sandstone of the Coconino formation. Generally sandstone in the Coconino formation is more indurated, is lighter colored, and contains less silt than does the Toroweap formation. In Jackass

Canyon, horizontally bedded sandstone at the base of the Toroweap formation is colored reddish brown; this is believed to characterize the base of the formation over wide areas (McKee, 1938, p. 14).

The complex regional characteristics of the Toroweap formation are discussed in detail by McKee (1938). In the Lees Ferry area the Toroweap formation is an easterly sandy phase of a thicker sequence of calcareous sediments to the west and southwest. The sand is believed to have accumulated in the presence of directional currents under nearshore marine or lagoonal environments and near a large and constant supply of sand. According to McKee (1938) marine conditions accompanying deposition of the Toroweap formation encroached from the west upon the dunal deposits of the Coconino sandstone. To the east in the Henry Mountains, San Rafael Swell, and the Green River Desert this unit has not been distinguished from the Kaibab limestone.

KAIBAB LIMESTONE

The Kaibab limestone, from Lees Ferry southwestward, underlies the broad platform on both sides of Marble Canyon and is exposed in tributaries to the Colorado River along the edge of Marble Canyon. At Navajo Bridge the formation is divided into two parts. The upper part, about 90 feet thick, consists of pale-gray to pale-yellow dolomitic limestone and sandy dolomitic limestone with iron-stained nodules of light-gray to white chert. The limestone is generally massive or poorly bedded, but thin beds of shale and flattened nodules of chert locally emphasize the bedding. These rocks contain marine fossils including brachiopods, corals, bryozoans, and crinoid stems. The lower part, about 235 feet thick, consists chiefly of sandy dolomitic limestone; this part also contains marine fossils.

The upper part of the formation crops out on the broad platform bordering Marble Canyon. In places these beds weather to ledges 3- to 10-feet thick. The lower thicker part of the formation forms a vertical cliff along the edge of Marble Canyon and its tributaries.

The formation varies in thickness from place to place. At Navajo Bridge it is 325 feet thick; at Jackass Canyon it is about 284 feet thick; and McKee (1938, p. 209–211) reports a thickness of 244 feet at a locality near the measured section in Jackass Canyon. The differences in thickness of the Kaibab limestone are believed to be due partly to the unconformities at the top and base of the formation. In Jackass Canyon the formation fills scours as much as 30 feet deep, in the underlying Toroweap formation, and near the Vermilion Cliffs Lodge the top of the formation, although characteristically a smooth surface, is scoured locally to depths of as much as 25 feet. Differences in thickness elsewhere in the area may be due partly to compaction or to beveling of the formation before deposition of the overlying Moenkopi formation.

TRIASSIC SYSTEM

In the Lees Ferry area rocks assigned to the Triassic system include the Moenkopi formation, of Early and Middle (?) Triassic age, and the Chinle formation, of Late Triassic age. Both formations are as distinctive in the map area as they are throughout most of the Colorado Plateau. Combined, they form a section of highly colored strata more than 1,500 feet thick. The formations are composed largely of shale, shaly siltstone, and mudstone with subordinate but fairly persistent beds of sandstone and conglomerate. These beds underlie the broad irregular apron below the Vermilion and Echo Cliffs and the irregular inner slopes along the canyon of the Paria River.

Rocks of the Moenkopi formation consist of even-bedded red siltstone and structureless mudstone with less extensive but discrete units of limestone, gypsum, sandstone, and conglomerate. These less extensive rocks characterize the formation in some regions, and suggest nearby source areas or peculiar local depositional conditions. The formation is between 320 and 550 feet thick depending mostly upon the amount of erosion represented by the unconformity at its top.

In the Colorado Plateau region the red beds of the Moenkopi formation probably accumulated largely on mud flats, deltas, and low-lying plains adjacent to highlands. These deposits also show an irregular progressive westward thickening and a gradual westward change from terrestrial to intermittently marine conditions of deposition (Gregory, 1948, p. 223; 1950, p. 59). In the map area rocks of the Moenkopi formation are believed to have been deposited largely on broad tidal mud flats. The history and stratigraphy of the Moenkopi formation are discussed by McKee (1945), and the reader is referred to his paper for a regional synthesis of the unit as well as for stratigraphic measurements in the Lees Ferry area.

Over wide areas in the Colorado Plateau region, the Chinle formation consists of thick, brightly colored bentonitic mudstone, thin inconspicuous strata of limestone near the top, and broadly lenticular strata of sandstone or sandy conglomerate in the basal part of the formation (Stewart and others, 1959). In the Lees Ferry area, the thickness of the Chinle formation differs by more than 250 feet in the two places where it has been measured. At Cathedral Rock (stratigraphic sections, p. 81) the formation is 1,045 feet thick, but within the zone of monoclinal folding where it is presumably more compacted than elsewhere the formation is believed to be somewhat thinner. The formation is nearly everywhere covered by talus or landslide debris or it is affected by sliding in such a way that differences in thickness from place to place particularly along the Echo monocline cannot be measured by ordinary methods.

In the Lees Ferry area the formation is divided into three members and an unnamed unit. These members are, from youngest to oldest, the Owl Rock member; the Petrified Forest member; an unnamed sandstone and mudstone unit that is probably equivalent to the Monitor Butte member in Monument Valley, Ariz.; and at the base of the formation the Shinarump member. The Shinarump member rests disconformably upon the Moenkopi formation, filling broad open depressions of almost imperceptible relief termed "swales" (Witkind, 1956) and other narrower, locally sinuous and locally spoon-shaped depressions or "channels." In the Colorado Plateau region these channels are significant because the Shinarump member that fills them locally contains minable deposits of uranium.

LOWER AND MIDDLE(?) TRIASSIC SERIES

MOENKOPI FORMATION

The Moenkopi formation (Ward, 1901, p. 403–404, 413) crops out in the southern half of the map area. At Lees Ferry, it forms the banks of the Colorado River but southwestward the soft shales are stripped from older more resistant rocks, and at the south edge of the map area the formation is at least 2 miles from either edge of Marble Canyon. Throughout the area it forms a pedestal that supports an irregular apron of debris at the base of Echo and Vermilion Cliffs. The Moenkopi is composed mostly of light-brown thin-bedded shaly siltstone and mudstone, but in the upper part a conspicuous bed of resistant cliff-forming limy sandstone forms a protective cover to the underlying softer rocks. The basal 5 to 10 feet of the formation is light-colored poorly bedded siltstone or fine sandstone containing angular fragments of chert. The contact with the underlying Kaibab limestone is well exposed in many places on the west side of Marble Canyon. The contact is an unconformity but without obvious angular discordance of the beds; locally the Moenkopi formation fills channels cut 10 to 25 feet into the underlying Kaibab limestone.

In the region west of the map area, three distinctive members of the formation are recognized; they are (1) the upper red member, (2) the Shnabkaib member, (3) the lowermost unit and the middle red member (Gregory, 1948, p. 225–226; McKee, 1954). In the map area the middle unit—the Shnabkaib member—is not distinctive and the upper and middle red members are so much alike that it is not practical to separate them. On the map, the formation is divided into two lithologic units that are convenient for local correlation.

The lower unit is the thickest and most conspicuous part of the formation. It consists of light-brown thin-bedded to laminated shaly siltstone and mudstone between 320 and 430 feet thick. Tiny flakes of muscovite nearly everywhere coat bedding planes. Gypsum is common and occurs as thin layers on the bedding planes, as crosscutting veinlets, and locally as earthy gypsiferous mudstone. Films of manganese oxide (?), carbon and rarely green mudstone also occur between the beds. In the extreme southwest corner of the map area the upper 15 to 20 feet of the lower unit is gypsiferous.

The upper unit is dark chocolate-brown even-bedded siltstone and sandy siltstone with two and locally three 4-inch to 6-inch beds of gray sandy limestone. At the base of the uper unit is a 15- to 40-foot thick stratum of massive pale-brown sandstone. This basal sandstone is sufficiently continuous and distinctive to form a marker bed, and it serves as a useful and convenient datum to measure the amount of relief in the unconformity at the top of the formation. In the southwest corner of the map area the upper unit is 120 feet thick, but in much of the area only the marker-bed portion of the upper unit is preserved, and locally the entire upper unit is absent. The upper unit is believed partly equivalent to the Upper Red member of Gregory (1948) and McKee (1954). West of the map area the stratum of massive sandstone at the base of the upper unit grades into gypsiferous beds of the Shnabkaib member.

In the upper unit the beds of sandy limestone are ripple laminated, and the beds of siltstone are trough cross-stratified on a small scale. In the lower unit rain prints, mud cracks, casts of salt crystals, and tracks and borings of various shallow-water creatures are found on beds. The sedimentary structures indicate that the deposits in the upper and lower units accumulated by both marine and subaerial processes, probably largely under a widespread tidal environment.

UPPER TRIASSIC SERIES

CHINLE FORMATION

Distribution of the Chinle formation (Gregory, 1917) of Triassic age in the Lees Ferry area is coincident with that of the Moenkopi formation, which it unconformably overlies. The Chinle everywhere underlies the broad apron of landslide debris that extends outward from the Vermilion and Echo Cliffs, and it extends in the canyon of the Paria River almost to the northwest corner of the map area. Outcrops are mostly limited to thin but resistant strata of limestone, sandstone, and conglomerate. The claystone and bentonitic mudstone which make up the bulk of the formation are mostly covered with landslide debris, although they are locally exposed in the bottoms of streams and directly beneath protecting cliffs.

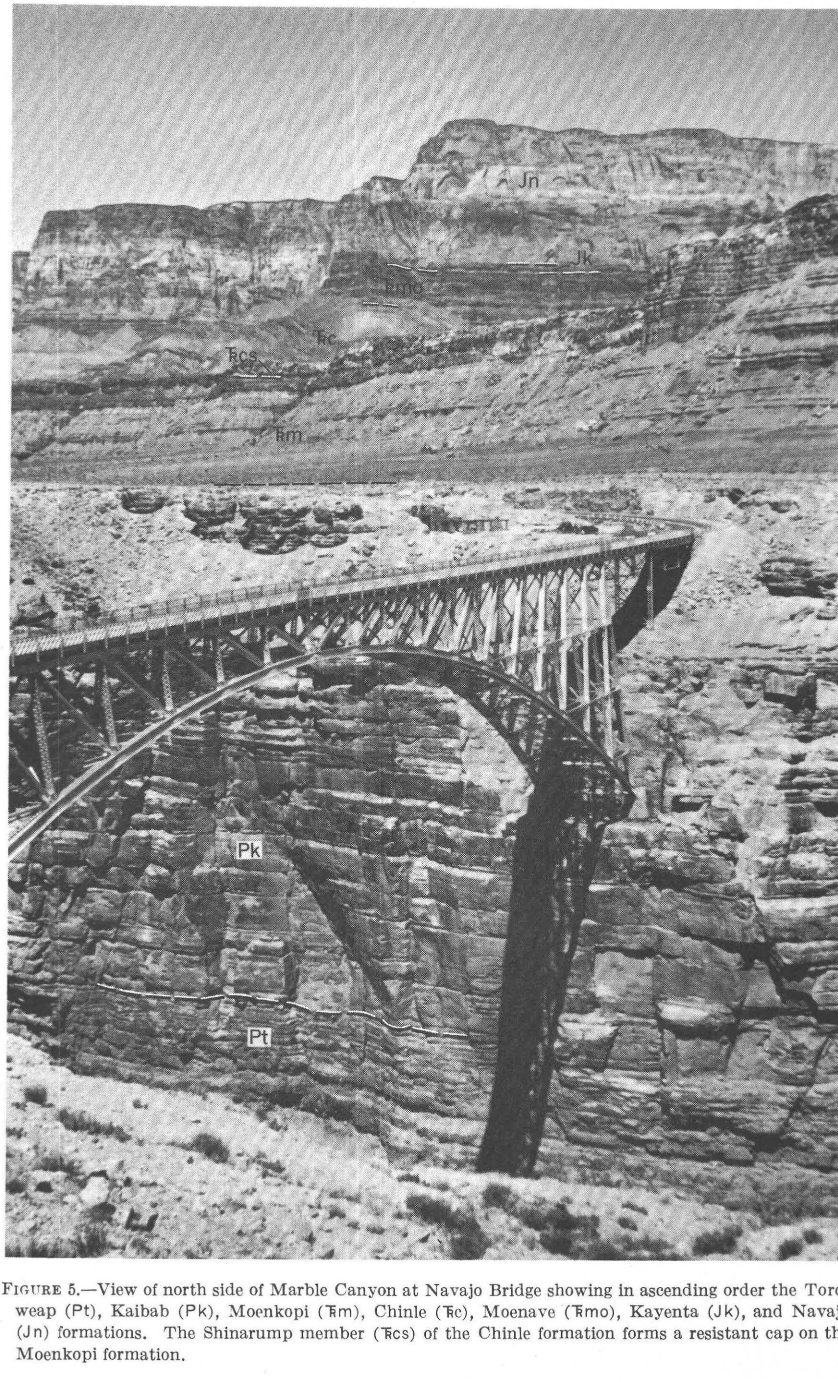

FIGURE 5.—View of north side of Marble Canyon at Navajo Bridge showing in ascending order the Toroweap (Pt), Kaibab (Pk), Moenkopi (Ꞧm), Chinle (Ꞧc), Moenave (Ꞧmo), Kayenta (Jk), and Navajo (Jn) formations. The Shinarump member (Ꞧcs) of the Chinle formation forms a resistant cap on the Moenkopi formation.

In the map area the cuestas that support the broad apron of debris beneath the Vermilion and Echo Cliffs are capped with resistant strata of the Shinarump member (fig. 5). Above the Shinarump member, is the unnamed sandstone and mudstone unit similar in appearance to the Monitor Butte member of the Mounment Valley region. Together these two units compose the lower one-third of the Chinle formation. The upper two-thirds of the formation is undifferentiated on the map, but it comprises a thick section of bentonitic mudstone, the Petrified Forest member (Gregory, 1950, p. 67), and at the top a thinner unit of mudstone and silicified limestone correlated with the Owl Rock member of Monument Valley (I. J. Witkind and R. E. Thaden oral communication, 1957).

The Chinle formation in the Lees Ferry area is like the Chinle formation in the Monument Valley area, about 70 miles to the east, where it has been subdivided in detail both by Gregory and by Witkind and Thaden. In the vicinity of Cathedral Rock the formation is 1,045 feet thick (stratigraphic section, p. 81); at Lees Ferry, where the formation is disturbed by folding along the Echo monocline, it is believed to be somewhat thinner (Wanek and Stephens, 1953).

SHINARUMP MEMBER

The Shinarump member of the Chinle formation consists of light-gray to light-tan, medium- to coarse-grained sandstone with conglomerate. Siltstone and mudstone form thin irregular lenses in the strata of sandstone, but the fine-grained sediments are not common and the coarse-grained sediments are usually clean and permeable. In most of the area, the coarse sediments are highly resistant to erosion, but they are only moderately well cemented by calcite and, locally, chalcedony. Pebbles of pink, pale-gray, and white quartzite and, more rarely, pebbles of fine-grained grantitic rocks are the chief constituents of the conglomerate. Carbonaceous wood and logs and worn fragments of wood replaced by silica are also present in these sediments, but they are more common in sediments above the Shinarump member.

The coarse-grained sediments are extensively crossbedded, exhibiting principally festoon bedding and planar cross-stratification. The prevailing dip direction of the planar and the festoon bedding is northwest (pl. 3), indicating that the streams probably flowed from southeast to northwest. In the map area the Shinarump member fills a broad swale in the top of the Moenkopi formation that is apparently at least 8 miles wide and trends northwest, as do the sedimentary structures in the Shinarump member. A profile of this broad valley-like structure is shown on figure 6, the datum of which is the base of the sandstone marker bed in the Moenkopi formation. The eastern

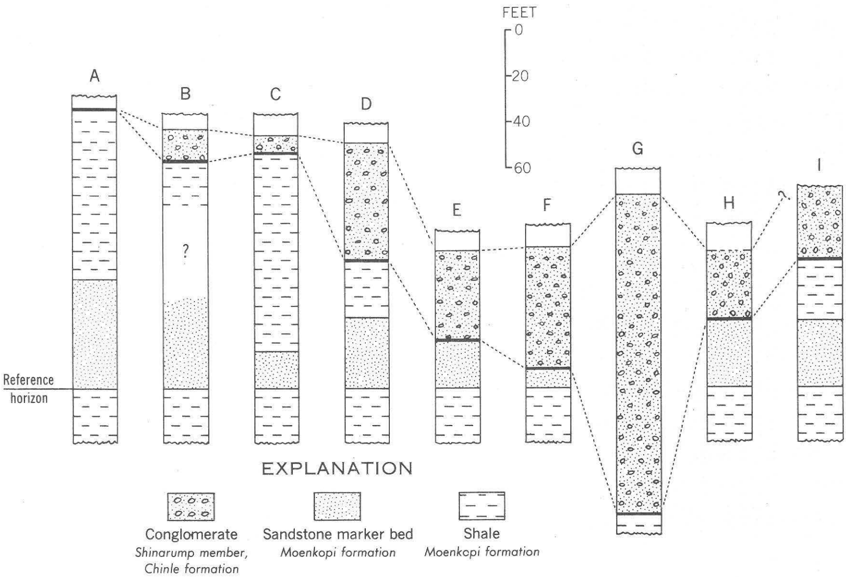

FIGURE 6.—Stratigraphic sections showing channeling of the Shinarump member of the Chinle formation into the Moenkopi formation, Lees Ferry area (locations shown on pl. 3).

part of a second broad lens of the Shinarump member is in the extreme southwest part of the map area, but the western pinchout of this body of sediment has not been mapped nor has its likely counterpart to the southeast along Echo Cliffs been determined. However, Wanek and Stephens (1953) show outcrops of the Shinarump member in many places along the Echo Cliffs to the south of Lees Ferry; probably broad lenses of the member—similar to those in the Lees Ferry area—occur also in this part of northern Arizona.

In the map area, the Shinarump member is broadly lenticular and discontinuous. In most places it is about 45 feet thick, but it is as much as 150 feet thick where it fills channels scoured in the underlying Moenkopi formation; locally it is absent, presumably because of nondeposition. It is thickest in the vicinity of Lees Ferry; to the southwest it thins to a featheredge.

Channels at the base of the Shinarump member are important because deposits of uranium are localized in the rocks that fill the channels. These channels range from 30 feet to more than 300 feet in width and from 10 feet to 75 feet in depth. Channels that are exposed on the cliff faces are symmetrical in cross section but in plan, where they have been explored by drill holes, they are sinuous. Some channels are oriented at right angles to the trend of the sedimentary structures in the upper part of the Shinarump member, but the average orientation of all the channels is about the same as is the average trend of sedimentary structures in the Shinarump member as a whole. Along nearly 20 miles of outcrop in the Lees Ferry area, 14 places were found where the member fills channels. Some of these places are probably the continuation from one outcrop to another of the same channel but at least 10 separate channels have been identified.

SANDSTONE AND MUDSTONE UNIT

Above the Shinarump member of the Chinle formation is a unit about 175 feet thick that contains broad lenticular strata of sandstone separated by silty mudstone. Usually two strata of poorly sorted, coarse- to fine-grained arkosic sandstone between 15 and 30 feet thick are contained in the unit, and they crop out as light-colored ledges above the Shinarump member. Bedding in the sandstone is usually inclined and either planar or festoon, but locally beds are horizonal and 6 inches to 4 feet thick. In places the sandstone is horizontally laminated, and the surfaces of the beds and laminae are sometimes coated with black opaque heavy detrital minerals, so that the bedding is conspicuous. Interstitial white or pale-green clay is a common intergranular constituent of the sandstone, and calcite and quartz cement the beds locally. In most places, however, this sandstone is quite friable. Mudstone that separates the strata of sandstone is dark red, gray, or gray green, but locally it is light yellow owing to impregnations of iron oxide mixed with jarosite and gypsum. Bedding is usually obscure in the mudstone because it weathers easily and forms rubble-covered slopes. However, where the mudstone is exposed it is thin bedded or locally laminated. Below some strata of sandstone the color of the mudstone is altered from red to gray or white, and in these places the altered mudstone appears contorted. It is cut by many randomly oriented fractures that are locally lined with gypsum. These zones of altered mudstone are from 2 to 10 feet thick.

At the base of the sandstone and mudstone unit are lenticular strata of dark dusky-green clay-rich arkosic sandstone that range from a featheredge to 40 feet in thickness. These strata are contorted locally, and in places they fill deep scours in the underlying Shinarump member. The sandstone is thin bedded or it is cross-laminated in sets of troughs that are 6 inches to 1 foot wide and 2 to 4 inches thick; this latter bedding gives the sandstone a characteristic flaky appearance on outcrop. These sediments commonly contain randomly oriented fossil logs, some of which are at least 60 feet long and 3 to 4 feet in diameter; the logs are replaced by drab-colored chalcedony. The sandstone on outcrop is stained nearly black with iron or manganese minerals, and locally cemented with silica. Where the sandstone is silicified—and this is so in many places—it weathers to odd-shaped cavernous blocks that ring melodiously when struck. These basal strata of the sandstone and mudstone unit are coextensive with the Shinarump member, but they also fill scours in the Shinarump member.

The sandstone and mudstone unit in the Lees Ferry area is believed to be partly equivalent to the Monitor Butte member of the Chinle formation in the Monument Valley area, 70 miles east of Lees Ferry. In Monument Valley the Monitor Butte member is mostly a grayish-green, clay-rich arkosic sandstone that contains numerous fossil logs. In these respects it is similar to beds at the base of the sandstone and mudstone unit; however, it does not contain the prominent ledge-forming sandstone strata that typify the lower part of the Chinle formation near Lees Ferry. Geologic mapping in the Lees Ferry area has been sufficiently extensive to show that the sandstone and mudstone unit is more than a local phase of deposition.

CHINLE FORMATION UNDIVIDED

The upper two-thirds of the Chinle formation, about 825 feet thick, comprises two units that are not shown on the map but that are distinct in the map area and throughout northern Arizona and southwestern Utah. The lower unit, the Petrified Forest member (Gregory, 1950, p. 67), about 625 feet thick, is composed of vari-

FIGURE 7.—View east toward Lees Ferry from lower slopes of the Chinle formation showing smooth rounded outcrops of the Petrified Forest member (Ꞧcp) in the foreground and resistant cap of Shinarump member (Ꞧcs) on cuestas in the middle background.

colored shale, siltstone, bentonitic clay and mudstone, and thin lenticular strata of limestone-pebble conglomerate and sandstone. In this member the coarse-grained sediments and local thin beds of marl or calcareous mudstone are sparse, but they are sufficiently resistant to crop out as thin ledges. Mostly the sediments are so homogeneous that they erode to smooth rounded slopes (fig. 7). Bentonite is present in the clays, so that they swell when wet, and outcrops of the unit are thus covered by a fluffy-textured layer that during every rain appears to melt away and to blend the various gray shades of blue, red and yellow that color the beds. Silicified wood is locally present in the sediments, and here and there the beds also contain nodules of chert. Undoubtedly the clays have undergone considerable compaction, for when the fresh rock is broken even into very small pieces it parts along curved surfaces that are slickensided.

The Petrified Forest member may consist of at least two phases that are sufficiently distinct to be recognized over a considerable part of northern Arizona and southern Utah. In the Lees Ferry area the lower half of the member is in various shades of red, gray green, and gray blue and consists largely of bentonitic mudstone of volcanic origin. The upper half of the member contains lenticular beds of limestone-pebble conglomerate particularly near the base; it is more silty, more highly dissected on outcrop, and is in grayish tints of pink and red. These and other color and lithologic separations in the Petrified Forest member have been recognized by Lawson (1913, p. 440) at Paria about 40 miles northwest of Lees Ferry, by Gregory (1950, p. 67) in the Zion Park region of southern Utah, by Wilson and Keller (1955, p. 26–27) along the Echo Cliffs for about 50 miles south of Lees Ferry, and by Schultz (1957) elsewhere in northern Arizona. They are likely indicative of subtle chemical changes in an otherwise almost uniform depositional environment.

In many places the bentonitic mudstone contains the remains of amphibians, reptiles, phytosaurs, and lung fish (Camp, 1930); and the bentonite is believed to have formed from widespread deposits of volcanic ash that fell in a lacustrine environment.

The Owl Rock member of the Chinle formation in the Lees Ferry area is covered in most places by landslide and talus debris. However, in the upper part of Paria Canyon and at the base of most of the sharp reentrants in the Echo and Vermilion Cliffs, erosion has exposed the Owl Rock member as soft-pink and light-red mudstone between beds of silicified limestone, limestone-pebble conglomerate and lenticular strata of crossbedded coarse sandstone (fig. 8). The beds of silicified limestone, 5 to 10 feet thick, are resistant to erosion, and in the deep canyons they usually form waterfalls; below these

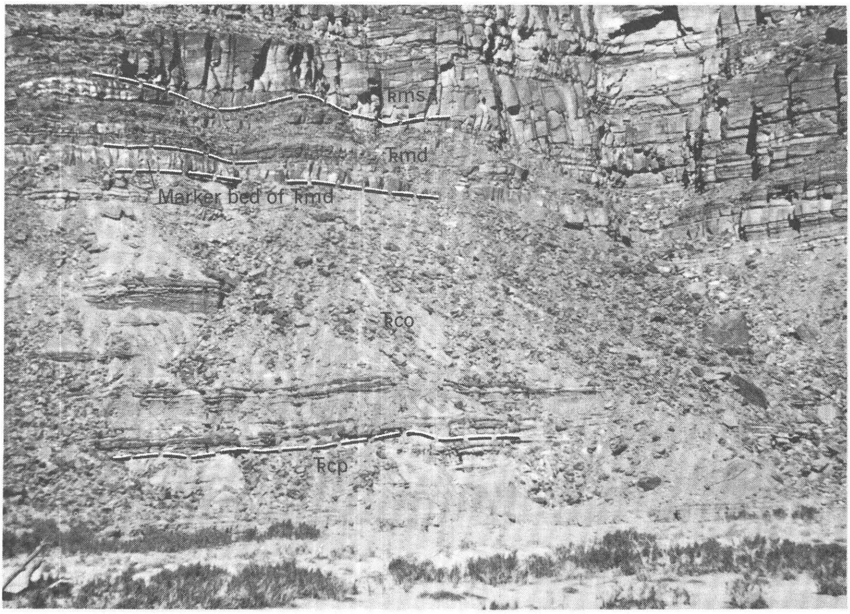

FIGURE 8.—View of the Owl Rock member (Ꞧco) and the upper few feet of the Petrified Forest member (Ꞧcp) of the Chinle formation in Paria Canyon about 9 miles upstream from Lees Ferry. Note the sandstone marker bed at base of the Dinosaur Canyon sandstone member (Ꞧmd), and the massive but lenticular sandstone strata of the Springdale sandstone member (Ꞧms) of the Moenave formation.

resistant beds are alcoves eroded in the soft mudstone. Along the Echo Cliffs and in the upper part of Paria Canyon the Owl Rock member is between 150 and 200 feet thick, and the beds of conglomerate and limestone make up about 50 percent of the member. Westward along the base of Vermilion Cliffs the Owl Rock member is about 200 feet thick. The conglomerate and limestone beds that characterize the unit in the Echo Cliffs are mostly absent along the base of the Vermilion Cliffs.

Locally sediments of the Owl Rock member have been altered. Directly below the overlying Glen Canyon group, mudstone and beds of limestone in the Owl Rock member are silicified to a light-pink chert containing knots and concretionary masses of gray-green chalcedonic chert and stringers and veinlets of red jasper. Below this highly cemented zone the concretionary masses of chalcedony are irregularly distributed throughout the mudstone, becoming less numerous lower in the section. Color transitions in the mudstone are from green to red downwards through a vertical interval of 30 or 40 feet, and they coincide with the gradual downward diminution of the silica nodules. This alteration may have been influenced by percolating ground water in the overlying Dinosaur Canyon sandstone member of the Moenave formation.

Upper Triassic fossils have been collected from conglomeratic strata in the Owl Rock member on the hillside about one-quarter of a mile northwest of Echo Peaks. They have been identified by J. B. Reeside, Jr. (written communication, 1956) as *Unio graciliratus* Simpson and *Unio* aff. *U. dumblei* Simpson, probably unnamed. He reports as follows:

These species were named from the Dockman of Texas, but not enough occurrences have been reported to define ranges within the Upper Triassic. Fresh-water faunas are usually characterized by abundance of individual specimens but paucity of species, and the collection is of that sort. The Unios in the Recent fauna are said to prefer a river environment, and this is probably true for the depositional environment of these Upper Triassic fossils.

TRIASSIC AND JURASSIC SYSTEMS

GLEN CANYON GROUP[1]

The Glen Canyon group is widely distributed in the Colorado Plateau, where it forms a thick layer of reddish fine-grained aeolian and fluvial sandstone. The group was named after Glen Canyon of the Colorado River.

In the Lees Ferry area the Glen Canyon group consists of three formations which are, from oldest to youngest, the Moenave formation (Harshbarger and others, 1957), the Kayenta formation (Baker, 1933), and the Navajo sandstone (Gregory, 1917). The Moenave formation is further subdivided, from oldest to youngest, into a Dinosaur Canyon sandstone member (Colbert and Mook, 1951, p. 151), and a Springdale sandstone member (Gregory, 1950), but these two units are not mapped separately everywhere on the geologic map. In the lower one-third of the Vermilion and Echo Cliffs the Moenave and Kayenta formations consist of horizontally bedded sediments, whereas the Navajo sandstone is a lighter colored cross-bedded unit that forms the most highly jointed and towering parts of the cliffs (fig. 9). Except for a small area near Lees Ferry, the walls of Glen Canyon are carved entirely in the Navajo sandstone.

The problem of assigning ages to the formations in the Glen Canyon group is discussed by Baker, Dane, and Reeside (1947), by Averitt and others (1955), and by Harshbarger and others (1957, p. 25–33), and it is complicated by problems in regional stratigraphic correlation as well as by a lack of good marker fossils. As no fossils were discovered in the Lees Ferry area to further clarify the age assignments of these rocks, the ages indicated by Harshbarger and his coworkers are used in this report. The Glen Canyon group is assigned to both the Triassic and Jurassic systems. The Moenave formation is Triassic(?), the Kayenta formation is Jurassic(?), and the Navajo sandstone is considered Jurassic and Jurassic(?) in age.

[1] See note, p. vi.

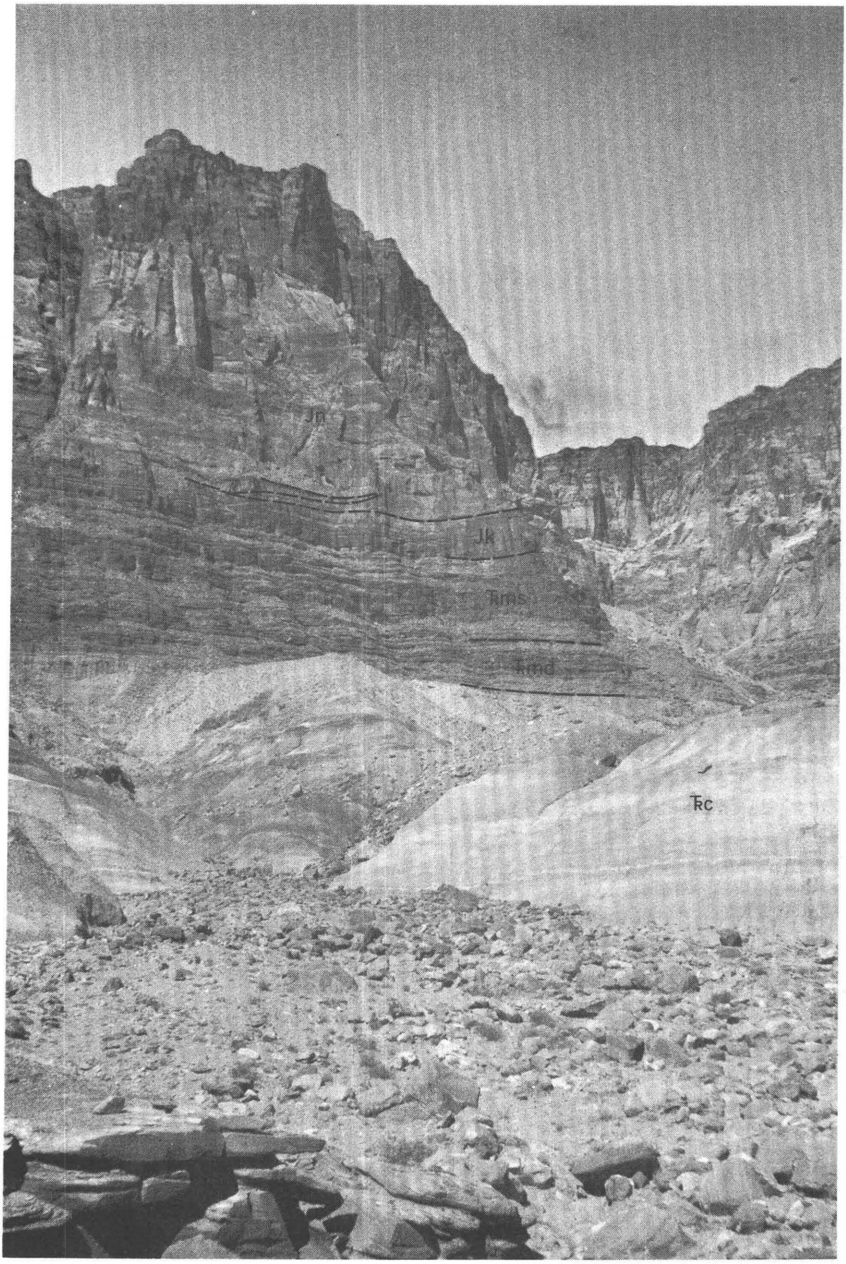

FIGURE 9.—View of the Glen Canyon group, Dinosaur Canyon sandstone member (Ŧmd), and Springdale sandstone member (Ŧms), of the Moenave formation; Kayenta formation (Jk); and Navajo sandstone (Jn), of Triassic and Jurassic age, resting on the Chinle formation (Ŧc), of Triassic age, Badger Canyon, Lees Ferry area.

In the Lees Ferry area, deposits of the Glen Canyon group rest unconformably upon the Chinle formation.

MOENAVE FORMATION

The Moenave formation (Harshbarger and others, 1957) is composed of two members: the Dinosaur Canyon sandstone member (Colbert and Mook, 1951), composing roughly the lower one-third to one-half of the formation, is a distinctive orange-red ledge-forming sandstone and siltstone unit; the Springdale sandstone member is a dark red-brown cliff-forming sandstone. Both members can be traced through the area without appreciable change in lithology. The formation differs in thickness from place to place. The Wingate sandstone of Wanek and Stephens (1953), since renamed the Moenave formation, is 443 feet thick at Lees Ferry, and in other parts of the map area their thickness—both estimated and measured—ranges from 270 to 443 feet.

DINOSAUR CANYON SANDSTONE MEMBER

The Dinosaur Canyon sandstone member of the Moenave formation of Triassic(?) age is exposed along the base of the Vermilion and Echo Cliffs and in Paria Canyon in the northwest corner of the map area. The member, which ranges in thickness from 90 to 220 feet, consists of reddish-orange and dark-red fine-grained friable sandstone, siltstone, and mudstone in beds 3 inches to 2 feet thick. These sediments are horizontally bedded, and the beds of sandstone crop out as thin ledges that are separated by the less resistant siltstone and mudstone.

The sandstone is poorly sorted, consisting of medium-sized grains of quartz and feldspar scattered at random in a matrix of fine sand or silt. Some of the quartz grains are well rounded and frosted, others are subangular; the feldspar grains are angular. Locally the sandstone is crossbedded in trough-shaped sets that resemble miniature festoon structures. Mudstone separating the beds of sandstone contains local concentrations of coarse sand grains and flakes of red mudstone and red and green chert. White mica is localized on bedding planes, where it imparts a glistening sheen to these surfaces. Casts of mud cracks and kidney-shaped mudballs are preserved in and at the base of some beds of siltstone and mudstone, and asymmetric ripple marks and current lineation, a stream lining of sand grains on the bedding, are preserved on the beds. Below Echo Peaks, at Lees Ferry, and along the walls of Paria Canyon the member contains a 6- to 8-foot-thick bed of massive sandstone at the base that serves as a convenient marker bed (fig. 16), but westward from Lees Ferry this bed thins to zero and cannot be recognized at the headwaters of Badger Canyon about 8 miles southwest of

Lees Ferry. No other distinctive lithologic changes in the member were recognized in the map area.

The Dinosaur Canyon sandstone member rests unconformably on the top of the Chinle formation and fills scour structures in it. Small chips of green and red chert and flakes of mudstone common in the basal beds of the member are probably derived from the Chinle formation. Above the disconformity the sandstone is commonly bleached to white in spots throughout a zone about 10 feet thick.

SPRINGDALE SANDSTONE MEMBER

The Springdale sandstone member of the Moenave formation ranges from 180 to 223 feet in thickness and averages about 200 feet. It was studied in detail at the headwaters of Badger Canyon, in the vicinity of Echo Peaks, at Lees Ferry, and in the upper reaches of Paria Canyon.

The Springdale sandstone member consists of dark to pale reddish-brown fine-grained sandstone and minor siltstone. The sandstone is in broadly lenticular strata that are as much as 15 feet in thickness. Several of the lenticular strata commonly form an irregular ledge. The member is composed of three and sometimes four of these dark-colored ledges. Locally, the two lowermost ledges in the member are separated by 10 to 15 feet of thin-bedded reddish-orange siltstone and fine-grained sandstone that resemble sediments in the underlying Dinosaur Canyon sandstone member. Elsewhere in the member, the strata of sandstone are separated by thin beds of mudstone and siltstone. As a rule the sandstone is moderately well sorted and porous, and locally coarse grains of sand and chips and flakes of mudstone are abundant and characteristic accessories. Some strata of sandstone are trough crossbedded in sets that are 2 to 6 feet thick, but others are horizontally bedded in beds that are 2 inches to 3 feet thick. Current lineation is also common on bedding planes that are horizontal. The Springdale sandstone member is the most highly jointed unit in the Glen Canyon group and small perennial springs discharge from near the base of the unit in most of the prominent reentrants in the Vermilion Cliffs.

KAYENTA FORMATION

The Kayenta formation of Jurassic(?) age is the least accessible of the formations in the Glen Canyon group, for it crops out mostly in cliff faces. The formation was studied in the upper part of Paria Canyon and east of Lees Ferry where the formation intersects the Colorado River, and in deep recesses of the Vermilion Cliffs. Two stock trails over the Echo Cliffs, one crossing at Echo Peaks and the other above Navajo Spring, also provide access to the formation. The Kayenta formation characteristically weathers to smooth

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rounded slopes along a bench at the base of the Navajo sandstone. Locally, the formation is difficult to distinguish from the underlying Springdale sandstone member of the Moenave formation, because like the Springdale it is darkly stained by iron and manganese oxides. Usually, however, in contrast to the Springdale, the Kayenta is lighter colored, less jointed, and the bedding, though locally thick, is parallel rather than lenticular.

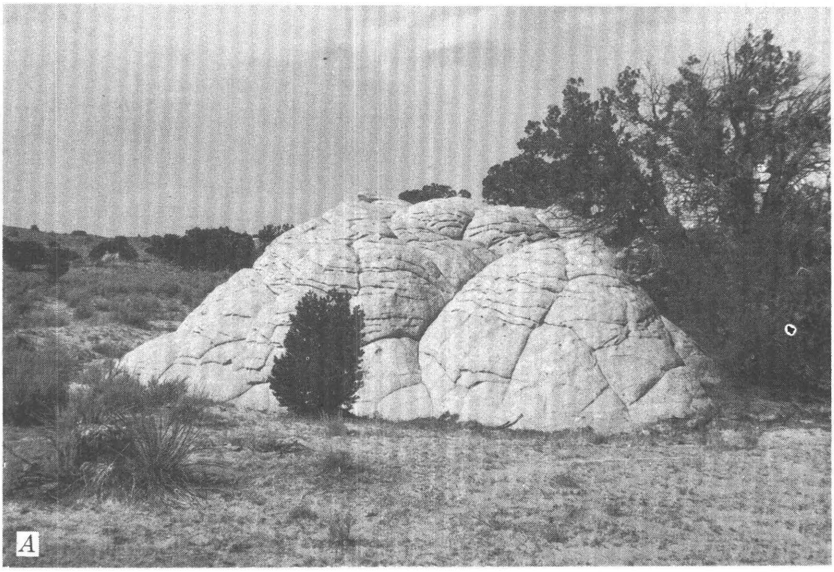
The lower part of the Kayenta formation is characterized by thin to thick even-bedded sandstone and siltstone, locally separated by thin beds of limestone. The sandstone is light red brown and medium to fine grained, with some well-rounded and frosted grains near the top of the formation. The siltstone is red brown and thin bedded; these beds are locally contorted. The limestone, in beds 6 to 8 inches thick, is gradational to limy siltstone, and in the vicinity of Lees Ferry it is locally silicified and cut by irregular veinlets of jasper. Near the top of the formation strata of sandstone 2 to 4 feet thick are tangentially crossbedded.

The upper part of the Kayenta formation and the lower part of the Navajo sandstone are colored alike, and close-spaced planar disconformities separating units of crossbedded sandstone in the Navajo resemble bedding in the Kayenta. The two formations also intertongue; but this relation was only observed in the upper part of Paria Canyon, where the formation is accessible. The top of the Kayenta formation is arbitrarily placed at the top of the uppermost horizontally bedded sandstone stratum, even though this may be above strata of tangentially crossbedded sandstone more typical of the Navajo sandstone. The Kayenta is 180 feet thick at Echo Peaks, 122 feet thick at Lees Ferry stratigraphic section, p. 79), 200 feet thick in Paria Canyon 3 miles northwest of the map area, and 169 feet thick at the head of Badger Canyon; on the map the formation is shown to be about 200 feet thick but this is the maximum thickness.

NAVAJO SANDSTONE

The Navajo sandstone of Jurassic and Jurassic(?) age crops out over more than half the Lees Ferry area and is the most widely exposed of all the mapped formations. It underlies the Paria and Kaibito Plateaus, and much of the unnamed plateau region northeast of Lees Ferry. It is also responsible for most of the spectacular scenery in the area, for it forms the sheer walls of Glen Canyon and the Vermilion and Echo Cliffs. The Navajo sandstone forms the abutments of Glen Canyon dam, and it will eventually border and underlie much of the lake formed by this dam.

On the high plateaus the Navajo sandstone erodes to low buttes, domes, and nipples, and in many places the bases of these land forms are indented with shallow caves and alcoves (fig. 10*A*, *B*). The upper



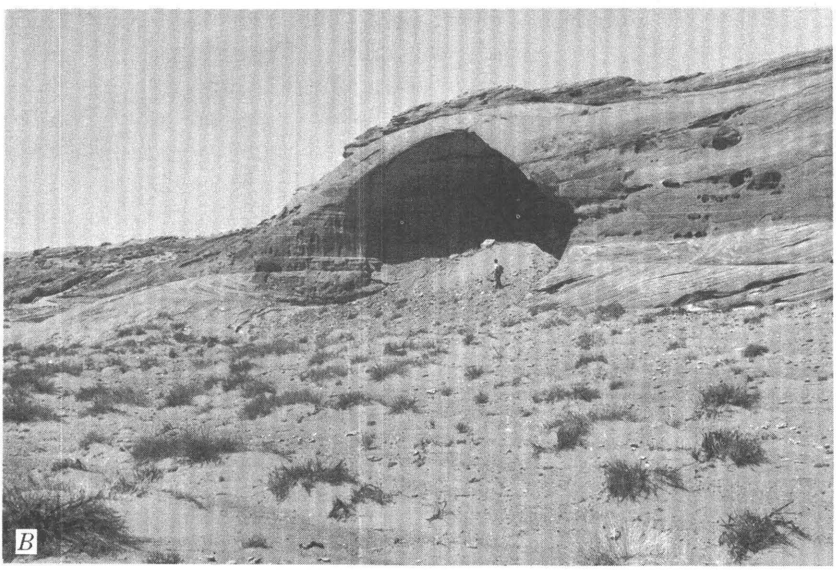


FIGURE 10.—Weathering features of the Navajo sandstone. *A*, polygonal jointing and domelike forms characteristic of weathered Navajo sandstone; *B*, Rawhide Cave, an alcove in the upper part of the Navajo sandstone near the Glen Canyon damsite.

part of the formation is extensively jointed, particularly near the Echo monocline, and the rocks are deeply eroded along these joints. This has resulted in the formation of spires and deep notches on the cliffs, and an almost impassable maze of vertical but interrupted walls of sandstone locally along the east flank of the Echo monocline.

The Navajo sandstone is the thickest and most conspicuous of the mapped units in the Lees Ferry area. A complete section of the formation can be measured on the west side of Cedar Mountain, where the top of the formation intertongues with the Carmel formation; there the Navajo is 1675 feet thick to the base of the intertonguing sedimentary rocks. About 20 miles southeast of Cedar Mountain in the vicinity of Rawhide Cave the tongue of Carmel-like lithology pinches out, and the formation thus thickens by the addition of about 182 feet of sandstone; in this area, therefore, the formation could be as much as 1,857 feet thick. In the floor of Glen Canyon in the vicinity of the damsite, the U.S. Bureau of Reclamation has drilled to a depth of 434 feet below river level without penetrating the underlying Kayenta formation. In this locality the Navajo is greater than 1,423 feet thick.

The Navajo sandstone consists of medium- to fine-grained sandstone together with very minor lenticular beds of chert that usually occur near the base of the formation. More than 85 percent of the rock is composed of coarse but well-rounded frosted grains of quartz and some grains of chert, orthoclase, albite, and tourmaline; locally, flakes of mica coat bedding planes. The chert beds are dark colored, 4 to 6 feet thick, and are continuous for ¼ to ½ mile; they are localized near the base of the formation. In places the chert is an interlocking mosaic of angular fragments 1 to 2 inches thick cemented in a matrix of equally dense chert; elsewhere it is unbroken and well bedded. Thin sections of the chert show it to be an almost total replacement of dense lighter-colored limestone, probably of fresh-water origin.

Sand grains in the Navajo sandstone are cemented chiefly by calcium carbonate and iron oxide. Locally these cementing minerals form clusters of grape-sized concretions near faults and along bedding. However, as a rule, carbonate and iron oxide minerals are evenly distributed throughout the formation or else distributed so as to give the formation a broadly banded appearance. In the Vermilion Cliffs the lower 300 to 400 feet of the Navajo sandstone is pale reddish brown and the remainder is grayish orange. At Powells Monument and other places on the Paria Plateau the top 50 to 100 feet of the formation is very pale orange, and this is underlain by about 100 feet of sandstone that is moderate reddish brown; below this the sandstone is white. The contacts between zones of color in

FIGURE 11.—Tangential crossbedding in the Navajo sandstone, on plateau north and west of Glen Canyon damsite.

the sandstone are irregular but broadly they parallel the base and top of the formation and are caused by differences in the quantity and color of the iron oxide cement. The zones of different colored sandstone in the Navajo sandstone are absent in the eastern and southeastern part of the area in the vicinity of Wahweap Creek, but in the northern and western part of the area they coincide with the distribution of the intertongue of the Carmel formation.

Locally the Navajo sandstone is structureless, or the bedding is confused and highly contorted as though by slumpage. Typically, however, broad tangential crossbeds characterize the formation (fig. 11). On outcrop the crossbeds are exposed in sweeping sets that are locally 40 feet thick. Near Ferry Swale in the northeast part of the area and near Echo Peaks in the southern part of the area, the direction of maximum dip in the crossbeds is southeast, and this direction is probably the direction of sediment transport for the upper part of the formation in the map area.

Near the top and bottom of the formation, widespread planar diastems truncate the bedding. At the base of the formation they are 5 to 15 feet apart vertically, and they merge with horizontally bedded sediments in the Kayenta formation; near the top of the formation along the upper edge of the Vermilion Cliffs, individual diastems can be traced for several miles. In places faceted pebbles are localized along the diastems. Sandstone cemented with calcite and iron oxide forms a thin dark-colored layer beneath some diastems and is sufficiently resistant to cap low buttes and mesas. The diastems probably represent local playalike areas of erosion that prevailed for short periods of time before they were buried later by shifting sand dunes.

INTERTONGUES OF NAVAJO AND CARMEL FORMATIONS

East of Wahweap Creek and in the southeastern part of the map area on the Kaibito Plateau, the Navajo sandstone is an uninterrupted sequence of crossbedded sandstone up to the base of the Carmel formation. However, in the vicinity of Rawhide Cave a thin zone of darkly stained Navajo sandstone appears along a planar diastem about 200 feet below the top of the formation. This zone of discolored crossbedded sandstone and the disconformity above it are traceable about 5 miles west to the Thousand Pockets area. Here, horizontally bedded fine-grained limy sandstone and siltstone in beds from 6 inches to 2 feet thick rest on the diastem and divide the Navajo sandstone into two parts, a thick lower unit—the bulk of the formation—and a thinner upper unit. These two units represent the easternmost limit of complex intertonguing that takes place between the Navajo and Carmel formations in regions to the west and northwest (D. D. Dickey and J. C. Wright, written communication, 1958). In this report names are proposed for these two units for

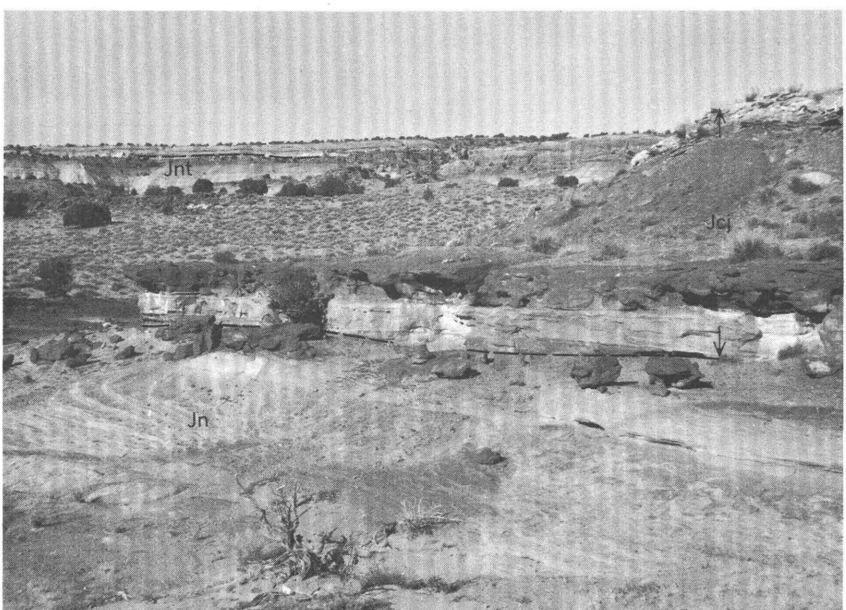


FIGURE 12.—View of the Judd Hollow tongue (Jcj) of the Carmel formation and the Thousand Pockets tongue (Jnt) of the Navajo Sandstone (Jn), Judd Hollow, Kane County, Utah.

the first time. The horizontally bedded intercalated sandstone is herein named the Judd Hollow tongue of the Carmel formation; the crossbedded sandstone correlative with the upper part of the Navajo sandstone is called the Thousand Pockets tongue of the Navajo sandstone after the locality in the Lees Ferry area where it first appears as a distinct unit.

The Thousand Pockets tongue crops out as a mappable unit in the Cedar Mountain area. Here it consists of pale yellowish-orange medium- to fine-grained tangentially crossbedded sandstone similar to that in the Navajo sandstone. Near Thousand Pockets, about 2½ miles north of and parallel to Glen Canyon, the unit forms a low gently rounded bluff; flanking the west and north side of Cedar Mountain, it underlies a broad dune-covered bench. The type section of this unit is on the north side of Judd Hollow about 2 miles north of the map area in the NW ¼ sec. 31, T. 43 S., R. 2 E., Kane County, Utah (fig. 12). At the type locality (stratigraphic section, p. 67) the unit is composed of light-gray to white to pale reddish-brown fine-grained to very finegrained quartzose silty sandstone that is 228 feet thick. The sandstone is tangentially crossbedded like the underlying Navajo sandstone, but it is finer grained throughout and more nearly resembles sandstone in basal strata of the overlying Carmel formation than sandstone in the underlying Navajo sandstone.

The Thousand Pockets tongue rests conformably upon horizontally bedded sediments of the Judd Hollow tongue and is overlain conformably by the Carmel formation of Jurassic age. J. C. Wright and D. D. Dickey have also found that the Thousand Pockets tongue can be traced northwestward from the type section at Judd Hollow for more than 60 miles. Along this line of outcrop the unit thins, becomes horizontally bedded, and becomes yellowish and finer grained, grading almost completely into a siltstone about 10 miles south of Lick Wash in southern Utah.

The Judd Hollow tongue consists of dark to red-brown fine- to medium-grained limy sandstone and siltstone in horizontal beds that are 2 to 6 feet thick. On Cedar Mountain the unit is about 20 feet thick; at Judd Hollow, the type section, the unit is 32 feet thick. According to Wright and Dickey the equivalent unit is 44 feet thick at Adairville (section 2 p. 64); 60 feet thick at Catstairs (section 1 p. 62); and 186 feet thick at Lick Wash close to its junction with the main mass of the Carmel formation. The unit is continuous with fossiliferous limestone in the lower part of the Carmel formation at Mount Carmel. The fossils from the lower part of the Carmel formation near Mount Carmel represent many species of mollusks that R. W. Imlay (written communication of March 9, 1961) considers to be Middle Jurassic (Bajocian) age.

SAN RAFAEL GROUP

The San Rafael group of Middle and Late Jurassic age was first established by Gilluly and Reeside (1928) in the San Rafael Swell of northeastern Utah. In the Lees Ferry area the group includes the Carmel formation of Middle and Late Jurassic age and the overlying Entrada sandstone of Late Jurassic age.

CARMEL FORMATION

The Carmel formation (Gregory and Moore, 1931, p. 69) is exposed along the flank of the Echo monocline in the north edge of the map area, where it rests upon the Navajo sandstone without angular discordance or perceptible relief. At most, wave action accompanying deposition of beds of the Carmel has reworked Navajo sandstone for about 2 feet below the contact. The formation is composed of 3 main units of generally contrasting lithology that total 401 feet thick; an upper mudstone unit about 115 feet thick, a middle ledge-forming cross-stratified sandstone unit about 143 feet thick, and a lower silty and locally slump-deformed unit also about 143 feet thick (stratigraphic section 4, p. 69). Stratigraphic sections 1, p. 62 and 6, p. 72, describe the Carmel formation as measured near but outside the map area. These sections show that the formation differs considerably in thickness from place to place. About 18 miles northwest of the map area, at the Catstairs (section 1), the formation is 204 feet thick. At the Wahweap locality (section 6) the formation is 299 feet thick.

The lower unit in the Carmel formation consists of moderate to dark reddish-brown thin-bedded siltstone in strata 2 to 4 feet thick that alternate with grayish-yellow medium- to fine-grained sandstone in strata 2 to 15 feet thick. Bedding in some of the sandstone strata is planar inclined and terminates against horizontal bedding planes above and below, but in most of them the bedding is horizontal. Locally, coarse angular grains of sand and angular pebbles are alined along bedding, or they are localized in small lenses or stringers, or scattered at random in the sandstone. Small concretions of calcite-cemented sandstone and spots of bleached sandstone ¼ to ½ inch in diameter are also scattered at random in the sandstone strata, and cylindrical bodies of sandstone that crosscut bedding are sufficiently abundant to help identify the formation (Phoenix, 1958). The units of siltstone are locally intercalated with thin beds of mudstone and fine-grained sandstone, but in most places the siltstone is massive. Where bedding is preserved in the siltstone it is contorted and broken by numerous interstratal faults.

The lower unit of the Carmel formation is distinguished from the Judd Hollow tongue principally by the slump and compaction structures and the small angular pebbles, grit, and coarse sand concentrated along bedding.

The middle unit of the Carmel formation is pale gray-brown to pale yellow-brown medium- to fine-grained sandstone, massive and thick bedded near the middle but interbedded with siltstone in the lowermost and uppermost parts. The massive thick-bedded sandstone weathers to rounded ledges with numerous potholes, but the interbedded sandstone and siltstone strata at the top and bottom of the unit weather to alternating ledges and smooth inclined slopes. The sandstone strata in the middle unit are mostly horizontally bedded, and current lineation oriented northeast is locally abundant on the bedding surfaces. Festoon-type crossbedding is conspicuous in some strata; or the bedding is planar inclined and terminates against horizontal bedding planes above and below.

The upper unit is reddish-brown thin-bedded siltstone and mudstone with local resistant beds of light-colored limy sandstone. The mudstone is blue green for a distance of 1 to 2 feet below the Entrada formation, but below this for about 5 feet it is mottled red and gray. The entire unit forms a dark-colored smooth slope broken here and there by thin but persistent pale gray-green ledges of silty sandstone.

The origin of the Carmel formation is discussed by Harshbarger and others (1957, p. 43–56), who suggest that it was deposited in an environment that fluctuated from a low-lying flood plain to a marshy tidal flat. It seems likely that the Carmel environment was first introduced by conditions favorable to planation of the Navajo sandstone such as an encroaching shoreline of a shallow sea. In the Lees Ferry area this was accompanied by at least one retreat of the shoreline as evidenced by intertonguing of the Navajo and Carmel formations. In the lower unit of the Carmel, strata of thin-bedded mudstone and siltstone were probably deposited in an environment of quiet shallow water; however, cylindrical bodies of sandstone that penetrate these and other strata in the lower unit also suggest that the deposits were formed near a tidal environment. Oriented sedimentary structures of various kinds in the sandstone strata of the middle unit; including foreset and festoon-type bedding and current lineation, suggest that these sediments were transported by directional currents that moved northeastward.

ENTRADA SANDSTONE

The prominent light-colored buttes in the northeast part of the Lees Ferry area are composed of the Entrada sandstone (Gilluly and Reeside, 1928, p. 76). The formation is about 650 feet thick and it consists of pale-gray, white, and locally pale-green or pale-brown fine-grained silty crossbedded sandstone. The sandstone is chiefly rounded quartz grains; it is porous, friable, and sparsely cemented with calcium carbonate. Tangential crossbedding is abundant throughout the formation in sets 4 to 25 feet thick. One set of crossbeds generally truncates part of another, but throughout the formation there are horizontal diastems that truncate crossbedding for distances of half a mile or more. Crossbedding in the Entrada sandstone is much like that in the Navajo sandstone and the two formations probably have a similar origin. In the north part of the map area, in the upper one-third of the formation, the direction of maximum dip of the crossbeds is S. 58° W. This is also the general dip direction of crossbeds throughout the formation.

Locally the sandstone is colored pale yellow brown or pale blue green to green. The yellow-brown color is concentrated along the bedding, particularly above and below diastems, and is due to a thin film of iron oxide that coats the grains. Samples of the faintly green or blue-green sandstone were analyzed spectrographically and were found to contain more iron, cobalt, and chromium in trace amounts than the surrounding white sandstone. The color is localized in the silty or clay fraction of the sandstone and occurs in bands that broadly parallel the bedding but crosscut bedding in detail. Locally the bands appear as "roll" structures like those of the vanadium deposits in the Morrison formation (Fischer, 1942, p. 382–385), but the bands of greenish sandstone in the Entrada sandstone are less well defined than are the vanadium bands. The greenish sandstone is commonnly localized between 250 and 300 feet below the top of the formation.

CRETACEOUS SYSTEM

DAKOTA SANDSTONE

Deposits of Cretaceous age overlie the Entrada sandstone on a small mesa about 8 miles west of Wahweap Creek, at the north edge of the map area. These deposits are included in the Dakota sandstone, and they are the oldest of the Upper Cretaceous rocks that crop out in the nearby Kaiparowits region to the north. In the map area the Dakota sandstone is not difficult to distinguish from older rocks, for it rests unconformably upon the Entrada sandstone, it contains a conspicuous basal conglomerate and locally contains coal.

The Dakota sandstone rests upon an erosion surface that locally channels and regionally bevels older rocks. In the Kaiparowits region northeast of the map area it rests upon the Morrison formation of Late Jurassic age. In the map area angular discordance in bedding between the Entrada sandstone and the Dakota sandstone is not noticeable and, if present, is less than 2°. However, channels cut in the top of the Entrada sandstone and filled with a basal conglomerate of the Dakota sandstone suggest that stream gradients were sufficient so that erosion was energetic on this surface. The possibility has been suggested that the conglomerate of the Dakota sandstone may represent a widespread pediment cover (Stokes, 1950). Southwestward beveling of progressively older rocks by the unconformity in southern Utah, suggests that the sediments were tilted gently prior to their erosion.

In the Lees Ferry area, beds assigned to the Dakota sandstone are about 100 feet thick and are overlain uncomformably by Quaternary alluvium. Sections in the nearby Kaiparowits region are between 40 and 80 feet thick (Gregory and Moore, 1931, p. 95–97). The formation contains an upper silty unit and a lower conglomerate unit. The upper unit is covered with alluvium in most places but consists chiefly of light-olive, dark greenish-yellow, and locally olive-brown ripple-laminated siltstone. Lenticular strata of fine-grained festoon-crossbedded sandstone occur near the top of the siltstone unit, where they crop out as one and sometimes two conspicuous ledges. The lower unit, 30 to 40 feet thick, is composed of lenticular strata of grayish-pink and light-brown conglomerate, interbedded locally with sandstone, siltstone, and mudstone. The conglomerate consists of well-rounded pebbles in a matrix of irregularly bedded coarse-grained gray to pale-brown sandstone. The pebbles are chiefly gray to pale-pink quartzite and chert ranging from 0.1 to 0.5 inch in diameter; angular fragments of friable sandstone, presumably from the underlying Entrada sandstone, are associated with these pebbles in the basal 1 or 2 feet of the formation. Locally the conglomeratic strata are darkly stained with iron oxide and are cemented with calcite; usually, however, they are friable, porous, and light colored. Lenticular beds of coarse- to medium-grained festoon-crossbedded sandstone are interbedded with the conglomerate, and mudstone and siltstone occur as thin seams, galls, and interstitial fillings in the sandstone and conglomerate. Lignite is a diagnostic constituent of the formation and usually occurs in and between the conglomeratic strata and in association with mudstone. Locally coal also occurs higher as thin beds in the finer grained parts of the formation.

The continental sediments included in the Dakota sandstone in the Lees Ferry area are typical of sediments assigned to this formation elsewhere in southern Utah, and they are probably of the same age. According to L. C. Craig (oral communication, 1958) beds of Dakota sandstone near Paria and Cannonville yield a continental flora and fauna of fresh-water pelecypods, pollen, and spores that are more certainly of Late, rather than Early, Cretaceous age. These beds are overlain without apparent unconformity by sandstone and shale that contain an Upper Cretaceous marine fauna. In the Lees Ferry area, strata mapped as the basal part of the Dakota sandstone of Cretaceous age can be traced to the continental beds in the Cannonville and Paria areas, and on this basis the Dakota sandstone in the Lees Ferry area, as originally surmised by Gregory (Gregory and Moore, 1931; Gregory, 1950), is considered to be of Late Cretaceous age.

QUATERNARY SYSTEM

Unconsolidated sedimentary rocks of diverse origin and age cover the consolidated rocks in the Lees Ferry area. They are derived mostly from the nearby sedimentary formations and include dune, talus, landslide, and alluvial fan deposits. Stream deposits of sand and gravel that border the rivers and cap the high plateaus are related to more distant sources. Almost without exception the distribution of the unconsolidated deposits is not shown on earlier more regional geologic maps, and therefore the relations between various deposits of alluvium in the Lees Ferry area and those in other parts of the Colorado Plateau are known only generally. The areas in which there is detailed information are scattered and, until data from contiguous areas are available, this interesting history must be generalized.

Unconsolidated deposits in the Lees Ferry area are discussed in the order of their age, the oldest first. However, the relative age of the unconsolidated deposits has not been determined with certainty, for they neither contain fossils nor are sufficiently eroded to show their stratigraphic sequence. Some deposits, like the dune sand and talus debris, are accumulating today and are related to the modern-day climate and topography. Other deposits, like the alluvial fan and landslide debris, are the result of an earlier and probably more humid climatic environment. These deposits show the effects of modern-day weathering and erosion. Fragments of still older deposits, such as terrace gravels that cap the high plateaus and the rims of Marble and Glen Canyons, provide only a glimpse into a much earlier Quaternary or possibly even Tertiary erosional history.

TERRACE GRAVELS

Isolated deposits of water-worn gravel are preserved at various elevations above the major drainages in the region. Although these deposits are most extensively preserved along the Colorado River and its tributary, Wahweap Creek, they are also found at scattered localities on the Paria Plateau and on Cedar Mountain. In the map area the deposits of gravel are from 20 feet to more than 3,500 feet above the level of the nearest main drainage, and they are believed to indicate earlier positions of the present drainage system.

The oldest terrace gravels in the region are believed to be those found on the Paria Plateau about 3,500 feet above the present level of the nearby Colorado River. These deposits are at only a few scattered localities on the surface of the plateau and at each locality they consist of from about 20 to probably not more than 200 water-worn cobbles of pale reddish-brown, grayish-orange, and yellowish-gray quartzite. Locally, the deposits are on the downthrown side of faults that cut the Navajo sandstone. If the deposits of gravel on the Paria Plateau are related to an ancestral position of the Colorado River then this river system has lowered its position more than 3,000 feet since their deposition.

Younger terrace deposits are present along the rims of Glen Canyon and Marble Canyon of the Colorado River and along and adjacent to Wahweap Creek. The deposits along and adjacent to Wahweap Creek are at several levels above the creek and consist of pebbles, cobbles, and boulders in a matrix of sand. The cobbles and boulders are yellowish-gray, grayish-orange, pale reddish-brown quartzite (85 percent), greenish-gray andesite porphyry (13 percent), and variously colored chert (2 percent). An isolated deposit of water-worn gravel on Cedar Mountain about 10 miles west of Wahweap Creek is also probably related to the deposits along Wahweap Creek, but this deposit contains disc-shaped cobbles of light bluish-gray limestone, in addition to igneous rocks like those found in the gravels along Wahweap Creek. The terrace deposits along the Colorado River occur on the lip of Glen Canyon both above and below the mouth of Wahweap Creek. They also cover terraces near Lees Ferry both along the Colorado River and for about 2 miles up the Paria River; small patches of gravel occur on the lip of Marble Canyon for about 9 miles downstream from Lees Ferry. The gravel deposits along the Colorado and Paria Rivers are composed mostly of pebbles and cobbles of quartzite, and less than 2 percent fine-grained igneous rocks, limestone, and chert.

LANDSLIDE DEPOSITS

In the Lees Ferry area landslide deposits are localized along the base of the Vermilion and Echo Cliffs and in the canyon of the Paria River. They coincide with the distribution of the Chinle formation, and the bentonitic clay in this formation combined with moisture has probably acted as a lubricant to their movement. These deposits consist of large shattered segments of the Glen Canyon group called Toreva-blocks by Reiche (1937), or they consist of poorly sorted blocks of brown and red sandstone cemented in a dense, cohesive mixture of fine sand, silt, and clay. Locally the poorly sorted debris has cascaded over cliffs of the Moenkopi formation, and has spread out as bulbous masses upon gently sloping surfaces. In most places, however, these deposits rest on the Chinle formation. Throughout the area the landslide deposits are deeply gullied and covered with younger deposits including sand dunes, talus debris, and the kitchen middens of ancient man.

The Toreva-blocks, some of them measuring 1,500 feet along the strike of the beds and 700 feet thick, are most numerous along the base of the Echo Cliffs where the Glen Canyon group is cut by a system of joints and faults that parallel the face of Echo Cliffs. In several places below Echo Cliffs, these wedge-shaped blocks of the Glen Canyon group have broken repeatedly, so that the outermost segment is lowest and the segments behind are like a series of giant treads that lead upward to unbroken rocks in the face of the cliff; the lower part of the block is usually buried beneath poorly sorted rubble. In most cases the dip of strata in these blocks is toward the cliffs and is greater than the dip of beds in the cliffs; thus it is believed that a certain amount of rotational movement accompanied their formation. Like the landslide debris, these blocks are locally mantled by younger sediments, and they are dissected. They have been described by Strahler (1940), who attributes their formation to a time when precipitation was greater than it is today.

ALLUVIAL FAN DEPOSITS

Alluvial fan deposits extending outward from the base of the cliffs cover the stripped surface of the Kaibab limestone in the vicinity of Badger Canyon and in the vicinity of Navajo Spring. These deposits consist of poorly sorted subangular to subrounded cobbles and boulders and fine sand, silt, and clay. The deposits are poorly sorted near the cliffs, where they contain large angular blocks of sandstone, some as large as a small house; but towards the toe of the fan the deposits become finer grained, better sorted, and locally well bedded. The alluvial fan deposits have been dissected and are partly covered by sand dunes.

TALUS DEPOSITS

After severe summer rains and during early spring, the Vermilion and Echo Cliffs sometimes resound with the noise of falling rocks. The blocks that fall are sometimes 15 or 20 feet in diameter, and these have fallen so recently that impact craters still show in the nearby soft earth. The rocks that fall are broken, mostly into small angular blocks, or are crushed to sand. This poorly sorted mixture of crushed and broken rock is in cone-shaped deposits at the base of cliffs, where it rests upon or merges with the landslide deposits. Talus obscures the upper part of the Chinle formation, but in many places talus cones also cover the Moenave formation. Were it not for these deposits, the stratified formations composing the base of the Vermilion Cliffs would be inaccessible.

FLUVIAL DEPOSITS

For the most part erosion is active in the Lees Ferry area and large volumes of sediment are transported from the area by streams. However, along the bed of the Colorado River and along the beds of tributary arroyos and creeks extensive deposits of sand and gravel have formed where the streams are locally aggrading their channels. Above Lees Ferry, for example, in the vicinity of the Glen Canyon damsite, test drilling has penetrated alluvium to a maximum depth of 95 feet beneath the bed of the Colorado River; in Wahweap Creek extensive deposits of gravel are being used in construction of the dam. The bed of the Paria River is underlain by sand and gravel, but these deposits are mostly very thin.

On the high plateaus alluvium of light-gray sand and silt is locally 20 feet thick. In many places this alluvium is drifted into hummocks by the wind and partly stabilized by desert shrubs and trees; but during heavy thunderstorms, when the rainfall and runoff are violent, this material is redistributed by sheet flow in such quantities that reservoirs built for stock ponds have been filled by sediment during a single storm.

WIND DEPOSITS

In places in the area, winds blow almost continuously, and on the edge of the Vermilion Cliffs and between the peaks along the Echo Cliffs wind velocities are almost always higher than on the plateaus or in nearby sheltered canyons. In these sheltered places, where wind velocities drop suddenly sand dunes are extensive. Dunes cover large areas on the broad apron below Vermilion Cliffs, and a thick deposit of wind-blown sand has formed on the east side of the Echo Cliffs about 1½ miles south of Lees Ferry. In the higher parts of the plateaus wind-blown sand is seasonally reworked by rain and is partly stabilized by plants, but in the lower parts of the plateaus, chiefly in the southeast part of the map area, where there is little rainfall, windblown sand covers vast areas of the bedrock and is migrating as dunes. These deposits consist of light-brown fine-grained sand and silt that are derived from the Glen Canyon and San Rafael groups.

STRUCTURE

The Lees Ferry area is near the western edge of the Colorado Plateau, and structures in the map area are characteristic of this province. The beds are contorted locally into monoclinal folds, but in most places they are only broadly warped. Faults are scarce, but where the beds are faulted the offset usually is normal and not large. Jointing is common in the massive rocks, and locally these rocks are so highly jointed that erosion has produced a veritable maze of sharp, steep-walled parallel canyons; but the jointing is localized in certain zones. Igneous intrusives are a common feature in parts of the Colorado Plateau, but in the Lees Ferry area there are no signs of igneous activity or structures related to igneous activity.

The Lees Ferry area lies athwart the Echo monocline, about 20 miles east of the Kaibab uplift and about 30 miles west of the Navajo Mountain dome (Eardley, 1951, p. 394; Kelley, 1955a, p. 23). The rocks in the Lees Ferry area dip between 1° and 2° N., and this northward tilt is also characteristic of strata in the region surrounding the Lees Ferry area. The Echo monocline is the major structural feature in the area; it has many counterparts in the Colorado Plateau (Luedke and Shoemaker, 1953; Kelley, 1955 a, b), and it is therefore probably related to stresses that operated similarly throughout the Colorado Plateau. Some structural features in the Lees Ferry area are also probably related to the threefold stratal arrangement of the rocks described in the introduction to the discussion of the stratigraphy.

The structure of sedimentary strata in the Lees Ferry area is shown on the geologic map (pl. 1) by means of contour lines, drawn on the base of the Navajo sandstone and referred to the mean sea level datum. The structure contour interval is 200 feet and the control for position of the contour lines is the elevation of the Navajo sandstone at the outcrop or the calculated elevation of this contact measured from other convenient formational contacts. In areas where the base of the Navajo is concealed, the base of the Carmel formation is used as an intermediate datum and from the elevation of this contact, 1,750 feet, the average thickness of the Navajo sandstone in the map area is subtracted to obtain the altitude of the base of the Navajo at as many different places as possible. Structure contours in the eastern part of the map area, near Wahweap Creek and Rawhide Cave, were compiled from altitudes obtained in this fashion. In areas where the Navajo sandstone is removed by erosion, contacts of older formations were used as an intermediate datum, above which appropriate formational thicknesses were added. Near Lees Ferry and along the Vermilion and Echo Cliffs, formational thicknesses were added to the top of all formations older than the Navajo sandstone down to and including the top of the Kaibab limestone.

The position and configuration of the structure contour lines are more accurate in some places than in others. In the eastern half of the area where the contours are beneath the surface, the position of the lines is in error by the amount represented by variations in regional thickness of the Navajo sandstone. These variations in thickness are not known, for the thickness of the Navajo can only be measured in one place in the map area. Where the base of the Navajo sandstone crops out on a cliff shown by 200-foot topographic contour intervals, the elevation of the contact is not as accurately determined as where the contact is shown on topography represented with a 40-foot contour interval; but even so, the base of the Navajo is in most places inaccessible, and the plotted position is subject to interpretation. The thicknesses of older formations differ from place to place in areas where the Navajo is destroyed by erosion; but where these differences are known, the elevation of the Navajo was calculated from thicknesses adjusted proportionate to the distance between the two nearest measured thicknesses. For the Chinle formation, as its thickness is known in only two places and the measured difference is about 350 feet, the lesser thickness was used in calculating the position of the structure contour lines in most places along the Echo monocline.

The position of the 200-foot structure contours at the outcrop is accurate to within one-half the topographic contour interval. Where the contour lines are greater than 1 mile from the outcrop they are probably no more accurate than one-half the structure contour interval.

Several terms are introduced in the discussion of the Echo monocline in addition to the terms introduced by Kelley (1955b, p. 792). The upper or anticlinal bend of the monocline is the sharp flexure in the sediments at the top of the monocline; the uper limb refers to beds beyond the upper bend and in the structurally higher side of the monocline. The lower or synclinal bend is the sharp flexure at the base of the monocline, and the lower limb refers to the beds beyond the lower bend and on the structurally lower side of the monocline. The inclination of the monocline is the dip of the plane connecting the axes of the upper and lower bends, and the width of the monocline is the distance on the map between the axes of the upper and lower bends, measured at right angles to the structure contour lines. The height or structural relief of the monocline is the difference in altitude between the upper and lower bends of the monocline. Where beds on the upper and lower limbs of the monocline are structurally deformed, these folds are described in conventional terms.

Where faults cut the Navajo sandstone, the displacement along them is shown by an appropriate displacement of the intersected structure contour lines. However, the displacement is shown at the surface along the trace of the fault rather than on the contour datum. In many places, this probably does not convey a greatly misleading concept of the location of the fault at the base of the Navajo sandstone, because most of the faults are vertical or nearly so. Faults in

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the Kaibab limestone are not extended to the contoured datum except where they have been traced to this datum in the field. Structure contour lines are not shown at the base of the Navajo sandstone in places where the formation is involved in landslides.

ECHO MONOCLINE

The Echo monocline is the major structural feature in the map area; it affects all the sedimentary formations. This monocline, beginning some 30 miles south of Lees Ferry, extends northward through the center of the map area and dies out about 10 miles north of the Utah-Arizona state line. Throughout its course of about 60 miles, it plunges between 1° and 2° N., and like other monoclines in the Colorado Plateau, is inclined to the east. In the map area a maximum inclination of about 20° is reached where the fold trends north, and a minimum inclination of about 8° is found where the fold deviates from a northward trend.

The width and trend of the fold are generally related. In places where the fold trends about N. 10° E. it is between 4,000 and 6,000 feet wide, but where the trend deviates from this direction the fold widens to as much as 16,000 feet. This increase in width is noticeable in the south edge of the map area where the fold trends about N. 30° E., and between Lees Ferry and Thousand Pockets where the fold trends about N. 30° W. The width and structural relief of the monocline are also related. In the southern part of the area where the monocline is only 3,800 feet wide the structural relief is about 1,450 feet. Near Lees Ferry, the monocline is about 6,000 feet wide and the structural relief is about 1,600 feet; but in the northern part of the area, where the monocline is 16,000 feet wide the structural relief is about 2,100 feet. These and similar measurements along the monocline indicate that the structural relief becomes somewhat greater as the monocline broadens.

The monocline is not a simple steplike flexure. The upper bend is along the eastern limb of a narrow asymmetric anticline, whereas the lower bend is along the western limb of a broad syncline. Both the associated anticline and syncline are somewhat discontinuous features along the strike of the monocline, and near Thousand Pockets where the monocline curves to the northwest these flexures die out. However, where the monocline resumes its northward trend they again appear. In most of the map area the upper bend and the lower bend show about the same degree of flexure, but along Echo Cliffs the upper bend is sharper than the lower, as though the beds were draped over a vertical offset in underlying, more brittle rocks.

STRUCTURAL CHARACTERISTICS OF MAJOR STRATIGRAPHIC COMPONENTS

Structures within each of the three major stratigraphic components are somewhat different and are therefore discussed in component groupings. There are also structural differences between individual formations in each component, but these differences are not as great as those between the major components of the stratigraphic section. However, a complication arises in a division of this kind; namely, that some formations are less favorably exposed than others and thus the structural pattern developed in one component may be of local origin, whereas the structure developed in another component may be regional. For example, the Navajo sandstone is the only formation that is widely exposed on both limbs of the Echo monocline; therefore, the behavior of this formation to monoclinal folding is best known. Formations older than the Navajo sandstone are exposed mostly west of the upper bend of the Echo monocline, so that their behavior within the zone of most intense deformation is not so well known. Formations younger than the Navajo sandstone crop out on both the upper and lower limbs of the Echo monocline, but they are limited to the northern part of the map area. Wherever possible the structures between major components of the stratigraphic section are related so as to describe better the structural pattern for the entire area.

The lower component—namely, the Kaibab, Toroweap, and Coconino formations of Permian age—is deformed locally by steep-sided narrow, troughlike synclines and by associated normal faults and joints. These and other minor structures in this component of rocks are all on the upper limb of the Echo monocline.

The troughlike synclines in the Paleozoic rocks are between Lees Ferry and Navajo Bridge. They are about one-half mile apart and they are exposed in the walls of Marble Canyon (fig. 13). South of Navajo Bridge in zones from ½ to 1 mile apart and subparallel to the folds, the rocks are offset by high-angle normal faults. The folds and the faults in this area are believed to be related to the Echo monocline; for they are localized along the upper bend of the monocline, and they curve convexly and diverge at a low angle from the upper bend. Displacement on the faults is down on the side nearest the upper bend of the monocline and ranges between 5 and 100 feet; displacement on all the faults is less as the distance from the monoclinal bend increases. Stratigraphic displacement on the synclinal folds dies out abruptly about 1 mile from the upper bend of the monocline.

Several miles west of the Echo monocline, minor structures—including low-amplitude folds and small normal faults—have been mapped

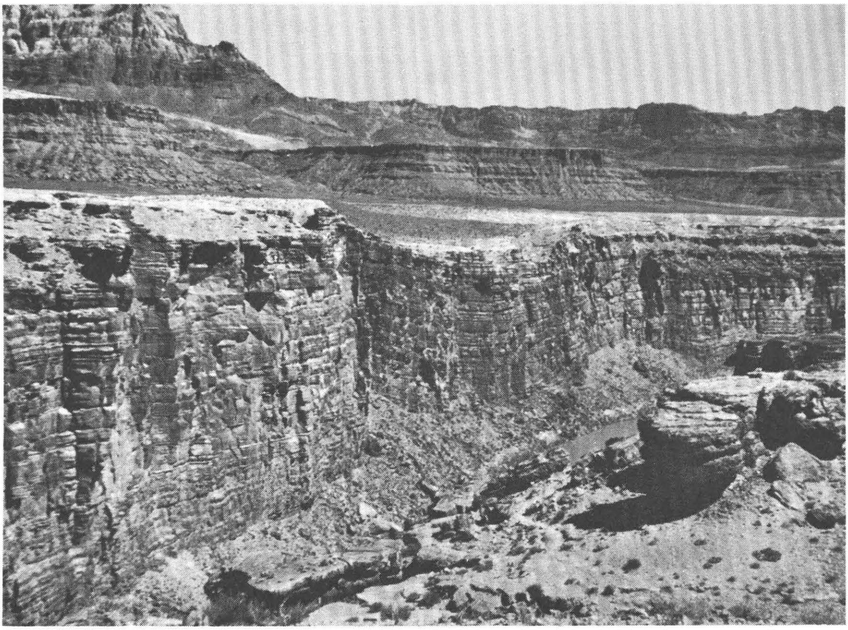

FIGURE 13.—Synclinal structure in the Kaibab and Toroweap formations one-half mile east of Navajo Bridge.

in the Kaibab limestone, but these structures have not been related to the Echo monocline. The most conspicuous of these minor structures is a small monocline in the Kaibab and Moenkopi formations near Vermilion Cliffs Lodge. Stratigraphic displacement on this fold is not more than 20 feet, the fold is inclined northward at a steep angle, it is about 100 feet wide, and it is continuous along strike for only about 1 mile.

Joints are not common in the lower component of the stratigraphic section, except where these rocks are folded or broken by faults. In general the joints parallel the trend of the faults and folds.

The plastic middle component, the mudstone and siltstone of the Moenkopi and Chinle formations, is largely covered by Quaternary alluvium. As the Chinle formation is more deeply covered than the Moenkopi formation, the study of the behavior of these rocks to deformation is based largely on observations of the Moenkopi formation and more specifically upon outcrops of this formation that are all on the upper limb of the Echo monocline. In general the structures in these strata are of two kinds: those that are contained only within the plastic middle component, and those that originate in other strata but die out within the middle component.

The deformation of the second type is shown by two folds in the Moenkopi formation, one near Lees Ferry and the other near Sunset

Rock. Both folds are near the base of the Moenkopi formation, and they are the manifestation of the synclinal folds in the underlying Kaibab limestone. In the Kaibab limestone these folds have a maximum amplitude of about 50 feet, but they die out upwards and the folding is not reflected in the thin layer of sandstone of the Shinarump, about 450 feet above the base of the Moenkopi formation.

Deformation of the first type—structures contained only within the middle component—is not common, for faults that cut the Moenkopi formation usually are not exposed in vertical cliffs. Locally, however, small faults in the plastic middle component offset beds from 2 inches to about 3 feet and die out vertically in distances of from 2 feet to a few tens of feet. Most common in the middle component and principally in mudstone of the Chinle formation are curved slickensided fractures that are exposed on almost all fresh surfaces of mudstone. In the dark-colored mudstone of the Moenkopi formation, near-vertical but discontinuous joints and small veins made conspicuous by linings of calcite and gypsum probably represent considerable internal readjustments of the component. The prevailing orientation of these structures is northward, parallel to the trend of the Echo monocline. The Shinarump member of the Chinle formation, a thin layer of sandstone in the lower one-half of the clay-rich middle component, is weakly jointed, and it is cut by faults in only two places. It is not as deformed as the upper or lower more brittle components, probably because it is separated from these two components by clay and mudstone that has behaved as a thick and plastic cushion.

Deformation in the youngest component, the sandstone in the formations of Triassic and Jurassic age, is inferred mostly from structures in the Navajo sandstone. This formation together with the lithologically similar Kayenta and Entrada formations constitutes more than two-thirds of the upper component. The structures in the upper component include reefs and linear bodies of sheared and crushed sandstone, step faults and grabens, and joints. In addition all the Jurassic and Cretaceous formations are folded into broad low-amplitude anticlines and synclines on both the upper and lower limbs of the Echo monocline.

Between the upper and lower bends of the Echo monocline and mostly near the upper bend, the Navajo sandstone is cut by reefs and northward-trending linear bodies of sheared and crushed sandstone (fig. 14*A*, *B*). These reefs are cemented by calcium carbonate and iron oxide, and the crushed rock is resistant to erosion. Nearly everywhere the cementing minerals are localized along crossbeds as well as within the zone of crushed rock, so that the margins of the reefs are highly irregular. Usually the reefs are 5 to 10 feet wide, and

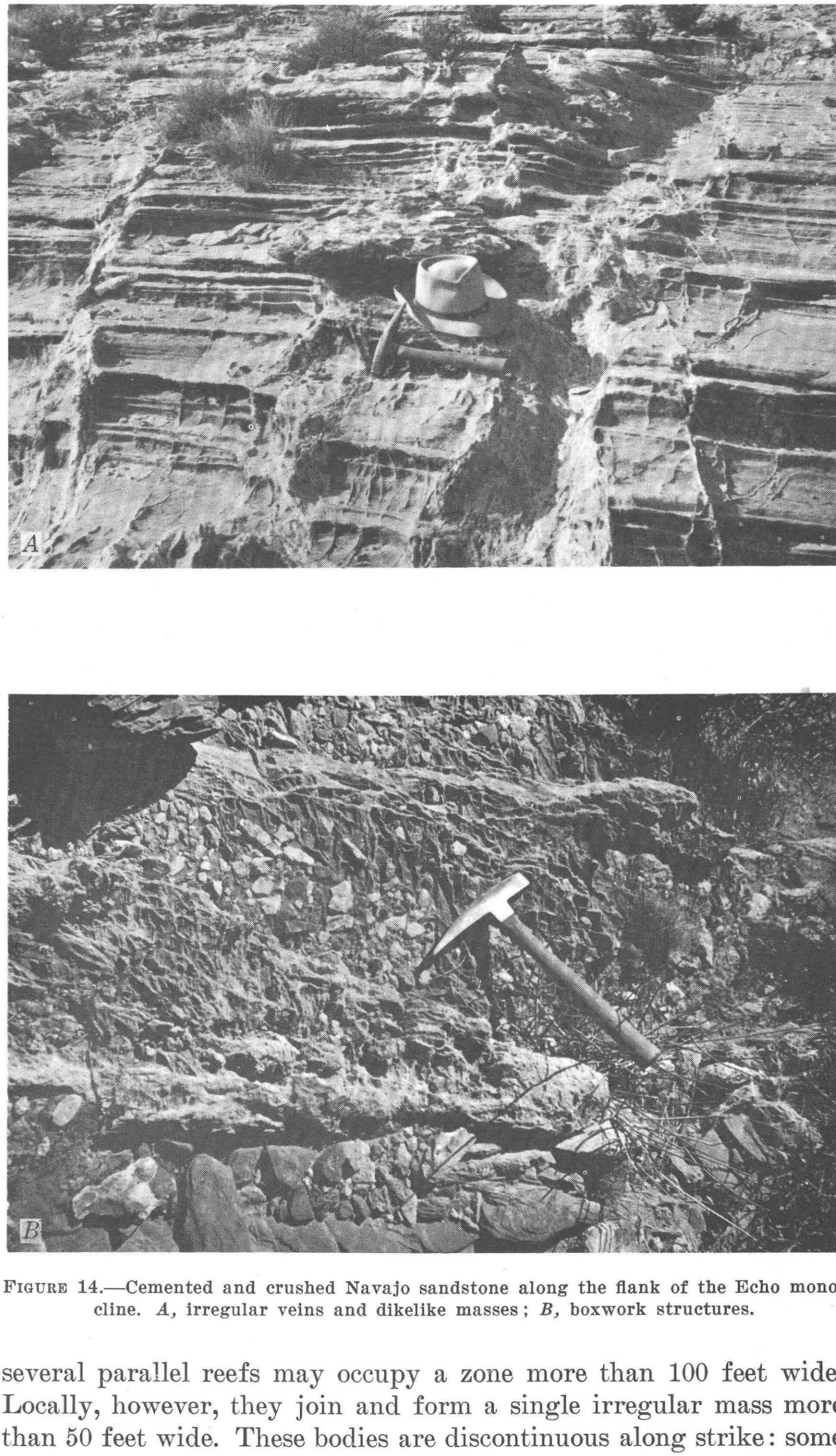

FIGURE 14.—Cemented and crushed Navajo sandstone along the flank of the Echo monocline. *A*, irregular veins and dikelike masses; *B*, boxwork structures.

several parallel reefs may occupy a zone more than 100 feet wide. Locally, however, they join and form a single irregular mass more than 50 feet wide. These bodies are discontinuous along strike: some of them are less than 300 feet long, others are continuous for more than a mile. Slickensided surfaces are common within the reefs, and the reefs probably coincide with faults in most places. However, the direction of movement on these faults could not be determined, for there are no marker beds in the Navajo sandstone and in no place were the reefs found below the base of the formation. The reefs characteristically occur in a zone between the upper bend and the middle of the Echo monocline; this may be significant with regard to the origin of the Echo monocline. To the writer's knowledge this and the nearby East Kaibab monocline are the only monoclinal structures in the plateau region that are associated with these reeflike structures.

The thick sandstone component is offset by high-angle normal faults that differ in orientation depending upon their location with respect to the Echo monocline. On the upper limb of the monocline, on the Paria Plateau, and on the west edge of Cedar Mountain, the beds are offset by normal faults that in general trend about N. 30° W. The displacement on these faults dies out along strike, and the faults are replaced by linear zones of close-spaced high-angle joints. These zones of fracture are believed to be tensional features related to the Echo monocline in the same way as the similarly oriented synclinal structures and associated faults exposed near Navajo Bridge in the lower component of limestone, quartzite, and shale of Permian age.

On the lower limb of the Echo monocline in the southeast part of the map area is a second set of high-angle normal faults. These faults are oriented about N. 45°–50° E. in contrast to the northwestward trending faults on the upper limb. Displacement on these faults ranges from 3 to 30 feet.

Faults between the upper and lower bends of the monocline are numerous at only two places. The first of these is in the vicinity of Thousand Pockets where the Echo monocline is broad. The faults in this area are vertical or nearly so, they are nearest the lower bend of the monocline, and they are parallel in a zone between ¼ and ½ mile wide and about 4 miles long. They occur along the Echo monocline, mostly south of where it begins to bend westward. (See pl. 1). The displacement of these faults is not systematic, although the downthrown side is usually on the side of the fault nearest the lower bend of the monocline. In no place does displacement along the faults exceed 100 feet, and along most of them it is less than 30 feet. In places these faults border narrow grabens; elsewhere the beds are offset step-wise down toward the lower bend of the monocline. Characteristically this type of fault dies out along strike in short distances, usually within a mile, and is replaced by close-spaced joints. The long narrow block of sandstone between faults appears to have sagged in the middle. Rocks along the faults are brecciated but as a rule they are not slickensided. This type of faulting may be much more extensive along the Echo monocline than is shown on the map, for only where the Judd Hollow tongue serves as a marker bed can the displacement be recognized.

The second area where faults influence the monoclinal structure is in the vicinity of Echo Peaks, where the monocline is steep and narrow. Here, a large pie-shaped segment of the sandstone component, principally the Navajo sandstone, is tilted northeast along two high-angle normal faults that nearly intersect about midway down the monocline. The faults trend almost at right angles to each other; one crops out on Echo Cliffs just south of Echo Peaks, near a trail that crosses the cliff, and the other intersects the cliff about 1½ miles to the north. Displacement on the southern fault is greater; and the offset, believed to be more than 200 feet, is up on the north side toward the upper limb of the monocline. In effect, it raises the south edge of the pie-shaped segment of sandstone. Displacement on the northern fault is the reverse of that on the southern fault and is also less. The beds along the fault are offset vertically only about 20 feet, and the offset is down on the south side of the fault; this fault depresses the northern edge of the pie-shaped segment of sandstone. Structure contours in this area indicate that displacement on both faults dies out on the upper limb of the monocline. These faults are also shown to bend, one toward the north, the other toward the south, and the displacement is shown to die out parallel to the monocline. The evidence for these latter relations is not conclusive, and the structure is shown in this manner because the faults cannot be traced into beds older than the sandstone component.

The most highly jointed rocks in the map area are those in the sandstone component, particularly in the upper part of the Navajo sandstone. The Moenave formation at the base of the sandstone component is also highly jointed, but the formation is only exposed on cliff faces so that the relation of joints in this formation to the Echo monocline is not clear. The pattern of the joints in the Navajo sandstone is shown on the geologic map (pl. 1). This pattern is closely related to the trend of faults in the sandstone component and to the monocline. Also the joints differ in orientation, depending upon whether they are on the upper or lower limb of the monocline and upon their relation to the upper and lower bends of the monocline. Between the limbs of the monocline there are two well-developed joint sets; but on the upper and lower limbs of the monocline there is only one set of joints.

In the upper half of the monocline, where the sandstone is cut by the linear bodies of cemented and crushed rock, joints are not numerous; but they are numerous in the lower part of the monocline and near the lower bend. In this part of the fold they occur in conjugate sets, one more pronounced than the other. The major set is dispersed in a somewhat poorly defined arcuate pattern, north and south of Lees Ferry. South of Lees Ferry the major set of joints, beginning almost at right angles to a line that parallels the center of the Echo monocline, trends at first almost due east and then, close to the lower bend of the monocline, swings arcuately to the northeast. At Lees Ferry the joints trend east. Again, north of Lees Ferry in the vicinity of Thousand Pockets, a set of joints first trends almost at right angles to a line that parallels the center of the Echo monocline; but near the lower bend and on the lower limb the trend swings arcuately to the southeast. It would appear as though one member of the conjugate set of joints was symmetrical around a point on the Echo monocline in about the vicinity of Lees Ferry. It might also be significant that from Lees Ferry northward the Echo monocline gradually curves to the northwest. The arcuate joint pattern may be related to some deep-seated cause in crystalline basement rocks such as might also influence the general trend of the monocline, but it may perhaps relate equally well to lithologic differences in one or more of the underlying sedimentary units.

The second well-developed set of joints on the monocline parallels the fold from Thousand Pockets southward to the Colorado River. South of the Colorado River, this set forms a pattern that gradually curves to the southeast away from the Echo monocline.

On the lower limb of the monocline, joints form a pattern that trends generally eastward, and they are not symmetrical to broad shallow folds in the Navajo sandstone. On the upper limb of the monocline, on the Paria Plateau, joints trend about N. 30° E., parallel to the faults in this area. However, on the west side of Cedar Mountain on the upper limb, the joints trend almost due west, parallel to the canyon of the Paria River.

PERIODS OF DEFORMATION

PRE-DAKOTA DEFORMATION

Prior to deposition of the Dakota sandstone of Late Cretaceous age, there were four periods during which diastrophism interrupted deposition, and beds were widely exposed to erosion. The earliest of these periods of erosion took place during Permian time, as is indicated by the unconformity separating the Kaibab limestone of Permian age and the Moenkopi formation of Early and Middle (?) Triassic age. In the Lees Ferry area, the Kaibab limestone is separated locally from shales of the Moenkopi formation by a thin layer of residual chert pebbles and sand, and the limestone is traversed in places by narrow channels that contain gravel. In general, however, the beds of Kaibab limestone and siltstone of the Moenkopi are conformable, indicating that no local deformation took place during the emergence and subsequent erosion of the Kaibab limestone. This relation seeems to be true in other areas as well, for Gregory (Gregory and Moore, 1931, p. 45) describes features of this unconformity in the western part of the plateau province that are similar to those in the map area, and he also concludes that the evidence suggests emergence accompanied by little or no orogenic activity. In the Lees Ferry area the beds of limestone may have been tilted westward so gently that angular discordance between formations is not noticeable, and this may account for a thicker section and an additional upper lithologic unit present in the Kaibab limestone some 20 miles west (J. D. Wells, oral communication, 1956).

The second period of erosion is indicated by the unconformity between the Chinle formation of Late Triassic age and the underlying Moenkopi formation of Early and Middle Triassic age. This unconformity is closely related to the occurrence of uranium, and it has been mapped and studied in detail throughout most of the Colorado Plateau. Nowhere in the western part of the Plateau province except in the salt-dome region of western Colorado and eastern Utah were these beds highly disturbed by folding prior to deposition of the Chinle formation. However, the contact between the Moenkopi and the Chinle is characterized by considerable local relief on top of the Moenkopi formation in the form of steep-sided sinuous channels and broad open valleylike depressions. The total relief on the contact is rarely more than 200 feet, and the broad depressions or swales are imperceptible to the naked eye. The channels trend about north or northwest from the southern margin of the Plateau province in central Arizona and western New Mexico, and in the Lees Ferry area they also trend northwest. It seems likely from these relations that the hiatus represented by the unconformity was initiated by epeirogenic uplift, but that deposition of the Chinle formation was initiated by orogenic activity in southern Arizona and New Mexico.

The third period of erosion separates rocks of quite dissimilar origin. In the Lees Ferry area, interbedded siltstone, conglomerate, and fresh-water limestone of the Owl Rock member of the Chinle formation of Triassic age are overlain unconformably by sandstone of the Moenave formation of Triassic(?) age. The Moenave formation marks the first appearance in the stratigraphic column of a thick section of continental aeolian and fluvial sandstones, and it is inferred that this change in lithology indicates a change in the provenance between the sediments of Triassic age and those that followed of Triassic(?) age. So far as could be determined there is no angular discordance between beds in the Chinle and Moenave formations; however, the contact is marked by local scour-fill structures including small channels filled with pebbles of chert and galls of mudstone, by flow casts (Gilbert, 1955), and by mud cracks.

The final pre-Dakota unconformity brings the Entrada sandstone of Jurassic age in contact with the Dakota sandstone of Late Cretaceous age. During the time interval separating these two formations, more strata are believed to have been eroded from the Lees Ferry area than during any previous period of erosion. The eastward and northeastward trends of channels and crossbeds in the basal part of the Dakota sandstone suggest that erosion was most severe to the west and southwest of the map area. Furthermore, several hundred feet of sandstone and shale of the Morrison formation, which occurs in the stratigraphic column northwest of the map area in the Kaiparowits and Straight Cliffs areas (Gregory and Moore, 1931, p. 92; Craig and others, 1955), are missing in the Lees Ferry area. That this period of erosion was also accompanied by northeastward tilting of the older rocks seems likely, even though no angular discordance between strata of the Dakota and Entrada sandstones could be measured.

POST-DAKOTA DEFORMATION

The greatest structural disturbance in the Lees Ferry area took place after deposition of the Dakota sandstone of Late Cretaceous age and before development of the present-day landscape. That no more exact date can be put on development of the major structural features in the area is due to the absence of younger deposits to record these events. However, by analogy with other areas where these younger deposits are preserved, parts of the tectonic history can possibly be resolved. Several periods of deformation are certainly involved in the post-Dakota structural history of the map area, and one or more of these periods may be related to the tectonic history of the Basin and Range province to the west.

The succession of events that produced the major structures in the map area began during Late Cretaceous time, after deposition of the continental Dakota sandstone. At this time the plateau region was mostly below sea level and was receiving marine deposits. The western edge of this marine basin was intermittently near the map area, as evidenced by the exposure about 15 miles north of the map area, of intertonguing marine and nonmarine sedimentary rocks of the Tropic, Straight Cliffs, Wahweap, and Kaiparowits formations. These formations accumulated to a thickness of at least 2,500 feet (Gregory and Moore, 1931, p. 100–113; Reeside, 1944; McKee, 1951). At the end of Cretaceous time the sedimentary rocks were uplifted and monoclinally folded. In northern Arizona this orogeny formed the East Kaibab and adjacent Echo monocline. Erosion subsequently beveled these folded rocks (Gregory and Moore, 1931, p. 116, 122), and they were finally buried beneath a cover of stream and lake sediments of the Wasatch and Green River formations of Eocene age. In central Utah these deposits of Eocene age are at least 7,000 feet thick; in the Kaiparowits region north of Lees Ferry they are at least 1,500 feet thick.

Sometime during this period the laccoliths in the central part of the Colorado Plateau region were intruded. They domed the overlying sedimentary rocks, as at Navajo Mountain about 35 miles east of Lees Ferry, and probably influenced surface drainage. Subcrustal transfer of molten rock accompanying their intrusion may have contributed toward a general subsidence of the crust in nearby areas, but if so, subsidence was slight. By early Miocene time epeirogenic uplift and subsequent erosion were initiated in the plateau region; and during late Miocene and probably early Pliocene time, deformation along the west edge of the Colorada Plateau was chiefly the result of block faulting. Drainage in the interior of the Colorado Plateau was probably well established, following generally the same lines as the present-day Colorado River drainage system. Finally, Cenozoic igneous structures were superimposed on this general orogenic pattern.

ORIGIN OF STRUCTURAL FEATURES

The structural pattern in the Lees Ferry area is a composite of features developed in three groups of strata with different physical characteristics. The major features are believed to have been formed by the end of Cretaceous time, probably soon after deposition of the Dakota sandstone, but deformation has been continuous to the present; most of the features are believed to have been formed beneath several thousand feet of younger deposits. Elements of the structural pattern—chiefly the diagonal faults and folds that strike northwestward from the upper bend of the monocline, the anticlinal folds that parallel the upper bend, the less obvious synclinal fold that parallels the lower bend, and the pie-shaped wedge of faulted sandstone in the monocline near Echo Peaks—are believed to be the result of compressional stresses directed either perpendicular or diagonal to the trend of the monocline. The beds are most highly deformed where the monocline trends north, and thus the monoclinal structure is believed to have been formed above a zone of subparallel high-angle northward-trending faults in the basement rocks. The curved and flatter segments of the fold may have developed above curved faults, but more likely they are above unfaulted segments in the basement rocks. The dikelike masses of brecciated and cemented sandstone in the Navajo sandstone are due possibly to tensional relief developed during formation of the monocline; the attendant escape of pore fluids is believed to be responsible for the cementing minerals. Tension also produced flowage of the underlying mudstone-siltstone component along bends of the monocline; this tension plus differential compaction in the mudstone-siltstone component may be responsible for seemingly unrelated sets of joints and for much of the broad, shallow folding in the Navajo sandstone. Finally, epeirogenic uplift of the Colorado Plateau region since Miocene time may have gently tilted and broadly folded the rocks in the Lees Ferry area.

GEOMORPHOLOGY AND RIVER HISTORY

In the map area, recorded events along the Colorado River and its tributaries are due to changes in stream energy such as might accompany regional changes in base level, long-term variations in climate, or changes in resistance of bedrock. The river has been undergoing almost continuous degradation since middle-Tertiary time. The map area is centrally located in the Colorado River basin. About 45 percent of the basin is above Lees Ferry, and the river grows almost to its full size from contributions above Lees Ferry (U.S. Dept. Interior, 1946, p. 55). The oldest alluvial deposits and land forms are scattered deposits of gravel and broad open valleys on the upper limb of the Echo monocline in Paris Plateau and on Cedar Mountain about 3600 feet above the Colorado River. There are more recent deposits of gravel on the lower limb of the monocline on both sides of Glen Canyon, but these deposits are only about 1,000 feet above the river.

On the lower limb of the Echo monocline, south of Glen Canyon on the Kaibito Plateau, the Navajo sandstone is beveled by an extensive erosion surface. This surface, which is at an altitude of about 5,600 feet, is overlain by sand and angular gravel about 10 feet thick. On the lower limb of the Echo monocline about 5 miles north of Glen Canyon a similar surface occurs at an altitude of only 4,200 feet. It bevels the Carmel and Entrada formations, and it also is overlain by sand and fragments of older formations. Between these two localities and bordering Marble Canyon are broad subbenches on which the Navajo sandstone has been dissected and partly buried by windblown sand. Most drainage systems on these surfaces follow joints. Locally, however, some streams occupy shallow valleys that curve as though they were once a part of the meander pattern of the Colorado River. Two such valleys are preserved in Ferry Swale and in its unnamed easterly counterpart, located behind the north wall of Glen Canyon about 4 miles northeast of Lees Ferry. The floors of each tributary, where they open to Glen Canyon, are only about 1,000 feet apart and about 400 feet above the river. Together these two tributaries, now partly filled by windblown sand, form a meander pattern that nearly duplicates the present-day Glen Canyon. Other more faintly preserved meander scars encircle the scattered buttes west of Beehive Rock and those on the mesas just east of the confluence of Wahweap Creek with the Colorado River.

In places, terrace gravels are associated with the erosion surfaces on the lower limb of the monocline. Southwest of the confluence of Wahweap Creek with the Colorado River, boulders are scattered on the dissected surface of the subbench and in the floors of the hanging valleys. Near the mouth of Wahweap Creek these deposits occur on both sides of the Colorado River, and they occur at several levels along Wahweap Creek.

The highest and probably oldest of the land forms and the terrace gravels are on the upper limb of the Echo monocline. These are the sand-filled Shed Valley on Paria Plateau, the small deposits of water-worn quartzite cobbles that occur on Horse Ridge and nearby low buttes near Shed Valley, the deposit of stream gravel that caps Cedar Mountain just north of the map area, and the several hanging U-shaped valleys along the upper bend of the Echo monocline. These features were probably formed prior to the present-day canyon of the Colorado River. Shed Valley is an underfit subsequent tributary to the Paria River, and the U-shaped valleys along the Echo monocline were probably formed prior to the incision of Paria Canyon. The gravel on Cedar Mountain is similar in composition to the gravel along Wahweap Creek, and it is therefore related to the terrace gravels on the lower limb of the Echo monocline.

Entrenchment of the Colorado River in Glen Canyon and Marble Canyon is believed to be the result of the superposition of a meandering, low-gradient stream upon structurally deformed layers of resistant and nonresistant strata. The history of the Colorado River was reconstructed by Hunt (1956, p. 73–87), and various steps in the development of the present-day canyons were reviewed by Gregory (Gregory and Moore, 1931; Gregory, 1948), Babenroth and Strahler (1945), and Strahler (1948). In general, a westward flowing meandering stream system is believed to have been developed on a nearby flat terrain in southern Utah and northern Arizona. Subsequently, and probably in response to headward erosion and to gradual regional uplift, this stream became entrenched into the undeformed lacustrine and marine sediments of Late Cretaceous and early Tertiary age that once covered the Lees Ferry area. Continual downcutting led to superposition of the stream across structurally deformed rocks: the Echo monocline in the Lees Ferry area and the Kaibab monocline to the west. As long as these strata were sufficiently resistant to withstand lateral corrasion, the river continued to incise its way downward, as it has done east of the Echo monocline in Glen Canyon, in order to preserve its meandering path. However, where the river after cutting through the sandstone strata encountered incompetent mudstone and shale of the Chinle and Moenkopi formations, as it did west of the Echo monocline, the meanders were obliterated by corrasion, and the resulting shorter path gave rise to a more energetic stream. The rejuvenated stream along this reach then deeply eroded its way into underlying more resistant rocks in the formations of Paleozoic age. West of the Echo monocline the stream is now entrenched in the deep gorge of Marble Canyon and the even deeper downstream equivalent, the Grand Canyon of the Colorado River. In this section it now has a gradient of between 4 and 6 feet per mile. East of the Echo monocline the Colorado River still follows a meander pattern that is probably inherited from a stage reached at an earlier time when its level was several thousand feet higher than it is today; in this section it has a gradient of about 1.5 feet per mile.

MINERAL RESOURCES

METALLIC MINERALS

At various times during the past the Lees Ferry area has been prospected for metallic mineral deposits. During each period of renewed activity the Chinle formation has been the focus of earnest if not always fruitful attention. In order of historic succession, gold, then mercury, and finally uranium have been the objects of search. To date, the deposits of uranium have been the most tangible mineral asset in the area.

GOLD

Sporadic efforts to mine gold from bentonitic mudstone in the Chinle formation near Lees Ferry were first made prior to 1913. According to Lawson (1913), samples of the mudstone averaged 2½ to 4 cents per ton gold, but the metal defied all efforts for economic recovery, probably because it was too fine grained. During 1957 gold-mining activities were renewed in the area. Reportedly the metal was being recovered from the sandstone and mudstone unit of the Chinle formation in a prospect about 6 miles above Lees Ferry in Paria Canyon. However, these activities must have been short lived, for during the latter part of the field season in 1957, the access road into Paria Canyon was destroyed by flood and two years later it had not been repaired. A study of the heavy detrital minerals in this sandstone from Badger Canyon, Lees Ferry, and Paria Canyon shows that gold is a very rare constituent of the heavy mineral suite in these rocks and occurs as tiny flakes associated with magnetite, ilmenite, rutile, garnet, and zircon.

MERCURY

Mercury has been recovered concurrently with gold from mudstone in the sandstone and mudstone unit and from the Petrified Forest member of the Chinle formation near Lees Ferry. Five rock samples collected for analysis gave from 0.0018 to 0.0059 percent mercury (Lausen, 1936); and in addition small globules of this metal were reportedly recovered by panning. Simultaneously with the discovery of mercury in the rocks it was reported that attempts were also being made to recover gold from these same rocks by amalgamation methods. The date at which mercury was first reported in the Lees Ferry area is uncertain but is believed to be about 1935.

In an attempt to identify the mercury minerals and to study this mineral occurrence, a prospect pit in the Chinle formation from which mercury had reportedly been recovered was systematically sampled and the samples were submitted to the willemite screen test for mercury. The prospect is in the SW¼NW¼ sec. 18, T. 40 N., R. 8 E., about 300 yards northeast of the U.S. Geological Survey gaging station headquarters at Lees Ferry. It consists of a small sidehill excavation in pale-gray-green laminated bentonitic mudstone of the Chinle formation. Several specimens of this nearly uniform rock were chosen for mercury tests; one sample was selected from a cross-cutting vein of calcite, another of pale-green laminated mudstone, and a third sample was collected from mudstone that contained flakes of carbon and was stained yellow brown with limonite. None of these samples contained mercury when tested in the laboratory using the willemite screen, a test sensitive to quantities as small as 1/1000 percent of mercury (Smith, 1953, p. 90–92). In a further search for this metal, 20 rock samples collected from a stratigraphic section of the entire Chinle formation near Badger Canyon were analyzed by the same method; these results were likewise negative.

URANIUM

Since about 1947 the search for uranium on the Colorado Plateau has been intense. In mining districts where the Shinarump member is the ore-producing unit, the deposits of uranium mostly occur in ancient sandstone-filled stream channels that contain carbonaceous material and mudstone beds; large deposits occur in channels near the regional pinchout of this member (Finch, 1959). In the Lees Ferry area the most productive deposits of uranium have been found in the two lower more permeable units of the Chinle formation, the Shinarump member and the overlying sandstone and mudstone unit, but as it is in other uranium districts, the upper part of the Chinle formation is also mineralized locally.

In the Shinarump member of the Chinle formation, oxidized uranium minerals and copper minerals are commonly localized in the lower parts or on the sides of channels. Exposures of the ore minerals in these places can be found in opencuts at the base of a channel in the SW¼ sec. 27, T. 39 N., R. 6 E.; in a channel exposed in the SW¼ sec. 1, T. 40 N., R. 7 E.; and at the El Pequito mine in the NW¼ sec. 14, T. 40 N., R. 7 E. At the El Pequito mine the mineralized channel is a small spoon-shaped offshoot from a much deeper and more pronounced channel exposed in cliffs about 300 feet south of the mine workings. The ore minerals coat pebbles and sand grains, and locally impregnate mudstone in the presence of carbonized wood. The mineral assemblage is pyrite, chalcopyrite, and uraninite in calcite veinlets. At the El Pequito mine a bleached zone up to 3 or 4 feet thick occurs beneath the Shinarump member. This zone is thickest under the deeper parts of the channel scours and beneath places enriched with uranium, but there is no apparent relation between the grade of mineralized localities and the thickness of bleached zones elsewhere in the Lees Ferry area.

At the Red Wing and Lehneer prospects (pl. 3) uranium minerals have been recovered from sandstone strata in the sandstone and mudstone unit of the Chinle formation. At these places both the upper and the lower sandstone strata in the sandstone and mudstone unit are mineralized, particularly where the sandstone is thick. Sparse amounts of black carbonaceous material are present where the sandstone is thick, and in these places green and yellow secondary uranium and copper minerals coat grains in the sandstone. At these two prospects the deposits of these minerals are tabular and small—they are rarely over 1½ feet thick and 20 feet wide and none has been explored by drifts longer than 15 or 20 feet.

The Petrified Forest member of the Chinle formation is mineralized at the Sam group of claims (pl. 3). Here uranium minerals occur in a 30-foot thick lens of grayish-red siltstone near the top of the member. The uranium minerals, betazippeite and metatorbernite, impregnate pore spaces in the siltstone and occur in pods 1½ feet by 3 feet in lenticular cross section. These pods parallel the bedding in the lower part of the lens.

Exploration for uranium has not been highly successful in the Lees Ferry area. Ore has been shipped from only one mine, the El Pequito, and the mines and prospects in the area have found only very low grade mineralization. Significantly the Shinarump member contains fewer lenses of mudstone and less carbonaceous material than it does in more productive areas, and these sediments are mostly colored shades of red or brown by limonite and related iron oxide minerals.

Plate 3 shows the distribution and trends of sedimentary structures of the Shinarump member in the Lees Ferry area. Sedimentary structures in the member are mostly oriented northwest, and the elongation of the member will probably follow this general trend. Even if deposits of uranium minerals occurred in these rocks it seems clear that this trend intersects the Echo monocline on the southeast side of the Colorado River and beneath the Paria Plateau on the northwest side of the river, where exploration for uranium deposits in the Shinarump member would have to be carried on at depths greater than 2,000 feet. However, in these places the Shinarump

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member has not suffered greatly from the influence of oxygen-charged percolating ground water. Considering that aspects of the Shinarump member in the outcrop area appear favorable to the localization of uranium ore minerals it seems reasonable to suppose that there are favorable places to explore.

NONMETALLIC MINERALS

In the Lees Ferry region at least two formations have been investigated for their nonmetallic minerals. The Kaibab limestone has been tested to determine its usefulness in making cement. Results indicate that the rock contains excesisve amounts of silica and magnesium carbonate (McKee, 1938, p. 62–66; Kiersch, 1955, p. 15; and Bollin [2]). The Chinle formation, particularly the Petrified Forest member, has been extensively sampled as a possible source of clay minerals. In the Lees Ferry area this member contains thin beds of nearly pure bentonite (Wilson and Keller, 1955), but these deposits have not been mined. Locally, flagstone and building stone have been quarried from the Moenkopi formation, but use of this rock is restricted to the few lodges and buildings in the area. Near the Glen Canyon damsite, dunes of fine-grained quartz sand have accumulated in large deposits; and it is possible that these, and parts of the parent formation, the Entrada sandstone, might be suitable for glass or filter sand. The coal described in the Dakota sandstone is only a minor accessory in the formation in the Lees Ferry area and is not economic.

In summary it would appear that the most valuable asset in the region is scenery; to this, the Glen Canyon reservoir will add greatly.

STRATIGRAPHIC SECTIONS

The Lees Ferry area is well located for regional stratigraphic studies, and for this reason the literature describes a number of geologic sections from the area. Table 2 is a list of previously published sections.

Stratigraphic sections 4, 5, 7, and 8 in this report describe formational units in parts of the Lees Ferry area where these rocks are readily accessible. Section 3, which describes previously unnamed units, the Judd Hollow tongue of the Carmel formation and the Thousand Pockets tongue of the Navajo sandstone, is about 2 miles north of the map area in Utah. Sections 1, 2, and 6, furnished through the courtesy of J. C. Wright and D. D. Dickey, have been included to indicate more clearly the characteristics of the intertonguing relations between the Navajo and Carmel formations out-

[2] Bollin, E. M., 1955, The geology of the Kaibab formation, Marble platform, Coconino County, Arizona: Arizona Univ. M.S. thesis.

side the Lees Ferry area. The locations of these 8 sections are shown on figure 1.

Description of the rocks generally follows standard terminology. The terminology proposed by McKee and Weir (1953) for depositional features in sedimentary rocks has been adopted, but other terms to which the writer is more accustomed have also been used. The standards of grain size, thickness of beds, degree of sorting, roundness, and sphericity are described in modern textbooks of sedimentary rocks, and these sources have been used for guidance. For the determination of color, rock fragments from the various units have been compared with the rock-color chart of the National Research Council (Goddard, 1948), and the color terms and related numbers are from this source.

TABLE 2.—*Published stratigraphic sections from the Lees Ferry area*

Reference	Formation	Locality
Longwell and others, 1925, p. 16.	Navajo sandstone, Wingate sandstone (Kayenta and Moenave formations of this report), Chinle formation, Moenkopi formation, Kaibab limestone, Coconino sandstone, partial for the Hermit shale and Supai formation.	Near Lees Ferry.
Gregory and Moore, 1931, p. 43–44.	Kaibab limestone, Coconino sandstone, Hermit shale (partial).	Wall of Marble Gorge opposite Badger Creek, 7½ miles below Paria River.
p. 48	Moenkopi formation	South side of Colorado River at Lees Ferry.
p. 54	Chinle formation (partial)	Eastside of Paria River at Lees Ferry.
McKee, 1938, p. 209–210	Moenkopi formation (partial), Kaibab limestone, Toroweap formation.	Marble Gorge opposite Badger Canyon, in secs. 16, 21, T. 39 N., R. 7 E.
Wanek and Stephens, 1953	Navajo sandstone (partial), Kayenta formation, Wingate sandstone (Moenave formation of this report). Chinle formation, Moenkopi formation.	Lees Ferry, in sec. 13, T. 40 N., R. 7 E., and sec. 18, T. 40 N., R. 8 E.
McKee, 1954, p. 108–112	Moenkopi formation	1.8 miles south of Navajo Bridge.
Do	do	1 mile southwest of Lees Ferry.
Do	do	2½ miles west of Navajo Bridge.
Do	do	Soap Creek, 8.8 miles west of Navajo Bridge.

UTAH—KANE COUNTY

1.—Catstairs section, N½ sec. 30, T. 42 S., R. 1 W., section is in West Cove north of the highway to the Glen Canyon Dam, with its base near the top of the Cockscomb

[Measured by J. C. Wright and D. D. Dickey, July 14 and Oct. 25, 1956]

	Thickness (feet)
Middle and Upper Jurassic:	
Carmel formation:	
15. Sandstone (45 percent), siltstone (45 percent), and claystone (10 percent) interbedded: Sandstone, light greenish-gray (5*GY* 8/1), very fine grained, poorly cemented; flat even beds about 1 to 8 ft thick. Siltstone, moderate reddish-brown (10*R* 4/6) to dark reddish-brown (10*R* 3/4); massive beds 1 to 5 ft thick; some siltstone beds show obvious contortions involving thin sandstone layers. Shale, dusky-red (10*R* 3/2), in beds a few inches to 3 ft thick. Whole unit generally very even bedded, but close inspection shows small-scale irregularities, particularly in the shale. Forms soft red-and-white banded cliff	144.0
Total Carmel formation (excluding Judd Hollow tongue)	144.0
Jurassic and Jurassic (?):	
Navajo sandstone:	
Thousand Pockets tongue (Middle and Upper ? Jurassic):	
14. Sandstone, yellowish-white (5*Y* 9/1), very fine grained, well-sorted; composed of rounded quartz grains and some feldspar grains; poorly cemented; weathers same color; abundant black spots about half a mm in diameter caused by black film on sand grains. Lower half of unit contains some beds of dusky-red (10*R* 3/2) even-bedded siltstone. Sandstone comprises low-angle cross strata, in sets of medium scale in lower half grading upward to large scale. Forms smooth, rounded ledge	174.0
13. Siltstone, moderate reddish-brown (10*R* 4/6); streaks of light greenish gray (5*G* 8/1); mostly massive, but partly shaly; locally shows contortions. Forms recess	14.0
12. Sandstone, yellowish-white (5*Y* 9/1), very fine to fine-grained with considerable coarse admixture, poorly to fairly sorted; bedding is indistinct, appears to be mostly crossbedded; weathers light gray (N 7)	40.0
Total Thousand Pockets tongue	228.0

NOTE.—Thousand Pockets tongue is generally conformable above the Judd Hollow tongue but locally fills scours, a few inches deep, in the Judd Hollow.

UTAH—KANE COUNTY—Continued

	Thickness (feet)
Middle and Upper Jurassic:	
Carmel formation:	
Judd Hollow tongue (Middle Jurassic):	
11. Siltstone and minor sandstone, dark reddish-brown (10*R* 3/6), very fine grained, thin-bedded, massive, contorted. Shale parting about 1 ft thick at top of unit; several inches of purple clay locally in shale	11.0
10. Claystone, silty, moderate reddish-brown (10*R* 4/6), very well cemented, laminated; a few thin limy beds, ripple-marked throughout. Forms ledge	3.0
9. Concealed; soil indicates siltstone and shale, reddish-orange (10*R* 5/6)	15.0
8. Claystone, dark reddish-brown (10*R* 3/4), laminated	2.5
7. Claystone, pale grayish-blue (5*PB* 6/2), laminated	2.0
6. Concealed; soil and float indicate light yellowish-green (5*GY* 7/2) shale	7.5
5. Concealed; reddish-brown (10*R* 4/4); soil indicates a reddish-brown siltstone	1.0
4. Limestone, silty, very light bluish-gray (5*B* 8/1); color grades upward to light greenish gray (5*GY* 8/1)	6.0
3. Siltstone, moderate reddish-brown (10*R* 4/6), partly concealed, thin-bedded	9.0
2. Covered	3.0
Total Judd Hollow tongue	60.0
Total Carmel formation (main mass plus Judd Hollow tongue)	204.0

NOTE.—Navajo-Carmel contact is even throughout locality; the featheredge of the Judd Hollow tongue of the Carmel formation is about 15 miles east.

	Thickness (feet)
Jurassic and Jurassic(?):	
Navajo sandstone:	
1. Sandstone, sweeping large-scale crossbeds. Bedding indistinct near top; upper 5 ft is even bedded and contains many 1- to 3-in. nodules very firmly cemented with calcite; 1½ miles southwest on Paria River the upper 5 ft is stained dark brown	>400
Total incomplete Navajo sandstone	>400

UTAH—KANE COUNTY—Continued

2. Adairville section, measured along a dry wash in East Cove that has its mouth on the Paria River at White House; NE¼, sec. 15, T. 43 S., R. 1 W.

[Measured by J. C. Wright and D. D. Dickey, Oct. 31, 1956]

	Thickness (feet)
Middle and Upper Jurassic:	
Carmel formation:	
22. Sandstone, reddish-brown and white; interbedded, like unit 20; fair exposures on dissected slope; contains purple clay partings a few inches thick. Upper contact transitional; thickness and amount of reddish-brown sandstone decreasing upward; contact placed at uppermost conspicuous red bed seen on line of section. Stratification of upper white sandstone of unit very indistinct, but each thick bed appears to comprise many thin wedge-shaped sets of small-scale cross laminae	57.0
21. Sandstone, white (*N* 9), fine-grained, poor to fair sorted, lithologically like the lighter colored sandstone of unit 20. A single tabular set of planar medium-scale medium-angle noncurved cross strata. Lower bounding surface flat and upper surface undulating, thickness varying from 1 to 3 ft. Unit forms widespread capping ledge protecting cliff of unit 20 below	2.0
20. Sandstone, like unit 19, but well exposed; reddish brown, very poorly sorted sandstone forms about 75 percent of total; and whitish, less poorly sorted sandstone, about 25 percent. Near top of unit are several purple clay partings about 1 in. thick. Reddish-brown sandstone beds are mostly structureless but in some places are involved with overlying white sandstone beds, 1 or 2 in. thick, in asymmetric flow casts. These ripplelike flow casts are elongate N. 45° W. in most places and their recumbent torn-off wispy crests point N. 45° E. Some reddish-brown sandstone beds are cut by light-colored sand dikes that appear to have filled mudcracks. Pipes of disturbed beds, 10 to 50 ft high and a few feet to 20 ft in diameter, are common throughout the unit. Generally beds near center of these pipes seem to have settled plastically a few feet. In at least one place, blocks of consolidated white sandstone appear to have sunk bodily through the apparently more plastic reddish-brown sandstone. Unit forms an even-bedded ledgy surface bearing conspicuous evidences of preconsolidation disturbances	100.0
19. Sandstone, partly covered, dark reddish-brown (10*R* 3/6), fine-grained, very poorly sorted; grains range from fine silt to coarse sand; composed of subangular to subrounded clear quartz grains and black iron oxides (10 to 20 percent); in massive beds ½ to 5 ft thick; poorly cemented by hematite; weathers same color. Contains subordinate interbeds of light grayish-orange (10*YR* 8/4) fine- to medium-grained poorly sorted (very fine sand to granules) sandstone; composed of subrounded to rounded	

UTAH—KANE COUNTY—Continued

Middle and Upper Jurassic--Continued

Carmel formation—Continued

	Thickness (feet)
clear quartz grains; abundant green, orange, and black accessory grains, and granule-size chips of the dominant reddish-brown sandstone of this unit. Some of the medium and coarse quartz grains are frosted and well rounded. Unit is indistinctly flat bedded to massive, in beds 1 to 3 ft thick. Whole unit forms weathered slope	19. 0
Total Carmel formation (excluding Judd Hollow tongue)	178.0

NOTE.—The Navajo-Carmel contact is flat and even over several hundred feet. Measurement of the upper beds was offset about 1 mile northwards along this contact.

Jurassic and Jurassic(?):

Navajo sandstone:

Thousand Pockets tongue (Middle and Upper ? Jurassic):

	Thickness (feet)
18. Sandstone, fine-grained, similar to unit 16; lacks any reddish-brown color. Most of the sets are very thick (20 to 30 ft); in the upper 15 ft are 2 or 3 horizontal truncation planes	105. 0
17. Sandstone, reddish-brown (10*R* 4/4) and white (*N* 9); lithologically like unit 16; very thin to thick flat beds; streaks of white indicate flat tops of beds but the lower contacts of these white streaks have eddy-like convolutions contorting the red portion of the same bed below it. Thicker beds show more general disturbances and disruptions. Forms red ledge. A few red shale partings with white sand wedges and a few 2-in-thick conglomeratic streaks containing volcanic pebbles. One 5-ft unit of cross-bedded sandstone is similar to unit 18. Entire 41-ft unit pinches out within 500 ft to the northeast, and also about 2 miles to the southeast, but reappears again slightly farther southeast	41. 0
16. Sandstone, white (*N* 9), very fine to fine-grained, fairly to well-sorted, rounded to subrounded, fairly well cemented with amber accessory grains; thick to very thick wedging planar sets of large-scale cross strata. Contains minor beds of pale reddish-brown (10*R* 5/4) sandstone that do not change color upon weathering. Forms steep cliffs	61. 5
15. Sandstone, silty, reddish-brown (10*R* 4/4), very fine grained, fair to poorly sorted; contains orange and black accessory grains; irregular thin flat beds weathers pale reddish-brown (10*R* 5/4). Forms poorly exposed slope. Lenticular units of this lithology (resembling Carmel formation) are common in this tongue of the Navajo for several miles around this locality	8.5

UTAH—KANE COUNTY—Continued

	Thickness (feet)
Jurassic and Jurassic (?)—Continued	
Navajo sandstone—Continued	
Thousand Pockets tongue—Continued	
14. Sandstone, white (*N* 9); stains orange-pink (10*R* 6/4); fine grained, well sorted; rounded grains, abundant yellow and orange accessory grains; fairly well cemented; thick wedging planar sets of large-scale cross strata. Top 2 ft is flat bedded. Forms vertical cliff	36.0
Total Thousand Pockets tongue of Navajo sandstone	252.0

NOTE.—The contact between tongues of Carmel and Navajo is generally even except for undulations at the top of unit 12.

	Thickness (feet)
Middle and Upper Jurassic:	
Carmel formation:	
Judd Hollow tongue (Middle Jurassic):	
13. Clay, dark grayish-blue (5*PB* 4/1); color unchanged by weathering; contains abundant biotite flakes and books about 1 mm in diameter; laminated. Forms recess	0.5
12. Sandstone, white (*N* 9), very fine grained, fair- to well-sorted; contains amber and black accessories; some interbeds of similar siltstone are generally grayish-red (10*R* 4/2); weathers light grayish-red (10*R* 5/2) to pale reddish-brown (10*R* 5/4). Overall, unit is essentially one flat bed; lower contact is flat and even but upper contact somewhat undulatory. Beds within unit are convoluted and contorted. Forms very irregular ledge	10.5
11. Siltstone, dolomitic, orange-pink (10*R* 6/4); weathers moderate reddish-orange (10*R* 6/6); effervesces when powdered; ripple-marked flat very thin beds and laminae. Forms jointed blocky-weathering ledge	7.0
10. Sandstone, limy, moderate orange-pink (10*R* 7/4); weathers moderate reddish-orange (10*R* 6/6); very fine to fine-grained, fair-sorted; well cemented with very abundant lime; ripple marked thin to very thin flat beds	1.5
9. Sandstone like unit 5 with one parting like unit 6, except that it is impure and silty	4.5
8. Siltstone, moderate orange-pink (10*R* 7/4), flat-bedded, fish-nest ripple-marked, well-cemented	.5
7. Sandstone like unit 5	7.5
6. Clay, dusky red-purple (5*RP* 3/2), laminated	.25
5. Sandstone, like unit 4, but very fine grained, silty and slightly clayey; forms slope	2.25

UTAH—KANE COUNTY—Continued

	Thickness (feet)
Middle and Upper Jurassic—Continued	
Carmel formation—Continued	
Judd Hollow tongue—Continued	
4. Sandstone, orange-pink (10*R* 6/4), weathering same, some streaks are bleached greenish-white (5*GY* 9/1); very fine to fine-grained, fair to poorly sorted; contains abundant fine orange accessory grains; well-cemented, limy, thin irregular flat beds with partings of similar but softer finer grained sandstone. Forms inconspicuous ragged ledge	5. 0
3. Covered, probably red sandstone, silty	2. 5
2. Sandstone, like unit 1 in color and lithology, but flat bedded	2. 5
Total Judd Hollow tongue of Carmel formation	44. 5

NOTE.—The Carmel-Navajo contact appears flat and even over distance of 1,000 ft. A few miles east of here, near Judd Hollow on the northwest side of Cedar Mountain, the tongue of Carmel formation present here pinches out, and is recognizable only as a few feet of blackish flat-bedded sandstone within the Navajo sandstone. Still farther east at Echo monocline, at Wahweap Creek, and at Crossing of the Fathers, the only possible indication of this tongue of the Carmel is a horizontal truncation plane at a distance below the top of the Navajo sandstone about equal to the thickness of the Thousand Pockets tongue.

	Thickness (feet)
Jurassic and Jurassic(?):	
Navajo sandstone:	
1. Description of only the upper 10 ft. Sandstone, grayish-orange-pink (10*R* 8/2) to moderate reddish-orange (10*R* 6/6), medium-grained, well- to fair-sorted; composed of rounded, clear quartz grains; some beds have an unusual amount of calcite cement; some beds contain considerable accessory white chert grains and reddish quartz; weathers in the paler pink shades. Thick wedging planar sets of large-scale cross strata extend downward for over 150 ft and are predominant for over 100 ft in which there are no lithologic breaks. Forms steep canyon walls	>150. 0

3.—Judd Hollow section, NW¼ sec. 31, T. 43 S., R. 2 E.

[Measured by D. A. Phoenix, December 1957]

Middle and Upper Jurassic:	
Carmel formation:	
10. Sandstone and siltstone, partly covered pale yellowish-orange (10*YR* 8/6) to pale reddish-brown (10*R* 5/4) in alternating resistant and nonresistant beds, forming a gentle slope with many small benches	80. 0

UTAH—KANE COUNTY—Continued

	Thickness (feet)
Middle and Upper Jurassic—Continued	
Carmel formation—Continued	
9. Sandstone, silty, conglomeratic, pale yellowish-orange (10*YR* 8/6) to moderate reddish-brown (10*R* 4/6), in beds 2 to 4 in. thick; conglomerate is concentrated in beds composing the lower 6 ft of the unit, and pebbles are angular fragments of chert, quartzite, and altered volcanic rock. Light-colored beds are limy and form resistant ledges, but entire unit forms a bluff. Bedding is contorted throughout, in folds of 6 in. to 3 ft, amplitude and bedding is offset by numerous intrastratal faults; near-vertical cylindrical bodies of sandstone 1 to 3 ft in diameter penetrate the beds for 8 to 10 ft and are truncated by younger beds of Carmel formation; the cylindrical units contain pebbles derived from lower part of Carmel formation	68. 0
8. Siltstone, pale-brown (5*YR* 5/2) to pale yellowish-brown (10*YR* 6/2); forms massive structureless ledge	2. 0
7. Siltstone, medium, to dark reddish-brown (10*R* 3/4), with drab-colored 1/16- to 1/4-in. angular pebbles of chert, quartzite, and altered volcanic(?) rocks; pebbles are distributed at random and comprise about 2 percent of the rocks; unit is massive with basal 8 in. of horizontally bedded siltstone that truncates crossbedding in underlying Thousand Pockets tongue of the Navajo sandstone	8. 0
Total of incomplete Carmel formation	158. 0
Jurassic and Jurassic(?)	
Navajo sandstone:	
Thousand Pockets tongue (Middle and Upper ? Jurassic):	
6. Sandstone, silty, very light gray (*N* 7) to white (*N* 9) to pale reddish-brown (10*R* 5/4); horizontally color banded in top 70 feet of unit; fine to very fine quartz grains and interstitial silt; unit is tangentially crossbedded like the underlying Navajo sandstone but finer grained throughout, resembling sandstone in the overlying Carmel formation; 63 ft above base of unit is a 2-ft-thick bed of pale red (10*R* 6/2) siltstone forming an extensive marker bed	182. 0
5. Sandstone, silty, fine-grained, light-brown (5*YR* 6/4), limy; lenticular along strike and fills local scours in underlying siltstone; between channels the unit is underlain by 6 in. to 2 ft of red siltstone. The unit forms an irregular ledge whose top is covered with sand dunes	6. 0
4. Sandstone to siltstone, fine-grained, white (*N* 9) to very light gray (*N* 8). Lower 6 ft to 10 ft of unit is structureless, but it is mostly tangentially crossbedded. Near middle of unit sandstone is stained light (5*YR* 5/6) to moderate (5*YR* 4/4) brown; cut by close-spaced short choppy high-angle crossbeds; forms a bench 3 to 5 ft thick	40. 0
Total Thousand Pockets tongue of Navajo sandstone	228. 0

UTAH—KANE COUNTY—Continued

Middle and Upper Jurassic:
Carmel formation:
Judd Hollow tongue (Middle Jurassic):

	Thicknes (feet)
3. Siltstone, moderate reddish-brown (10*R* 4/6) to pale-red (10*R* 6/2) to moderate reddish-orange (10*R* 6/6); basal 6 in. of unit is horizontally bedded pale yellowish orange (10*YR* 8/6) siltstone, top 8 to 14 in. of unit is pale-brown (5*YR* 5/2) horizontally bedded and ripple-laminated silty limestone. Top of unit is in middle of 4-ft-high ledge	20. 0
2. Sandstone, mostly dusky-brown (5*YR* 2/2) but locally pale yellowish-orange (10*YR* 8/6), fine-grained; low-angle crossbedding; beds sharply truncated by planar diastems at top of unit	10. 4
1. Sandstone, moderate to dark reddish-brown (10*R* 4/6–10*R* 3/4), medium- to fine-grained; forms a thin but conspicuous dark-colored ledge	2. 0
Total Judd Hollow tongue of Carmel formation	32. 4

Jurassic and Jurassic(?):
Navajo sandstone: Undescribed.

ARIZONA—COCONINO COUNTY

4.—Echo monocline SE¼ sec. 33, T. 42 N., R. 7 E., unsurveyed

[Measured by D. A. Pheonix and D. W. Peterson, October 1956]

Upper Jurassic:
Entrada sandstone: Undescribed.
Unconformity: Planar; reworked mudstone of Carmel formation in basal 3 ft of Entrada sandstone as pellets, galls and interstitial fillings.

Middle and Upper Jurassic:
Carmel formation:

8. Siltstone, mudstone, and sandstone: siltstone and mudstone are moderate to reddish brown (10*R* 4/6) to dark reddish brown (10*R* 3/4), thin bedded, weathering to shaly slopes; sandstone is pale gray to white, fine grained, horizontally bedded and limy from 14 to 19 ft, 49 to 56 ft, and 90 to 96 ft, forming ledges	115. 0
7. Sandstone and siltstone: sandstone is very light gray (*N* 8) and light-brown (5*YR* 6/4), massive, medium to fine grained in beds 2 to 10 ft thick; it alternates with light-brown (5*YR* 5/6), thin-bedded siltstone; current lineation on bedding in sandstone; coarse sand grains along bedding locally; sandstone forms ledges	34. 0
6. Sandstone, light-brown (5*YR* 5/6) to moderate reddish-brown (10*R* 4/6), fine-grained to silty, medium-scale bedding accentuated by differences in color; strata show lenticular trough crossbedding; forms ledges	29. 0

ARIZONA—COCONINO COUNTY—Continued

Middle and Upper Jurassic—Continued

Carmel formation—Continued

	Thickness (feet)
5. Sandstone, grayish-orange (10*YR* 7/4) grading downwards into dark reddish-brown (10*R* 3/4), medium- to fine-grained, poorly sorted, thick-bedded; abundant current lineation on bedding that trends between N. 25° E. and N. 85° E.; unit weathers to rounded ledges with numerous potholes; grades into underlying unit	80. 0
4. Sandstone, dark reddish-brown (10*R* 3/4), medium- to fine-grained, in beds 1 to 18 in. thick, friable; weathers to rounded ledges and soil-covered slopes; in some strata bedding is contorted and displaced by intrastratal faults; planar low-angle crossbedding in some strata, but mostly horizontally bedded in. beds 6 in to 2 ft thick; coarse sand to grit scattered indiscriminately through the sandstone as lenses 2 in. thick and as disseminated grains	28. 0
3. Sandstone and siltstone interbedded; sandstone is dark reddish brown (10*R* 3/4) to white (*N* 9), medium to fine grained, and poorly sorted in beds 2 to 10 ft thick; siltstone is dusky red (5*R* 3/4) to pale yellowish orange (10*YR* 8/6), massive or with contorted bedding locally; angular granule conglomerate as lenses ½ to 3 in. thick and scattered at random throughout the sandstone; siltstone and sandstone cemented with sparsely disseminated calcite or with calcite in small concretions; iron oxide as freckles and coatings on sand grains; bedding throughout lower 115 ft of unit contorted and locally displaced by intrastratal faults; cylinders of sandstone 4 to 10 ft high and 1 to 3 ft in diameter penetrate siltstone in a zone beginning about 40 ft above base of formation; lowermost bed 3 to 6 ft thick contains reworked Navajo sandstone	115. 0
Total Carmel formation	401. 0

Unconformity: Planar, truncates crossbeds.

Jurassic and Jurassic(?):

Navajo sandstone (incomplete):

2. Sandstone, grayish-yellow (5*Y* 8/4) to grayish-orange (10*YR* 7/4), medium- to fine-grained, massive, poorly sorted; thickness variable, 2 to 4 ft; contains well-rounded frosted sand grains; forms highly broken and dissected topography	4. 0
1. Sandstone, grayish-orange (10*YR* 7/4), medium- to fine-grained; contains well-rounded frosted sand grains; lenticular concave crossbeds in sets 4 to 10 ft thick	100. 0
Total incomplete Navajo sandstone	104. 0

ARIZONA—COCONINO COUNTY—Continued

5.—Section in NW¼SE¼ sec. 35, T. 42 N., R. 7 E., unsurveyed

[Measured by D. A. Phoenix and D. W. Peterson, October 1956]

	Thickness (feet)
Quaternary:	
Alluvium undifferentiated.	
Unconformity.	
Upper Cretaceous:	
Dakota sandstone:	
7. Sandstone, pale yellowish-orange (10*YR* 8/6), fine-grained and silty; as ledge-forming lenticular strata 3 to 8 ft thick	4. 0
6. Siltstone, micaceous, grayish-olive (10*Y* 4/2) to light olive-brown (5*Y* 5/6); bedding is thin to laminated and ripple marked; forms soil covered slope	6. 0
5. Sandstone, pale yellowish-orange (10*YR* 8/6), fine-grained and silty; in broadly lenticular units 6 to 18 in. thick, separated by thinner lenticular units of siltstone; forms ledges	13. 0
4. Siltstone, mainly light-olive (10*Y* 5/4) and dark greenish-yellow (10*Y* 6/6), locally moderate olive-brown (5*Y* 4/4); bedding is thin to laminated and ripple marked; top 2 ft of unit is pale green (5*G* 7/2) mudstone overlain locally by 2-in. bed of coal; forms soil-covered slope and thin resistant ledges	41. 0
3. Sandstone and siltstone: sandstone, grayish-yellow (5*Y* 8/4) to grayish orange-pink (5*YR* 7/2) and light-brown (5*YR* 5/6), fine-grained; contains abundant contorted bedding with thin seams of mudstone and siltstone locally; as lenticular strata continuous along strike for 300 to 400 ft, forms ledge; grades laterally into moderate greenish-yellow, laminated siltstone; weathers to smooth slope covered with flakes and chips of siltstone	18. 0
2. Coal, lignitic, silty; contains macerated plant fragments; overlain locally by 2-in. bed of contorted grayish-green (10*GY* 5/2) mudstone; cut by irregular veinlets of gypsum coated locally with jarosite; forms alcove	2. 0
1. Pebble conglomerate and sandstone. Conglomerate, grayish orange-pink (5*YR* 7/2) and light-brown (5*YR* 5/6); less than 5 percent sandstone in matrix; pebbles mostly of quartzite with sparse chert, light-gray (*N* 7) to dark-gray (*N* 3) and pinkish-gray (5*YR* 8/1), 0.1 to 1.5 in. in diameter; contains fragments of reworked Entrada sandstone at base; in lenticular strata 3 to 9 ft thick. Sandstone, pale yellow-brown, as lenticular beds 6 in. to 2 ft thick, medium- to fine-grained, crossbedded throughout; fills scours in top of underlying Entrada sandstone that are locally 30 ft deep, but contact is mostly planar	13. 0
Total Dakota sandstone	97. 0
Unconformity, locally channeled.	
Upper Jurassic:	
Entrada sandstone; Undescribed.	

UTAH—KANE COUNTY

6.—*Wahweap section, Navajo and Carmel formations measured in W1/2 sec. 4, T. 44 S., R. 4 E., and the Entrada sandstone in NW1/4 sec. 32, and S1/2 sec. 29, T. 43 S., R. 4 E. Along Wahweap Creek and on cliffs north of creek, just north of the Utah-Arizona border.*

[Measured by J. C. Wright and D. D. Dickey, October 1956]

NOTE.—The Entrada sandstone is overlain by about 110 ft of sandstone and conglomeratic sandstone assigned to the Morrison formation. This is unconformably overlain by the Dakota sandstone which caps the mesa.

	Thickness (feet)
Upper Jurassic:	
Entrada sandstone:	
51. Sandstone, greenish-gray (5*GY* 7/1), greenish-gray-weathering; lower part very fine to fine grained; upper part fine- to medium-grained, fair-sorted, contains silt-size amber and black accessory grains and sand-size white chert grains; in upper part white chert becomes abundant and conspicuous, particularly in lower laminae of cross sets, where commonly coarse grained; thin to thick beds of medium- to large-scale simple and wedging planar cross laminae; beds and cross sets are commonly separated by partings, a few inches thick, of very fine grained greenish-gray (5*GY* 6/1) sandstone, that is soft, silty and slightly clayey; these partings sometimes contain sand wedges (sand-filled mud cracks). Unit forms greenish steep cliff; may be equivalent to the Bluff sandstone of southeastern Utah	137.0
50. Interbedded sandstone (50 percent) and siltstone (50 percent): sandstone, like unit 48 in color and lithology, in thin flat beds with indistinct probably flat lamination; siltstone, reddish brown (10*R* 4/4) in part bleached to light greenish gray (5*GY* 8/1), very well cemented, limy, slightly sandy, in irregular thin flat beds having disturbed to disrupted laminae. Unit forms a ribbed cliff in a recess. This is the persistent red recess which is prominent from a distance. This unit may be equivalent to the Summerville formation of eastern Utah	11.5
49. Sandstone like unit 48 in color and lithology, but weathering very light gray (*N* 8); lower 12 feet slightly finer grained and more limy than bulk of unit 48, indistinctly flat bedded. Within unit minor greenish-gray (5*GY* 6/1) streaks are probably caused by clay film on grains. Upper part of unit composed of thin wedging planar sets of small- and medium-scale cross laminae, the siltiest of which are locally colored reddish brown (10*R* 4/4) and weather dark reddish-brown (10*R* 3/4). This unit cannot be distinguished as a separate unit from a distance, but is probably as persistent as the bedding plane below it	36.5

UTAH—KANE COUNTY—Continued

	Thickness (feet)
Upper Jurassic—Continued	
Entrada sandstone—Continued	
48. Sandstone, like unit 47 in color and lithology except it weathers yellowish white (5*Y* 9/1); beds range from very fine to fine grained with good to fair sorting; as well as contains sparse red opaque grains and other accessories; thick to very thick (as much as 40 feet thick) wedging planar sets of large-scale cross-strata. Lower part of unit forms a rounded "slickrim" covered by sand dunes; upper part forms steep cliffs. Inconspicuous horizontal truncation planes, fairly common, can be traced a few hundred yards but may persist farther. At 270 ft above base is a streak of reddish-orange (10*R* 5/6) silty very fine grained sandstone, crossbedded and otherwise like the rest of the unit, a few feet thick. At 282 ft above base is a similar orange band, composed of thin wedging planar sets of medium-scale cross strata. This band persists over a few miles. The upper contact of unit 48 is a sharp extensive horizontal truncation plane, very easy to see on the outcrop but difficult to see from a distance	476. 0
47. Sandstone, white (*N* 9), light greenish-gray-weathering (5*GY* 8/1), very fine grained, well-sorted; composed of rounded clean clear quartz grains with accessory silt-size amber quartz, black grains and pale-green chert or quartz; poorly cemented; thin flat beds. Forms vertical cliff in canyon where it is protected from erosion by overlying unit; over most of area it underlies a broad bench	22. 0
Total Entrada sandstone	683. 0

NOTE.—The Carmel-Entrada contact is conformable as seen in exposures over a few hundred feet. An offset of about 1 mile to the northwest was made here in order to measure the upper beds along a dry wash extending from the NW¼ sec. 32 to approximately the center of sec. 29.

Middle and Upper Jurassic:	
Carmel formation:	
46. Shale like that in unit 39 with subordinate interbedded siltstone like that in unit 42	11. 0
45. Siltstone, orange-pink (10*R* 6/4), upper beds bleached white; well-cemented, limy thin to thick massive beds that weather as hoodoos; shale like that of unit 39 makes partings between the sandstones. This unit is almost identical to the earthy Entrada of the San Rafael Swell. Units 43 through 46 at line of section have locally failed and slumped so as to destroy their contacts. Much of this contortion of the contacts may be apparent and illusory; possibly where fresh these units may form hoodoo cliffs, and where more badly weathered the same rock will form a shaly slope	16. 5

UTAH—KANE COUNTY—Continued

	Thickness (feet)
Middle and Upper Jurassic—Continued	
Carmel formation—Continued	
44. Sandstone, white, like those in unit 40, but very fine grained and silty	2.5
43. Siltstone, clayey, reddish-brown (10*R* 4/4) to grayish-red (10*R* 4/2) very fine silt, laminated, shaly	4.5
42. Siltstone, reddish-orange (10*R* 5/6), with bleached white spherical spots as much as 5 mm in diameter, flat, thin bedded to indistinctly bedded: includes a few beds of shale like that in units 39 and 40. Forms soil-covered bench and slope	24.0
41. Sandstone, white, like white sandstones in unit 40. This unit forms a very persistent white band near the base of the red slopes under the Entrada cliffs	1.0
40. Sandstone and shale like unit 39; complete exposures reveal much more very fine than fine-grained sand. Shale probably aggregates 30 percent of the unit. Two thin beds of sandstone, white (*N* 9), fine to very fine grained, well-cemented with abundant calcite; contains abundant amber and pale-yellow accessory grains and sparse silt-sized black and green accessory grains; flat to small-scale crossbedding. Unit forms low slope	24.5
39. Very poorly exposed on broad bench. Sandstone and probably subordinate interbedded shale. Sandstone, reddish-orange (10*R* 5/6), very fine to fine-grained, poorly sorted; contains abundant fine- to medium-grained rounded spherical gray frosted "Entrada berries"; thin, flat bedded; contains a few gritty sandstones similar to unit 7, and at least one associated conglomeratic stringer with a great variety of subangular granules similar to the stringer in unit 10. Shale, reddish-brown (10*R* 4/4), nearly pure clay, thinly laminated; seen only at a few exposures, but probably present throughout unit; weathers to soil-covered, light grayish-red bench (10*R* 5/2). Unit 40 is probably similar in all respects, but has better exposure owing to protection of overlying beds. Possibly the shales contain material similar to that in purple clay partings which occur elsewhere on the Colorado Plateau	37.0
38. Sandstone, silty, white (*N* 9), yellowish-gray weathering (5*Y* 8/1), very fine grained, well-cemented; abundant calcite obscures lithology; common amber and black, and sparse vivid green, accessory grains, mostly silt-size; small-scale crossbedding to flat bedding. Forms narrow white stripe on bench	.5
37. Poorly exposed on broad bench. Siltstone and sandy siltstone, moderate reddish-brown (10*R* 4/6), fair to poorly sorted; probably thin- and flat-bedded. Weathers to soil on bench	9.5

NOTE.—Offset half a mile northwest to measure beds above.

UTAH—KANE COUNTY—Continued

	Thickness (feet)
Middle and Upper Jurassic—Continued	
Carmel formation—Continued	
36. Sandstone, white (*N* 9) to moderate reddish-orange (10*R* 6/6), weathers to conspicuous white ledge, very fine grained, slightly silty, fair-sorted; contains amber and black accessory grains; well cemented, very limy, indistinctly bedded. Forms white band on bench and ledge on slope	2. 0
35. Shale, reddish-orange (10*R* 5/6), nearly pure clay, thinly laminated. Weathers to soil-covered slope	3. 0
34. Sandstone, moderate reddish-orange (10*R* 6/6); top 3 ft white; very fine grained, fair to poorly sorted; lithologically probably similar to unit 33 (into which it grades), but obscured by red iron stain; mostly thin, flat bedding. Poorly exposed. Forms slope	11. 0
33. Sandstone, white (*N* 9), fine-grained, well-sorted; composed of rounded quartz grains with pink, black, amber, and vivid green accessory grains; limy, with well cemented nodules as much as 1 or 2 cm in diameter. Poorly exposed	12. 0
32. Sandstone, moderate reddish orange (10*R* 6/6), very fine grained, fair-sorted, laminated. Weathers into thin curving plates	2. 0
31. Sandstone, white (*N* 9), very fine grained, well-cemented, limy; contains finer amber, black and sparse vivid green accessory grains; small-scale cross lamination. Grades upward into unit 32	1. 0
30. Partially exposed. Siltstone reddish-orange (10*R* 5/6), probably thin bedded. Forms earthy slope	7. 0
29. Sandstone like unit 24	1. 0
28. Sandstone like unit 23. At some places along the outcrop there is a purple, laminated siltstone parting which separates units 27 and 28. White sand wedges are also present in this shaly unit	6.0
27. Sandstone like unit 21	5.5
26. Clay, grayish-red (10*R* 4/2), laminated, slightly silty; beds immediately above and below are bleached white for a thickness of 2 in	.5
25. Sandstone, pale reddish-brown (10*R* 5/4), weathers same, fine to very fine grained, fair-sorted, poorly cemented, slightly calcareous; contains irregular laminae of coarse-grained sandstone; flat bedding with same small-scale low-angle cross-laminae. Nonresistant to weathering and generally only poorly exposed	6.5
24. Sandstone like unit 23, but flat bedded instead of massive	5.5
23. Sandstone, orange-pink (10*R* 6/4), very fine grained, fairly sorted; well-cemented with calcite; contains abundant nodules of dolomite as large as 1 cm in diameter. Forms massive ledge. Laterally along the outcrop, units 21, 22, and 23 form a persistent unit which grades into a single, massive, better sorted crossbedded sandstone, without partings locally	6.0

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UTAH—KANE COUNTY—Continued

	Thickness (feet)
Middle and Upper Jurassic—Continued	
Carmel formation—Continued	
22. Shale, purple, laminated	.5
21. Sandstone, pale reddish-brown (10*R* 5/4), fine-grained, like unit 7 in all other characteristics	4.0
20. Shale, reddish-brown (10*R* 4/4), nearly pure clay with interbeds of moderate orange-pink (10*R* 7/4) clayey, ripple laminated siltstone	1.5
19. Sandstone, pale reddish-brown (10*R* 5/4), orange-pink-weathering (10*R* 6/4), medium to very fine grained, fair-sorted; composed of rounded grains, a large proportion of which look like "Entrada berries"; laminated to very thin bedded, cross stratified. Soft and only partly exposed in lower half; upper half well exposed	11.5
18. Sandstone like unit 7. Forms top of ledge with unit 17	2.0
17. Sandstone like unit 15, in thin to thick beds separated by subordinate finer grained beds like unit 14. Upper half grades to a pale reddish-brown (10*R* 5/4) very fine to fine-grained sandstone that forms a persistent massive ledge with indistinct even laminae	17. 0
16. Siltstone, sandy, like unit 14 with similar subordinate shale interbeds	5. 5
15. Sandstone, moderate orange-pink (10*R* 7/4) to white (*N* 9), very fine and fine-grained, fair-sorted composed of rounded grains with abundant amber quartz accessory grains, some gray frosted well-rounded medium-grained quartz, iron oxides, sparse green grains and volcanic granules, and much calcite cement; very thin flat beds to small-scale crossbedding	2. 5
14. Siltstone, sandy, orange-pink (10*R* 6/4) weathering same; hematite and calcite cement obscures grains; thin beds with small-scale cross lamination. Subordinate interbeds of shale like that in unit 13 forms recesses; generally forms a covered slope	3. 0
13. Interbedded siltstone (60 percent) and shale (40 percent). Siltstone, reddish-orange (10*R* 5/6), with white (*N* 9) bleached spherical spots as much as 3 cm in diameter; massive thin to very thin even beds with a very faint suggestion of disrupted laminations within beds. Shale, pale reddish-brown (10*R* 5/4), mostly nearly pure clay, with some silty clay; evenly laminated; forms recesses a few inches to a foot thick between the siltstone beds. One foot above the base of the unit is a few inches of clay shale, grayish red-purple (5*RP* 4/2); this color is characteristic of some types of altered volcanic material. Generally forms covered slope	7. 5
12. Limestone, very clayey and shaly, otherwise like unit 11 in general color and lithology	2. 0

UTAH—KANE COUNTY—Continued

	Thickness (feet)
Middle and Upper Jurassic—Continued	
Carmel formation—Continued	
11. Limestone, very pale red (5*R* 7/2); some bedding planes bleached light greenish gray (5*GY* 8/1), very evenly laminated, weathers to thin plates. Many bedding planes have ripple marks, small rill marks, and rectangular crack patterns filled with limy silt. Nodules of clear calcite, 1 to 3 mm in diameter occur in the lower few inches. Forms ledge and bench	4.0
10. Sandstone, like unit 7 in color and lithology except that the coarser material is less common and not quite as coarse. Thin irregular massive beds form ragged ledges, separated by very thin flat-bedded, very fine grained sandstone that is similar to unit 7 but better sorted. Silt or clay in some recesses. A 1-in. stringer of very hematitic conglomeratic sandstone noted. Contains angular granules and small pebbles of quartz, chert, and feldspar(?). Float of the sandstone shows casts of conspicuously linear grooves a few millimeters wide and deep and many centimeters long, apparently imprinted from the bottom of massive sandstone beds	19.0
9. Sandstone, white (*N* 9) to moderate reddish-orange (10*R* 6/6), very fine to fine-grained, very poorly sorted, with both silt- and granule-size material included; larger granules angular and probably volcanic; fewer coarse grains at top; also contains sparse fine to medium well rounded grains of a vivid-green soft mineral; bulk of the sand is rounded clear quartz; very well cemented with calcite which gives it the white color; small-scale cross lamination; upper foot is flat, very thin bedded. Forms ledge	2.0
8. Sandstone like unit 7, but shows remnants of bedding. Forms base of ledge	.5
7. Sandstone, reddish-brown (10*R* 4/4), weathering same, very fine grained, silty; very poorly sorted, with scattered coarser inclusions as much or 3 mm in size. Inclusions are generally angular to subangular, aphanitic volcanic pieces with either phenocrysts or other volcanic fragments included. On one face a clay chip (probably very fine volcanic tuff) 3 cm across is exposed. The bulk of the matrix is sand grains which are stained with red hematite, but appear to be well-rounded quartz grains. Entirely massive; neither bedding structure nor grading can be observed. The upper 3 in. is impregnated by black hematitic cement and has signs of flat lamination. Forms soil-covered slope	8.5
6. Clay, light grayish-red (10*R* 5/2), weathering same, silty in lower part, purer clay at top, laminated. Weathers papery to shaly. The lower 2 in. of the overlying unit is bleached white, suggesting that this unit may be similar to the thinner volcanic purple partings on the Colorado Plateau northeast of here	2.0

UTAH—KANE COUNTY—Continued

Middle and Upper Jurassic—Continued Carmel formation—Continued	*Thickness (feet)*
5. Clay, red (5*R* 5/6), slightly silty, laminated. Weathers to a largely concealed, pale reddish-brown (10*R* 5/4), soil-covered slope	5. 5
4. Sandstone, moderate orange-pink (10*R* 7/4); streaked with greenish-white (5*GY* 9/1); stained moderate reddish-orange (10*R* 6/6) by overlying beds; very fine to fine-grained, fair sorted; composed of rounded grains with amber quartz accessory grains and gray frosted well-rounded medium grains; contains prominent better cemented nodules several centimeters in diameter; very thin flat beds. Top surface of this unit has sparse, scattered, subangular to angular, very coarse grains of white chert	. 5
Total Carmel formation	299. 0
Total San Rafael group	982. 0

NOTE.—The Navajo-Carmel contact is even and appears parallel to both the truncation plane at base of unit 2 and the overlying flat-bedded Carmel formation. The contact as seen over several square miles has no detectable relief.

Jurassic and Jurassic(?):	*Thickness (feet)*
3. Sandstone, moderate reddish-orange (10*R* 6/6), orange-pink-weathering (10*R* 6/5), very fine to medium-grained, fair to poorly sorted; composed of subrounded grains with accessory chert and larger, well-rounded grains like unit 2; very fine grains predominate over coarser sizes; thick (10 to 20 ft.) tabular simple cross laminae separated by horizontal truncation planes and small amounts of flat-bedded reworked sandstone; these planes do not make prominent breaks on the cliff and their extent cannot be determined. Some beds in the upper third of the unit are yellowish gray (5*Y* 7/2) and weather very light gray (*N* 8) (possibly bleached); otherwise these beds appear to be similar to the rest of the unit. Forms bare rock slopes and benches	126. 0
2. Sandstone, moderate reddish-orange (10*R* 6/6); weathers moderate reddish-orange to moderate orange-pink (10*R* 7/4); fine- to medium-grained; medium-grained laminae well sorted with rounded spherical grains, and the fine-grained laminae fair sorted with less well rounded grains, and both containing gray to white accessory chert, generally fine-grained; both contain conspicuous larger gray, frosted, rounded spherical grains; thick to very thick wedging planar sets of cross strata; no extensive horizontal truncation planes except at the top contact; contains a few lenticular thin beds, moderate-red (5*R* 5/4), of finer grained material along contacts of cross sets; these form recesses. Unit dissected in canyon	70. 0

UTAH—KANE COUNTY—Continued

Jurassic and Jurassic(?)—Continued

Navajo sandstone (incomplete)—Continued — *Thickness (feet)*

1. Several hundred feet of Navajo sandstone is exposed above the mouth of Wahweap Creek on the Colorado River. In the lowermost 200 feet the wedging planar cross sets are very thick (about 30 to 50 ft); through most of the remainder of the formation the crossbeds are about 10 to 30 ft thick. The general color is approximately orange-pink (10*R* 6/4). The uppermost 50 ft, below unit 2 is very light gray (*N* 8) and is composed largely of wedging planar sets 5 to 10 ft thick, of low angle cross strata. Slump structures as described by Kiersch (1950, p. 939) are common throughout the formation. The lithology of the upper few feet of this unit is: sandstone, white (*N* 9), medium- to coarse-grained, fair sorted; composed of rounded to subrounded grains; a few laminae contain conspicuous coarse-grained accessory yellow, amber, and orange quartz, and purple-red to light-gray chert. Top of unit defined by about half a foot of flat-bedded similar material which horizontally truncates the underlying cross strata. This truncation plane extends for at least a mile and forms bench. No other horizontal truncation plane was observed below this one ---------- >300. 0

Total of incomplete Navajo sandstone ---------- >496. 0

ARIZONA—COCONINO COUNTY

7.—Lees Ferry section NE¼ sec. 19, T. 40 N., R. 8 E. Line of section starts at east end of cableway on east bank of Colorado River and follows up a small draw to the base of a near vertical cliff of Navajo sandstone; hieroglyphic inscribed on outcrop at base and top of section

[Measured by David A. Phoenix, September 1956]

Jurassic and Jurassic(?):

Navajo sandstone: — *Thickness (feet)*

Sandstone, moderate reddish-orange, medium-grained; tangentially crossbedded; individual sand grains well rounded and frosted; unmeasured.

Jurassic(?):

Kayenta formation:

10. Sandstone, medium- to fine-grained, moderate reddish-orange (10*R* 6/6); horizontally bedded in beds 2 to 6 ft thick with interbeds of locally silicified limy siltstone in beds 6 to 8 in. thick; sandstone is locally crossbedded in sets 2 ft thick; contains well-rounded frosted sand grains; veinlets of jasper locally crosscut the beds of limy siltstone. Uppermost 20 ft of formation is massive medium- to fine-grained pale red-brown sandstone. Contact with Navajo sandstone is planar and distinct but similarity in color of the two formations make it indistinct from a distance ----- 96. 0

ARIZONA—COCONINO COUNTY—Continued

	Thickness (feet)
Jurassic (?)—Continued	
Kayenta formation—Continued	
9. Siltstone and fine-grained sandstone, pale reddish-brown (10*R* 5/4); in horizontal beds 1 to 3 in. thick, altered to light greenish-gray (5*G* 8/1) at top, forms rubble-covered slope in most places	26. 0
Total thickness of Kayenta formation	122. 0
Triassic(?):	
Moenave formation:	
Springdale sandstone member:	
8. Sandstone, medium- to fine-grained, moderate to red (5*R* 5/4) to pale reddish-brown (10*R* 5/4) in horizontal beds 3 to 10 ft thick and individual beds are cross-laminated; unit forms massive ledge	136. 0
7. Quartzitic sandstone, medium-grained, light-gray (*N* 7), with randomly distributed compressed galls of red-brown mudstone	4. 0
6. Siltstone, reddish-brown, thin-bedded to laminated locally; forms ledges 4 to 6 ft thick	48. 5
5. Siltstone, pale reddish-brown (10*R* 5/4), laminated and thin-bedded; forms rubble-covered slope	13. 5
4. Sandstone, dark reddish-brown (10*R* 3/4); crossbedded in sets 18 in. to 2 ft thick; forms massive ledge	21. 0
Total Springdale sandstone member	223. 0
Dinosaur Canyon sandstone member:	
3. Siltstone and fine-grained sandstone, moderate reddish-orange (10*R* 6/6), in beds 10 in. to 6 ft thick separated by beds of dark reddish-brown (10*R* 3/4) silty mudstone. Imprints of mudcracks, polygonal joints, and asymmetric ripple marks on bedding in the siltstone; siltstone is crossbedded in sets 2 to 3 in. thick between horizontal bedding planes; current lineation on some beds. Randomly distributed spots of light greenish gray (5*G* 8/1) in the siltstone near base of unit. Top of unit marked by a 6-in.-thick bed ripple-marked limy sandstone	165. 0
2. Sandstone, fine-grained, moderate reddish-brown (10*R* 4/6), faintly bedded; forms massive ledge	40. 0
1. Siltstone, moderate reddish-brown (10*R* 4/6) altered light-gray at base (*N* 7), bedding mostly parallel and 3 to 8 in. apart but contorted locally	15. 0
Total Dinosaur Canyon sandstone member	220. 0
Total Moenave formation	443. 0

ARIZONA—COCONINO COUNTY—Continued

8.—Cathedral Rock section, W1/2 sec. 32, T. 40 N., R. 7 E. Section is 1¼ mile southwest of Cathedral Rock with its base at the edge of the cliff

[Measured by D. A. Phoenix and D. W. Peterson, October 1956]

	Thickness (feet)
Triassic(?):	
Moenave formation undifferentiated.	
Unconformity.	
Triassic:	
Chinle formation:	
Owl Rock member:	
16. Chert, pale-green (5*G* 7/2) to grayish-green (10*R* 4/2), with crosscutting veinlets of grayish-pink (5*R* 8/2) to very dark red (5*R* 2/6) jasper, massive; forms ledge	4. 0
15. Mudstone, dark reddish-brown (10*R* 3/4); bedding obscured by weathered bentonitic clay; forms slope	2. 0
14. Chert, pale-green (5*G* 7/2) to grayish-green (5*G* 5/2), massive; forms ledge	4. 0
13. Mudstone and siltstone interbedded, dark reddish-brown (10*R* 3/4) and gray-greenish (10*GY* 5/2), thin-bedded; forms rubble-covered slope	32. 0
12. Chert, mottled pale-green (5*G* 7/2) to grayish-green (5*G* 5/2) with crosscutting veinlets of grayish-pink (5*R* 8/2) to dark-red (5*R* 2/6) jasper, massive; forms ledge	8. 0
11. Mudstone, pale reddish-brown (10*R* 5/4), interbedded with siltstone and sandstone, pale greenish-yellow (10*Y* 8/2) to yellowish-gray (5*Y* 7/2); sparse thin to medium bedding, fine grained; forms rubble-covered slope	120. 0
10. Conglomeratic sandstone and mudstone; sandstone light-brown (5*YR* 5/6) and light olive-gray (5*Y* 6/1) medium- to fine-grained in beds 18 in. to 2 ft thick interbedded with mudstone pale-green (5*G* 7/2) and very dusky red-purple (5*RP* 2/2) in beds 3 to 6 in. thick; conglomerate of gray, black, green, and red chert pebbles ¼ to 1 in. in diameter; sandstone and conglomerate trough cross-stratified	39. 0
Total Owl Rock member	209. 0
Petrified Forest member:	
9. Mudstone and siltstone, alternating and intergradational, grayish orange-pink (5*YR* 7/2) and pale-red (10*R* 6/2), thin-bedded; thin lenticular strata of muddy sandstone locally; erodes to steep slopes but mostly covered by talus and landslide debris	192. 0
8. Mudstone, varicolored pale-red (10*R* 6/2), grayish red-purple (5*RP* 4/2), pale-blue (5*PB* 7/2), and pale blue-green (5*BG* 7/2) in horizontal bands 2 to 15 ft thick; bentonitic and swells when wet, bedding obscure; erodes to rounded slopes, but mostly covered by talus	314. 0

ARIZONA—COCONINO COUNTY—Continued

	Thickness (feet)
Triassic—Continued	
Chinle formation—Continued	
Petrified Forest member—Continued	
7. Sandstone, grayish-red (10*R* 4/2), coarse-grained with abundant intersitial clay; locally crossbedded in sets 18 in. to 4 ft thick; interbedded with siltstone and mudstone, grayish red-purple (5*RP* 4/2) in beds 6 to 8 in. thick; forms weak ledge	95. 0
6. Mudstone, grayish-purple (5*P* 4/2), pale-blue (5*B* 6/2) and moderate-red (5*R* 5/4), massive; contains nodules of pale-red (5*R* 6/2) and pale-green (5*G* 7/2) chert in 2- to 3-ft zone near base of unit; forms smooth slope	26. 0
Total Petrified Forest member	627. 0
Sandstone and mudstone unit:	
5. Sandstone, light-gray (*N* 7) and greenish-gray (5*GY* 6/1), fine- to coarse-grained, thin- to thick-bedded in strata 3 to 8 ft thick separated by silty mudstone; laterally the strata become thin bedded, with current lineation on bedding accentuated by black opaque minerals; where strata are thick bedded, trough cross-strata well-developed locally in sets 2 to 3 ft thick and 5 ft wide	34. 0
4. Sandstone, pale yellowish-brown (10*YR* 6/2) thin- to thick-bedded; coarse grained with pebbles and abundant interstitial clay; forms persistent layer in its entirety but comprises 4 to 6 distinct strata that are broadly lenticular and that are separated by fine-grained sandstone, siltstone, and mudstone; these sedimentary units are thin bedded to laminated; thick sandstone strata weather to ledges, alcoves locally, but unit as whole forms persistent ledge	56. 0
3. Mudstone with sandstone interbedded; mudstone, grayish yellow-green (5*GY* 7/2) to dark-gray (*N* 3), massive; forms slopes; sandstone, grayish red (10*R* 4/2), coarse to fine grained, with matrix of white (*N* 9) to light-gray (*N* 7) clay; forms 4-ft ledge 20 ft above base of unit; coarse-grained sandstone shows trough cross strata in sets 6 in. thick and 3 ft wide; current lineation trend westerly on thin beds in fine-grained sandstone	40. 0
2. Sandstone with siltstone, mixed; light olive-gray (5*Y* 6/1), olive-gray (5*Y* 4/1), and dark reddish-brown (10*R* 3/4); ripple laminated throughout; bedding distinct and contorted locally; forms irregular lenticular strata 2 to 3 ft thick; locally silicified and darkly stained with iron oxide on outcrop; contains abundant fossil logs locally	45. 0
Total sandstone and mudstone unit	175. 0

ARIZONA—COCONINO COUNTY—Continued

Triassic—Continued

Chinle formation—Continued

Shinarump member:

	Thickness (feet)
1. Sandstone and conglomerate; pale yellowish-orange (10*YR* 8/6), light-brown (5*YR* 6/4), light olive-gray (5*Y* 6/1) but darker colored on outcrop; sandstone, coarse to fine grained; conglomerate pebbles 1/4 to 2 in. in diameter consisting largely of white (*N* 9) to pinkish-gray (5*YR* 8/1) quartzite and light- to dark-gray (*N* 7–*N* 3) and moderate-brown (5*YR* 3/4) chert; pebbles localized along bedding and in lenses and pods in the sandstone; trough cross strata abundant in sandstone in sets 6 in. to 3 ft thick throughout the unit	34. 0
Total Shinarump member	34. 0
Total Chinle formation	1045. 0

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