# Geology of the Paleozoic Rocks, Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah

GEOLOGICAL SURVEY PROFESSIONAL PAPER 521-C

*Prepared in cooperation with the Bureau of Indian Affairs and the Navajo Tribe*

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*By* J. H. IRWIN, P. R. STEVENS, *and* M. E. COOLEY

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# GEOLOGY OF THE PALEOZOIC ROCKS, NAVAJO AND HOPI INDIAN RESERVATIONS, ARIZONA, NEW MEXICO, AND UTAH

By J. H. IRWIN, P. R. STEVENS, and M. E. COOLEY

## ABSTRACT

Sedimentary rocks of Paleozoic age are present throughout the 25,000 square miles that comprises the Navajo and Hopi Indian Reservations, or Navajo country, in the south-central part of the Colorado Plateaus physiographic province. These rocks are exposed only in the Monument Valley, the Defiance Plateau, the Zuni Mountains, and the southwestern part of the reservations.

Pre-Pennsylvanian Paleozoic rocks crop out only in the lower reaches of the canyon of the Little Colorado River, Grand Canyon, and Marble Canyon, but they have been penetrated in deep oil tests in Black Mesa basin and in the Four Corners area of Arizona, New Mexico, Utah, and Colorado. These rocks are represented by Cambrian, Devonian, and Mississippian strata and have a combined thickness of nearly 1,500 feet at the confluence of the Colorado and Little Colorado Rivers and 1,200 feet in the Four Corners area. They thin eastward and southeastward across the area and are absent in the southeastern part of the reservations.

The lower boundary of the Cambrian is represented by an erosion surface in the Grand Canyon and in the adjoining part of the Navajo Indian Reservation. The hiatus between Precambrian and Cambrian deposition includes an unknown quantity of late Precambrian time, part of early Cambrian time in the Grand Canyon area, and considerably more of Cambrian time in areas to the east. In the Grand Canyon area, Cambrian rocks are designated as the Tonto Group and include, in ascending order, the Tapeats Sandstone, the Bright Angel Shale, and the Muav Limestone. Between 250 and 750 feet of Cambrian rocks is recognized in drill cuttings from oil tests in the Four Corners area. These rocks consist of a basal sandstone that grades upward through shale into limestone and dolomite and have been correlated with the Cambrian section in the Grand Canyon and the Cambrian strata of central Utah.

Rocks of definite Ordovician and Silurian ages do not occur in the Navajo country.

The Temple Butte Limestone of Devonian age is exposed discontinuously in the lower part of the canyon of the Little Colorado River and in Marble Canyon. Devonian rocks have also been recognized in oil tests in the northern and west-central parts of the reservations. None are exposed in the Defiance Plateau.

The Mississippian rocks are represented by the Redwall Limestone in the reservations. The Redwall is present in the subsurface, except near the Defiance Plateau and the Zuni Mountains in the southeastern part of the reservations.

Pennsylvanian and Permian rocks are described in their principal exposures—in the southwestern part of the Navajo country, in the Defiance Plateau, and in Monument Valley. Although they are also exposed in the Zuni Mountains, the Pennsylvanian and Permian rocks in that area are discussed only briefly in this report. Thicknesses of these rocks are 2,000 feet near the mouth of the Little Colorado River, 1,100 feet in the Defiance Plateau, and 3,600 feet in Monument Valley. These rocks are assigned different names in each of their principal areas of outcrop.

The nomenclature of the Pennsylvanian and Permian rocks in the southwestern part of the Navajo country is basically the same as that used in the eastern part of the Grand Canyon. The formations, in ascending order, are the Supai Formation of Pennsylvanian and Permian age and the Hermit Shale, Coconino Sandstone, Toroweap Formation, and Kaibab Limestone of Permian age. The Supai Formation, in the Mogollon Slope and along the Mogollon Rim, has been divided into three members—the upper, middle, and lower members. The Supai is underlain by the Naco Formation, which is present under much of the Mogollon Slope area along the southern boundary of the reservations. The Coconino Sandstone and its lateral equivalents, the De Chelly and Glorieta Sandstones and the De Chelly Sandstone Member of the Cutler Formation, form an important aquifer system in the southern part of the Colorado Plateaus.

Permian rocks, resting on granitic and metamorphic rocks of Precambrian age, are the oldest Paleozoic strata in the Defiance Plateau. The Permian rocks are the Supai Formation, which rests unconformably on the Precambrian rocks, and the De Chelly Sandstone, which conformably overlies the Supai. An upper and a lower member of the De Chelly Sandstone are recognized in the Defiance Plateau. The upper member is present throughout the Defiance Plateau, but the lower member is recognized only in the Fort Defiance–Hunters Point area. The two members of the De Chelly are separated by a prominent tongue of the Supai Formation in the Hunters Point area.

Discontinuous deposits of probable Permian age overlie the De Chelly Sandstone in places in the Defiance Plateau. A sequence of grayish-red and pale-reddish-brown silty sandstone occurs between the conglomeratic Shinarump Member of the

Chinle Formation of Late Triassic age and the crossbedded De Chelly Sandstone in Bonito Canyon. During the drilling of water wells near Window Rock, 22 feet of limestone, which may be correlative to the San Andres Limestone in the Zuni Mountains, was penetrated. The limestone apparently cannot be correlated with the red beds that overlie the De Chelly Sandstone in Bonito Canyon.

In Monument Valley the Pennsylvanian and Permian rocks consist, in ascending order, of the Molas, Hermosa, Rico, and Cutler Formations. Pennsylvanian rocks crop out only in San Juan Canyon. Permian rocks are widespread in the Monument Valley area and show rapid lateral changes in lithology. They appear to be transitional between the Permian deposits in southwestern Colorado and those in the Grand Canyon area. The Molas Formation is not exposed in the Monument Valley area but has been recognized in well cuttings in the subsurface in the Four Corners area.

Conformably overlying the Molas is the Hermosa Formation, which is gradational with the overlying Rico Formation. The Molas and Hermosa Formations are considered to be Pennsylvanian in age, and the Rico Formation is considered to be Pennsylvanian and Permian in age.

The Cutler Formation of Permian age rests conformably on the Rico Formation and is divided into four members, which are, in ascending order, the Halgaito Tongue, the Cedar Mesa Sandstone Member, the Organ Rock Tongue, and the De Chelly Sandstone Member.

The lower and upper contacts of the Halgaito Tongue are gradational, and the tongue is irregular in thickness. The lithologic characteristics of the Cedar Mesa Sandstone Member vary regionally because of its lateral transition into red beds. The Cedar Mesa Sandstone Member grades eastward into red beds at a point somewhere between Boundary Butte and Gypsum Wash. The Organ Rock Tongue grades into the underlying Cedar Mesa and the overlying De Chelly Sandstone Members.

The Navajo and Hopi Indian Reservations were part of a relatively stable platform or shelf region on the east margin of the Cordilleran geosyncline during Pennsylvanian and Permian times. Adjustments of the shelf area caused eastward transgressions and regressions of the seas, whose deeper parts were generally to the northwest, west, and south. The central part of the reservations received clastic sediments derived mainly from the Uncompahgre Highlands to the northeast.

## INTRODUCTION

Sedimentary rocks of Paleozoic age are present throughout the Navajo and Hopi Indian Reservations. Where exposed, these rocks have been carved superbly into buttes, monuments, mesas, and canyons —the most spectacular are Grand Canyon, Marble Canyon, Canyon de Chelly, and the mesa-and-butte country of Monument Valley.

### LOCATION, ACCESSIBILITY, AND LAND-NET SYSTEMS

The Navajo and Hopi Indian Reservations are in the south-central part of the Colorado Plateaus. The Navajo Indian Reservation is in parts of Apache, Navajo, and Coconino Counties in northeastern Arizona; San Juan and McKinley Counties in northwestern New Mexico; and San Juan County in southeastern Utah (fig. 1). The Hopi Indian Reservation is in the central part of the Navajo Indian Reservation in Arizona. The reservations have an area of about 25,000 square miles, which is about three times the area of New Jersey.

In this report the term "Navajo country" (Gregory, 1917, p. 11) is used broadly to include the Navajo and Hopi Indian Reservations and the area lying principally between the Colorado, San Juan, and Little Colorado Rivers. The reservations are divided by the Bureau of Indian Affairs into 18 administrative districts. Districts 1–5 and 7–18 are in the Navajo Indian Reservation, and district 6 is the Hopi Indian Reservation. Few detailed maps of the reservations were available at the time of this study, but 15-minute planimetric maps compiled from aerial photographs were available. These maps are numbered arbitrarily from 1–151, starting in the upper right corner of the reservations and continuing from right to left in rows (fig. 1).

### PURPOSE, SCOPE, AND ORGANIZATION

In 1946 the U.S. Geological Survey, at the request of the Bureau of Indian Affairs, made a series of hydrologic investigations to help alleviate the water shortage in several places on the reservations. In 1950, the U.S. Geological Survey, in cooperation with the Bureau of Indian Affairs, began a comprehensive regional investigation of the geology and ground-water resources of the reservations. The principal objectives were to determine the feasibility of developing ground-water supplies for stock, institutional, and industrial uses in particular areas and at several hundred well sites scattered throughout the reservations and in adjoining areas owned by the Navajo Tribe; to inventory the wells and springs; to investigate the geology and ground-water hydrology; and to appraise the potential for future water development.

This report is the third chapter of U.S. Geological Survey Professional Paper 521, which describes the geology and hydrology of the reservations. This chapter discusses only the sedimentary rocks of Paleozoic age. The chapter was written in 1955 and updated during the 1960's. Discussions of the ground-water hydrology of these formations are to appear in other chapters, and only a few of the pertinent geologic-hydrologic relations are noted in this report.

Stratigraphic descriptions of the uppermost Triassic and the Jurassic rocks were described by Harshbarger, Repenning, and Irwin (1957). The

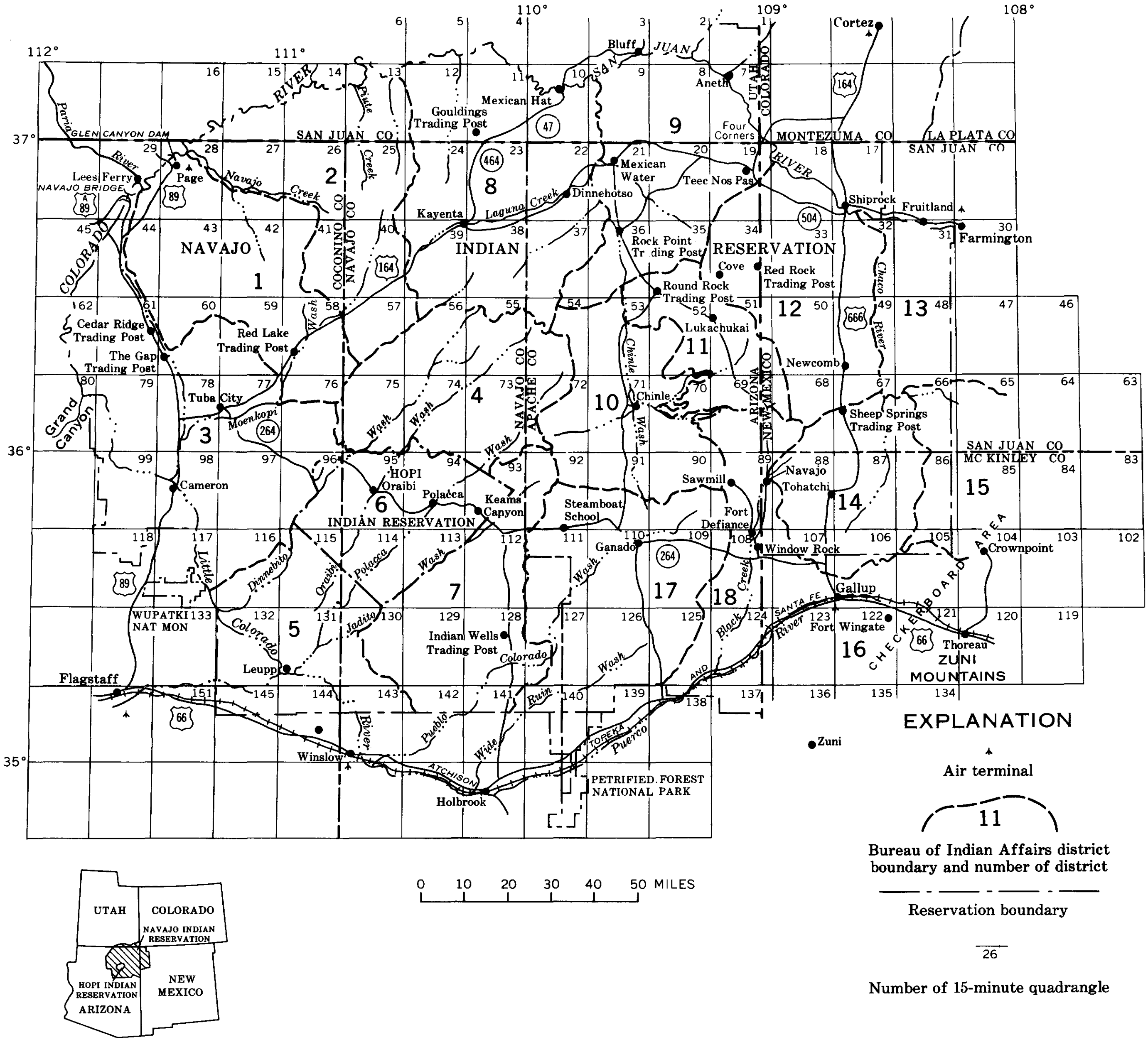

FIGURE 1.—Bureau of Indian Affairs administrative districts and 15-minute quadrangles.

basic geohydrologic data—records of wells and springs, selected chemical analyses, and selected drillers' logs, lithologic logs, and stratigraphic sections—have been published (Davis and others, 1963; Kister and Hatchett, 1963; Cooley and others, 1964, 1966; McGavock and others, 1966). The detailed geologic maps of the reservations and descriptions of the sedimentary features are included in Cooley, Harshbarger, Akers, and Hardt (1969).

The generalized outcrops of the Paleozoic formations are shown on plate 1 in this chapter, and detailed stratigraphic relations are shown on plate 2.

## FIELDWORK AND COMPILATION OF DATA

The Navajo and Hopi Indian Reservations were studied in detail, and reconnaissance work was done in parts of the nearby valley of the Little Colorado River and the Zuni Mountains. The fieldwork, part of the overall investigation of the geology and ground-water resources, consisted principally of the measurement and description of stratigraphic sections, study of sample cuttings from new wells drilled in the area, correlation of stratigraphic units, and geologic mapping. For the most part, the physical character of the Paleozoic rocks was described at the surface exposures in the Grand Canyon, Defiance Plateau, and Monument Valley area.

Considerable time was spent on the study of sample cuttings and drillers' logs, because most of the Paleozoic rocks are beneath Mesozoic and younger strata. The contacts between the major stratigraphic units are recognized easily, even in drillers' logs. The contacts between some of the minor units are more difficult to recognize, although unit boundaries were determined when samples were available.

A stratigraphic fence diagram was constructed to show regional relations of the stratigraphic units, variations in thickness, and the distribution of the water-bearing strata (mostly sandstone beds) of the Pennsylvanian and Permian rocks (pl. 2). The contact between the Triassic and Permian rocks, although irregular, is present throughout the Navajo country; consequently, it is used as a datum to which all measurements and correlations are referred. Thicknesses shown in the fence diagram are not adjusted for perspective; thus, the vertical scale is constant in all parts of the diagram, although the horizontal scale decreases from front to back. The thicknesses are from measured sections and well data at points indicated on the diagram; thicknesses at intermediate points are approximate because of the perspective projection of the diagram. Intertonguing relations are shown diagrammatically and indicate only the direction of tonguing.

### ACKNOWLEDGMENTS

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## PRE-PENNSYLVANIAN PALEOZOIC ROCKS

The pre-Pennsylvanian Paleozoic rocks crop out in the Navajo Indian Reservation only in Marble Canyon and in the lower reaches of the canyon of the Little Colorado River, but they are present in the subsurface in the western and northern parts of the reservations. These rocks were not studied in detail during this investigation, because they have small exposures and are present elsewhere, generally at depths of more than 2,000 feet. Most information describing these rocks was obtained from the literature. During the past few years, wells have been drilled in the Four Corners area and in the Black Mesa basin; however, the subsurface geologic information resulting from the drilling of these wells is not included in this report.

The pre-Pennsylvanian Paleozoic rocks have a combined thickness of nearly 1,500 feet at the confluence of the Colorado and Little Colorado Rivers and about 1,200 feet in the Four Corners area. They thin progressively southeastward and are not present in the southeastern part of the reservations.

### PREVIOUS INVESTIGATIONS AND TERMINOLOGY

The early investigators of the Paleozoic rocks in the southern part of the Colorado Plateaus concentrated their efforts chiefly in the Grand Canyon area. Marcou (1856, p. 156) and Newberry (1861, p. 56) were the first to recognize rocks of Paleozoic age. Later, Gilbert (1874, p. 109) named the Cambrian strata of the Grand Canyon the Tonto Group. The Tonto Group was divided by Noble (1914, p. 61–65) into three formations: the Tapeats Sandstone, named for Tapeats Creek; the Bright Angel Shale, named for exposures in Bright Angel Canyon; and the Muav Limestone, named for Muav Canyon.

Cambrian rocks 250 to 750 feet thick are recognized in drill cuttings from deep oil tests in the Four Corners area. These rocks have been correlated with the Cambrian section in the Grand Canyon and with the Cambrian strata of central Utah—the Tintic Quartzite, Ophir Formation, and Bowman and Hartmann Limestones undifferentiated, which were considered by Cooper (1955, p. 59–61) to be tentatively correlative with the Tapeats Sandstone, Bright Angel Shale, and Muav Limestone, respectively.

Devonian strata in the Grand Canyon were first noted by Walcott (1880). Walcott (1890, p. 50) named these strata the Temple Butte Limestone for Temple Butte, a prominent feature 3 miles south of the confluence of the Colorado and Little Colorado Rivers. In central Arizona in the southern border region of the Colorado Plateaus, the Devonian rocks are represented by the Martin Limestone (Ransome, 1904, p. 33). In the Four Corners area, deep wells have penetrated rocks of probable Devonian age which may be correlative with the Elbert Formation and Ouray Limestone of southwestern Colorado.

Mississippian rocks are represented by the Redwall Limestone and, in the Four Corners area, by the Leadville Limestone. The Redwall Limestone was named by Gilbert (1875, p. 161) for the red-stained limestone cliff that forms part of the Grand Canyon. Darton (1910, p. 21) later designated Redwall Canyon as the type locality for the limestone.

## CAMBRIAN ROCKS

Cambrian rocks are exposed only in Marble Canyon and in the canyon of the Little Colorado River. They are in the subsurface, however, in the western and northern parts of the reservations, where they generally are overlain by more than 3,000 feet of younger strata. Cambrian rocks are absent in the Zuni Mountains and on the Defiance Plateau, where the younger strata overlie Precambrian igneous and metamorphic basement rocks.

### LOWER BOUNDARY OF THE CAMBRIAN

In the Grand Canyon and in the nearby part of the Navajo country, the lower boundary of the Cambrian is represented by a widespread erosion surface, which has truncated igneous, metamorphic, and sedimentary rocks of Precambrian age. This surface, often called the Ep-Algonkian surface, is well exposed and has been discussed by many geologists. The Early Cambrian topography was of low relief but irregular and hilly. The Tapeats Sandstone, basal unit of the Tonto Group, was deposited in hollows between the hills, and the Bright Angel Shale shows a progressive overlap around these hills, which finally were buried during the deposition of the Muav Limestone. In exposures 4 miles south of the confluence of the Colorado and Little Colorado Rivers, Cambrian rocks rest on the Dox Sandstone, the uppermost unit of the Precambrian Grand Canyon Series. There, McKee (1945, p. 142) reported that the top beds of the Dox Sandstone are beveled and weathered along a surface having low relief. To the west, Wheeler and Kerr (1936, p. 5) reported as much as 800 feet of relief along the unconformity where Cambrian strata overlie crystalline rocks. East of the Grand Canyon, deep oil tests that penetrate the basement rocks show little evidence of relief along the surface underlying the Cambrian rocks. The hiatus between Precambrian and Cambrian deposition may represent considerable late Precambrian and Early Cambrian time.

### GRAND CANYON AREA

Rocks of Cambrian age comprise the Tonto Group, which overlies the Precambrian basement rocks. The group thins generally southeastward and records the earliest Paleozoic marine invasion in the Navajo country. The group is 1,500 feet thick in the western Grand Canyon and progressively thins to 1,000 feet at the mouth of the Little Colorado River and to 750 feet in an oil test near Kaibito; it is absent from the Defiance Plateau Highlands–Zuni Highlands.

#### TAPEATS SANDSTONE

The Tapeats Sandstone, where exposed, erodes to form a cliff; in the Grand Canyon it caps a prominent bench above an unconformity cut chiefly on rocks of Precambrian age. The sandstone is moderate orange pink (5*YR* 8/4) to light gray (*N* 7)—color designations by Goddard and others (1948)—and weathers to hues of reddish brown and brown. It is composed of very fine to very coarse subrounded to subangular poorly sorted clear, white, and pink quartz grains. Pink orthoclase is a common to abundant accessory mineral, and chlorite is present locally; in some zones the feldspar is weathered. The sandstone is thin to thick bedded, and crossbedding is displayed in most exposures. The crossbedding is usually of the planar-tabular type, and the crossbeds are medium to low angle and medium to large scale. Lenses of conglomerate and conglomeratic sandstone occur throughout the unit, but they are more common near the basal contact. Pebbles in the conglomerate are rounded to subrounded and consist mainly of white, clear, and pink quartz and chert and subordinately of gneiss, schist, and granite. Mudstone and siltstone beds are intercalated in the Tapeats and are common in the upper part of the sandstone. Locally, the uppermost beds form a transitional zone with the overlying Bright Angel Shale. The Tapeats generally is well cemented by siliceous material, and in many places it is a quartzite.

The Tapeats Sandstone is between 250 and 300 feet thick near the confluence of the Little Colorado and Colorado Rivers (McKee, 1945, p. 141). The unit thins eastward and southward toward the Defiance Plateau, where it was never deposited or was removed by later erosion.

The Tapeats Sandstone is not considered an aquifer because it is generally buried by more than 3,000 feet of strata. It is generally well cemented and does not transmit water rapidly unless fractured, and it probably contains highly mineralized water. The salt seeps issuing from this unit near the mouth of the Little Colorado River have been a source of salt for the Hopi Indians for centuries.

#### BRIGHT ANGEL SHALE

The middle unit of the Tonto Group, the Bright

Angel Shale, erodes to form a continuous steep slope between the cliff-forming Tapeats Sandstone below and the Muav and Redwall Limestones above. The formation consists of broad lithologic zones. These are, in ascending order, soft green micaceous sandy shale and thin partly crossbedded sandstone, olive-gray limestone, soft green micaceous sandy shale, and alternating layers of shale and purplish-brown sandstone. Glauconite is the principal constituent of some shale beds but may be absent in others. The basal contact is in a transitional zone containing interbedded sandstone, silty sandstone, and shale. The contact between the Bright Angel Shale and the Tapeats Sandstone is placed arbitrarily at the top of coarse Tapeats-like sandstone.

The Bright Angel Shale is 324.5 feet thick in the middle part of the Grand Canyon (McKee, 1945, p. 141–142). The formation thins eastward, and in the small and inaccessible outcrops in Marble Canyon it is about 300 feet thick. At the Sinclair Oil Co. Navajo Tribal 1 oil test near Kaibito, 255 feet of sediment assigned to the Bright Angel was recognized in the subsurface. Except for one seep in Marble Canyon, ground water is not known to discharge from the Bright Angel Shale in the Navajo Indian Reservation; on the contrary, the formation restricts movement of water and forms a thick confining layer below the ground-water system of the Muav and Redwall Limestones.

#### MUAV LIMESTONE

The uppermost unit of Cambrian age is the Muav Limestone, which forms "the predominantly calcareous part of the Tonto group" (Noble, 1914, p. 64). In Muav Canyon the limestone units are "impure thin-bedded bluish-gray limestones which have a mottled appearance, imparted by infinitely numerous thin bands or lenses of buff or greenish shaly material" (Noble, 1914, p. 64). The limestone becomes more impure and the number and thickness of clastic beds increase notably as the Muav is traced eastward through the Grand Canyon (McKee, 1945, p. 103–104). Near the mouth of the Little Colorado River, the Muav Limestone consists of a lower shale and sandstone interval, a middle limestone interval, and an upper shale and sandstone interval having a thin limestone bed as the topmost unit. The Muav is gradational with the underlying Bright Angel Shale.

McKee (1945, p. 141) measured 414.5 feet of Muav and "unclassified Cambrian" east of Lava Canyon. During the drilling of the Sinclair Oil Co. Navajo Tribal 1 oil test, 315 feet of sediment believed to be correlative with the Muav was penetrated.

In the reservations the Muav Limestone is the lower and less productive unit of a multiple aquifer system, which consists of the Muav and Redwall Limestones. Only a few small springs issue from the Muav in Marble Canyon and the canyon of the Little Colorado River, although considerable water discharges from this formation in the Grand Canyon area (Johnson and Sanderson, 1968, table 1).

#### FOUR CORNERS AREA

Rocks of probable Cambrian age have been penetrated during the drilling of some of the deep oil tests in the Four Corners area. The rocks range in thickness from about 250 to 750 feet and consist, in ascending order, of sandstone, shale, and limestone beds. Sample cuttings from wells that penetrated these rocks were not studied during this investigation, and the water-bearing potential of the rocks is unknown, although it is probably similar to that of the Tonto Group in the western part of the Navajo country.

#### REGIONAL RELATIONS

Correlation of the Cambrian rocks in the Navajo country is hampered by the smallness and inaccessible nature of the outcrops and the difficulty of identifying Cambrian deposits in the widely separated oil-test wells. In addition, Resser (1946, p. 184) stated that

> Middle Cambrian faunas generally are still too largely undescribed to permit precise correlation but there appears to be a definite relationship, as shown by faunas, between the Cadiz formation of southern California and the Bright Angel-Muav formations. Likewise there is a definite relationship between the Middle Cambrian fauna of southern Nevada and that of Grand Canyon.

Based on the fossils described in the Grand Canyon, the age of the Tonto Group is considered to be Early to Middle Cambrian.

The relations of the rocks of probable Cambrian age in the Four Corners area are not established clearly, although the rocks possibly are lateral equivalents of the Tonto Group. Cooper (1955, p. 59–61) suggested that these rocks are correlative with most of the Cambrian strata of central Utah. He also indicated tentative correlation with the Tonto Group —the Tintic and Ophir Formations as equivalents of the Tapeats Sandstone and Bright Angel Shale, respectively, and the Bowman and Hartmann Limestones undifferentiated as equivalents of the Muav Limestone. The Lynch Dolomite, the youngest unit in central Utah, apparently is not correlative with any part of the Cambrian section in the Grand Canyon.

### PRE-DEVONIAN UNCONFORMITY

A major erosional unconformity separates the Middle Cambrian Muav Limestone from the overlying rocks of Devonian age. Despite the great time interval represented by the unconformity, the surface is an inconspicuous feature because it is parallel to the bedding in the Muav Limestone. However, there was slight relief on the old erosion surface, and, locally, shallow channels were cut into the underlying beds.

Rocks of definite Ordovician or Silurian age are not known to occur in northern Arizona, although Clair (1952, p. 38) suggested the presence of beds of questionable Ordovician age in several oil tests in the Four Corners area. Whether Ordovician and Silurian deposits were laid down and subsequently removed by pre-Devonian or pre-Mississippian erosion cannot be determined from the available geologic information.

### DEVONIAN ROCKS

In the reservations, rocks of Devonian age are exposed in Marble Canyon and the lower part of the canyon of the Little Colorado River. Rocks of probable Devonian age have been recognized in the deep oil tests drilled in the northern and western parts of the reservations; the maximum thickness of these rocks is 500 feet near Mexican Hat. The discontinuous Devonian beds in Marble Canyon are generally less than 100 feet thick, and Devonian strata are not present in exposures in the central part of the Defiance Plateau and in the Zuni Mountains, where rocks of Permian age overlie granitic basement rocks of Precambrian age. Devonian strata, however, are recognized in the northern Chuska (Lukachukai) Mountains and in the northern part of the Defiance Plateau.

Devonian strata in the Grand Canyon were first noted and named the Temple Butte Limestone by Walcott (1880; 1883, p. 437–438; 1890, p. 50). These strata have not been studied extensively in the eastern Grand Canyon area. The following brief description of the Devonian rocks was prepared by E. D. McKee (written commun., 1956):

> Rocks of Devonian age are exposed at many places along the walls of Marble Canyon in the Navajo Indian Reservation, from mile 37 [along the Colorado River downstream of Lees Ferry] to the head of Grand Canyon. These strata are referred to as the Temple Butte limestone from Temple Butte in the Grand Canyon. They consist largely of lavender to purple sugary limestone and gray fine-grained silty dolomites. Locally, beds are gnarly and contorted, and everywhere they fill irregular channels cut into the underlying Muav limestone. Because of contrasts in color and hardness, Devonian deposits filling such pockets are conspicuous features in the canyon walls, some of them extending downward into the Cambrian sequence as much as 130 feet.

In central Arizona, rocks of Devonian age are assigned to the Martin Limestone (Ransome, 1904, p. 33). Subsurface tracing by Huddle and Dobrovolny (1945) indicated that Devonian strata, possibly the Martin Limestone, are present south of the Navajo Indian Reservation. The penetration of Devonian and Mississippian rocks by oil tests in the Black Mesa basin in the central part of the reservations confirms the statement by Huddle and Dobrovolny (1952, p. 82), who wrote: "Devonian and Mississippian strata are probably present in normal thicknesses in Black Mesa basin." Sizable thicknesses of strata of Devonian age are present in western Grand Canyon and in Black Mesa basin, which indicates that the eastern Grand Canyon area was a high and that most of the Devonian strata were stripped off by erosion during the parts of Devonian and Mississippian time prior to the deposition of the Redwall Limestone.

In the Four Corners area, several wells have penetrated deposits that are of probable Devonian age. The top of the deposits is indicated by a bright-green waxy shale. These rocks probably are correlative with the Elbert Formation and the Ouray Limestone of southwestern Colorado rather than with the Temple Butte Limestone to the west and the Martin Limestone to the south. The Temple Butte Limestone and the other Devonian rocks are known to have yielded some water during the drilling of deep oil tests in the Black Mesa basin and in the Four Corners area.

### MISSISSIPPIAN ROCKS

The Mississippian rocks crop out only in the canyons of the Colorado and Little Colorado Rivers, but they are present in the subsurface except in the southeastern part of the reservations. In the Grand Canyon area, Mississippian rocks are referred to as the Redwall Limestone. In the Four Corners area, rocks of Mississippian age are usually referred to as the Leadville Limestone.

Gutschick (1943, p. 5) and McKee (1960, p. 244) divided the Redwall Limestone in the Grand Canyon into four members. According to McKee:

> The four members of the Redwall limestone are tentatively designated as: (a) member A—the basal thick-bedded unit, 70 to 130 feet thick in Grand Canyon, consisting of limestone in the western part but of dolomite in the eastern part; (b) member B—65 to 105 feet thick, composed of alternating beds of chert and carbonate rock 1 to 6 inches thick and which form a conspicuous banded cliff in most places; (c) member C—a very thick-bedded, massive, cliff-forming unit, 200 to 400

feet thick, composed of both aphanitic limestone and coarse-grained, largely crinoidal limestone; and (d) member D—40 to 100 feet thick, thin-bedded, mostly aphanitic limestone, with some chert beds.

After a detailed study of the Redwall Limestone formal names were applied to the members of the Redwall, in ascending order: the Whitmore Wash Member (member A), the Thunder Springs Member (member B), the Mooney Falls Member (member C), and the Horseshoe Mesa Member (member D) (McKee, 1963, p. C21).

The Mississippian rocks thin progressively southeastward across the reservations and are not recognized in the subsurface east of Holbrook. The Redwall Limestone is about 600 feet thick in Marble Canyon and is more than 400 feet thick at Salt Trail in the canyon of the Little Colorado River. The Mississippian rocks are between 200 and 400 feet thick in the Four Corners area.

The Redwall Limestone appears to be solid and massive when seen from a distance, but closer inspection shows that it contains numerous solution channels and cavities developed along bedding planes, faults, and joints. In Marble Canyon, small springs issue from some of these solution channels near the level of the Colorado River. In the canyon of the Little Colorado River, Blue Spring—the largest spring on the Colorado Plateaus—discharges about 90 cfs (cubic feet per second) from fractures and solution channels along faults in the Redwall. Blue Spring and smaller springs downstream issuing from the Redwall and Muav Limestones maintain

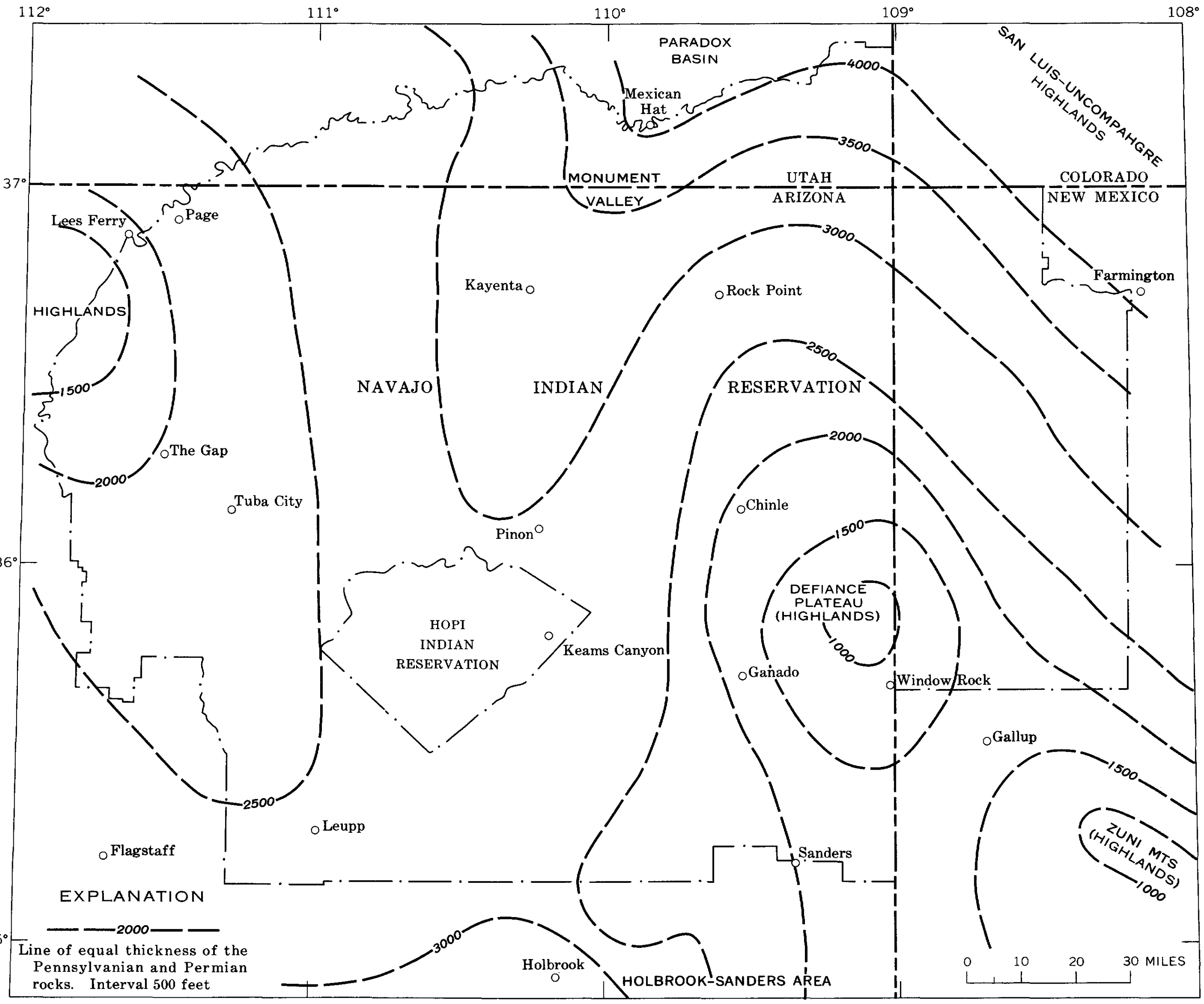


**FIGURE 2.**—Thickness of the Pennsylvanian and Permian rocks.

the perennial flow in the lower reach of the Little Colorado River, which is about 220 cfs. Travertine precipitated by the spring flow forms irregular mounds and dams at several places in the canyon bottom.

## PENNSYLVANIAN AND PERMIAN ROCKS

The main exposures of Pennsylvanian and permian rocks in the Navajo country are in the Defiance Plateau area, Monument Valley area, and the southwestern area—which includes eastern Grand Canyon, Marble Platform, and the Mogollon Slope. They also occur to the southeast in the Zuni Mountains area. Thicknesses of these rocks are 1,100 feet in the Defiance Plateau, 3,500 feet in the central part of Monument Valley, 2,000 feet near the mouth of the Little Colorado River (at the Navajo Reservation boundary southwest of Gap), and 1,500 feet in the Zuni Mountains (fig. 2). These rocks include the thick sequence of red beds that is spectacularly displayed in exposures throughout the Navajo country. The red-bed sequence of the Permian and Pennsylvanian rocks is from 1,000 to more than 2,500 feet thick (fig. 3). The thickest red-bed sequence is in the south-central part of the reservations.

### PREVIOUS INVESTIGATIONS AND TERMINOLOGY

The stratigraphic nomenclature used for Pennsylvanian and Permian rocks basically is that presented by Baker and Reeside (1929), as modified by Read and Wanek (1961). These rocks are assigned different names in each of their principal areas of out-

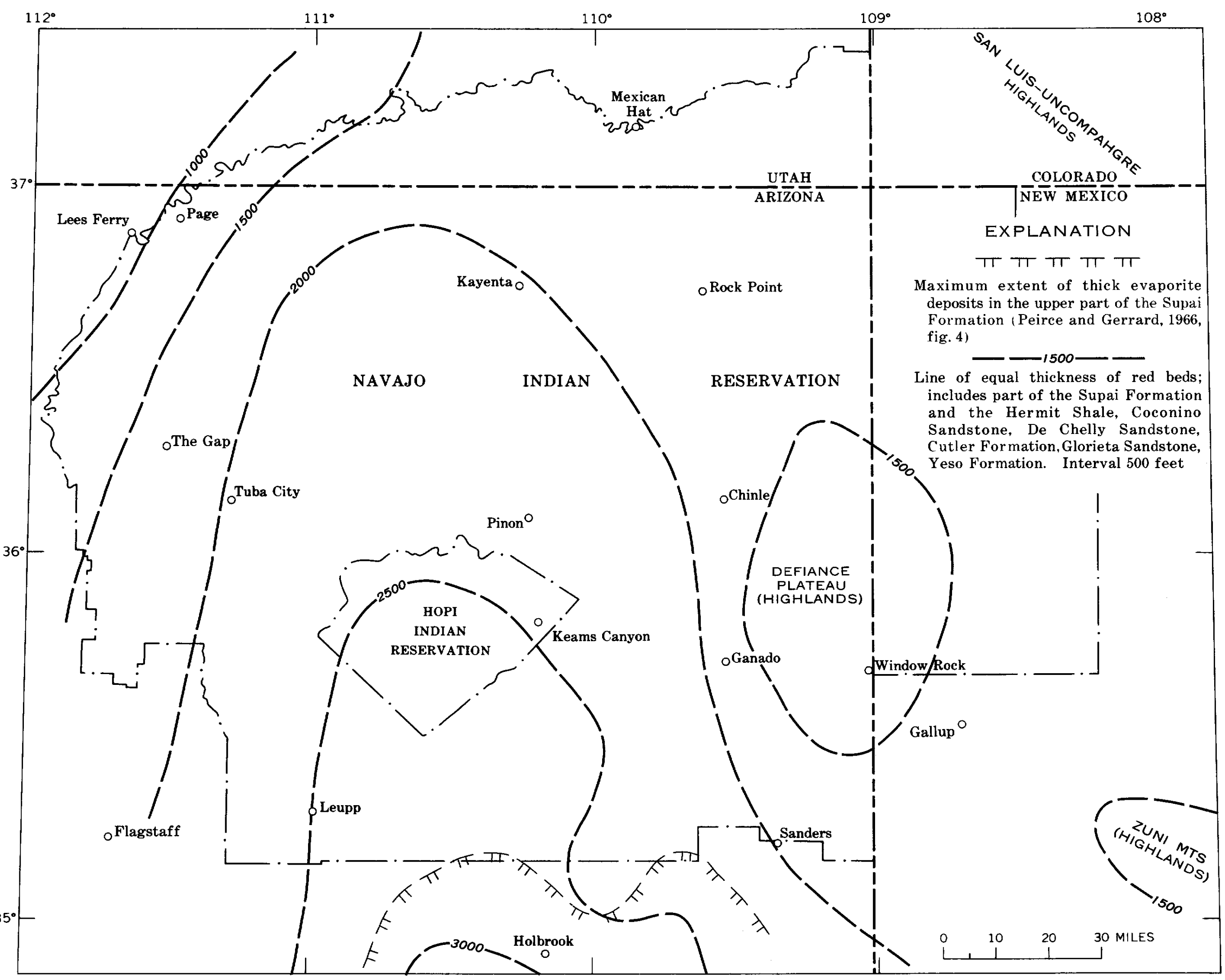


FIGURE 3.—Thickness of the Pennsylvanian and Permian red beds, and maximum extent of thick evaporite deposits in upper part of the Supai Formation.

TABLE 1.—*Stratigraphic nomenclature of the Pennsylvanian and Permian rocks.*

| System | Period | Subdivisions: Colorado Plateaus | Subdivisions: West Texas | Southwestern area: Grand Canyon | Southwestern area: Northern Mogollon Slope | Defiance Plateau area | Monument Valley area | Zuni Mountains area |
|---|---|---|---|---|---|---|---|---|
| | Permian | Upper | Ochoa | Erosion | Erosion | Erosion | Erosion | Erosion |
| | Permian | Upper | Guadalupe | Erosion | Erosion | Erosion | Erosion | Erosion |
| | Permian | Lower | Leonard | Kaibab Limestone; Toroweap Formation; Coconino Sandstone; Hermit Shale (Aubrey Group) | Kaibab Limestone; Coconino Sandstone; Upper member (Supai Formation) | San Andres(?) Limestone; Red beds in Bonito Canyon; De Chelly Sandstone: Upper member, Lower member | Erosion; De Chelly Sandstone Member; Organ Rock Tongue; Cedar Mesa Sandstone Member; Halgaito Tongue (Cutler Formation) | Erosion; San Andres Limestone; Glorieta Sandstone; Yeso Formation: San Ysidro Member, Meseta Blanca Sandstone Member |
| | Permian | Lower | Wolfcamp | Supai Formation (Aubrey Group) | Middle member; Lower member (Supai Formation) | Supai Formation | Rico Formation | Abo Formation |
| Carboniferous | Pennsylvanian | | Virgil | Supai Formation (Aubrey Group) | Lower member (Supai Formation) | Erosion | Rico Formation | Erosion |
| Carboniferous | Pennsylvanian | | Missouri | Erosion | Lower member (Supai Formation) | Erosion | Hermosa Formation | Erosion |
| Carboniferous | Pennsylvanian | | Des Moines | Erosion | Naco Formation | Erosion | Hermosa Formation | Erosion |
| Carboniferous | Pennsylvanian | | Atoka | Erosion | Naco Formation | Erosion | Molas Formation | Erosion |
| Carboniferous | Pennsylvanian | | Morrow | Erosion | Erosion | Erosion | Erosion | Erosion |

crop—the Grand Canyon, Defiance Plateau, Monument Valley, and Zuni Mountains (pl. 1; table 1). Detailed stratigraphic relations of the Pennsylvanian and Permian rocks as inferred from their main outcrop areas and from subsurface data are shown on plate 2.

The terminology in the southwestern area of the reservations is that used chiefly in the eastern Grand Canyon. The first reference to Permian rocks in this area was made by Marcou (1856, p. 153) and Newberry (1861). Gilbert (1875, p. 176–185) assigned the term "Aubrey Group" to the Permian and Pennsylvanian sedimentary sequence in the Grand Canyon, deriving the name from the Aubrey Cliffs near Seligman, Ariz. Gilbert, however, did not name the units comprising the group, but later names were assigned to them, in ascending order: the Supai Formation (Darton, 1910, p. 25), Hermit Shale (Noble, 1922, p. 26), Coconino Sandstone (Darton, 1910, p. 27), and Kaibab Limestone (Darton, 1910, p. 28). (See table 1.) Later, McKee (1938) recognized an unconformity at the base of the massive resistant cliff-forming upper unit of the Kaibab Limestone. He removed the beds below this unconformity from the Kaibab Limestone and assigned them to the Toroweap Formation. The Aubrey Group now consists of the Supai Formation, Hermit Shale, Coconino Sandstone, Toroweap Formation, and Kaibab Limestone. The Supai Formation in the Mogollon Slope and in exposures along the Mogollon Rim—the south boundary of the Colorado Plateaus—was divided by Huddle and Dobrovolny (1945) into upper, middle, and lower members (table 1). An additional formation—the Naco Formation, named originally the Naco Limestone by Ransome (1904)—underlies much of the Mogollon Slope area along the southern boundary of the reservations.

The Pennsylvanian and Permian rocks of the Defiance Plateau consist of two formations (McKee, 1934a; Read and Wanek, 1961)—the De Chelly Sandstone, named by Gregory (1915), and the Supai Formation. All or part of these formations previously were assigned to the Cutler Formation, Coconino Sandstone, and Moenkopi Formation (Gregory, 1917; Darton, 1925; Baker and Reeside, 1929). In the Defiance Plateau, the De Chelly Sandstone is divided into an upper member, which is present throughout the area, and a lower member, which is present only in the central part of the area (Read and Wanek, 1961, table 1).

The nomenclature of the upper Paleozoic rocks in Monument Valley principally is that used by Baker and Reeside (1929) and Baker (1936). The Pennsylvanian and Permian rocks consist, in ascending order, of the Molas, Hermosa, Rico, and Cutler Formations. The Molas Formation, between the

Leadville Limestone of Mississippian age and the Hermosa Formation of Pennsylvanian age, was recognized by Huddle and Dobrovolny (1945) in sample cuttings from wells drilled in Monument Valley. The Cutler Formation is subdivided, in ascending order, into the Halgaito Tongue, the Cedar Mesa Sandstone Member, the Organ Rock Tongue, and the De Chelly Sandstone Member (table 1). The Hoskinnini Tongue of the Cutler Formation (Baker and Reeside, 1929; Baker, 1936) was reassigned as the basal member of the Moenkopi Formation (Stewart, 1959) and may be either Triassic(?) or Permian in age.

In the Zuni Mountains the Permian rocks are divided into four formations, which, in ascending order, are the Abo Formation, Yeso Formation, Glorieta Sandstone, and San Andres Limestone (Read and Wanek, 1961, pl. 1). The Yeso Formation is subdivided, in ascending order, into the Meseta Blanca Sandstone Member and the San Ysidro Member. No rocks of an established Pennsylvanian age are exposed on the summit of the mountains, but they have been reported in deep oil tests drilled in the adjoining part of San Juan basin.

### BOUNDARIES

Pennsylvanian rocks overlie the Redwall Limestone of Mississippian age in the western and northern parts of the Navajo country. The basal Pennsylvanian units wedge out generally along the flanks of the Defiance Plateau Highlands–Zuni Highlands, and only rocks of Permian age are present on top of these highlands.

The lower boundary of the Pennsylvanian rocks is not exposed in Monument Valley and is known only from information from deep oil tests. It is the contact between the Molas Formation and the Redwall (Leadville) Limestone. The Molas Formation consists of red calcareous shale and sandstone, containing chert, limestone, and quartzite pebbles, and thin lenses of fossiliferous limestone. Where the Molas is exposed in Animas Canyon north of Durango, Colo., it rests unconformably on the Leadville Limestone and in places fills sinkholes that had formed as part of a karst topography.

The lower boundary of the Pennsylvanian rocks in the western part of the Navajo country was examined on Salt Trail, which leads into the canyon of the Little Colorado River 5½ miles east of the confluence of the Colorado and Little Colorado Rivers. Here, the Supai Formation fills channels as much as 30 feet deep cut into the eroded Redwall Limestone surface. The basal unit of the Supai is a light-brown (5*YR* 6/4) conglomerate and ranges in thickness from 20 to 50 feet. It is composed of poorly sorted sand and gravel and has a firm calcareous cement. The sand is subangular coarse- to fine-grained quartz, and the gravel consists of angular to rounded pebbles, cobbles, and boulders of limestone, chert, sandstone, and mudstone. The bedding in the basal unit is laminated in the finer grained parts and thick and gnarly in the coarser beds. The unit appears to be similar to the basal "red residual member" of the Naco Formation described by Huddle and Dobrovolny (1952, p. 88–90) in central Arizona. Huddle and Dobrovolny (1952, p. 90) stated that "the red residual member of the Naco formation is similar in lithology and origin to the Molas formation of Colorado."

Permian rocks overlie granitic basement rocks of Precambrian age in much of the Defiance Plateau and Zuni Mountains. The Supai Formation is the basal Permian unit of the Defiance Plateau and unconformably rests on highly fractured and weathered granite and metamorphosed rocks 1 mile south of Hunters Point (pl. 1). The relief along the unconformity is from 15 to more than 50 feet. Northwest of Fort Defiance in Bonito Canyon, the Supai was deposited unconformably on a dense quartzite, which is generally considered to be of Precambrian age (Gregory, 1917, p. 17–18). The quartzite was eroded to a surface of rounded domes and knobs, and this surface has a relief of about 100 feet. In the Zuni Mountains, the Abo Formation is the lowermost Permian unit, and it rests on granite or in places on "a thin sequence of argillaceous limestone" (Read and Wanek, 1961, p. 3), which is of questionable Pennsylvanian age.

The boundary between the Pennsylvanian and Permian rocks is placed arbitrarily in the Supai Formation in the western and southern Navajo country and in the Rico Formation in the Four Corners area.

### SOUTHWESTERN AREA

The Permian and Pennsylvanian rocks are exposed chiefly in the canyons of the Colorado River, and only the Kaibab Limestone covers an extensive area on Marble Platform, the Coconino Plateau, the San Francisco Plateau, and the Mogollon Slope (pl. 1). Away from the canyons, formations older than the Kaibab Limestone are exposed only in a few places along the margins of the Coconino Plateau and near Holbrook.

The term "Aubrey Group," as a designation of the Permian rocks of the Grand Canyon area, is still retained in formal writing, although it is no longer used by many geologists working in the area. The distinctive lithology of the several units and the presence of an unconformity at the base of the Kaibab Limestone tend to emphasize the individual formations rather than the group. In general, the term "Aubrey Group" is not used to describe rocks east of the Grand Canyon in the contiguous regions of the San Francisco Plateau and the Mogollon Slope.

### SUPAI FORMATION AND HERMIT SHALE

The type locality of the Supai Formation, as described by Darton (1910, p. 25), is the conspicuous exposures of as much as 1,500 feet of red sandstone and shale near the Supai Indian village in Cataract Creek (Havasu Canyon)—a tributary of the Colorado River in the western part of the Grand Canyon. The Hermit Shale was named by Noble (1922) after the Hermit basin in the Grand Canyon. In the southwestern area of the Navajo country the Hermit Shale and Supai Formation crop out only in Marble Canyon and the lower 25 miles of the canyon of the Little Colorado River. The Hermit Shale is not easily separated from the Supai Formation in logs or in drill cuttings from wells.

#### GENERAL DESCRIPTION AND FIELD RELATIONS

The Supai Formation and Hermit Shale of the Grand Canyon area consist of a series of alternating red siltstone and sandstone beds that form a bench-slope topography above massive cliffs of the Redwall Limestone. The siltstone units of the Supai are moderate red (5*R* 4/6), weather to pale reddish brown (10*R* 5/4), and are flat and lenticularly bedded. The sandstone units are usually light brown (5*YR* 6/4) and are frequently stained red from weathering of the overlying siltstone units. The sandstone beds are composed of fine to very fine grained subrounded to subangular clear and amber quartz grains. Some of the grains show a thin coating of iron oxide, which is partly responsible for the color of the unit. The unit has a weak to firm calcareous cement. Crossbedding in the sandstone units is of the small-scale low-angle wedge-planar type. Studies of crossbedding in the Supai Formation in the eastern part of the Grand Canyon were made by McKee (1940, p. 821), who stated: "The interpretation that best explains all the features of the Supai cross laminations is that they were developed as individual sets on the advancing fronts of small, local deltas or cones, built up presumably on the topset surface of a major river delta or flood plain."

In Marble Canyon the Supai Formation is divisible into three broad units: an upper and a lower sandy siltstone to silty sandstone, which form irregular slopes and are typical of the Supai Formation farther south, and a middle crossbedded sandstone, which erodes into irregular ledges and small cliffs. The narrowest part of the Colorado River channel is in the short reach that is enclosed by the middle sandstone unit in Marble Canyon. The sandstone is generally moderate orange pink (5*YR* 8/4) to reddish orange brown (10*R* 5/6), and a reconnaissance study indicates that it is mainly well to fairly sorted and very fine to fine grained. The unit displays large-scale high- to low-angle trough crossbeds, most of which dip southward to southeastward. In overall appearance the middle sandstone unit is similar to the Cedar Mesa Sandstone Member of the Cutler Formation in Monument Valley. Farther south in the area, near the confluence of the Colorado and Little Colorado Rivers, the crossbedded sandstone is not as prominent, and all the units in the Supai Formation are lithologically similar. In Marble Canyon a few apparently lenticular gray limestone beds are present in the basal 50–100 feet of the Supai Formation near the level of the Colorado River. These limestone beds are dense and hard and are more than 5 feet thick. The limestone beds tongue out southward because limestone of this type is not present in the Supai in eastern Grand Canyon or in the canyon of the Little Colorado River.

The Hermit Shale overlies the Supai Formation and consists of red sandy shale and fine-grained friable sandstone. It is generally similar to the Supai Formation but usually lacks the crossbedded sandstone beds. Shrinkage cracks, ripple marks, and rain prints occur in many of the beds. An unconformity is present at the base of the Hermit Shale in the Grand Canyon, but it has not been recognized in the Navajo Indian Reservation. The Hermit thins eastward across the Grand Canyon area, and near Desert View Point it has been estimated to be from 75 to 100 feet thick (Darton, 1925, p. 90).

As seen in exposures in Oak Creek Canyon and as described in logs of wells drilled between Flagstaff and the reservations, the uppermost 100–200 feet of the Supai is generally a pale-red sandstone similar in lithology to the overlying Coconino Sandstone. The crossbeds, however, are not as large scale and were deposited at lower angles than those in the Coconino. This sandstone unit of the upper part of the Supai apparently thins northward from Oak Creek Canyon, because it is not exposed in the canyon of the Little Colorado River west of Cameron, although it is recognized in the logs of some of the deep water wells drilled near Wupatki Ruin. The unit, however, thickens northeastward from Oak Creek Canyon to Black

Mesa basin, where subsurface studies of the strata penetrated by oil tests indicate that about 600 feet of sandstone, which contains some interbeds of siltstone and sandy siltstone, comprises the upper part of the Supai Formation (H. W. Peirce, oral commun., 1968).

The sandy deposits of the Supai Formation become finer grained southeastward from the Grand Canyon–Oak Creek Canyon area and comprise a thick sequence of siltstone and silty sandstone, which is interbedded with gypsum, limestone, and salt. These thick evaporite deposits in the Supai occur only in the southern part of the reservations and the Mogollon Slope (Peirce and Gerrard, 1966).

The Supai Formation in the Mogollon Slope area consists of three members( Huddle and Dobrovolny, 1945). The lower member is chiefly a limy sandstone to sandy siltstone with interbedded limestone. The middle member generally is sandier and contains considerable gypsum locally. The upper member contains most of the evaporite deposits, including salt (halite and potash) in the area generally south of the Puerco River (fig. 3). The Supai conformably overlies the Naco Formation or rests unconformably on older Paleozoic and Precambrian basement rocks.

The combined thickness of the Hermit Shale and Supai Formation is 830 feet along Salt Trail in the canyon of the Little Colorado River. Examination of drill cuttings of the Burrell-Collins oil test 2½ miles west of Gap indicates 943 feet of Hermit Shale and Supai Formation. The presence of Hermit Shale could not be determined in the Sinclair Oil Co. Navajo Tribal 1 oil test, and the 1,700-foot interval between the Coconino and the Redwall was assigned to the Supai and Cutler Formations. Between 1,600 and 1,700 feet of strata is assigned to the Supai Formation in Black Mesa basin, where several oil tests have been drilled in the Hopi Indian Reservation.

Neither the Supai Formation nor the Hermit Shale is considered to be an aquifer in the southwestern part of the Navajo country. The Hermit Shale is not known to yield water to wells or springs in the reservations. The Supai yields water to a few deep wells drilled between the reservation boundary and Oak Creek Canyon (Akers and others, 1964; McGavock, 1968). Only one well, however, may tap water in the Supai in the southwestern part of the reservations.

#### AGE

No fossils have been described from the Hermit Shale or Supai Formation in the western part of the Navajo country. In the Grand Canyon area to the west, however, plant fossils from the Hermit Shale have been described by White (1929) as being in the "upper Rothliegende"—the upper part of the Lower Permian. C. B. Read stated that the plants are of Leonard age (written commun., 1964).

When redefining the Supai Formation, Noble (1922, p. 62) included limestone beds containing invertebrates of Pennsylvanian age previously assigned to the underlying Redwall Limestone. McNair (1951, p. 523) found that the lower part of the Supai, which intertongues with the upper part of the Callville Limestone in the western part of the Grand Canyon, is of latest Pennsylvanian age. Huddle and Dobrovolny (1945) indicated that the Supai probably ranges in age from Des Moines (Middle Pennsylvanian) through Leonard (late Early Permian) in central and northeastern Arizona. Therefore, the Supai Formation in the western and southwestern parts of the Navajo country is assigned to the Permian and Pennsylvanian, and the Hermit Shale is considered Permian in age.

### COCONINO SANDSTONE

The name "Coconino Sandstone" was proposed for the "crossbedded gray to white sandstone of the Aubrey Group that is so conspicuous in the walls of the Grand Canyon" (Darton, 1910, p. 27). Typically, the Coconino, in combination with the Toroweap Formation and Kaibab Limestone, forms a vertical blocky cliff above the steep slopes of the Hermit Shale and Supai Formation. A specific type locality was not designated by Darton, but he implied that the formation derived its name from the exposures on the north edge of the Coconino Plateau in the Grand Canyon area. McNair (1951, p. 533) stated that a section at Aubrey Cliffs can be considered as the type section. The name "Coconino" is a Havasupai Indian word meaning "little water" (Barnes, 1954); nevertheless, the Coconino Sandstone is one of the chief aquifers in the Navajo country. In Marble Canyon a white band of calcium carbonate deposits outlines a prominent seepline at the base of the Coconino.

#### GENERAL DESCRIPTION AND FIELD RELATIONS

The Coconino Sandstone crops out only in the canyons of the Colorado and Little Colorado Rivers and on Coconino Point in the reservations; south of the reservations it crops out as far east as Holbrook. It is continuous in the subsurface of Black Mesa basin and areas to the south and west and is easy to recognize in drill cuttings from wells.

The Coconino Sandstone ranges from very pale orange (10*YR* 8/2) to grayish orange (10*YR* 7/4) and is almost white (*N* 8) in places. Samples obtained from water wells drilled into the Coconino in the southwestern part of the reservations show that the sandstone consists of very fine to medium-grained well-sorted rounded to subangular clear, stained, and frosted quartz grains. Results of McKee's (1934b, p. 112) regional study indicate that the grains of the Coconino are coarse "at the southern limits of the formation along the Mogollon Rim, but that, in general, they grade into much finer material to the north [in the Grand Canyon area]." The sandstone is cemented principally with a siliceous bonding agent, but in some places it includes also some calcareous material. Accessory minerals are rare. McKee (1934b, p. 92) noted the presence of occasional grains of feldspar in the Grand Canyon area.

Crossbedding is one of the most characteristic features of the Coconino. It is principally of the wedge-trough type with medium- to large-scale and medium- to high-angle crossbeds, although tabular-planar crossbedding types are present locally. The crossbeds in different sets are inclined in different directions, but they have an average dip to the southeast (Stewart and others, 1957, fig. 79). The sandstone of the different sets is remarkably uniform in lithology. Ripple marks are common, have wide amplitudes and low crests, and are found on the foreset bedding planes (McKee, 1934b, p. 101); ripple marks are commonly found on the leeward face of modern sand dunes. The ripple marks, crossbedding, and good sorting are characteristic of windblown deposits; therefore, the Coconino Sandstone is considered to be of eolian origin (McKee, 1934b, p. 112–114; Reiche, 1938, p. 916–918).

The maximum thickness of the Coconino Sandstone is about 900 feet near the Wupatki National Monument southwest of the Navajo Indian Reservation boundary, and the sandstone is about 600 to 800 feet thick in the southwestern area near the Little Colorado River. The Coconino is about 600 feet thick at the confluence of the Little Colorado and Colorado Rivers, thins northward to only 60 feet thick near Navajo Bridge, and wedges out near the Arizona-Utah State line. The Coconino thins eastward from the southwest area and has an average thickness of about 450 feet near Holbrook. According to H. W. Peirce (oral commun., 1967), the sandstone interval generally assigned to the Coconino Sandstone in the Sinclair Oil Co. Navajo Tribal 1 oil-test well near Kaibito and in the oil-test wells in the Hopi Indian Reservation includes both the Coconino and the De Chelly Sandstones; the Coconino is 360 feet thick in the Sinclair Oil Co. Navajo Tribal 1 oil test and about 400–450 feet thick in the Hopi oil tests.

The lower contact of the Coconino with the Hermit Shale is in a gradational zone 20–25 feet thick in outcrops near the Colorado River. In the central and western parts of the Grand Canyon, the Hermit-Coconino contact is usually sharp, marked by an abrupt change from red shale to lighter colored crossbedded sandstone. The Supai-Coconino contact seems also to be gradational in areas south of the reservations. Near Holbrook, the two formations are separated by a transitional zone containing well-sorted sandstone and silty sandstone; this is indicated by drill cuttings from wells. In Oak Creek Canyon the Coconino is separated from the topmost layers of the Supai on the basis of the crossbedding. In a zone between 50 and 100 feet thick, beds displaying the high-angle crossbeds of the Coconino are intercalated with beds having the low- to medium-angle crossbeds of the Supai Formation.

The Coconino Sandstone is one of the chief aquifers in the Navajo country. The Coconino and its lateral equivalents—the Glorieta Sandstone, De Chelly Sandstone, and the De Chelly Sandstone Member of the Cutler Formation—are connected hydraulically and form a multiple-aquifer system, which is the main water-bearing stratum in the southern part of the Colorado Plateaus. The Coconino yields several hundreds of gallons of water per minute to most wells; the amount of drawdown in wells is small. South of the reservations the Coconino contains water of generally good chemical quality and furnishes water to stock, irrigation, industrial, and municipal wells. In the Navajo country, except southwest of Leupp and in the northern part of the Black Mesa basin, the water in the Coconino contains excessive amounts of dissolved solids and may be unfit for any use.

#### AGE

Diagnostic fossils have not been found in the Coconino Sandstone, although vertebrate footprints and worm and other invertebrate trails have been preserved in places. White (1929) placed the age of the Hermit Shale in the late Early Permian, and McKee (1938) assigned a similar age to the Kaibab Limestone. Thus, it would seem that the Coconino Sandstone, which is between these units, is also late Early Permian in age.

### TOROWEAP FORMATION

The Toroweap Formation was named by McKee (1938, p. 12) from exposures in Toroweap Valley in the western Grand Canyon area. McKee divided the formation into three phases—the western phase, intermediate transition phase, and eastern phase. Only the eastern phase is present in the reservations. It is composed of light-colored cross-laminated sandstone, the red beds and limestone of the western phase being absent as a result of facies changes (McKee, 1938, p. 25).

#### GENERAL DESCRIPTION AND FIELD RELATIONS

The Toroweap Formation crops out in the walls of Marble Canyon and in the canyon of the Little Colorado River. It is present also at the base of Grand Falls and in shallow canyons on the sides of the Coconino Plateau. The Toroweap forms irregular and vertical cliffs in most outcrops, but where the formation is friable and contains silty lenses, it weathers to a steep slope—a feature that greatly aids geologic mapping in the canyons.

In general, the Toroweap is composed of light-colored crossbedded, flat-bedded, and gnarly bedded sandstone containing some siltstone lenses. The sandstone is very pale orange (10*YR* 8/2) to white (*N* 8), and the siltstone is pale yellowish orange (10*YR* 8/6). The formation weathers to an overall grayish orange (10*YR* 7/4) or yellowish gray (5*Y* 7/2). The crossbedded sandstone is composed of medium to very fine subrounded to subangular poorly to well-sorted clear and stained quartz grains. The medium- to low-angle and medium-scale crossbeds are of the planar and trough types. The gnarly sandstone beds are only a few inches thick and contain distorted and wavy crossbedding patterns of the small-scale trough type.

In the canyon of the Little Colorado River, the lower one-third of the Toroweap Formation is composed of crossbedded and flat-bedded sandstone, and the upper two-thirds consists mainly of gnarly bedded sandstone. In many places a crinkly limy bed about 12 feet thick is present between 50 and 60 feet above the base.

Argillaceous material in the Toroweap is common in the interstices between the sand grains and, locally, composes as much as 10 percent of the formation. The sandstone is weakly bonded by a calcareous cement and is generally friable, although secondary silica is present in some places, which makes the sandstone more resistant to erosion.

The Toroweap Formation is 117 feet thick along the Salt Trail; in Marble Canyon, opposite the mouth of Badger Canyon, it is between 149 and 175 feet thick (McKee, 1938, p. 190–191, 211). The difference in thickness is the result of post-Toroweap–pre-Kaibab erosion. In the Burrell-Collins oil test, 100 feet of sandstone is assigned to the Toroweap Formation, and about 10 miles west of Cameron the formation is 35 feet thick (pl. 2).

The contact between the Coconino Sandstone and the Toroweap Formation is flat and sharp where exposed in the Navajo country. The contact is a surface that bevels the crossbeds of the Coconino Sandstone. Small irregularities in the contact were reported by McKee (1938, p. 15–17) in places south of the Little Colorado River. The surface on which the Toroweap was deposited does not represent a long hiatus and was probably formed by the reworking and beveling of the unconsolidated Coconino sand by the transgressing water in which the Toroweap Formation was deposited.

The Toroweap Formation is not known to yield water to wells and springs, although the sandstone probably allows the formation to transmit a small amount of water.

#### AGE

In the reservations the Toroweap Formation, like the Coconino Sandstone, lacks a datable fossil record; thus, the age determination is based on the stratigraphic occurrence of the formation between the units containing fossils—the Hermit Shale and the Kaibab Limestone. The Toroweap, therefore, is considered to be late Early Permian in age.

### KAIBAB LIMESTONE

The Kaibab Limestone crops out or is in the subsurface in most of the western quarter of the Navajo country. Nearly continuous outcrops extend from Lees Ferry southward across Marble Platform to the Coconino Plateau and Black Point areas and southwest of Leupp. The Kaibab weathers to form widespread stripped surfaces or blocky irregular cliffs.

Noble (1922, p. 41) measured in detail a section of the formation in the Kaibab Plateau in the Grand Canyon area. The most comprehensive study of the Kaibab Limestone to date was made by McKee (1938), who reassigned the lower part of the Kaibab to the Toroweap Formation and divided the remaining part, in descending order, into the Alpha, Beta, and Gamma Members of the Kaibab Limestone. The Gamma Member was deposited during a time of advancing seas, the Beta Member during a time of extended seas, and the Alpha Member during a time of receding seas. The Alpha and Beta Members of the Kaibab Limestone crop out in the Navajo Indian Reservation, but the Gamma Member is restricted to an area along the western part of the Mogollon Rim.

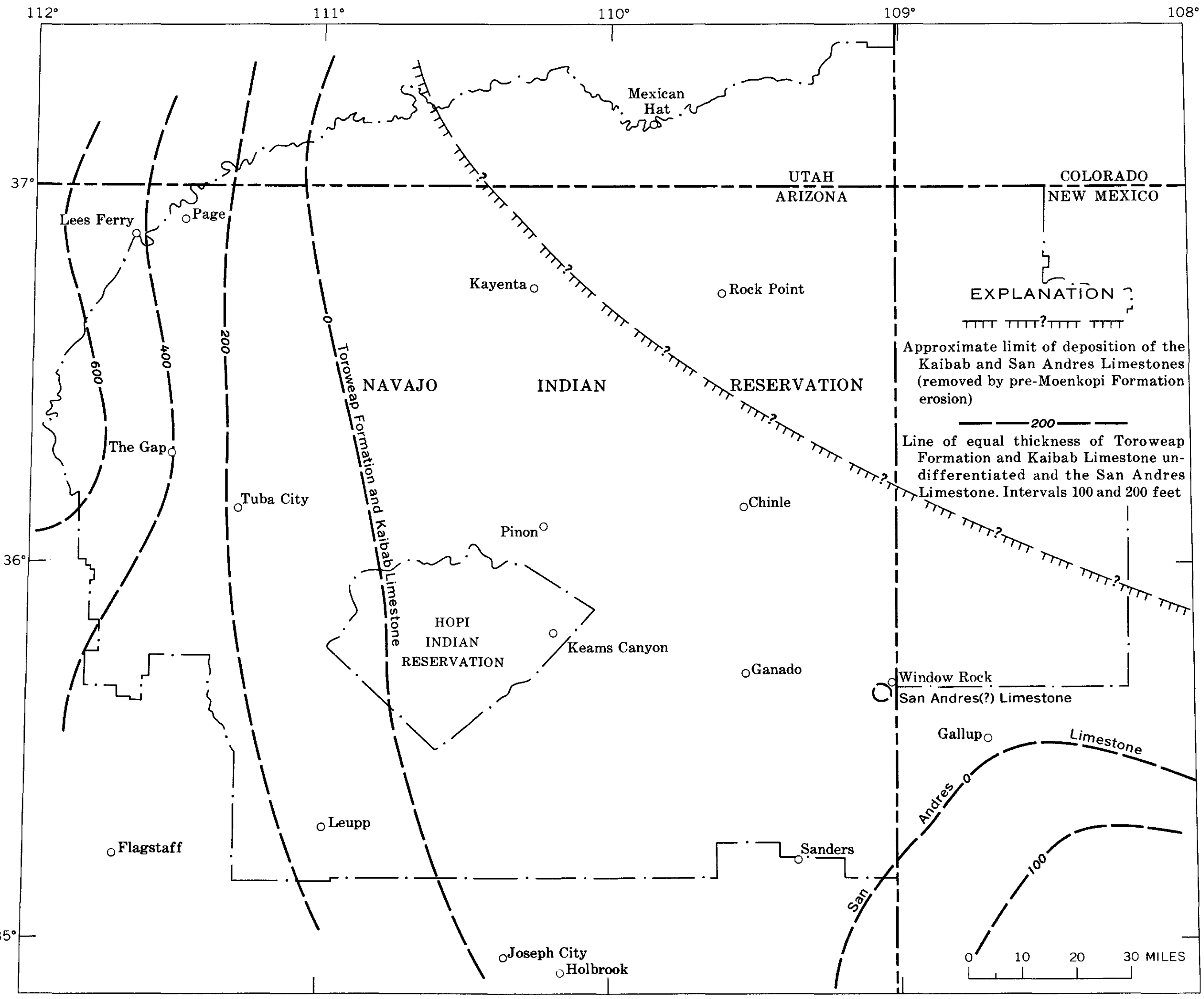


FIGURE 4.—Thickness of the Toroweap Formation and Kaibab Limestone undifferentiated and the San Andres Limestone.

The Kaibab is 420 feet thick along the Salt Trail and 340 feet thick in the Burrell-Collins oil test; the thicknesses at these two places are incomplete because the topmost beds of the Kaibab have been removed by erosion. McKee's sections (1938, p. 191–192) show 391.5 feet of Kaibab along the Little Colorado River and 249.5 feet in Marble Canyon opposite Badger Canyon. The Kaibab thins progressively eastward and pinches out along a line trending north-northwest several miles west of Joseph City (pl. 2 and fig. 4). Water wells near Leupp penetrated between 160 and 120 feet of Kaibab. One oil test in the western part of the Hopi Indian Reservation penetrated about 35 feet of Kaibab Limestone, but limestone was not recognized in the other wells drilled east of this test in Black Mesa basin (H. W. Peirce, oral commun., 1968).

The Kaibab Limestone unconformably overlies the Toroweap Formation in Marble Canyon, in the canyon of the Little Colorado River, and at Grand Falls. Evidence supporting the unconformity, as established by McKee (1938, p. 28–35), is the local occurrence of a conglomerate at the top of the Toroweap Formation, deposition of the Kaibab Limestone around "mounds" of the gnarly bedded Toroweap sediments, and the truncation of the upper wavy sandstone beds of the Toroweap Formation prior to deposition of the flat-lying basal limestone of the Kaibab.

The Kaibab Limestone has been fractured extensively by jointing and faulting. In places, the resulting cracks have been enlarged by solution, are nearly 5 feet wide, and penetrate through the formation. These cracks intercept runoff and act as conduits for the downward movement of water from the surface to the Coconino Sandstone. Only a few wells have been completed in the Kaibab, because in most of the reservations where it crops out or is at shallow depth, the regional water table is in the underlying Coconino Sandstone.

#### BETA MEMBER

The Beta Member of the Kaibab Limestone consists of thick- to thin-bedded limy sandstone and sandy magnesian limestone. The sandstone ranges from yellowish gray (5*Y* 7/2) to very pale orange (10*YR* 8/2)) on a fresh surface and weathers to yellowish gray (5*Y* 7/2) and light gray (*N* 7). It is composed mainly of medium to very fine rounded to subangular clear, stained, and rarely frosted quartz grains that are fairly to poorly sorted. Some argillaceous material and a few coarse rounded to well-rounded clear, frosted, and pitted quartz grains also are present. The sandstone units are thick to thin bedded. They consist of flat-bedded layers and some cross-bedded layers that display low- to medium-angle small- to medium-scale crossbeds.

Thick to thin layers of silty, very sandy, finely crystalline, dolomitic limestone are interbedded with the sandstone of the Beta Member. The limestone ranges from yellowish gray (5*Y* 7/2) to grayish yellow (5*Y* 8/4) on a fresh surface and weathers to light gray (*N* 7) and light olive gray (5*Y* 5/2). The sand in the limestone is quartz and is mostly medium to fine grained; occasional coarse grains are present. The medium to fine grains are subrounded to subangular, and the coarse grains are rounded to well rounded and frequently are frosted and pitted. Quartz geodes are common in many places and usually occur in the dolomitic limestone.

Bedded chert, usually a good clue to the Beta Member, occurs near the top of the unit, and two or more conspicuous chert beds are present locally in exposures along the Little Colorado River. The chert is grayish red, yellow, and light gray and resistant, ranges from nearly pure to earthy types, and is in beds ranging from a few inches to a few feet thick.

#### ALPHA MEMBER

The Alpha Member of the Kaibab Limestone consists mainly of thin-bedded finely crystalline dolomitic limestone. It ranges from light brown (5*YR* 5/6) to light gray (*N* 7) on fresh and weathered surfaces. The limestone weathers smooth and pitted, probably owing to slight differences in composition. The smooth-weathering limestone usually includes some fine to very fine grained quartz sand. The pitted limestone has little sand and contains many molds of mollusks. Flat and crossbedded pale-brown (5*YR* 5/2) to very pale orange (10*YR* 8/2) limy sandstone layers are interbedded throughout the Alpha Member. The sandstone beds rarely are more than 1 foot thick and are composed of coarse to very fine grained rounded to subangular clear and stained quartz. The sandstone has poor to fair sorting and is weakly to firmly cemented.

The boundary between the Alpha and the underlying Beta Member of the Kaibab Limestone is difficult to determine, because the minor differences in the lithologies of the two members are gradational. In most of the area the boundary is placed arbitrarily at the base of the lowermost thin-bedded dolomitic limestone, which is above the bedded chert that identifies the Beta Member.

#### AGE

The invertebrate fauna of the Kaibab Limestone has been a subject of study since the time of the earliest geologic exploration of the Colorado Plateaus (Marcou, 1856; Newberry, 1861). Since the turn of the 20th century, there has been almost unanimous agreement that the Kaibab is of Permian age. McKee (1938, p. 169–172) investigated the brachiopod fauna of the Kaibab and compared it with the Permian fauna of the Glass Mountains in west Texas. He concluded that the Kaibab is equivalent to the upper part of the Leonard Series of the Glass Mountains (late Early Permian).

## DEFIANCE PLATEAU AREA

The Permian rocks comprising the Supai Formation and the De Chelly Sandstone are the oldest Paleozoic strata that crop out in the Defiance Plateau. They are exposed on the summit of the plateau and in the canyons along its flanks. Erosion of these rocks has resulted in the formation of irregularly carved canyons and valleys, of which the most spectacular are Canyon de Chelly, Bonito Canyon, and the canyon of Black Creek. Older Paleozoic rocks have been identified in the subsurface from oil tests along the flanks of the plateau (pl. 2).

### SUPAI FORMATION

The Supai Formation is exposed from Bonito Canyon northward to Buell Park. It also crops out in the canyon of Black Creek, near Hunters Point, and in Canyon de Chelly. Complete sections of the Supai are exposed only in Bonito Canyon and near Hunters Point.

The Supai Formation consists of a series of alternating moderate-reddish-brown (10*R* 4/6) and moderate-reddish-orange (10*R* 6/6) sandstone and siltstone units. It is firmly to weakly cemented with calcareous materials. Differential weathering and erosion of the units have formed irregular ledges and slopes. The sandy units range from silty sandstone to sandstone and are composed of very fine to fine subrounded to subangular quartz grains. The sandstone is flat and thin to thick bedded and frequently contains siltstone partings. Some tabular-planar type crossbedding showing small-scale medium-angle crossbeds is in the lower part, and large-scale crossbedding is in the upper part, which forms a transitional zone and intertongues with the De Chelly Sandstone. The siltstone strata are thin to thick bedded, and some layers are crinkled. Beds of impure limestone and lenses of mudstone-pellet conglomerate are scattered throughout the unit. Several beds of gypsiferous sandstone are exposed in the upper part of the formation near Buell Park. Calcite stringers and geodes, salt casts, ripple marks, and leached zones and bands are present in the upper part of the formation. Abundant fossil plant fragments were collected by C. B. Read and A. A. Wanek (written commun., 1952) in a zone about 40–55 feet above the base of the Supai in the Bonito Canyon area.

An important marker bed in the Supai Formation is a grayish-red to yellowish-gray massive siliceous thin-bedded limestone, which is well exposed at Black Creek. This limestone may correlate with the limestone shown by Read and Wanek (1961, pl. 2) near the middle of the San Ysidro Member of the Yeso Formation in the Zuni Mountains. The limestone exposed at Black Creek pinches out to the north and is not present in Bonito Canyon.

Well cuttings from the Creager State oil test to the southwest indicate that a limestone bed occurs about 400 feet below the top of the Supai Formation (T. G. Roberts, written commun., 1954). The limestone bed in this oil test may correlate with the limestone beds exposed along Black Creek and possibly with the one in the Zuni Mountains. Another limestone bed occurs about 250 feet below this limestone bed and 700 feet beneath the Coconino Sandstone. In subsurface studies this lower limestone bed was considered by Peirce and Gerrard (1966, fig. 7) to be a northward extension of the Fort Apache Member. According to Peirce and Gerrard (1966), the Fort Apache Member occurs stratigraphically beneath the thick evaporite deposits in the upper part of the Supai along the southern boundary of the Navajo Indian Reservation (fig. 3).

A basal conglomerate usually is present in the small exposures in Bonito Canyon and near Hunters Point. It consists of a matrix of reddish-orange very fine to fine subrounded sand grains that encloses abundant granules to boulders composed predominantly of quartzite. The conglomerate includes some limestone fragments, abundant calcite stringers, and geodes. Near Hunters Point it contains pebbles of quartzite, granite, and volcanic rocks (Lance, 1958, p. 69–70). It generally ranges in thickness from 2 to 5 feet, but locally it is absent and siltstone or mudstone lie on the Precambrian rocks. The unconformable contact between the Precambrian rocks and the overlying Supai Formation has between 50 and 75 feet of relief in Bonito Canyon and from 15 to more than 50 feet of relief near Hunters Point.

Logs of oil tests in the Defiance Plateau indicate that the Supai is about 595 feet thick near Nazlini and 1,250 feet thick south of the canyon of Black Creek. Read and Wanek (1961, pl. 2) showed about 450 and 750 feet of Supai in Bonito Canyon and at Hunters Point, respectively; they reported incomplete thicknesses of 545 feet of Supai exposed in the canyon of Black Creek and 181 and 242 feet in two places in Canyon de Chelly.

### DE CHELLY SANDSTONE

The De Chelly Sandstone is exposed on the top of the Defiance Plateau between Bonito Canyon and the canyon of Black Creek. It forms vertical cliffs that display an interwoven network of crossbeds "etched" in the sandstone in the canyon walls. Horizontal bedding planes can be traced laterally for distances of more than 1 mile in the sandstone, and they weather into niches, alcoves, or deep recesses. Many of the recesses house ruins of the ancient Pueblo Indians.

The upper and lower members of the De Chelly Sandstone are recognized in the Defiance Plateau. The upper member extends throughout the plateau, but the lower member is present only in the Fort Defiance–Hunters Point–Canyon de Chelly area. A tongue of the Supai Formation separates the two members of the De Chelly; the tongue is particularly prominent near Hunters Point and at Bonito Canyon (pl. 2). Red beds overlie the De Chelly in outcrops near Fort Defiance, and a limestone bed was tapped between the Chinle Formation and the upper member of the De Chelly Sandstone in a water well drilled at St. Michaels Mission.

Peirce (1964) combined the De Chelly Sandstone of Read and Wanek (1961), the included tongue of the Supai Formation, and the overlying red-bed rocks as the De Chelly Sandstone and divided it into five members.[1] The Hunters Point Member, the basal unit, is equivalent to the lower member of Read and Wanek (1961). It is overlain by the Oak Springs Cliffs Member, which is equivalent to the tongue of Supai Formation that separates the upper and lower members of the De Chelly of Read and Wanek (1961). The upper member of the De Chelly was divided into the White House and Black Creek Members. Peirce's (1964) topmost member of the De Chelly Sandstone is the Fort Defiance Member, a name assigned to the red beds and limestone that overlie the upper member of the De Chelly Sandstone in the Fort Defiance–Window Rock area.

The major differentiating feature between the upper and lower members of the De Chelly Sandstone is the crossbedding. The lower member contains crossbedding of the asymmetrical trough and planar types, and the crossbeds are medium to high angle and medium to large scale. In comparison, much of the upper member contains crossbedding of the wedge and trough types, and the crossbeds are high angle and very large scale. Some of the crossbedded units are more than 100 feet thick and extend laterally for more than a quarter of a mile. A characteristic feature of the crossbedded units is the frequent coarse-grained material along the surfaces bounding individual crossbeds. Measurements made by Read and Wanek (1961) showed that the crossbeds of the upper member dip to the southwest or south-southwest, and those of the lower member dip to the southeast.

The lower member of the De Chelly, called the Hunters Point Member of the De Chelly Sandstone (Peirce, 1964), consists of moderate-reddish-orange (10*R* 6/6) layers of fairly sorted fine- to medium-grained sandstone and flat-bedded silty sandstone. Silty beds in the lower member are more common to the south, southwest, and north from Hunters Point, as indicated from surface outcrops and drill cuttings of wells (Peirce, 1962, p. 78–86). The unit is composed principally of subangular clear, stained, and frosted quartz grains with accessory feldspar and black minerals. The cementing material is chiefly calcareous, but locally it is siliceous and ferruginous.

The White House Member of the De Chelly Sandstone (Peirce, 1964) consists of sandstone that has large-scale high-angle crossbeds. It is displayed only in Canyon de Chelly and in the lower part of the exposure in Bonito Canyon. It is composed of grayish-orange-pink (10*R* 8/2) to moderate-reddish-orange (10*R* 6/6) fairly to well-sorted, subangular to subrounded fine to medium quartz grains with some feldspar. The sandstone is firmly bonded with calcareous, ferruginous, and siliceous cementing material mixed in varying proportions.

South of Bonito Canyon the White House Member thins, and at Black Creek only the Black Creek Member remains (pl. 2). The Black Creek Member contains an almost equal proportion of interbedded flat and crossbedded sandstone units; the crossbeds are medium to high angle and medium to large scale. The sandstone of the Black Creek Member is lighter colored and more firmly cemented with silica than the sandstone of the White House Member. The exact lateral relations between the White House and the Black Creek Members are not known. Farther south, in outcrops near Pine Springs, the Black Creek Member includes an increasing proportion of siltstone beds, and two well drilled through the De Chelly interval near Lupton penetrated considerable silty sandstone.

The De Chelly Sandstone has a maximum thickness of 743 feet at Canyon de Chelly and thins in all directions (pl. 2). The lower member of the De Chelly is 240 feet thick at Canyon del Muerto, 235 feet in Canyon de Chelly (including sediments that may be lateral equivalents of the Supai tongue), and 205 feet in Bonito Canyon. It can be traced south from Bonito Canyon to northeast of Oak Springs, where it is 174 feet thick (Peirce, 1962, table 1). South of this point the lower member tongues out in the Supai Formation, and it is absent in an exposure near Black Creek, 7 miles south of the point northeast of Oak Springs. The lower member is not known to be present west of the Black Mountain oil test. The maximum thickness of the upper member of the De Chelly is 503 feet at Canyon del Muerto; it is 225 feet thick in Buell Park, 270 feet thick at Bonito Canyon, and 200 feet thick at Oak Springs. The De Chelly Sandstone (upper member) was recognized by Peirce (1967, fig. 4) west of the Defiance Plateau. It is about 450 feet thick in the Black Mountain oil test and from 250 to 300 feet thick in oil tests drilled in the Hopi Indian Reservation and in the Sinclair Oil Co. Navajo Tribal 1 oil test near Kaibito (H. W. Peirce, oral commun., 1967).

Data obtained from more than 50 water wells drilled in the Defiance Plateau area have strengthened these interpretations of the stratigraphic relations and added information about the water-bearing characteristics of the De Chelly Sandstone. The differences in water-bearing characteristics are espe-

[1] The five members named by Peirce have not been adopted by the U.S. Geological Survey.

cially apparent in the upper member. In places where the upper member of the De Chelly is silty, the yield of water to wells is noticeably less. Near Lupton, the upper member is so tight that it is dry. The lower member of the De Chelly Sandstone yields only a small amount of water, and in some wells penetrating below the base of the upper member, drillers have reported no measurable increase in yield.

#### AGE OF THE SUPAI FORMATION AND DE CHELLY SANDSTONE

The De Chelly Sandstone was deposited conformably on the Supai Formation, but the two formations intertongue, and the lower member and part of the upper member of the De Chelly are the lateral equivalents of the Supai. The contact between the lower member of the De Chelly and the Supai is placed in a transitional interval that ranges in thickness from 25 to 100 feet. The contact between the upper member of the De Chelly and the Supai is flat and generally much sharper; the gradational interval is rarely more than a few feet thick. Only a few fossils have been collected from the Supai Formation or the De Chelly Sandstone on the Defiance Plateau. Fossil-plant remains from the Supai were collected by C. B. Read (written commun., 1954), and he identified them as being similar to those from the Hermit Shale. Near Ganado, many vertebrate and invertebrate tracks similar to those in the Coconino Sandstone in the Grand Canyon area have been described by McKee (1934b). Read (1951, p. 83) designated the De Chelly Sandstone to be of Leonard age, or late Early Permian.

#### PERMIAN ROCKS OVERLYING THE DE CHELLY SANDSTONE

Rocks of Permian age that overlie the De Chelly Sandstone are known in two isolated areas near Window Rock. One is in Bonito Canyon, where a sequence of grayish-red (10*R* 4/2) and pale-reddish-brown (10*R* 5/4) flat-bedded fine-grained sandstone and silty sandstone is between the conglomeratic Shinarump Member of the Chinle Formation and the crossbedded De Chelly Sandstone (Cooley, 1957, p. 9, 296–302; Peirce, 1962, p. 25). The rocks in Bonito Canyon are nearly 120 feet thick, and they were deposited on a flat erosion surface. The units are thin to very thick bedded, and some of the layers show small-scale trough and planar crossbedding. Lithologically, these rocks are somewhat similar to those of the Supai Formation, less similar to those of the De Chelly Sandstone, and unlike those of the Triassic Moenkopi or Chinle Formations exposed on the Defiance Plateau.

The other area was located during the drilling of a water well at St. Michaels Mission, 4 miles southwest of Window Rock, where 22 feet of limestone was found. The limestone is light olive gray, dense, and fairly pure in composition. The nearest limestone exposures are those of the San Andres Limestone in the Zuni Mountains, and, lithologically, the limestone in the school well is like the San Andres. The limestone at St. Michaels Mission may be a remnant preserved in a "low" which was not removed by pre-Moenkopi Formation–pre-Chinle Formation erosion. Relations between the limestone and the red beds overlying the De Chelly Sandstone in Bonito Canyon are not known because the deposits are not in contact with each other. Baars (1962, p. 208), however, suggested that the red beds are a shoreward facies of the San Andres Limestone.

### MONUMENT VALLEY AREA

Monument Valley (pl. 1) is in part of a highly dissected area where Paleozoic rocks have been carved into a multitude of spires, steep-sided buttes, and skeletonlike mesas. Pennsylvanian rocks crop out only in San Juan Canyon, but Permian rocks are widely exposed in the Monument Valley area. Although the Permian rocks show rapid lateral changes in lithology, they appear to be transitional between the Permian rocks in southwestern Colorado and those in the Grand Canyon area. The upper Paleozoic units exposed in the Monument Valley area, in ascending order, are the Hermosa, Rico, and Cutler Formations; although the Molas Formation is not exposed, it has been recognized in well cuttings.

#### MOLAS FORMATION

Deposits of the Molas Formation have been identified in cuttings from deep oil tests between the Redwall (Leadville) Limestone of Mississippian age and the Hermosa Formation near the San Juan River in southeastern Utah (Huddle and Dobrovolny, 1945). In the type area at Molas Lake in southwestern Colorado, the Molas Formation is between 40 and 120 feet thick (Wengerd, 1957, p. 135), and the Leadville-Molas contact is extremely irregular. The uppermost part of the Leadville Limestone shows evidence of solution along bedding planes and joints to depths of 100 feet, and, locally, a karst topography was developed. The basal part of the Molas is an aggregate of light-gray limestone blocks weathered from the Leadville and cemented in a matrix of red deposits. The red deposits, which form most of the formation, are mainly siltstone, limy shale, and lesser arkosic sandstone. In the Four Corners area the Molas Formation has an irregular thickness, which is usually less than 100 feet. It is Pennsylvanian in age and ranges from Atoka to Des Moines (Wengerd, 1957, p. 135). No water has been reported in the Molas.

### HERMOSA FORMATION

The Hermosa Formation (Cross and others, 1899, p. 8; Cross and Spencer, 1900, p. 48) is named for the stratigraphic section displayed in Animas Canyon and at Rico, Colo. In much of southeastern Utah and southwestern Colorado it is separated into an upper and a lower member by a thick evaporite sequence, formerly called the Paradox Formation (Baker, 1933, p. 18–20) but now referred to as the Paradox Member of the Hermosa Formation (Bass, 1944). The Paradox Member is present only in the extreme northeastern corner of the Navajo Indian Reservation, which is at the south edge of evaporite deposition. It consists of anhydrite, gypsum, black shale, and some thin beds of dolomite and limestone. Beyond the limits of evaporite deposition, the Pennsylvanian section is composed of beds showing few dissimilarities, and in this report the Hermosa Formation is not divided into members. Wengerd (1957), in studies of the Pennsylvanian System of the Four Corners area, gave the Hermosa Formation group status and divided the group into three formations, in ascending order: the Pinkerton Trail, Paradox, and Honaker Trail Formations.[2] Wengerd's units are equivalent to the lower part of the Paradox and the upper member of the Hermosa Formation (Bass, 1944).

#### GENERAL DESCRIPTION AND FIELD RELATIONS

The Hermosa Formation is exposed, in part, only in San Juan Canyon at the Goose Necks and on Raplee anticline; it consists of flat thin to very thick bedded limestone and interbedded clastics. The limestone is medium dark gray (*N* 4) to light gray (*N* 7) on fresh and weathered surfaces, dense, and finely crystalline to aphanitic in texture, and it contains some oolitic beds and layers of fragmental or bioclastic limestone. Nodular and bedded chert and jasper are included in the limestone beds. Some of the dark-gray pure limestone beds at river level show fluting from the erosive action of river currents. Other limestone beds contain medium to very fine subrounded clear quartz grains and some argillaceous material.

Interbedded with the limestone are beds of limy shale and sandstone. The shale is medium gray (*N* 5) to black (*N* 1), but near the top of the formation some beds are pale red purple (5*RP* 6/2). The shale is laminated to very thin bedded and is composed of claystone, mudstone, and siltstone, which in places grade laterally into argillaceous limestone. Shale beds in the upper part of the formation are frequently sandy and micaceous. The sandstone is medium light gray (*N* 6) to very light gray (*N* 8), yellowish gray (5*Y* 8/1), or light brown (5*YR* 6/4) and is thin to very thick bedded. It is composed of medium to very fine rounded to subrounded fairly to well-sorted clear quartz grains and is firmly to well cemented. Feldspar is a rare to common accessory mineral.

Subsurface information indicates that the Hermosa Formation is 1,000 feet thick in the oil test on Hoskinnini Mesa, 1,200 feet thick in the Shell Oil Co. East Boundary Butte 1 test, 1,330 feet thick in the Table Mesa oil test, 700 feet thick near Tocito Dome, and about 500 feet thick in the northern part of the Defiance Plateau.

The Hermosa Formation is brittle and strongly jointed. At the level of the San Juan River, sulfur-depositing springs, which have a strong odor of hydrogen sulfide gas, and a few oil seeps issue from the joints. Some of the springs were recorded by Miser (1924a, p. 72) and are still visited as a scenic attraction by river parties floating down the San Juan River.

#### AGE

The Hermosa Formation of the Monument Valley area contains abundant marine fossils of Pennsylvanian age, which establish its correlation with the type Hermosa of southwestern Colorado. Because the formation is in the subsurface in most of the Four Corners area, tracing of units in the formation has to be done by examination of drillers' logs and sample cuttings from deep oil tests. The formational boundaries of the Hermosa, and to a lesser extent those of the Rico Formation, are based on minor lithologic differences. Beds considered typical of the Hermosa or Rico Formations transgress time boundaries, as evinced by faunal remains. For these reasons, the age of the Hermosa Formation apparently includes much of Pennsylvanian time (Roth, 1934; Bass, 1944; Wengerd and Strickland, 1954; and Clair, 1952).

### RICO FORMATION

The Rico Formation was named by Cross and Spencer (1900, p. 59) and described by Cross and Ransome (1905) for exposures in the Rico Mountains in southwestern Colorado. In the type area the formation consists of 300 feet of sandstone, conglomerate, and intercalated sandy shale and thin fossil-

[2] Wengerd's Hermosa group has not been adopted by the U.S. Geological Survey.

iferous limestone. The pebbles in the conglomerate are chiefly schist and quartzite. The Rico in the reservations is composed chiefly of limestone and fine-grained clastic deposits.

#### GENERAL DESCRIPTION AND FIELD RELATIONS

The Rico Formation is exposed along the San Juan River in Utah from Comb Ridge to the mouth of Grand Gulch. At the Goose Necks it forms the upper part of San Juan Canyon and extends on the surface for some distance back from the brink of the canyon (pl. 1).

Erosion of the limestone and sandstone units forms small ledges and steplike cliffs, which are separated by steep slopes formed from the siltstone units. The siltstone ranges from pale reddish brown (10*R* 5/4) to moderate reddish orange (10*R* 6/6) or reddish purple (5*RP* 3/2) and is thin to thick bedded. The sandstone units are pale red (10*R* 6/2) to light gray (*N* 7), thin to thick bedded, and composed of very fine to medium quartz grains; mica and feldspar are accessory minerals. The sandstone and siltstone beds are highly calcareous. The limestone units are medium gray (*N* 5) and crystalline, and some show a "honeycomb" structure. Many of the limestones are fossiliferous and contain mollusks, brachiopods, and corals. The faunal assemblages in the Rico are similar to those in the Hermosa Formation but have more mollusks and fewer brachiopods.

The Rico lies conformably on the Hermosa Formation, and "at many localities the boundary must be selected arbitrarily within a zone of 15 to 25 feet thick" (Baker, 1936, p. 21). The Rico is conformable with the overlying Halgaito Tongue of the Cutler Formation, and the contact usually is placed at the top of the highest fossiliferous limestone unit in the Rico. Baker (1936, p. 27) indicated that this uppermost limestone in the Rico may not always be at the same horizon and that slight intertonguing may take place between the Rico and the Halgaito Tongue of the Cutler Formation. In a section measured at the mouth of Grand Gulch (Cooley and others, 1964, p. 111–114), fossiliferous limy sandstone and limestone grade upward into silty sandstone and sandy siltstone, which have features suggestive of either a residual-soil zone or at least a highly weathered zone. In this exposure, a sharp contact separates this zone from the overlying Cutler Formation. The Rico-Cutler contact is gradational 2 miles southwest of Mexican Hat and is in a transitional zone about 100 feet thick that contains thin lenticular limestone beds in the lower part.

Because the upper and lower boundaries are gradational, there is a variance in the reported measured thickness of the Rico in the Monument Valley area. Baker (1936, p. 25) considered the upper 458.5–468.5 feet of the Goodridge Formation (of former usage) measured by Miser (1924b, p. 127–130) at Honaker Trail to be included in the Rico. Gregory (1938, p. 41), using faunal boundaries, limited the Rico to 300–325 feet. Baker and Reeside (1929, p. 1435) reported about 350 feet of Rico near Gypsum Wash and between 300 and 350 feet in San Juan Canyon. Read and Wanek (1961, p. 7) reported 335 feet of Rico in San Juan Canyon at the Goose Necks.

#### AGE

The age of the Rico Formation has not been established firmly, although the Rico is fossiliferous. The underlying Hermosa Formation contains an abundant fauna of Pennsylvanian age, and the overlying Cutler Formation is considered to be Permian in age on the basis of a few continental fossils; thus, the intervening Rico Formation is considered to be Pennsylvanian and Permian in age. Baker (1936, p. 24) and Gregory (1938, p. 40) considered the Rico in the Monument Valley area to be Permian in age on the basis of fossils identified by G. H. Girty (in Baker, 1933, p. 26), who correlated the Rico in this area with the Rico of the type area in Colorado and the Rico of the Moab, Utah, area. Wengerd and Strickland (1954, p. 2174) stated that: "The member transgresses time-surfaces ranging from Virgil to Middle Wolfcamp" (Lower Permian).

### CUTLER FORMATION

Cross, Howe, and Ransome (1905) named the Cutler Formation for exposures on Cutler Creek near Ouray, Colo. In the type locality the Cutler is a complex of red sandstone and conglomerate with alternating beds of sandy shale and sandy limestone; the Cutler rests conformably on the Rico Formation and is unconformably overlain by the Dolores Formation of Triassic age. Baker and Reeside (1929, p. 1443) introduced the term Cutler Formation to the Monument Valley area and included in it all beds from the top of the Rico Formation to the unconformity at the base of the Early and Middle(?) Triassic Moenkopi Formation. They also divided the Cutler into five members, which are, in ascending order, the Halgaito Tongue, the Cedar Mesa Sandstone Member, the Organ Rock Tongue, the De Chelly Sandstone Member, and the Hoskinnini Tongue, which is now considered part of the Moenkopi Formation of Triassic age. The four remaining members of the Cutler Formation are recognized southwest of Monument Valley in the Sinclair Oil Co. Navajo Tribal 1 oil test near Kaibito (H. W. Peirce, oral commun., 1967).

The Hoskinnini Tongue was separated from the Cutler Formation and is now considered the basal member of the Moenkopi Formation of Triassic age (Stewart, 1959). This separation is based on the description of the contacts between the Hoskinnini and the overlying and underlying strata. The lower contact, between the Hoskinnini Member and the Cutler Formation, is sharp and generally well defined; but the upper contact, between the Hoskinnini Member and the lower siltstone member of the Moenkopi, generally is not well defined in Monument Valley. In many exposures to the west and north, however, a channeled erosion surface marks the upper contact of the Hoskinnini (Thaden and others, 1964, p. 35; Cooley, 1965, p. 19, 40, 103). The Hoskinnini, therefore, was reassigned to the basal member of the Moenkopi. The Hoskinnini has been traced from the type area at Hoskinnini Mesa eastward across the central part of Monument Valley; westward, it is traceable to Piute Mesa—its westernmost exposure in the reservations (pl. 2). The member is not recognized in the subsurface south and southeast of Monument Valley, nor is it exposed on the Defiance Plateau or along the Echo Cliffs.

The Cutler Formation is about 1,700 feet thick in a deep oil test drilled on Hoskinnini Mesa; it thickens slightly to the northeast across Monument Valley and is about 2,400 feet thick at the Four Corners. In an oil test on Nokai Dome the Cutler is 1,550 feet thick. Other well-test data indicate that it thins northwestward to about 1,050 feet on the Kaiparowits Plateau.

In contrast to the Permian rocks in other parts of the reservations, the sandstone units of the Cutler Formation yield only small amounts of water. The amount of water that can be withdrawn by wells is limited by cementation in the sandstone, the small areal extent of the units that can be recharged effectively, and the beds of low permeability that overlie them.

#### HALGAITO TONGUE

The Halgaito Tongue is named for Halgaito Spring, and the type area is in San Juan Canyon northeast of Douglas Mesa (pl. 1). It is exposed along the San Juan River near the mouth of Oljeto Wash and eastward almost to Comb Ridge.

In the type section the Halgaito consists of about 425 feet of sandstone and subordinate mudstone and clay-pellet conglomerate (Baker, 1936, p. 30); it also contains several unfossiliferous limestone beds and some gypsiferous sandstone. The units display graded bedding; thus, in any single layer, the particle sizes range from coarse at the base to fine at the top. Oscillation ripple marks are common to abundant in the mudstone units. Lenticular silty limestone beds, less than 2 feet thick, in the upper part are light bluish gray (5*B* 7/1) to medium gray (*N* 5) and consist of dense finely crystalline limestone, nodular limestone, and limestone conglomerate composed of subangular to rounded limestone pellets in a matrix of very fine grained limestone. All the limestone beds weather to rough or pitted surfaces.

Near Mexican Hat the Halgaito Tongue is composed of moderate-reddish-brown (10*R* 4/6) to pale-reddish-brown (10*R* 4 /5) silty sandstone, sandy mudstone, and sandy siltstone, which contain thin lenses of gray silty limestone. The sandy material is composed mainly of fine to very fine quartz grains with small amounts of medium and coarse grains. The grains are subangular to subrounded and are iron stained, which gives the beds their red color.

At Grand Gulch, the Halgaito Tongue (Cooley and others, 1964) consists of very fine to fine-grained silty sandstone and sandstone that is pale red (10*R* 6/2) to moderate reddish brown (10*R* 4/6) and moderate orange pink (10*R* 7/4). Most of the silty reddish-brown sandstone is flat and lenticular and very thin to thick bedded; some of the sandstone units are fairly to well sorted and contain medium- to large-scale crossbeds suggestive of eolian deposition. Thin nodular limestone beds, shrinkage cracks, poorly formed ripple and current marks, raindrop (?) impressions, and nondescript plant impressions are scattered throughout the section.

The lower and upper contacts of the Halgaito Tongue are gradational, and there are slight differences in thickness in the Monument Valley area. C. B. Read and A. A. Wanek (written commun., 1952) reported that the Halgaito Tongue is 475 feet thick at Cedar Mesa near the Goose Necks; Baker (1936, p. 29–30) measured thicknesses of 465 feet at Johns Canyon and 380 feet near the mouth of Slickhorn Gulch. To the east the Halgaito was measured by Gregory (1938, p. 68), who reported a thickness of 402 feet about 10 miles northeast of Mexican Hat. During the drilling of the oil test on Hoskinnini Mesa, 440 feet of red siltstone and sandstone reported to be Halgaito was penetrated.

The Halgaito Tongue is not known to yield water to wells or springs in the Monument Valley area.

#### CEDAR MESA SANDSTONE MEMBER

The Cedar Mesa Sandstone Member of the Cutler Formation was named for the broad Cedar Mesa northwest of Mexican Hat. In the sides of canyons and mesas where the Cedar Mesa Sandstone Member is flat lying, it erodes to huge perpendicular-walled cliffs, and where the member is tilted it forms cuestas and hogbacks; in areas where dissection has not been severe, a rough irregular stripped surface has developed on the member. In the reservations the member crops out south of the San Juan River from Monitor Butte southeastward to Comb Ridge; a small outcrop of the member is in San Juan Canyon at Nokai Dome.

The Cedar Mesa Sandstone Member is a very thick bedded sandstone containing a few beds of siltstone and lenses of gray silty limestone. It is light colored, in striking contrast to the darker surrounding red beds. It is moderate orange pink (5*YR* 8/4) to reddish orange brown (10*R* 5/6) and in places has been bleached to a greenish gray (5*GY* 6/1), and it weathers very pale orange (10*YR* 8/2) to moderate reddish orange (10*R* 6/6) and light gray (*N* 7). It is composed of very fine to fine well to poorly sorted rounded to subangular stained, clear, amber, and frosted quartz grains. Argillaceous material is common in the sandstone south of Douglas Mesa.

Many of the beds are well sorted, but others contain variable quantities of silt. Dark accessory minerals are rare, and mica is concentrated along the crossbeds and in some of the silty units. The sandstone is firmly to weakly cemented by calcareous material, but in some places it has a ferruginous cement; hematite concretions are common in places. Moderate-reddish-orange (10*R* 6/6) siltstone units, generally sandy and containing a few elongate limestone nodules, are interbedded with the sandstone. The contacts between the sandstone and siltstone beds are sharp and even.

The sandstone is very thick bedded—individual beds attain thicknesses of more than 30 feet—and the units usually are crossbedded. The Cedar Mesa Sandstone Member displays thin to very thick bedding and crossbedding of the trough and planar types. The units showing trough crossbedding contain large-scale high- to low-angle crossbeds, which are probably the result of eolian deposition; the units showing planar crossbedding contain small- to medium-scale low- to medium-angle crossbeds and are waterlain deposits—possibly derived from reworked windblown sand.

In exposures on Douglas Mesa the member consists mainly of very thick bedded sandstone units, which have large-scale crossbeds suggestive of eolian deposition, and siltstone beds are few. Southeastward across the Monument Valley area, the transition is to finer grained red-bed deposits.

Near Monument Pass the member has more siltstone beds and is thin to thick bedded; crossbedding is mostly of the planar type. The member is more calcareous and contains several arenaceous limestone beds, which form cap rocks on low buttes. Gypsiferous sandstone units are interbedded with the sandstone and siltstone strata chiefly in the lower part of the member in the Monument Pass area. A few miles southeast of Monument Pass, in the upper part of Gypsum Wash, the lateral change is principally to a flat-bedded argillaceous sandstone and sandy siltstone. The member is weakly cemented and gypsiferous and contains lenses of silty limestone conglomerate and abundant mica as an accessory mineral. Very sparse trough crossbedding is present. Several reddish-brown siltstone and mudstone units are interbedded with the silty sandstone. Farther to the east and southeast, no deposits similar to those of the Cedar Mesa are found in oil tests near Boundary Butte, and the unit is believed to have graded into red beds between this area and Gypsum Wash (pl. 2).

The maximum thickness of the Cedar Mesa is in the western part of the Monument Valley area. It is 800 feet thick in an oil-test well on Nokai Dome and 705 feet thick in a test hole on Douglas Mesa. In the oil test on Hoskinnini Mesa, 390 feet of sandstone—containing thin beds of siltstone, mudstone, limestone, and some gypsum—was assigned to the Cedar Mesa Sandstone Member. The Cedar Mesa is 370 feet thick just west of Monument Pass and 135 feet thick at Gypsum Wash (Read and Wanek, 1961, pl. 2).

Locally, the Cedar Mesa Sandstone Member yields some water to wells between Douglas Mesa and Oljeto Wash and near Oljeto Trading Post. The occurrence of water is controlled in part by fractures and in part by the amount of silt present in the sandstone. Thus, the member yields little water to wells in the central part of Monument Valley, where it includes many silty sandstone and siltstone beds. Many thin sandy siltstone beds overlie large bedding planes; these tend to form small perched bodies of water, which maintain the flow of several springs near Oljeto Wash.

ORGAN ROCK TONGUE

Organ Rock, a prominent landmark about 7 miles northwest of the Oljeto Trading Post, has been carved by erosion from the dark-reddish-brown rocks for which the Organ Rock Tongue of the Cutler Formation is named. The Organ Rock generally crops out only in the sides of mesas, buttes, and canyons in the central and western parts of Monument Valley. In the eastern part of the valley, the Organ Rock underlies valleys and wide dune-covered slopes. It is also exposed where the Balanced Rock anticline is crossed by the San Juan River.

The Organ Rock Tongue consists of very thin to thick parallel-bedded layers of silty sandstone, sandy siltstone, siltstone, and a few beds of impure limestone. Where firmly cemented, it forms small ledges and hoodoos; and where friable or weakly cemented, it weathers to niches or recesses. Most of the beds split shaly and crumbly; most of the unit is cemented by calcareous material. Because of the gradational contacts between units and the slight differences in lithology and cementation, stratification is poorly developed in many exposures. Crossbedding is not strongly developed, but some units contain low-angle medium- to large-scale crossbeds, and these grade laterally into pseudocrossbedded and featureless units. A few beds are contorted and have some primary slumpage.

In the central part of Monument Valley the Organ Rock Tongue consists of silty sandstone, mudstone, and siltstone interbedded with an occasional limy mud-pellet conglomerate and thin grayish-pink (5*R* 8/2) limestone. The mudstone and siltstone units are pale reddish brown (10*R* 5/4) and moderate reddish orange (10*R* 6/6) and are usually flat and thin bedded. The mudstone and limestone units decrease in abundance to the west from Monument Pass.

At Nokai Dome, near the San Juan River, exposures of the Organ Rock Tongue are sandier than in the central part of Monument Valley; no mudstone is present, and the unit is composed of silty sandstone and sandy siltstone. Included with the silty sandstone are light-brown (5*YR* 6/4) and moderate-reddish-orange (10*R* 6/6) beds of generally fair-sorted sandstone, which contain many lenticular and tabular low-angle small- to large-scale crossbeds.

The Organ Rock Tongue grades into the underlying Cedar Mesa Sandstone Member and the overlying De Chelly Sandstone Member. In the transitional zones crossbedded sandstone units of the Cedar Mesa and De Chelly alternate with flat-bedded mudstone and siltstone units of the Organ Rock Tongue. The transitional zone with the Cedar Mesa Sandstone Member in San Juan Canyon downstream from Clay Hills Crossing is 100–150 feet thick; locally, a transitional interval with the De Chelly Sandstone Member is as much as 25 feet thick.

The Organ Rock Tongue thickens eastward and southeastward from Nokai Dome (Baker, 1936). It is 500 feet thick near Monitor Butte and 696 feet thick at Monument Pass (Baker, 1936, p. 34). Read and Wanek (1961, pl. 2) showed 565 feet of Organ Rock (including the transitional zones) at Nokai Dome, 550 feet in the upper part of Copper Canyon, 552 feet at the northeast point of Hoskinnini Mesa, 520 feet near Monument Pass, and 636 feet at Comb Ridge. Variability in thicknesses of the tongue has been reported for the same area and is probably due to the arbitrary nature of the contacts of the unit.

A small amount of ground water occurs in the Organ Rock Tongue. The yield is generally not more than 1 or 2 gallons per minute, and the occurrence of water is sporadic. Water in this unit usually is unfit for domestic purposes and may contain more than 2,000 parts per million total dissolved solids.

DE CHELLY SANDSTONE MEMBER

The De Chelly Sandstone Member of the Cutler Formation is one of the most prominent stratigraphic units of the Monument Valley area. It forms the perpendicular sides of the many spectacular monuments and buttes that characterize the area; where it is not protected by a more resistant cap rock, the De Chelly weathers to rounded forms. It is exposed along the cliffs that extend south from Monitor Butte to Comb Ridge (pl. 1).

The De Chelly is a thick to very thick bedded moderate-reddish-orange (10*R* 6/6) to very pale orange (10*YR* 8/2) sandstone and is commonly stained red by material from the overlying Moenkopi Formation. The sandstone consists of fine to medium subangular to rounded poorly sorted clear quartz grains that are commonly coated with a thin film of iron oxide. The unit is firmly to weakly cemented by calcareous and ferruginous materials. The sandstone shows large-scale high- to low-angle trough crossbedding.

The maximum reported thickness of the De Chelly Sandstone Member is 550 feet (Witkind and Thaden, 1963, p. 13) in the southern part of Comb Ridge near the Arizona-Utah State line. Northwest of this area the De Chelly thins to 375 feet near Monument Pass, 310 feet on the northeast corner of Hoskinnini Mesa, and 102 feet on the east side of Copper Canyon (Baker, 1936, p. 36). The sandstone is 60 feet thick on the north side of Piute Mesa and is 142 feet thick in the oil test drilled on the summit of Nokai Dome. The De Chelly wedges out near Monitor Butte (Baker, 1936) but reappears at the northwest corner of the mesa at the level of the San Juan River, where it is 25 feet thick (Mullens, 1960, pl. 27).

In some places the lower boundary of the De Chelly is gradational with the Organ Rock Tongue, and the precise contact cannot be determined. In parts of Monument Valley the De Chelly–Organ Rock boundary is in a zone less than 30 feet thick (Baker, 1936, p. 36). In other places the contact is well defined and horizontal and marks the boundary between the two distinct lithologies of the Organ Rock Tongue and the De Chelly Sandstone Member. Along the San Juan River, a few sandstone dikes extend downward from the base of the De Chelly Sandstone into the upper part of the Organ Rock Tongue.

The late L. F. Brady (oral commun., 1959) made casts of footprints of reptiles from the De Chelly Sandstone Member in western Monument Valley; he believed that these tracks show a strong similarity in type, size, and shape to those found in the Coconino Sandstone in the Grand Canyon area.

The De Chelly Sandstone Member yields water to a few wells and springs. The water is of good chemical quality and is used for domestic and stock purposes. In much of Monument Valley the member is highly dissected and drained or is overlain by rocks that are tapped more easily by wells.

#### AGE

The Cutler Formation is considered to be Permian in age on the basis of fossil evidence and regional stratigraphic relations. Baker (1936, p. 30) reported vertebrate remains in the clay-pellet and limestone conglomerates of the Halgaito Tongue of the Cutler Formation. The fossils were examined by E. C. Case, who identified a caudal vertebra of a pelycosaur, probably *Ephiacodon* or *Sphenacodon*; either form is indicative of a Permian age. Other fossils of Permian age are fragmental vertebra remains and fossil plants collected by Baker (1936, p. 35) from the Organ Rock Tongue. Read and Wanek (1961) recently found fossil plants in the upper part of the Halgaito, which they determined to be the same age as the Hermit Shale.

The Cutler Formation conformably overlies the Rico Formation, the upper part of which is Permian in age; the De Chelly Sandstone Member of the Cutler seems to be continuous with the Coconino Sandstone of the Grand Canyon area, which is overlain by the Kaibab Limestone of late Early Permian age. These relations, plus the fossil evidence, indicate that the Cutler Formation in Monument Valley is of Permian age.

### REGIONAL RELATIONS OF THE PENNSYLVANIAN AND PERMIAN ROCKS

During Pennsylvanian and Permian time, the Navajo country was part of the relatively stable platform or shelf region on the east margin of the Cordilleran geosyncline. Slight movements of the shelf area caused eastward transgressions and regressions of the seas, whose deeper parts lay generally to the west and south. The northern and central parts of the reservations received clastic sediments derived mainly from the Uncompahgre Highlands in what is now southwestern Colorado. Along the south border of the reservations, the Pennsylvanian and Permian deposits form nearly an unbroken and gradational sequence. Beds of Pennsylvanian age probably are not exposed on the Defiance Plateau, although oil tests in the northern part of the plateau area penetrated some Pennsylvanian strata. More than 3,500 feet of Pennsylvanian and Permian deposits was laid down near the margin of the reservations in the Holbrook-Sanders and Four Corners areas, and between 1,000 and 1,500 feet was laid down on positive areas in the southeastern and northwestern parts of the reservations (fig. 2).

Reconstruction of the Pennsylvanian patterns of marine sedimentation suggest that a shallow trough connected the Paradox basin of the Four Corners area with the Winslow-Holbrook area. The distribution of the limestone units of the Hermosa, Molas, and Naco Formations indicates that the trough was west of the Defiance Plateau Highlands–Zuni Highlands area and east of the Grand Canyon (fig. 5). These limestone units do not crop out in the Defiance Plateau Highlands–Zuni Highlands, and only a few limestone beds are exposed in the broad highland area in the western part of the reservations. The recent drilling in and near the Dineh bi Keyah oil field shows more than 500 feet of limestone of Pennsylvanian age. The limestone marks the margin of the Defiance Plateau Highlands, which now are known to occupy only the central and southern parts of the Defiance Plateau.

The red-bed deposits of the Supai Formation, Hermit Shale, and Yeso, Abo, and Cutler Formations—broad equivalents of each other—progressively overlapped the flanks of the Paleozoic highlands and by Late Pennsylvanian time had buried much of the western highlands at Marble Canyon and the eastern Grand Canyon and the Defiance Plateau highlands.

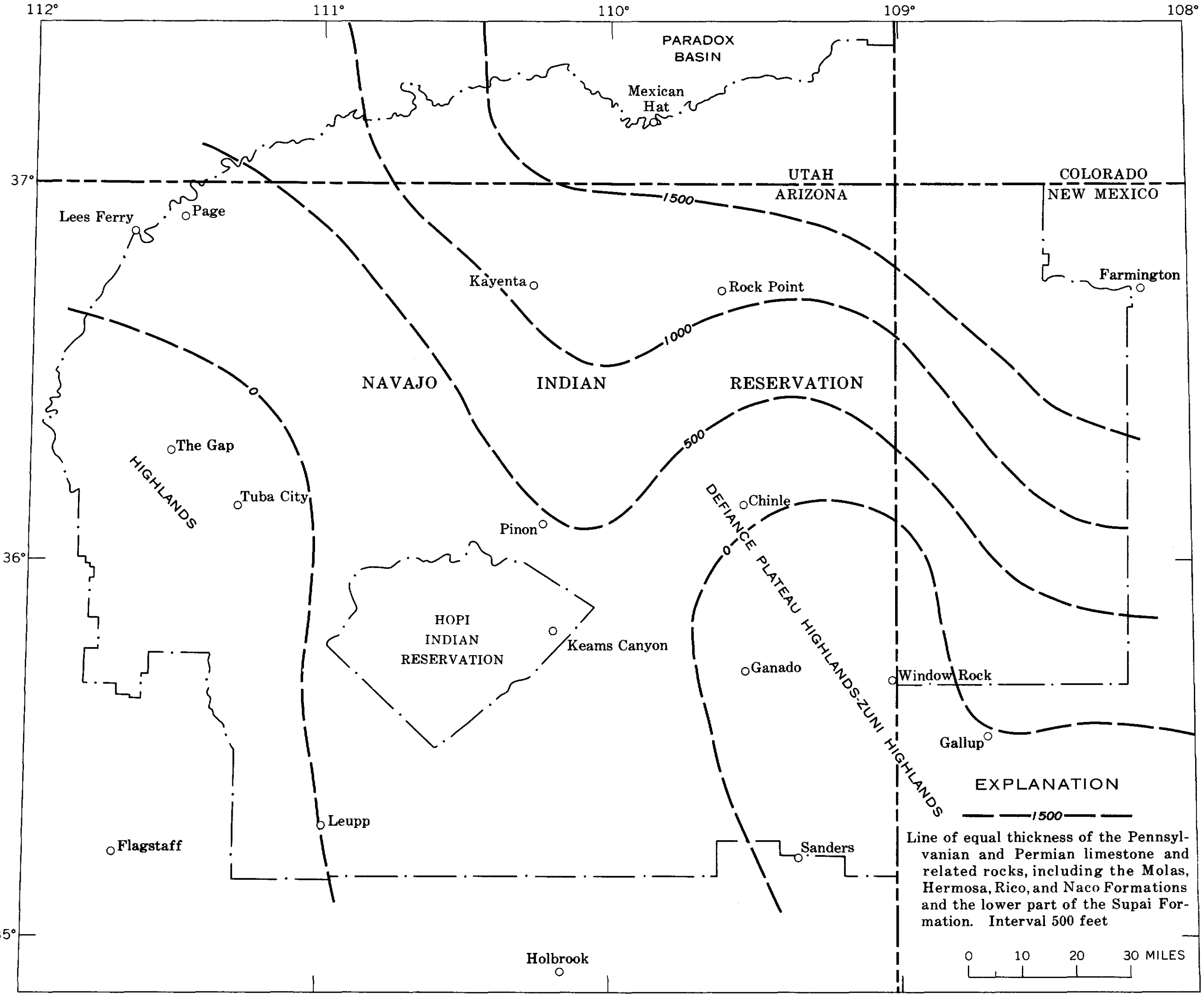


FIGURE 5.—Thickness of the Pennsylvanian and Permian limestone and related rocks, including the Molas, Hermosa, Rico, and Naco Formations and the lower part of the Supai Formation.

These highlands probably were not buried completely until Permian time. The general absence of coarse-grained material indicates that these highlands were relatively stable and were not important sources of Pennsylvanian or Permian deposits as compared with the Uncompahgre Highlands. The continual deposition of Permian red beds filled the Paradox basin and restricted the distribution of the late Paleozoic seas mainly to areas outside the Navajo country. South of the reservations, however, the large thicknesses of evaporites in the upper part of the Supai Formation indicate the presence of restricted lagoons or a relic sea in the Holbrook-Sanders area, which was cut off temporarily from the open sea of the Cordilleran geosyncline southwest of the Colorado Plateaus and the seas south and southeast of the plateaus. More extensive evaporite deposits are in the Yeso Formation in west-central New Mexico. The few limestone and gypsum beds in the Supai Formation in the Defiance Plateau and in the Cutler Formation in Monument Valley may reflect local extensions of these lagoons.

In the Defiance Plateau the lower member of the De Chelly Sandstone intertongues with the upper part of the Supai Formation and with beds of the Cutler Formation. The lower member is restricted to the Defiance area and is considered, in part, to be shoreline deposits (C. B. Read and A. A. Wanek, written commun., 1952) separating the more fluviatile Cutler Formation from the more marine Supai Formation. Rocks similar to the lower member of the De Chelly Sandstone are not recognized in the Zuni Mountains, Monument Valley, or the Grand Canyon areas.

The upper member of the De Chelly Sandstone, the Coconino Sandstone, the De Chelly Sandstone Member of the Cutler Formation, and the Glorieta Sandstone occupy the same stratigraphic interval in the southern part of the Colorado Plateaus (pl. 2). This correlation is strengthened by the fact that ground water is in this sandstone interval throughout the western three-fourths of the Navajo country. These sandstone formations comprise the main units of the C multiple-aquifer system (Cooley, 1963; Cooley and others, 1969), which is utilized extensively in areas in the Arizona part of the Colorado Plateaus. In addition, the White Rim Sandstone Member of the Cutler Formation (Baker and Reeside, 1929) exposed in the northern part of the Glen Canyon area of Utah is correlative and probably continuous with the De Chelly Sandstone Member in Monument Valley. These deposits present a series of complex stratigraphic relations, owing to their lenticular or wedge shape, slight differences in lithology, and their close association with the underlying red beds of the Supai and Cutler Formations. The greatest differences between the deposits are the amount of silt and the types of crossbedding. The Coconino Sandstone is a well-sorted clean crossbedded sandstone. The upper member of the De Chelly Sandstone—the White House Member of Peirce (1964)—generally is crossbedded but is somewhat less well sorted and contains some silt. In the southern part of the Defiance Plateau, however, a phase of this unit—the Black Creek Member of Peirce (1964)—is silty and relatively flat bedded. The De Chelly and White Rim Sandstone Members of the Cutler Formation are similar to the crossbedded upper member of the De Chelly Sandstone, and the Glorieta Sandstone is similar to the silty and flat-bedded phase.

The latest transgressions of Permian seas from the southeast, south, and west inundated the western and southern parts of the reservations and resulted in deposition of the limy marine beds that comprise the Toroweap Formation and the Kaibab and San Andres Limestones. The Coconino and its approximate correlatives were transgressive beach and bar deposits along the margin of the Permian seas (C. B. Read, written commun., 1964). The sediments of the Toroweap Formation were deposited only in the western quarter of the area. The last marine advance in the Navajo country is recorded by the Kaibab Limestone in Arizona and the San Andres Limestone in New Mexico (fig. 3). Pre-Moenkopi erosion was responsible mainly for removing much of the limestone in the Defiance Plateau and in the southern part of the reservations.

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