Stratigraphy of the Chinle and Moenkopi Formations, Navajo And Hopi Indian Reservations Arizona, New Mexico, and Utah

GEOLOGICAL SURVEY PROFESSIONAL PAPER 521-B

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

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By C. A. REPENNING, M. E. COOLEY, *and* J. P. AKERS

HYDROGEOLOGY OF THE NAVAJO AND HOPI INDIAN RESERVATIONS
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CONTENTS

ILLUSTRATIONS

TABLE

STRATIGRAPHY OF THE CHINLE AND MOENKOPI FORMATIONS, NAVAJO AND HOPI INDIAN RESERVATIONS, ARIZONA, NEW MEXICO, AND UTAH

By C. A. Repenning, M. E. Cooley, and J. P. Akers

ABSTRACT

The Chinle and Moenkopi Formations of Triassic age are present throughout most of the Navajo and Hopi Indian Reservations, an area of about 25,000 square miles. The formations are 1,700 feet thick in the valley of the Little Colorado River and thin northwestward to 1,100 feet at Lees Ferry and 1,300 feet in San Juan Canyon. The Chinle and Moenkopi Formations comprise a thick sequence of shaly beds and contain several relatively thin sandstone beds. The shaly beds generally are not water bearing, but a few persistent sandstone beds—mainly in the southeastern part of the report area—yield water to springs and drilled wells.

The lower boundary of the Triassic rocks is marked by an extensive erosion surface of slight relief cut on the Permian rocks. In most of the Navajo Indian Reservation, the erosion occurred from Late Permian time until the deposition of the Moenkopi Formation in Early and Middle(?) Triassic time. In general, the basal Triassic rocks in the eastern part of the report area are younger than those in the western part.

In the reservations the Moenkopi Formation is of Early and Middle(?) Triassic age, and where the Hoskinnini Member, the basal member of the Moenkopi, is present, the formation is of Triassic(?) and Early and Middle(?) Triassic age. The Moenkopi was deposited in a broad trough that formed part of a stable shelf east of the Cordilleran geosyncline between the Mogollon Highlands of central Arizona and New Mexico and the Uncompahgre Highlands of Colorado. The lithology of the Moenkopi reflects a westward transition from continental to generally marine depositional environments. The streams that deposited the fluvial parts of the Moenkopi Formation flowed generally northwestward across the reservations.

In the southern and western parts of the reservations, the Moenkopi is divided into the Wupatki Member at the base, composed of siltstone and silty sandstone; the overlying Moqui Member, composed of siltstone, silty sandstone, and gypsum; and the Holbrook Member at the top, composed of sandstone and siltstone. Only the Holbrook Member is present on the Defiance Plateau. In Monument Valley the formation consists, in ascending order, of the Hoskinnini Member of Triassic(?) age, composed of silty sandstone and siltstone, and the lower siltstone, middle sandstone, and upper siltstone members. In the Zuni Mountains, siltstone, sandstone, and conglomerate are referred to as the upper sedimentary rocks of the Moenkopi(?) Formation.

The Moenkopi Formation thins generally eastward and southward across the reservations from Lees Ferry, where it is 517 feet thick. The thickness of the Moenkopi is 349 feet near Cameron, 158 feet near Holbrook, 150 feet in the central part of Monument Valley, and between 30 and 100 feet along the north flank of the Zuni Mountains.

Regional upwarping terminated the deposition of the Moenkopi Formation and caused a general withdrawal of the Triassic seas. Recurrent uplift of the Mogollon and Uncompahgre Highlands formed a generally northwestward-flowing drainage system. At first, there were degrading streams entrenched in valleys and large channels having more than 150 feet of relief cut into the Moenkopi Formation and older rocks. This erosion marks one of the more conspicuous breaks in deposition in the Mesozoic rocks of the southwest. Later, beginning with the deposition of the Chinle Formation, the streams began to aggrade. Conglomeratic and sandy sediments of the basal members of the Chinle Formation filled the valleys and channels, and eventually deposits of the Chinle Formation were laid down over all of what is now the reservations and adjacent areas.

Exposures of the Chinle Formation in Chinle Valley, the type area, are representative of the formation in the reservations. East of Chinle Valley the formation contains several resistant sandstone beds, but west of the valley such beds in the main body of the Chinle are virtually insignificant. The formation thickens southeastward across the reservations from about 800 feet along the Colorado and San Juan Rivers to 1,500 feet in the Zuni Mountains.

The Chinle Formation consists of, in ascending order, the Shinarump, Mesa Redondo, sandstone and siltstone, Monitor Butte, Petrified Forest, Owl Rock, and Church Rock Members. In the eastern part of the report area, the Petrified Forest Member is divided into an upper and a lower part, which are separated by the Sonsela Sandstone Bed. The Shinarump Member and Sonsela Sandstone Bed are composed mainly of sandstone and conglomerate. The Mesa Redondo and Monitor Butte Members consist of siltstone and mudstone containing sandstone beds. The Monitor Butte and Petrified Forest Members undifferentiated are made up principally of claystone, mudstone, and siltstone. In addition to the Sonsela Sandstone Bed, the Petrified Forest Member has several thin sandstone beds in the southeastern part of the area. The Owl Rock Member consists of calcareous siltstone layers that alternate with thin beds of limestone and cherty limestone. In the Monument Valley area, a red-bed sequence of siltstone, silty sandstone, and sandstone, included in the Church Rock Member, is subdivided into four units termed "reddish-orange siltstone unit," "lower ledge," "lower silty part of the Church Rock Member," and "Hite

bed." All members and units of the Chinle Formation form a gradational and intertonguing depositional sequence, although several local intraformational unconformities are present chiefly in the southeastern part of the report area.

INTRODUCTION

The varicolored red, brown, blue, and gray Chinle and Moenkopi Formations of Triassic age crop out throughout most of the Navajo and Hopi Indian Reservations and have been intricately dissected into painted-desert badlands in the area of the Little Colorado and Puerco Rivers and in Chinle Valley. The formations are 1,700 feet thick in the area drained by the Little Colorado River, and they thin northwestward to 1,100 feet at Lees Ferry and 1,300 feet in San Juan Canyon.

The Chinle and Moenkopi Formations comprise a thick sequence of shaly beds, which contain several relatively thin sandstone beds. These formations are, in general, confining beds between the aquifer systems of the Permian Coconino Sandstone and the Triassic(?) and Jurassic Navajo Sandstone, which are the main water-bearing units in the reservations. A few persistent sandstone beds in the Chinle and Moenkopi Formations, mainly in the southeastern part of the report area, yield water to springs and drilled wells.

LOCATION AND LAND-NET SYSTEM

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, extends into San Juan and McKinley Counties in northwestern New Mexico, and in southeastern Utah covers part of San Juan County (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 nearly three times the size of New Jersey.

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 in 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 to 151, starting in the upper right corner of the reservations and continuing consecutively from right to left in rows (fig. 1).

PURPOSE AND SCOPE OF THE REPORT

In 1946 the U.S. Geological Survey, at the request of the Bureau of Indian Affairs, made a series of hydrologic investigations to study and make recommendations 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 second chapter of U.S. Geological Survey Professional Paper 521, which will describe the geology and hydrology of the reservations. The first draft of this chapter, under the present authorship, was completed in August 1955. Since then, considerable time has been spent in reorganization and addition of material to keep the report current with other studies. The work done since 1955 has been by Akers and particularly Cooley, without whose attention the report may have never been published.

The geology of the uppermost Triassic and the Jurassic rocks has been published as Professional Paper 291 (Harshbarger, Repenning, and Irwin, 1957).

The basic geohydrologic data—that is, records of wells and springs, selected chemical analyses, selected drillers' logs, lithologic logs, and stratigraphic sections —are published separately as Arizona State Land Department Water-Resources Reports 12–A (Davis and others, 1963), 12–B (Kister and Hatchett, 1963), 12–C (Cooley and others, 1964a), 12–D (Cooley and others, 1966), and 12–E (McGavock and others, 1966).

This chapter of Professional Paper 521 describes the distribution and regional stratigraphy of the Chinle and Moenkopi Formations of Triassic age. Although the ground-water hydrology of these formations will be discussed in a later chapter, a few of the pertinent hydrogeologic relations are noted briefly in this report.

The geologic maps of the reservations are included in chapter A (Cooley and others, 1968) of Professional Paper 521. The generalized outcrops of the Chinle and Moenkopi Formations are shown on plate 1 of this report. Definitions of the terms describing the sedimentary features are included in chapter A and are not discussed in this report.

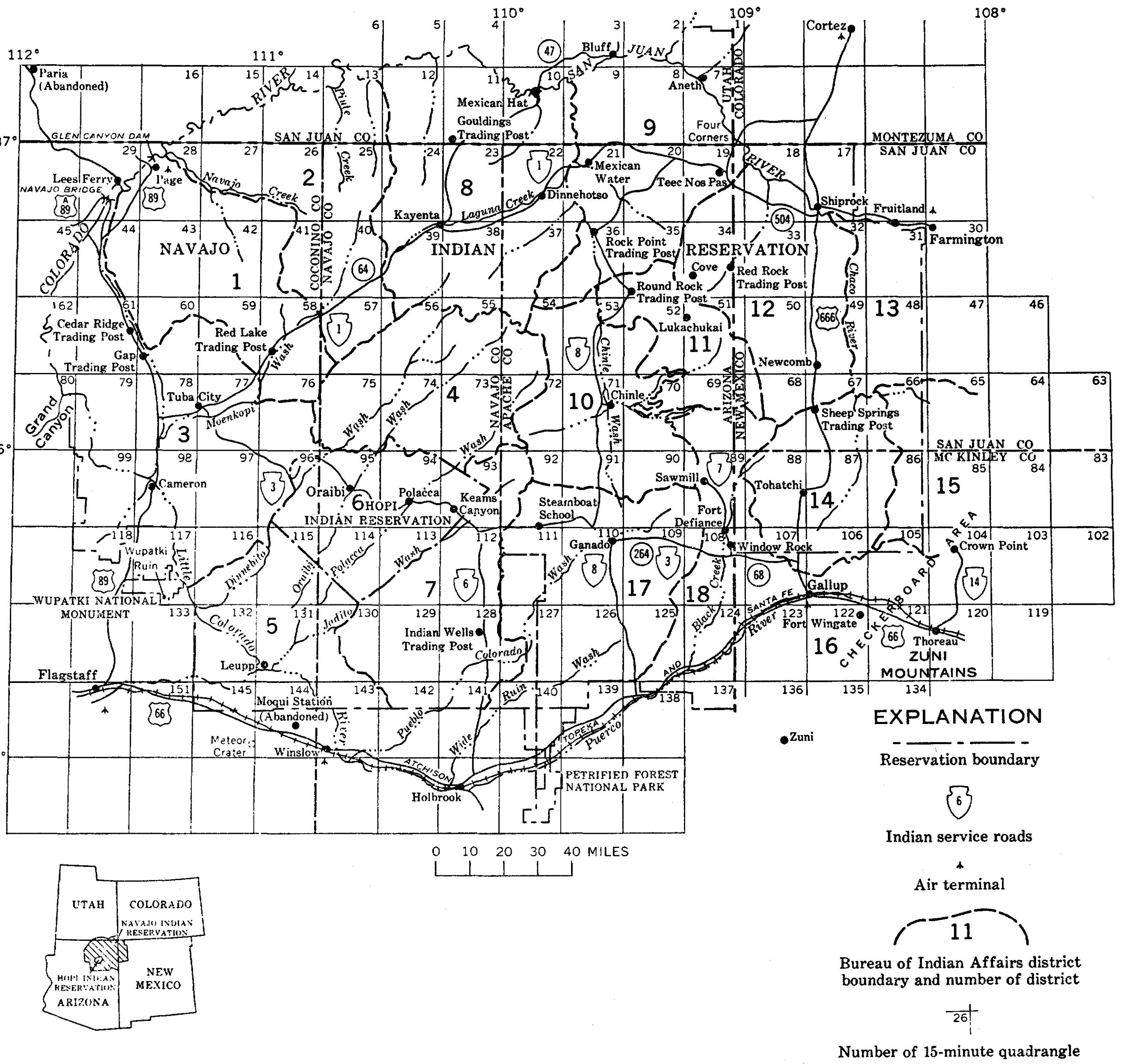

FIGURE 1.—Bureau of Indian Affairs administrative districts and 15-minute quadrangles.

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.

Considerable effort was spent on the study of sample cuttings and drillers' logs to determine the distribution, change in lithology, and thickness of the units, and other factors affecting the stratigraphy and hydrology of the reservations. In much of the area the strata are nearly horizontal, and an accurate thickness of the Chinle Formation is difficult to measure; therefore, wherever possible, the thickness was obtained from well logs.

PREVIOUS INVESTIGATIONS AND TERMINOLOGY

The Moenkopi Formation of Early and Middle(?) Triassic age (and, where the Hoskinnini Member is present, of Triassic(?) age) was named by Ward (1901), who described it from exposures at the mouth of Moenkopi Wash—a tributary to the Little Colorado River. Different nomenclature is used for the members of the Moenkopi in the various parts of the reservations (table 1) because stratigraphic changes occur in the formation as a result of pinchout, overlap, and facies changes of the units. In the area of the Little Colorado River, McKee (1954, p. 19) divided the Moenkopi into three members, which are, in ascending order, the Wupatki, Moqui, and Holbrook Members. The Holbrook Member, which is the upper member of the Moenkopi in the Winslow-Holbrook area, previously was called the Holbrook Sandstone (Hager, 1922). In southwestern Utah, Huntington and Goldthwait (1903, p. 48) recognized five subdivisions of the Moenkopi Formation. Reeside and Bassler (1922, p. 60) later applied the names Virgin Limestone Member and Shnabkaib Shale Member to two of these subdivisions, and Gregory (1948, p. 227) named a sixth member the Timpoweap. The Moenkopi Formation of southwestern Utah now consists of, in ascending order, the Timpoweap Member, the lower red member, the Virgin Limestone Member, the middle red member, the Shnabkaib Member, and the upper red member. The Moenkopi Formation of Monument Valley now consists of the basal Hoskinnini Member of Triassic(?) age, which was previously considered to be the uppermost unit of the Cutler Formation of Permian age but which is now assigned to the Moenkopi (Stewart, 1959), and three members referred to in this report as the lower siltstone member, the middle sandstone member, and the upper siltstone member (table 1).

The Upper Triassic strata, broadly correlative with the Chinle Formation, were described in reports on the earliest expeditions in the area. In the valley of the Little Colorado River, Ward (1901; 1905) called some of the Triassic units the Leroux and Lithodendron Members of the Shinarump Formation. The term "Shinarump" subsequently was restricted to the basal part of the Lithodendron Member, and the rest of the sequence was renamed the Chinle Formation by Gregory (1917), who designated the valley of Chinle Wash as the type area.

The Shinarump Conglomerate in southwestern Utah was first named by Gilbert (1875). It is now considered a basal member of the Chinle Formation in the Navajo country and is called the Shinarump Member (Stewart, 1957, p. 442). Gregory (1917, p. 42–43) recognized four units in the Chinle Formation above the Shinarump Member. These units were defined on the basis of broad lithologic differences, and Gregory informally called them divisions A, B, C, and D. Division A, the youngest unit, is now assigned to the Church Rock Member in Monument Valley (Stewart, 1957, p. 459; Witkind and Thaden, 1963), including the Hite bed (R. B. O'Sullivan, written commun., 1965). Gregory also applied the name division A to strata now called the Dinosaur Canyon Sandstone Member of the Moenave Formation (Averitt and others, 1955; Harshbarger and others, 1957) in the Echo Cliffs area and the Rock Point Member of the Wingate Sandstone (Averitt and others, 1955; Harshbarger and others, 1957) elsewhere in the Navajo Indian Reservation. Stewart (1957, p. 458) and Witkind and Thaden (1963) renamed division B the Owl Rock Member of the Chinle Formation. Gregory (1950) renamed division C the Petrified Forest Member of the Chinle Formation because the division is well exposed in the Petrified Forest National Park. In the eastern part of the reservations, the Petrified Forest Member is subdivided into an upper part and a lower part, separated by the conspicuous Sonsela Sandstone Bed (Akers and others, 1958, p. 89). Division D includes the Monitor Butte Member (Stewart, 1957, p. 452), previously referred to as the lower red member by Akers and others (1958) and Cooley and others (1964a), in the Monument Valley and Defiance Plateau areas, the Mesa Redondo Member (Cooley, 1958) in the southern Defiance Plateau, and the sandstone and siltstone member (J. H. Stewart, written commun., 1965), previously referred to as a northwestern extension of the Mesa Redondo Member by Repenning and others (1965), which is assigned to strata between the Shinarump and Petrified Forest Members.

Much of the information concerning the directions of streams that deposited the fluvial part of the Moenkopi and Chinle Formations is from Poole (1961).

ACKNOWLEDGMENTS

The authors are grateful for the assistance, cooperation, and information given by the late J. J. Schwartz, former head of the Bureau of Indian Affairs' water-development program for the Navajo Indians; M. H. Miller, engineer, Bureau of Indian Affairs; C. M. Sells, superintendent, Ground Water Development Department of the Navajo Tribe; J. M. Holmes, hydrologist for the Navajo Tribe; Buster Kinsley, supervisor for the Hopi Indians, Bureau of Indian Affairs; the Navajo Tribal Council; and other personnel of the Bureau of Indian Affairs and the two tribes.

R. A. Cadigan, L. C. Craig, E. D. McKee, R. B. O'Sullivan, J. H. Stewart, J. D. Strobell, F. G. Poole, R. F. Wilson, and D. G. Wyant of the U.S. Geological Survey supplied field data and discussed the many complex stratal problems of the Moenkopi and Chinle Formations with the authors.

TABLE 1.—*Nomenclature and correlation of the Chinle and Moenkopi Formations in the Navajo country*

Age	Formation	Southwestern Utah	Lees Ferry area	Little Colorado River area: Cameron area	Little Colorado River area: Holbrook area	Defiance Plateau	Zuni Mountains	Monument Valley: Southern and western areas	Monument Valley: Eastern area
Triassic: Late	Chinle							Church Rock Member: Hite bed; Lower silty part	Hite bed; Lower silty part; Lower ledge
Triassic: Late	Chinle		Owl Rock Member	Owl Rock Member	Owl Rock Member	Owl Rock Member	Owl Rock Member	Owl Rock Member; Reddish-orange siltstone unit	Owl Rock Member; Reddish-orange siltstone unit
Triassic: Late	Chinle	Petrified Forest Member	Petrified Forest Member: Gray unit and blue unit	Petrified Forest Member: Red unit, gray unit and blue unit	Petrified Forest Member: Upper part; Sonsela Sandstone Bed; Lower part	Petrified Forest Member: Upper part; Sonsela Sandstone Bed; Lower part	Petrified Forest Member: Upper part; Correo(?) Sandstone Member; part; Sonsela Sandstone Bed; Lower part	Petrified Forest Member; Petrified Forest and Monitor Butte Members undifferentiated	Petrified Forest Member; Petrified Forest and Monitor Butte Members undifferentiated
Triassic: Late	Chinle		Sandstone and siltstone member	Sandstone and siltstone member	Monitor Butte Member	Monitor Butte Member; Mesa Redondo Member	Monitor Butte Member	Monitor Butte Member	Monitor Butte Member
Triassic: Late	Chinle	Shinarump Member	Shinarump Member	Shinarump Member	Shinarump Member	Shinarump Member	Shinarump Member	Shinarump Member	Shinarump Member
? Middle (?)	Moenkopi	Absent	Absent	Holbrook Member	Holbrook Member	Absent	Absent; Moenkopi(?) Formation	Absent	Absent
Middle (?) ?	Moenkopi	Upper red member	Absent	Holbrook Member	Holbrook Member	Holbrook Member	Absent	Upper siltstone member; Middle sandstone member	Upper siltstone member; Middle sandstone member
Early	Moenkopi	Shnabkaib Member	Absent	Moqui Member	Moqui Member	Absent	Absent	Lower siltstone member	Lower siltstone member
Early	Moenkopi	Middle red member	Wupatki Member: Upper sandstone unit; Mudstone and siltstone unit, sandy siltstone unit, and conglomerate unit	Wupatki Member	Upper sandstone unit; Lower siltstone unit	Absent	Absent	Lower siltstone member	Lower siltstone member
Early	Moenkopi	Virgin Limestone Member; Lower red member; Timpoweap Member	Absent	Absent	Absent	Absent	Absent	Lower siltstone member	Lower siltstone member
Triassic(?)	Moenkopi	Absent	Absent	Absent	Absent	Absent	Absent	Hoskinnini Member	Hoskinnini Member

LOWER BOUNDARY OF THE TRIASSIC ROCKS

The lower boundary of the Triassic rocks on the Colorado Plateaus is marked by an extensive erosion surface of slight relief cut on Permian rocks. Throughout most of the Navajo Indian Reservation the erosion occurred from Late Permian time until the deposition of the Moenkopi sediments in Early and Middle(?) Triassic time. In most of the Four Corners area, Moenkopi deposits were not laid down or were removed by pre-Chinle erosion. In the Zuni Mountains area, and perhaps in the southeastern corner of the reservations, pre-Chinle channel erosion removed part of the Moenkopi Formation, and locally, southeast of Thoreau, the Chinle Formation lies on the San Andres Limestone of Permian age.

In the Lees Ferry area, channels as much as 15 feet deep cut in the top of the Kaibab Limestone interrupt the general flatness of the unconformity. The channels are filled with angular chert and limestone fragments eroded from the underlying Permian Kaibab Lime stone. In many other places in the northwestern part of the Navajo country, the lower boundary is marked by a sequence of thin discontinuous yellow mudstone and cherty conglomerate beds (fig. 2). In the southwestern part of the reservations, the Moenkopi-Permian contact is virtually a flat surface and has a relief of less than 3 feet. Near Holbrook the Kaibab Limestone was stripped off or was never deposited, and Triassic rocks rest on the Coconino Sandstone of Permian age. In the southern part of the Defiance Plateau, the unconformity has a relief of 1–2 feet and is between the Holbrook Member of the Moenkopi Formation and the De Chelly Sandstone of Early Permian age.

In Monument Valley the Hoskinnini Member, the basal unit of the Moenkopi Formation, rests unconformably on the De Chelly Sandstone Member and the Organ Rock Tongue of the Cutler Formation. The unconformity is relatively flat, showing only broad swales that have a relief of 10 feet in a lateral distance of a quarter of a mile. The contact is obscure where the lowermost beds of the Hoskinnini Member consist of reworked material derived from the underlying De Chelly Sandstone Member and in areas where the Hoskinnini Member rests on the Organ Rock Tongue. In other places, there is a well-defined contact between the flat-lying beds of the Hoskinnini Member and the cross-bedded De Chelly Sandstone Member.

The lower boundary of the Triassic rocks outlines a karst topography which formed on the San Andres Limestone in the Zuni Mountains south of the reservations (Smith, 1954, p. 8). Locally, well-defined channels about 50 feet deep were cut through the San Andres Limestone into the Glorieta Sandstone of Permian age. Siltstone, silty sandstone, and rubble breccia, which are cemented by calcareous and siliceous material, occupy depressions in the karst topography. In an exposure 3 miles south of Thoreau, a silty and sandy deposit containing small petrified logs seems to be a cave filling in the San Andres Limestone (Cooley, 1959b).

The basal Triassic rocks in northeastern Arizona are

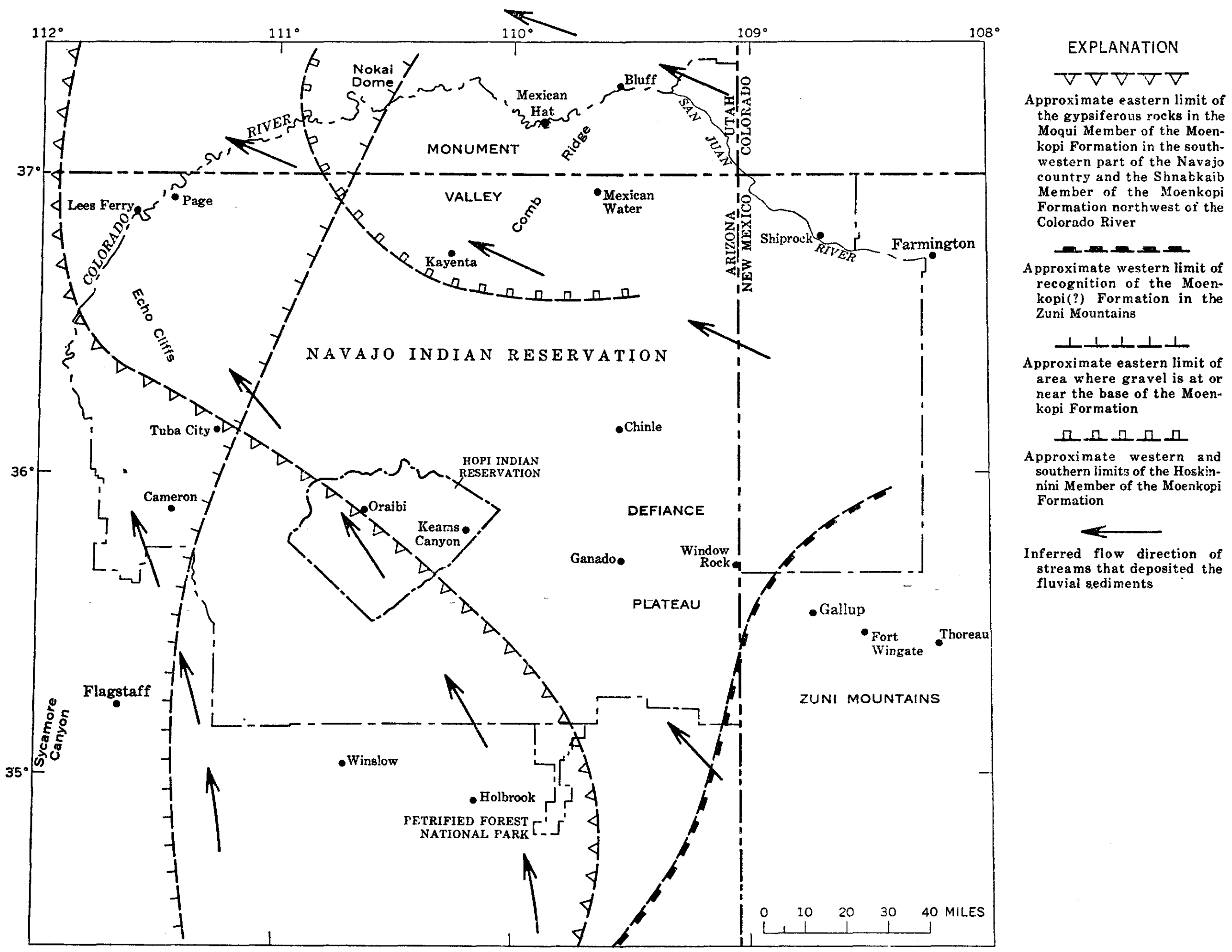

Figure 2.—Distribution of units of the Moenkopi Formation.

younger than those in western Arizona. In northeastern Arizona on the Defiance Plateau and south of the reservations, Lower Permian rocks are overlain by the Holbrook Member of the Moenkopi Formation of Early and Middle(?) Triassic age or the Chinle Formation of Late Triassic age. In the western part of the reservations, the Wupatki Member of probable Early Triassic age overlies Permian rocks. Therefore, progressively less Triassic time is represented by the unconformity from east to west in the Navajo country.

MOENKOPI FORMATION

The Moenkopi Formation was deposited in a broad trough that trended west-northwestward between the Mogollon Highlands of central Arizona and New Mexico and the Uncompahgre Highlands of Colorado (fig. 3). Uplift of the Triassic Mogollon Highlands south of the Navajo country is recorded by the siliceous gravel at the base of the Moenkopi in Sycamore Canyon southwest of Flagstaff (Brady, 1935, p. 11) and by gravel in the Holbrook Member in central Apache County and the Moenkopi(?) Formation of the Zuni Mountains (Cooley, 1959a, p. 68). The streams that deposited this gravel (fig. 2) and other fluvial material of the Moenkopi Formation flowed generally northwestward across the area that is now the Navajo country.

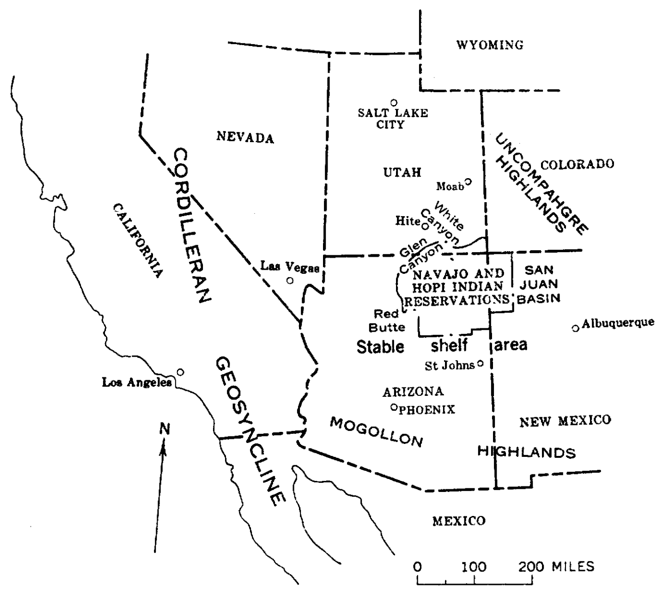

FIGURE 3.—Regional structural features that influenced Triassic sedimentation in the area of the Navajo and Hopi Indian Reservations.

AREAL DESCRIPTION

The Moenkopi Formation crops out in a continuous band in the western and southern parts of the Navajo country, in scattered exposures on the Defiance Plateau, in Monument Valley, and in the Zuni Mountains (pl. 1). The members of the Moenkopi are shown on the stratigraphic fence diagram (pl. 2). The lithology of the Moenkopi in the Navajo country reflects a westward transition from a continental depositional environment on a somewhat stable shelf to a generally marine depositional environment toward the center of the Triassic Cordilleran geosyncline (fig. 3). This transition is most apparent in the Little Colorado River area and to the west in northwestern Arizona and southwestern Utah.

LITTLE COLORADO RIVER AREA

In the valley of the Little Colorado River, the Moenkopi Formation consists, in ascending order, of the Wupatki, Moqui, and Holbrook Members (table 1). The Wupatki Member is divided into two units: a lower sequence of siltstone and silty sandstone beds and an upper sandstone bed that forms a prominent ledge that McKee (1954, p. 19) referred to as the lower massive sandstone.

WUPATKI MEMBER

The Wupatki Member of the Moenkopi Formation was named for Wupatki Ruin, Wupatki National Monument. In the valley of the Little Colorado River, the lower unit of the Wupatki Member is a pale-reddish-brown (10*R* 5/4) (color designation by Goddard and others, 1948) very thin bedded to thin-bedded siltstone, which weathers into uniformly steep slopes interrupted at intervals by thin ledges of silty sandstone. The ledge-forming beds commonly display ripple marks and casts of salt crystals. The sandy beds generally are ripple laminated and pseudocrossbedded; this bedding is common in the Moenkopi Formation and was defined by McKee (1939, p. 73). In places, discontinuous lenticular beds of yellowish-gray (5*Y* 8/1) sandstone and pebbly sandstone less than 2 feet thick are exposed at the base of the Wupatki Member. Abundant vertebrate trackways have been preserved in some thin resistant beds of the member (Peabody, 1948), and amphibian remains are common locally in the Cameron and Meteor Crater areas (Camp and others, 1947; Reeside, 1957; Welles and Cosgriff, 1965).

The upper unit of the Wupatki Member is a grayish-pink (5*R* 8/2) to grayish-red (10*R* 4/2) poorly to fairly well sorted very fine grained to fine-grained sandstone, which locally contains minor amounts of silt. The upper unit becomes siltier toward the top and grades upward into the Moqui Member. The upper unit and other sandstone beds in the Wupatki are composed of stained quartz grains. The sandstone is about 20–40 feet thick, is lenticularly bedded, and commonly contains simple and trough crossbedding displaying small- to medium-scale crossbeds dipping at low angles. The base is sharp and has a relief of 1 or 2 feet, but locally it is marked by small, narrow channels cut into the underlying siltstone.

The Wupatki Member is divided into four main units at Lees Ferry (table 1): a basal 35-foot ledge-forming conglomerate, a 196-foot slope-forming sandy siltstone, a 215-foot mudstone and siltstone, and a 43-foot cliff-forming upper sandstone. The three lower units are equivalent to the lower unit of the Wupatki Member near the Little Colorado River. The fourth unit is a northwestern extension of the upper sandstone unit of the Wupatki Member (pl. 2). At Lees Ferry, strata overlying the upper sandstone unit of the Wupatki Member (pl. 2) were removed by erosion before deposition of the Chinle Formation. West of Lees Ferry, the upper sandstone unit is overlain by the upper red member of the Moenkopi Formation, which is the topmost unit of the Moenkopi Formation in southwestern Utah (table 1).

The basal conglomerate consists of chert, limestone, and mudstone pebbles and sandstone boulders as much as 3 feet in diameter that are set in a matrix ranging from clay to coarse-grained sand. The unit is irregularly bedded and shows some crossbedding in the finer grained parts; its exposed surface is pitted and knobby due to differential weathering. The basal conglomerate is similar to the Timpoweap Member, the lowermost member of the Moenkopi Formation farther west. It it not continuous with the Timpoweap, however, and is associated with strata that are younger than the Timpoweap.

At Lees Ferry the sandy siltstone unit of the Wupatki Member is a series of very thin to thin sandy siltstone and silty fine-grained sandstone beds. The sandstone beds, some of which are crossbedded, are mainly in the lower part of the unit. The sandy siltstone unit is moderate brown (5*YR* 4/4), contains well-formed ripple marks, and includes gypsum veinlets that are common in the upper part of the unit. The unit is gradational into the underlying conglomerate and the overlying mudstone and siltstone unit.

The mudstone and siltstone unit is similar to the sandy siltstone unit but contains less sandstone. Its uppermost beds include thin and lenticular layers of gypsum, gypsiferous mudstone, and veinlets of gypsum. These beds can be traced westward into the Shnabkaib Member of the Moenkopi Formation. Most of the mudstone and siltstone unit and the lower sandy siltstone unit of the Wupatki Member at Lees Ferry are lateral equivalents of the middle red member of the Moenkopi to the west (McKee, 1954, fig. 8).

The cliff-forming upper sandstone unit (pl. 2), which is the uppermost unit of the Moenkopi Formation at Lees Ferry, is grayish-red (10*R* 4/2) firmly cemented silty sandstone and sandy siltstone. It is composed of silt, very fine grains of stained quartz, and mica as an accessory mineral. The bedding is flat to gnarly and ranges from very thin to thick. The amount of sand and crossbedding in the upper sandstone unit decreases northward from the Little Colorado River on Marble Platform and along the Echo Cliffs. West of Lees Ferry the unit can be traced into the upper part of the Shnabkaib Member of the Moenkopi.

The Wupatki Member is not known to yield any ground water to wells or springs. The sandstone units are too thin and silty to allow appreciable movement of water. Fractures along bedding planes and joints are not well formed and do not collect sufficient water to maintain seeps and springs.

MOQUI MEMBER

McKee (1954) probably named the Moqui Member of the Moenkopi Formation from exposures along Moqui Wash 8 miles west of Winslow, Ariz. The Moqui Member is 85 feet thick at Holbrook and less than 50 feet thick east of Holbrook. The Moqui is not present on the Defiance Plateau but is in the subsurface in much of the southwestern part of the reservations.

The Moqui Member, consisting of pale-brown (5*YR* 6/4) gypsiferous mudstone and siltstone beds, is a lighter shade of brown than the Wupatki and Holbrook Members. It is generally characterized by an abundance of gypsum nodules, stringers, and layers as much as 5 feet thick that constitute as much as 25 percent of the member in the southwestern part of the reservations (fig. 2). The solution of the gypsum in the Moqui Member detrimentally affects the small amount of ground water in the Moenkopi, and, in some places, the water in the underlying Coconino Sandstone and Kaibab Limestone. East of Holbrook gypsiferous sediments grade laterally into very thin bedded pale-red (5*R* 6/2) to pale-reddish-brown (10*R* 5/4) siltstone. The Moqui erodes into a uniform, and usually covered, slope below the cliff-forming Holbrook Member. The member displays broad lenticular bedding and contains sharply defined channels where it is well exposed. The channels are filled with silty very fine grained to fine-grained sandstone that has large-scale very low angle to low-angle crossbeds.

The Moqui Member does not yield ground water to wells or springs in the Navajo country. The high silt content of the member limits movement of ground water.

HOLBROOK MEMBER

Sandstone beds in the Holbrook Member of the Moenkopi Formation form an irregular line of bluffs north of the Little Colorado River between Holbrook, which is the type area (Hager, 1922), and Cameron. The member underlies covered slopes on the Defiance Plateau and is continuous in the subsurface in the southern part of the Navajo country west of the Arizona-New Mexico State line (pl. 2).

Pale-red (10*R* 6/2) thin- to thick-bedded channel deposits of sandstone form most of the Holbrook Member at Holbrook. The sandstone is composed of very fine to medium poorly sorted quartz sand grains and contains considerable silt. The sandstone beds are lenticular and wedge shaped and have small- to medium-scale low- to medium-angle crossbeds. The sandstone beds commonly grade laterally into lenses of limestone and mudstone-pellet conglomerate. The limestone-conglomerate beds are more numerous in the lower part of the member, and in places a mudstone-pellet conglomerate is the basal bed. Lenticular thin-bedded siltstone layers are intercalated with the sandstone and conglomerate and are generally more prevalent near the top of the member.

On the Defiance Plateau the Holbrook Member is finer grained than in its type area and is composed of siltstone and mudstone beds not more than 50 feet thick and silty sandstone and sandstone beds less than 15 feet thick. The sandstone is generally very fine to fine grained, but some beds are medium to coarse grained and have lenses of limestone and mud-chip conglomerate. Some of the units have small- to medium-scale crossbeds.

West of Holbrook the member has fewer sandstone beds, and the siltstone beds increase; crossbedding also diminishes westward. The Holbrook Member is believed to be correlative with and to grade into the upper red member, which is exposed west of the reservations. Near Cameron, thin crossbedded sandy limestone lenses locally contain an abundance of small bivalves. These shells are poorly preserved, and it is not known whether they are fresh- or brackish-water forms, although the regional relations of the Moenkopi Formation suggest that the limestone beds are brackish-water deposits associated with shallow lagoons. Many amphibian and some reptilian remains are found in the Holbrook Member in outcrops in the valley of the Little Colorado River (Welles, 1947; Peabody, 1948).

Locally, sandstone beds in the Holbrook Member are sufficiently permeable to yield small amounts of water to wells and springs. Generally, however, this member forms a barrier to ground-water movement, as do the Wupatki and Moqui Members.

MONUMENT VALLEY AREA

The Moenkopi Formation in the Monument Valley area (pl. 1) erodes into steep ledgy slopes between cliffs of the Shinarump Member of the Chinle Formation and the Cutler Formation. In this area, the Moenkopi Formation consists of the basal Hoskinnini Member, lower siltstone member, middle sandstone member, and upper siltstone member (table 1). All the members of the Moenkopi in Monument Valley contain a large amount of silt and yield no ground water to wells or springs. In most exposures the members are easily recognized. In places, however, the contacts between the members are placed arbitrarily, and the thicknesses of the members may vary considerably owing to intertonguing of the middle sandstone member with the upper and lower siltstone members. The formation, not including the Hoskinnini Member, thins southeastward from 278 feet on the north side of Piute Mesa by the San Juan River to about 50 feet along Comb Ridge. The members also thin southeastward and grade into an undivided sequence of silty sandstone and sandy siltstone beds. The upper and lower siltstone members form debris-strewn irregular slopes, and the Hoskinnini Member and middle sandstone member erode into ledges and low cliffs.

HOSKINNINI MEMBER

The Hoskinnini Member of Triassic(?) age overlies the Lower Permian De Chelly Sandstone Member and the Organ Rock Tongue of the Cutler Formation of Permian age. The member was named by Baker and Reeside (1929; see also Baker, 1936, p. 28–29) for Hoskinnini Mesa in the western part of Monument Valley. 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, is not well defined. The Hoskinnini, therefore, was reassigned from the topmost unit of the Cutler Formation to the basal member of the Moenkopi by Stewart (1959). 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 Nokai Dome, which is its westernmost exposure in the reservations (fig. 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 Hoskinnini Member is characterized by horizontal partly contorted strata, which are more lenticular than the Organ Rock Tongue of the Cutler Formation and not as thinly laminated as the overlying beds of the Moenkopi. The member consists mainly of dark-reddish-brown (10*R* 3/4) to light-brown (5*YR* 6/4) very fine grained to fine-grained silty sandstone; some beds contain varying amounts of medium- and coarse-grained sandstone. Ripple-laminated beds are common locally and appear to grade laterally into "structureless" zones. A few ripple and current marks have been preserved, but no casts or molds of plant fragments or other remains were found. At one place on the east side of Nokai Dome, however, a few tubular-shaped concretions 3/8–5/8 inch in diameter—possibly burrows—are in the upper part of the sandstone. Many exposures show diagenetically crinkled bedding features.

In many places the lower part of the member is composed of a thick-bedded light-brown (5*YR* 6/4) sandstone unit, which lenses into the more typical darker silty sandstone. The sandstone unit is composed of quartz grains derived principally from the underlying De Chelly Sandstone Member of the Cutler Formation and displays small- to large-scale low-angle to very low angle crossbeds in lenticular, tabular, and wedge-shaped layers.

In the central part of Monument Valley, the upper part of the Hoskinnini Member contains thin-bedded crinkled siltstone and siliceous limestone, but these beds are not present in the eastern part of the valley. In the upper part of the Hoskinnini, there are usually two limestone beds about 2 feet apart; the lower bed is as much as 3 inches thick, and the upper bed is only about an inch thick. The limestone beds and the crinkled bedding suggest that the Hoskinnini Member was laid down in the quiet water of lagoons and tidal flats.

CONTACT BETWEEN THE HOSKINNINI MEMBER AND THE LOWER SILTSTONE MEMBER

The Hoskinnini-lower siltstone contact is not everywhere well defined in the Monument Valley area because of the similar composition and texture of the units. Ripple lamination and small amounts of coarse sand are present in the basal part of the lower siltstone member and in the Hoskinnini Member. The ripple lamination, however, is conspicuous only in the lower siltstone member; in the Hoskinnini Member, it is poorly formed and can be observed only in exceptionally good exposures. Slight differences between the two units are the excellently preserved ripple marks and the generally thinner beds of the lower siltstone member and the crinkled stratification in the Hoskinnini Member. Much of the Hoskinnini weathers massive and is structureless.

Baker (1936, p. 39–40) described the Hoskinnini-lower siltstone contact in Monument Valley as follows:

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

Stewart (1959, p. 1862), however, gave the following description of the upper contact of the Hoskinnini Member in southeastern Utah:

> The contact of the Hoskinnini member with the overlying part of the Moenkopi appears conformable in almost all areas. Locally, in the White Canyon area [near Hite, Utah], the unit overlying the Hoskinnini consists of a sandstone and conglomeratic sandstone that fills channels cut into the Hoskinnini. Most of the channels are less than a foot deep, and the surface of erosion probably represents only a local break in deposition. In places where the top 10–30 feet of the Hoskinnini does not contain disseminated fine to coarse quartz grains, the upper contact of the member is difficult to determine and is located entirely on the basis of typical stratification and topographic expression. In many places, the top of the Hoskinnini coincides with the base of the lowest ripple-laminated siltstone in the overlying part of the Moenkopi and, as the Hoskinnini is not known to contain ripple-laminated siltstone, this feature is used in connection with other lithologic characteristics to locate the contact.

At Monitor Butte (pl. 1) the thin-bedded crinkled zone described by Baker (1936, p. 39) is absent locally, but the upper contact of the Hoskinnini Member seems to be at the top of a silty sandstone. The silty sandstone is partly structureless, partly thin, and lenticularly bedded and shows evidence of weathering prior to the deposition of the overlying units. This contact may correspond to the boundary selected by Baker (1936). Above this more massive and weathered bed, pale-reddish-brown (10*R* 5/4) sandstone beds were deposited on a well-defined and flat surface. These sandstone beds contain some medium- to low-angle crossbeds of the trough type, and they grade upward into ripple-laminated silty sandstone units characteristic of the Moenkopi Formation. Although no crinkled bedding or limestone beds were observed in the Hoskinnini Member at Monitor Butte, some crinkled bedding and primary slumpage structures were noted farther west at Nokai Dome. No crinkled bedding has been reported in the overlying units of the Moenkopi Formation in the Monument Valley area.

In its westernmost exposure at the north base of Piute Mesa (pl. 2) along the San Juan River, the Hoskinnini Member is separated from the lower siltstone member by a fairly well-defined erosion surface (Cooley, 1965, p. 40). The surface cut on the Hoskinnini Member is channeled and has a local relief of 3 feet. The channels are filled with conglomeratic sandstone similar to that at the base of the Moenkopi Formation at Lees Ferry and in the Glen Canyon area north of the reservations. The upper part of the Hoskinnini Member on Piute Mesa seems to be composed of residual or weathered material.

In areas where the basal part of the lower siltstone member is composed of conglomerate, a slightly channeled erosion surface is discerned easily between the lower siltstone member and the Hoskinnini Member. The channeling seems to have a wide distribution and extends northward at least as far as White Canyon, Utah (observation by Cooley, 1958), where it may be as much as 25 feet deep (Thaden and others, 1964, p. 36). In the Monument Valley area east of Piute Mesa, however, the conglomerate is absent, and the contact between the Hoskinnini Member and the lower siltstone member is difficult to locate.

LOWER SILTSTONE MEMBER

The lower siltstone member is composed of alternating moderate-brown (5*YR* 4/4) and pale-reddish-brown (10*R* 5/4) thin- to thick-bedded siltstone, claystone, and silty sandstone beds; the bedding is irregular or lenticular. Some layers of silty sandstone contain low-angle to very low angle small-scale crossbeds and grade laterally and upward into ripple-marked beds. Other layers display cuspate ripple marks as much as 8 inches wide. Many of the siltstone units contain shrinkage cracks as much as 8 inches deep and 1 inch wide. Locally, small channels 1–6 feet deep were cut into the beds containing the shrinkage cracks. These channels are now filled with sandstone. In other places, sand was deposited across the surface and in the shrinkage cracks with no accompanying erosion. Most of the sandstone beds are silty and are composed of clear, stained, and amber quartz grains that are very fine to fine and rounded to subangular. In many places, medium quartz grains are in the lower few feet of the member. Muscovite, concentrated on the surface of the ripple marks or as flakes scattered throughout the units, is the most common accessory mineral. Much of the siltstone splits shaly or fissile. Nodular beds of satin spar and alabaster at Monitor Butte are the only occurrence of gypsum in the Moenkopi Formation in the western Monument Valley area south of the San Juan River. Some gypsum was reported by Mullens (1960, p. 279) in the upper siltstone member of the Moenkopi on the Clay Hills escarpment north of the San Juan River.

A cherty conglomeratic sandstone is the basal unit of the lower siltstone member on the north side of Piute Mesa along the San Juan River. This unit is 1–4 feet thick and consists of subangular to angular white chert pebbles less than an inch in diameter embedded in a matrix of fine- to medium-grained sandstone. The unit is well to firmly bonded by calcareous and siliceous cement and contains low-angle medium-scale crossbeds.

The lower siltstone member thins eastward across the Monument Valley area (pl. 2). It is 65 feet thick at Piute Mesa, 59 feet thick on Monitor Butte, and about 30 feet thick in the central part of Monument Valley.

MIDDLE SANDSTONE MEMBER

The middle sandstone member of the Moenkopi Formation is between the lower and upper siltstone members (pl. 2). The thickness of the member is variable, ranging from 50 to 100 feet, because of the intertonguing relations with the siltstone members. In the Monument Valley area, regional trends in thickness and lithology are not readily apparent.

The member is composed mainly of lenticular units of sandstone, sandy siltstone, and siltstone; sandy siltstone, however, is predominant. The sandstone beds are light moderate brown (5*YR* 5/4) to pale reddish brown (10*R* 5/4) and form irregular ledges. They are composed of very fine to fine quartz grains that are clear or stained, subrounded to subangular, fairly well to poorly sorted, and firmly to weakly cemented. Mica and dark accessory minerals are present almost everywhere. Bedding is very thin to very thick and is flat or lenticular. Crossbedding, chiefly of the trough type but containing some planar sets, is common; the crossbeds were deposited at low to medium angles, range from small to large scale, and, in many places, grade laterally into ripple-laminated beds.

Siltstone and sandy siltstone beds in the middle sandstone member are from 1 to 40 feet thick. Along the eastern escarpment of Monitor Butte, the member is divided into two distinct units by a siltstone bed. The siltstone bed is as much as 30 feet thick and contains a few lenticular mudstone layers, which have fissile partings. Shrinkage cracks, ripple marks, and other current marks are common in these units. Most of the silty beds probably represent sedimentation in quiet fluvial areas near channels now filled with the crossbedded sandstone.

UPPER SILTSTONE MEMBER

The upper siltstone member of the Moenkopi Formation in Monument Valley is composed of alternating grayish-red (10*R* 4/2) sandy siltstone, siltstone, and silty sandstone beds. The siltstone is very thin to thin bedded, weakly cemented with calcium carbonate, and ripple marked on many bedding surfaces. Gypsum seams and bleached zones are present in some places. The sandstone beds are weakly cemented and are composed of very fine to fine quartz grains that are clear or stained. The upper part of the unit displays "hoodoo" erosional forms in some places, but most outcrops are covered with fluffy, platy, and flaggy colluvial material. The thickness is variable, ranging from less than 50 to more than 110 feet; the main cause of this variation is the erosion preceding the deposition of the overlying Chinle Formation.

ZUNI MOUNTAINS AREA

Several lithologic units not typical of Triassic formations exposed near the Little Colorado River or on the Defiance Plateau were deposited in the Zuni Mountains (fig. 2). These units have been included in the Moenkopi Formation by most investigators. The beds are between the channeled regional erosion surface underlying the basal Shinarump Member or the Monitor Butte Member of the Chinle Formation and the karst topography on top of the Permian San Andres Limestone. The thickness of the Moenkopi(?) is inconstant because of the unconformities; the sequence is usually less than 75 feet thick but in several exposures is more than 100 feet.

According to Cooley (1959a, p. 68–69), the Moenkopi(?) is divided into a lower slope-forming unit about 75 feet thick and an upper ledge-forming unit about 25 feet thick in the Fort Wingate area. The lower unit is composed principally of grayish-red (10*R* 4/2) to blackish-red (5*R* 2/2) flat-bedded sandy siltstone and crossbedded silty fine-grained sandstone. The lower unit contains many channels filled with sandstone; the largest one seen is 30 feet deep and 150 feet wide. The upper unit is composed of sandstone and conglomerate containing medium- to low-angle small- to large-scale crossbeds of the trough type. The conglomerate consists of quartz, jasper, and quartzite pebbles as much as 3½ inches in diameter, which are set in a fine-grained to very coarse grained sandstone.

The Moenkopi(?) on the northeast flank of the Zuni Mountains near Thoreau consists of five lenticular units, all of which may or may not be present at a particular site. These units are, in ascending order, a bleached greenish- or yellowish-white siltstone and mudstone containing limestone breccia cemented by chert; a thin-bedded reddish-brown mudstone, siltstone, and silty sandstone; a conglomeratic sandstone containing quartz and jasper pebbles; a reddish-brown mudstone and siltstone; and a crossbedded very fine grained to fine-grained sandstone.

The Moenkopi(?), in contrast with the Moenkopi Formation elsewhere, yields some water of good chemical quality to wells near Fort Wingate. The extent of the area in which the Moenkopi(?) yields water is unknown.

RANGES IN THICKNESS

The Moenkopi Formation decreases in thickness to the east and southeast, as noted by Gregory (1950, p. 59). In the Navajo country the thickest section of the Moenkopi Formation is in the Lees Ferry area, where it is 517 feet thick. The formation thins from 310 feet in a wildcat oil test near Kaibito to 150 feet in the central part of Monument Valley; it is less than 50 feet thick along Comb Ridge (fig. 4) and is not present in the northern part of the Defiance Plateau.

The Moenkopi thins south of Lees Ferry and is 241 feet thick near Cedar Ridge Trading Post; however, it thickens again farther south and is 349 feet thick near Cameron. It thins gradually east of Cameron and is 158 feet thick at Holbrook. In the southeastern part of the reservations, pre-Chinle erosion of the Moenkopi rocks caused local variations in the thickness; in the southern part of the Defiance Plateau, the Moenkopi is 100–200 feet thick, and along the north flank of the Zuni Mountains, it is 30–100 feet thick. In general, the thicknesses of the Moenkopi indicate that maximum deposition was along the northwestern and southern flanks of the reservations and that a high area or ridge extended westward across the center of the reservations from the Defiance Plateau to Cedar Ridge Trading Post (McKee, 1954, fig. 7).

AGE ASSIGNMENT

The age of the Moenkopi Formation has been considered Permian, Triassic, or both, but since 1919, when Shimer (1919, p. 492–497) reported on the marine fauna of the Moenkopi Formation in northwestern Arizona, the formation has been considered Triassic in age. No fossils diagnostic of age were found in the Moenkopi in the Navajo country or nearby areas until 1932, when R. T. Bird, on a motorcycle tour through Arizona, discovered the palatal impression of an amphibian southwest of Winslow. Brown (1933, p. 4) described the specimen as being most similar to forms from the "Lower and Middle Triassic of other continents."

Later, Welles (1947, p. 285–286), Peabody (1948, p. 413), and, most recently, Welles and Cosgriff (1965, p. 97) described tetrapod material and discussed the age of the Moenkopi on the basis of these remains. The vertebrate material comes from two main zones referred to by Welles (1947, p. 242) and Peabody (1948, p. 300) as the "lower" and "upper" Moenkopi, which correspond to the Wupatki and Holbrook Members, respectively. In summarizing the faunal evidence of the entire Moenkopi Formation of the valley of the Little Colorado River, Welles (written commun., 1952) stated: "The fauna of the lower Moenkopi west of Winslow to Meteor Crater, etc., is approximately upper Bunter, i.e.,

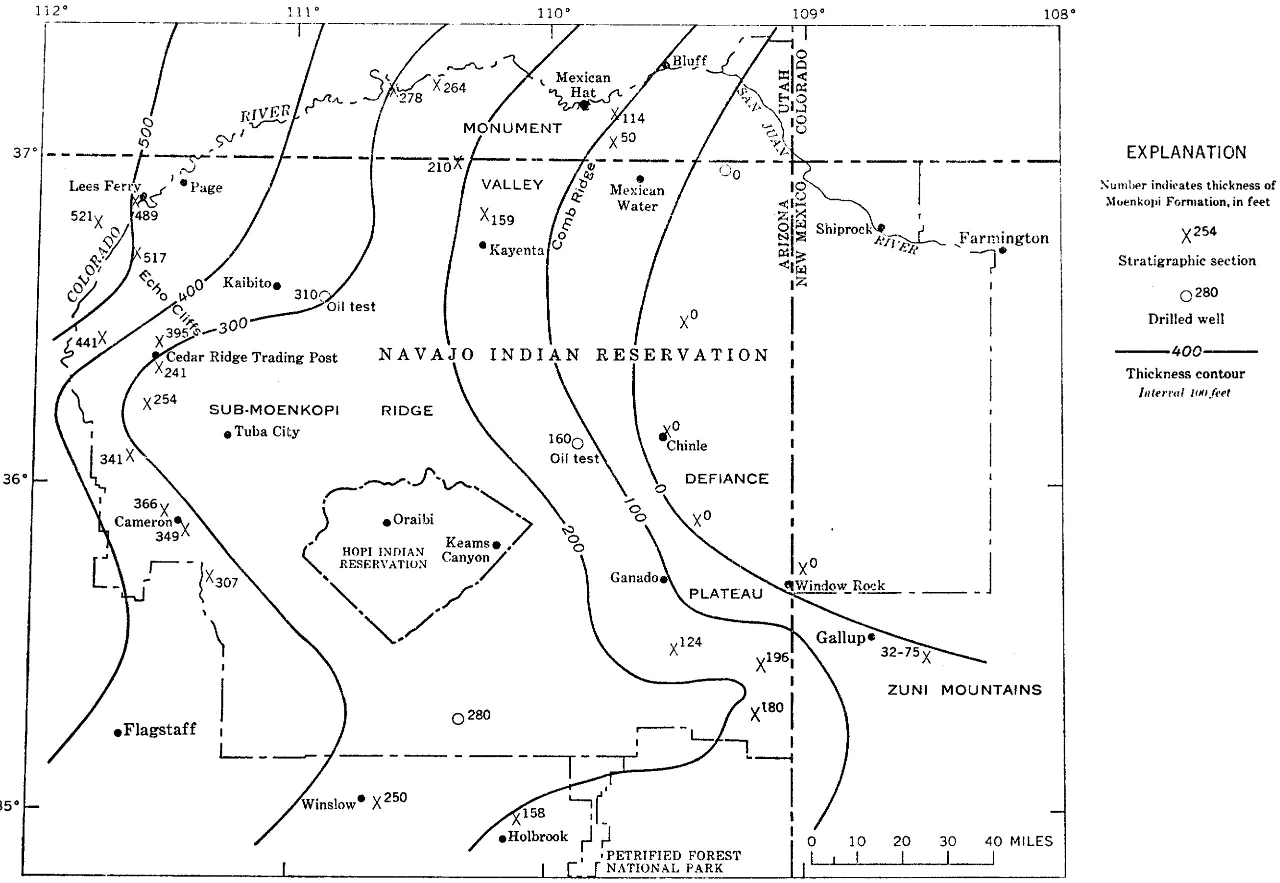

FIGURE 4.—Thickness of the Moenkopi Formation. Modified from McKee (1954, fig. 7).

upper Lower Triassic. The upper Moenkopi fauna at Cameron, Holbrook, etc., is more advanced and is lower Muschelkalk, i.e., lower Middle Triassic." There is some uncertainty, however, regarding the fauna of the upper part of the Moenkopi, as Welles (1947, p. 286) stated that the fish, two amphibians, and the reptiles from the Holbrook locality are Early Triassic forms but that one amphibian seems to be similar to the form from the Upper Triassic Keuper of Europe.

Poborski (1954, p. 993) reported the occurrence of *Tirolites* 107 feet below the top of the Virgin Limestone Member of the Moenkopi in southwestern Utah and concluded that the Virgin Limestone Member is in the upper part of the Lower Triassic sequence. He further suggested that a part of the overlying members are Middle Triassic in age.

Using stratigraphic evidence, McKee (1954, p. 24) correlated the Moenkopi Formation of the Little Colorado River valley with the upper part (above the Virgin Limestone Member) of the Moenkopi of southwestern Utah. This correlation and Poborski's evidence suggest that much of the Moenkopi of the Navajo country is Middle Triassic in age. In the Navajo and Hopi Indian Reservations, the Moenkopi Formation is considered Early and Middle(?) Triassic in age on the basis of the stratal and paleontological evidence, but in Monument Valley where the Triassic(?) Hoskinnini Member is present, the Moenkopi is Triassic(?) and Early and Middle(?) Triassic.

UNCONFORMITY BETWEEN THE MOENKOPI AND CHINLE FORMATIONS

Regional upwarping terminated the deposition of the Moenkopi Formation and caused a general withdrawal of Triassic seas. Moreover, recurrent uplift of the Mogollon and Uncompahgre Highlands (fig. 3) formed a generally northwestward-flowing drainage system (fig. 5). The streams were degrading and were entrenched in valleys and large channels that had more than 150 feet of relief. Later, these streams began to aggrade, and conglomeratic sediments of the basal members of the Chinle Formation filled the valleys and channels; eventually, deposits of the Chinle Formation were laid down over all the Navajo country and adjacent areas.

The unconformity between the Moenkopi and Chinle is one of the more conspicuous breaks in deposition in the Mesozoic rocks of the Southwest; basal crossbedded conglomeratic rocks of the Chinle Formation overlie the silty horizontally bedded Moenkopi Formation. In

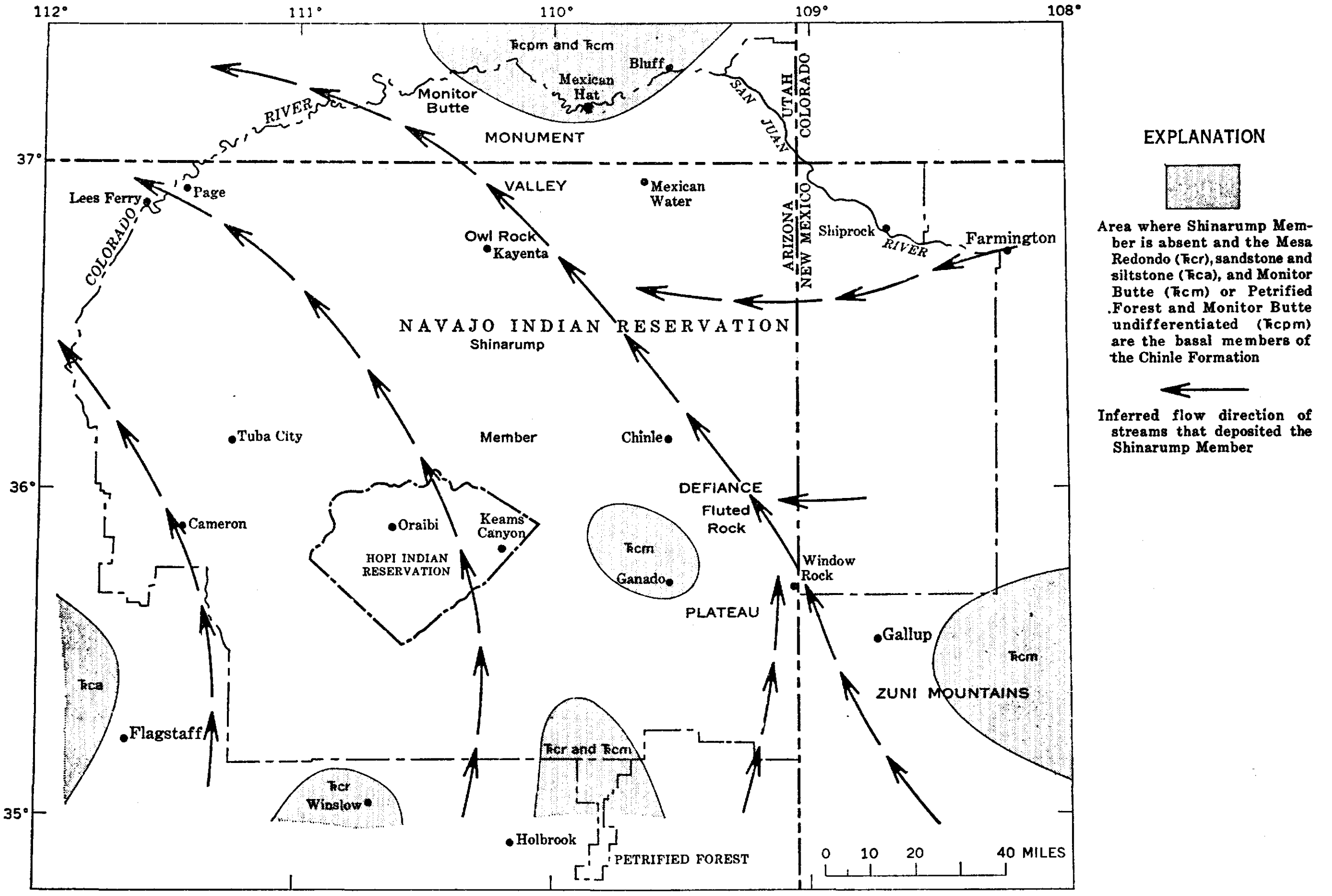

FIGURE 5.—Distribution of the Shinarump Member of the Chinle Formation and hypothetical drainage during the time of its deposition.

most of the Navajo country, the unconformity is marked by a channeled surface of moderate relief. This relief averages about 30 feet but is greater in the Monument Valley area; well-defined channels are as much as 275 feet deep (Evensen, 1958, p. 95). A relief of 150 feet is shown in a channel 7 miles west of Navajo Bridge, and other channels in the Lees Ferry–Paria Plateau area are more than 100 feet deep (Akers, 1960). Channels at the base of the Chinle Formation in the Zuni Mountains are more than 50 feet deep and are cut through the Moenkopi(?) to considerable depths into the San Andres Limestone (Cooley, 1959a, p. 69).

The individual channels filled by the Shinarump Member vary in size, general shape, and in steepness of the channel sides. In the deep channels formed in Monument Valley, the cross-sectional profile is controlled by the lithology of the underlying Moenkopi Formation and by the physiographic position of the channel in respect to the formation of meanders along the old pre-Chinle stream courses. Evensen (1958, p. 95) concluded from test drilling and surface exposures that "Mudstones form moderately low-angle slopes, whereas siltstones and sandstones form steep slopes or, locally, cliffs." On the cutting side of meanders, the bases of the channels contain large scours as much as 100 feet deep. Many of the channels are discontinuous, form symmetrical and asymmetrical troughs, and have longitudinal profiles that are gently concave upward (Witkind, 1956).

In the Little Colorado River and southern Defiance Plateau areas, broad ridges and valleys were formed on the Moenkopi Formation and De Chelly Sandstone during the pre-Chinle erosional period. Buried ridges and hills as much as 200 feet high indicate the drainage divides of the pre-Chinle surface. The conglomeratic Shinarump Member of the Chinle Formation was deposited in the valleys between the ridges. Within the confines of the reservations, the Shinarump completely filled most of the valleys before the Monitor Butte and Mesa Redondo Members were deposited, but elsewhere to the south it filled only parts of the valleys. Channels from 15 to more than 50 feet deep are present on the pre-Chinle surface. Most of the channeling preceded the deposition of the Shinarump Member, but there is evidence that some erosion continued during its deposition.

The Moenkopi Formation is not present in the central and northern parts of the Defiance Plateau because of pre-Chinle erosion, or perhaps nondeposition, and the Shinarump Member rests on the De Chelly Sandstone of Early Permian age. Near the Canyon de Chelly National Monument, many of the pre-Chinle channel sides are "steep and in some places overhanging" (Evensen, 1958, p. 95).

If the Moenkopi Formation of the Navajo country contains beds as young as Middle Triassic in age, the hiatus represented by the unconformity between the Moenkopi and Chinle is restricted chiefly to Middle Triassic time. The break in deposition represents a greater time interval northeast of the Navajo country where the Moenkopi is absent.

CHINLE FORMATION

Some of the information concerning the Chinle Formation in this section of the report was obtained from theses by Evensen (1953) and Grundy (1953). Since first prepared in 1955, the report has been revised to include data from theses by Cooley (1957), Smith (1957), and Akers (1960).

The Chinle Formation is noted for its abundance of fossil wood, which is conspicuously exposed in the Petrified Forest National Park, and for its "painted deserts." The Chinle is the most colorful formation in the Navajo country.

Exposures of the Chinle Formation in Chinle Valley, the type area (Gregory, 1917), are representative of the formation in the reservations. East of Chinle Valley the formation contains several resistant sandstone beds, but west of the valley such beds are rare above the Shinarump Member (pl. 2). The formation ranges in thickness from 1,500 feet in the Zuni Mountains to about 800 feet near the Colorado and San Juan Rivers (fig. 6). The thickness of the Chinle varies because of thinning and pinchout of the members, the amount of regional channeling at the basal contact, and the inclusion or exclusion of rocks that have been assigned arbitrarily to other units.

In the reservations the Chinle Formation consists of, in ascending order, the following members: Shinarump, Mesa Redondo, sandstone and siltstone, Monitor Butte, Petrified Forest, Owl Rock, and Church Rock. Not all these members, however, are present at any given locality on the reservations (table 1). In this report, the strata assigned to the Church Rock Member in south-

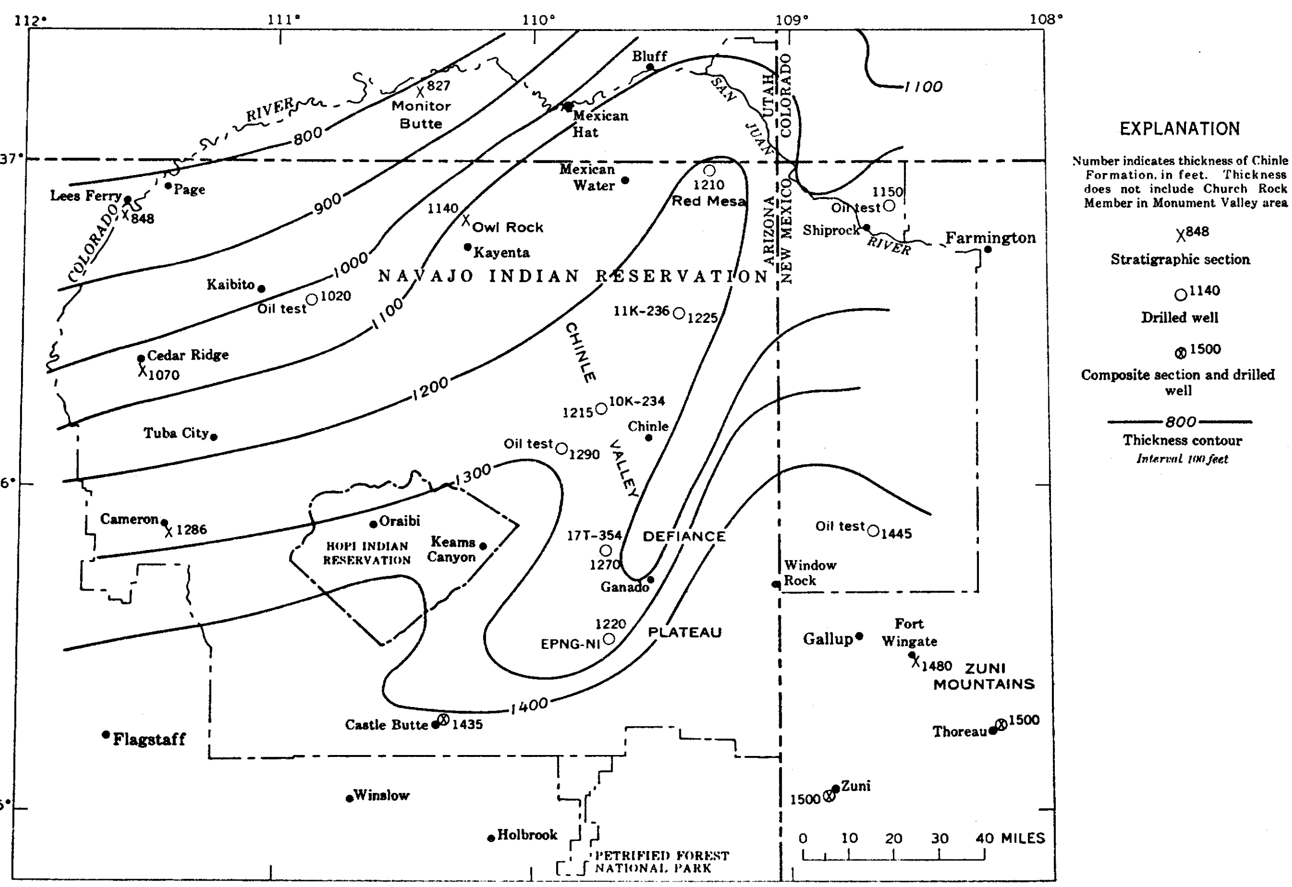

FIGURE 6.—Thickness of the Chinle Formation (not including the Church Rock Member).

ern Monument Valley, as defined by Witkind and Thaden (1963), are divided into the lower silty part and the Hite bed. The name Hite bed was originally used by Stewart and others (1959) for exposures near Hite, Utah. In northern Monument Valley, however, the Church Rock Member, as recognized by Stewart and others (1959), in places includes, in ascending order, a reddish-orange siltstone unit, a lower ledge, and an upper Hite bed. All the members form a gradational and intertonguing depositional sequence, although, in the southeastern part of the area near the source of much of the Chinle sediment, several local intraformational unconformities are present.

SHINARUMP MEMBER

The firmly cemented sandstone and conglomerate beds of the basal Shinarump Member of the Chinle Formation are exposed as prominent cliffs or ledges between the slopes carved from the underlying Moenkopi Formation and the overlying members of the Chinle Formation. The Shinarump Member is a blanket deposit in most of the reservations and, in general, is between 25 and 100 feet thick. It is absent, however, in small areas near Ganado, north of the Petrified Forest National Park along the southern boundary of the reservations, and east and north of Monitor Butte in the northern part of Monument Valley (fig. 5).

The Shinarump Member consists of lenticular crossbedded units of sandstone and conglomerate and mudstone. The sandstone units range from yellowish orange (10*YR* 8/6) and grayish purple (5*RP* 4/2) to yellowish gray (5*Y* 7/2); some are mottled by splotches of pale brown (5*YR* 5/2). The mudstone units range from pale red (10*R* 6/2) to light greenish gray (5*GY* 8/1).

The sandstone and the matrix of the conglomerate are composed of subrounded to subangular clear quartz grains that are very fine to very coarse. Dark minerals, mica, weathered feldspar, and, locally, argillaceous materials make up most of the accessory minerals in the matrix. The average percentage of soluble material, as determined in the laboratory, is 1.20 percent by weight.

The conglomerate of the Shinarump Member is composed of well-rounded to subangular pebbles and cobbles of quartz, quartzite, jasper, chert, and petrified wood. Most of the pebbles are less than 2 inches in diameter, but some as large as 4 inches were deposited in the southern and western parts of the reservations. It has become customary to think of the conglomerate of the Shinarump Member as unique and unlike other conglomeratic units in the southern part of the Colorado Plateaus; however, the Sonsela Sandstone Bed and other sandstone beds of the Chinle Formation contain siliceous gravel, and conglomerate similar to the Shinarump is present in places in the Dakota Sandstone of Cretaceous age and the Ojo Alamo Sandstone of early Tertiary age. McKee (1937) found Permian fossil invertebrates in chert pebbles of the Shinarump Member near Cameron and in sandstone beds of the Petrified Forest Member in the Petrified Forest National Park. He considered them typical of the upper member of the Kaibab Limestone. These and other Permian invertebrate fossils found in the Chinle Formation in the southern part of the Navajo country west of the Zuni Mountains and cross-strata studies (Poole, 1961) indicate a southern source for much of the Chinle Formation. The conglomerate makes up as much as 75 percent of the Shinarump Member near the main stream arteries where fast-moving water transported coarse materials. Away from the main channelways, however, there is less conglomerate, and in many areas only a few pebbles are present.

Mudstone in the Shinarump Member occurs as short, irregular lenses in the upper part of the member and as lumps and pellets in the lower part of the member. The mudstone is greenish gray (5*GY* 6/1) to yellowish gray (5*Y* 8/1) and in some places resembles material from the Moenkopi Formation. It frequently grades into sandy siltstone, which is micaceous and pseudocrossbedded.

The Shinarump Member is lenticularly bedded and consists of a maze of thin to thick interlaced channel deposits. The sandstone and conglomerate units commonly have trough crossbedding, and the small- to medium-scale crossbeds dip at low and medium angles. Small- to large-scale crossbeds dipping at low and very low angles are formed in some of the sandstone beds. Much of the mudstone has small-scale crossbeds visible in fresh clean exposures; however, some of the mudstone units are thin and horizontally bedded. Cuspate ripple marks and ripple laminations are common in the sandstone beds. Some of the beds containing ripple marks have been stained brown by iron oxide, which may be a result of weathering.

In the southern part of the Defiance Plateau, the Shinarump Member is composed of two units: a conglomerate typical of the member in the Navajo country and a conglomeratic sandstone, peculiar to the plateau and locally derived from the underlying De Chelly Sandstone. In poorly exposed outcrops of the conglomeratic sandstone in the southern part of the Defiance Plateau, the Shinarump Member can be differentiated from the De Chelly only by differences in the type and scale of the crossbedding.

The average thickness of the Shinarump Member is about 80 feet in the Navajo country. In areas of above-average thickness, especially in the Defiance Plateau, irregularities of the basal contact and intertonguing with the overlying members make regional thickness trends difficult to detect. An area of above-average thickness is centered along the Arizona-New Mexico State line in the eastern part of the reservations; excellent exposures show an eastward coalescing of ledge-forming sandstone units of the Monitor Butte Member with the Shinarump Member and a tonguing-out of the included mudstone and siltstone beds of the Monitor Butte Member. Thus, the Shinarump Member is about 50 feet thick at Chinle but nearly 170 feet near Lukachukai. Thicknesses of 200 feet are present in the western Monument Valley area, where the Shinarump Member fills channels ranging from a few hundred feet to several miles wide. Along Echo Cliffs and near the Little Colorado River, the Shinarump Member is generally between 30 and 60 feet thick. Along the southern border and south of the reservations, nearer its source, the Shinarump is present only in broad channels and is not a continuous deposit (Cooley, 1959a, fig. 5); it is absent in the area between Ganado and Fluted Rock (fig. 5).

The sandstone and conglomerate of the Shinarump Member are relatively permeable and yield water to many wells on the Defiance Plateau and to a few wells near Cameron and in Monument Valley. In the Defiance Plateau area, the specific capacities of wells that withdraw water from both the De Chelly Sandstone and the Shinarump Member are larger than those of wells completed only in the De Chelly. On the Defiance Plateau and in Monument Valley, small springs issue from the Shinarump from small perched zones of water above thin nearly impervious siltstone beds, which are along the basal contact or within the member.

MESA REDONDO MEMBER

The Mesa Redondo Member of the Chinle Formation, named by Cooley (1958) for the Mesa Redondo, which has exposures of the member at its base, is recognized only in the southern Defiance Plateau and in the area south of the reservations east of the Sunset Buttes (figs. 3, 7). The member consists of three units at its type section 35 miles southeast of Holbrook: lower and upper mudstone and siltstone units separated by a medial conglomeratic sandstone (Cooley, 1958, p. 9). In its type area, the Mesa Redondo intertongues with and lies between the Shinarump and Petrified Forest Members, but in the southern Defiance Plateau area, the member

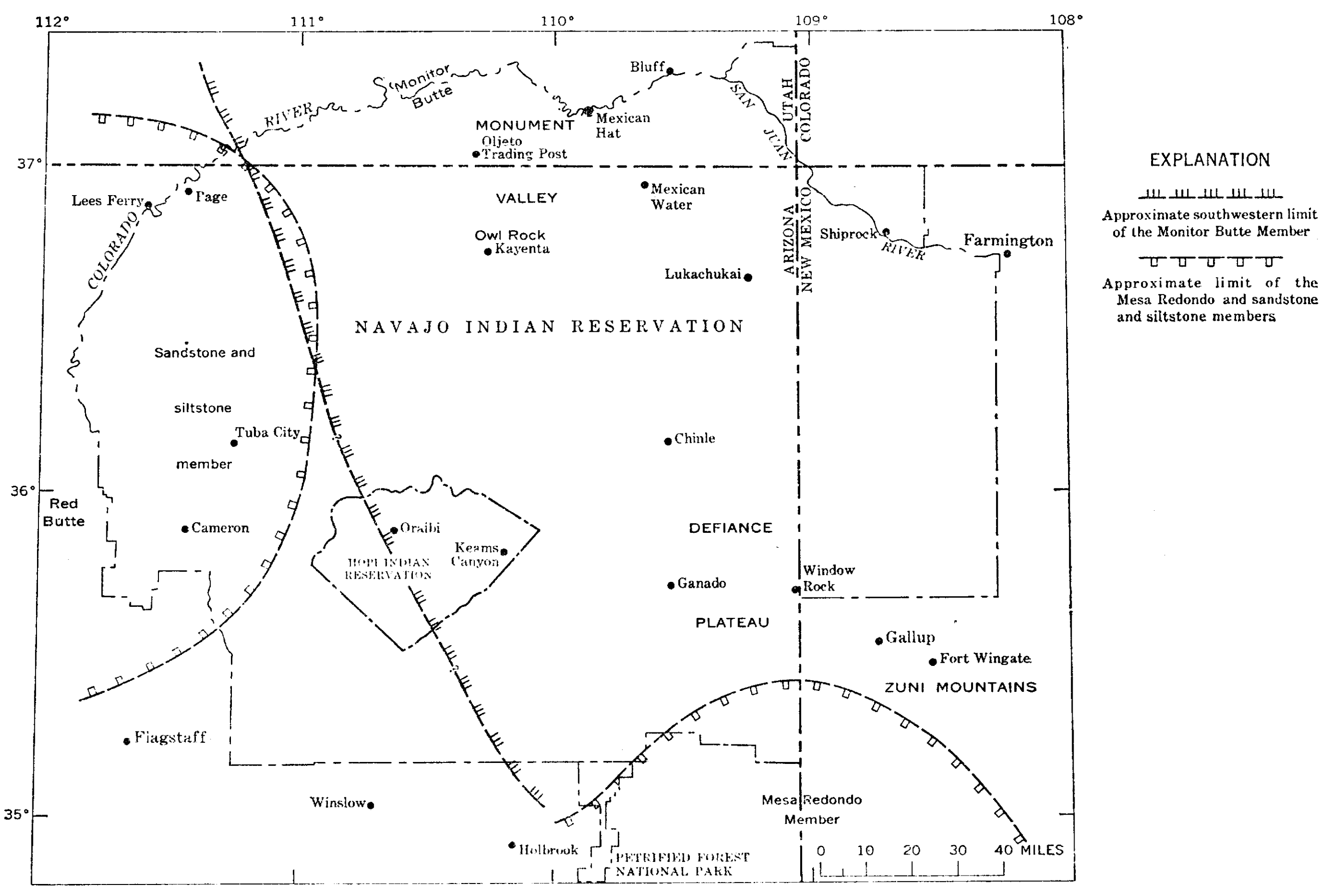

FIGURE 7.—Distribution of the Mesa Redondo Member, sandstone and siltstone member, and Monitor Butte Member.

is between the Shinarump and Monitor Butte Members.

On the Defiance Plateau the Mesa Redondo Member consists only of very dusky red purple (5*RP* 2/2), mottled grayish-red (5*R* 4/2), and grayish-pink (5*R* 8/2) sandstone containing quartz-jasper pebbles and a few lenses of conglomerate. The sandstone bed is about 30 feet thick and probably is correlative with the medial sandstone unit in the type section to the south. The sandstone is composed of mostly clear quartz grains that are very fine to coarse and subrounded and subangular. Pebbles are concentrated in the lower part of the member and are less than 2 inches in diameter. The unit is made up of channel-type deposits having medium- to large-scale lenticular and wedge-shaped trough and planar crossbedding deposited chiefly at low angles.

Although the Mesa Redondo Member is composed of sandstone, it is not known to yield water to wells or springs in the reservation. It combines hydraulically with the sandstone beds of the Shinarump Member. Some wells in the Sanders area are reported to obtain water from the Shinarump, but they also may withdraw some water from the Mesa Redondo Member.

SANDSTONE AND SILTSTONE MEMBER

In the southwestern part of the reservations, the sandstone and siltstone member consists of sandstone, mudstone, and conglomerate. The member is chiefly a sandstone at Cameron, but northward along the Echo Cliffs and southeastward toward Grand Falls, it is predominantly a mudstone and siltstone. It is a transitional unit between the Shinarump and Petrified Forest Members. The sandstone and siltstone member previously has been referred to as the Lowery Spring Member (Akers, 1960), sandstone and mudstone unit (Phoenix, 1963, p. 20–21), and Mesa Redondo Member (Repenning and others, 1965).

The sandstone beds show conspicuous color banding and range from very light gray (*N* 8) and pale reddish purple (5*RP* 5/2) to grayish red purple (5*RP* 6/2) and moderate yellowish brown (10*YR* 5/4). The beds are composed of poorly sorted subrounded to angular fine- to coarse-grained quartz and feldspar and contain accessory mica. Some beds are conglomeratic and contain well-rounded pebbles averaging about half an inch in diameter. The sandy beds commonly display medium- to large-scale low- to medium-angle crossbeds and are marked by bleached bands along the laminae. Several thin sandstone lenses contain small-scale crossbeds. On the whole, the sandstone beds are not as crossbedded or as conglomeratic as the Shinarump Member.

The mudstone beds are sandy and in some places grade laterally into silty sandstone. They range from light bluish gray (5*B* 7/1) to grayish orange pink (5*YR* 8/4) and pale red (10*R* 6/2). Many small sandstone lenses in the mudstone are as much as 10 inches thick and 15 feet long. The mudstone units are very lenticular and range in thickness from less than 5 feet to more than 50 feet.

Conglomerate in the sandstone and siltstone member ranges from pale blue (5*PB* 7/2) to light brownish gray (5*YR* 6/1). The matrix consists of medium to coarse poorly sorted and rounded to subangular quartz grains and minor amounts of biotite, chert, and jasper. Chert and jasper pebbles average about three-quarters of an inch in diameter; the maximum diameter is 1½ inches. Most of the pebbles are well rounded west of Navajo Bridge, but they are commonly subrounded near Lees Ferry and are subrounded to subangular in other areas.

Along Echo Cliffs north of the Cedar Ridge Trading Post (pl. 2), the sandstone and siltstone member is divided into two conspicuous units (Akers, 1960). The lower unit erodes into irregular and covered slopes and is composed of lenticular beds of mudstone, siltstone, and silty sandstone. The upper sandstone unit forms an irregular ledge between the lower slope-forming unit and the overlying Petrified Forest Member. The sandstone and siltstone member thins along Echo Cliffs from 235 to 280 feet at Lees Ferry to about 100 to 160 feet at Cameron (pl. 2). The thinning of the member is mainly the result of the southward pinchout of the lower slope-forming unit between the upper sandstone unit and the Shinarump Member (pl. 2). The upper sandstone unit combines with the Shinarump Member at Cameron and may be mistaken for it. Southeastward from Cameron the sandstone and siltstone member thickens to more than 150 feet, and near Grand Falls it comprises an upper ledge-forming sandstone and a lower slope-forming unit, which are probably equivalents of the upper and lower units along Echo Cliffs.

The sandstone and siltstone member intertongues with the Petrified Forest Member in the northern part of the Paria Plateau and is absent at Paria, Utah. It was not recognized in an oil-test well near Kaibito. In Piute Canyon, however, there are a few lenses of banded purple and greenish-gray sandstone similar to the upper sandstone unit along Echo Cliffs. The lower slope-forming unit apparently grades laterally into the Petrified Forest Member, but the upper sandstone unit tongues out into the Petrified Forest Member to the north and northeast. West of Cameron at Red Butte and in a few exposures near Coconino Point, the sandstone and siltstone member is the basal unit of the Chinle Formation.

The sandstone and siltstone member is relatively impermeable and is not known to yield water to springs. In the southwestern part of the reservations, however, where coarse sandstone units of this member overlie the Shinarump Member, a few wells yield small amounts of water from both members. In the Cameron area, uranium-test holes had an inflow of water from the sandstone and siltstone member and the Shinarump Member (P. B. Blakemore, oral commun., 1960).

MONITOR BUTTE MEMBER

The Monitor Butte Member (table 1) of the Chinle Formation is recognized in the eastern part of the reservations (fig. 7) and is exposed in three principal areas—Monument Valley, Defiance Plateau, and Zuni Mountains. In this report, the term "Monitor Butte Member" replaces the term "lower red member" of the Chinle Formation, which has been used in previous reports on the Navajo country. The member consists mainly of interstratified lenticular beds of mudstone, sandstone, and sandy conglomerate. It weathers into irregular ledges and slopes and commonly forms low buttes.

In the Defiance Plateau area very dusky red (10*R* 2/2) to grayish-red (10*R* 4/2) mudstone, which is weakly bonded by calcareous cement, makes up most of the member. The member contains many discontinuous layers of silty ripple-marked sandstone and lenses of limestone conglomerate. The mudstone units, composed of claystone and sandy siltstone, are as much as 40 feet thick and weather into ledgy, rolling, or covered slopes.

The sandstone units form ledges and are 1–25 feet thick. They are very dusky red (10*R* 2/2), pale reddish purple (5*RP* 6/2), brownish gray (5*YR* 4/1), and light gray (*N* 7), but grayish red (5*R* 4/2) is predominant. The sandstone units are composed of clear and stained quartz grains that are very fine to medium and well rounded to angular intermixed with accessory mica and argillaceous material, all of which are held together by a firm to weak calcareous cement. The sandstone is lenticular and thin to thick bedded and commonly has crossbedding of the wedge, planar, and trough types; small- to medium-scale crossbeds dip at low angles. Coarse-grained sandstone beds are similar to those of the Shinarump Member in the Defiance Plateau and have siliceous pebbles scattered in the units or concentrated in small lenses. Other beds are composed of silty very fine grained to fine-grained sandstone and show well-formed pseudocrossbedding patterned by the rhythmic advance of ripple marks. Many of the sandstone beds are multiple units formed by overlapping lenses of sandstone, mudstone, and conglomerate.

The conglomerate beds of the Monitor Butte Member are generally brownish gray (5*YR* 4/1) or light olive gray (5*Y* 5/2). They are composed mainly of subrounded to subangular limestone pebbles and contain minor amounts of petrified-wood chips, flattened mud pellets, and bone scarp, all of which are cemented in a matrix of calcareous siltstone and sandstone. The beds erode into rounded and irregular ledges as much as 25 feet thick. They are very lenticular and contain many channels from half a foot to more than 10 feet deep and as much as 30 feet wide. Each of the channels is filled by a different material ranging in composition from conglomerate to crossbedded or ripple-laminated sandstone.

In the Zuni Mountains the Monitor Butte Member is divided into two units: an upper sandstone and a lower siltstone. These units can be traced from Fort Wingate to Bluewater Lake (Cooley, 1959a, p. 70). The upper sandstone unit is 25–40 feet thick; the lower siltstone unit is as much as 350 feet thick and consists of alternating lenticular thick-bedded and very thick bedded units ranging in composition from claystone to silty sandstone. Near Bluewater Lake the lower unit forms the basal Chinle strata and rests on a channeled erosion surface. Some of the deeper channels are filled with grayish-blue (5*PB* 5/2) very fine grained silty sandstone. The upper sandstone unit is very fine to fine grained and has large-scale crossbeds deposited at low angles. Near Fort Wingate the upper sandstone unit contains a few quartz pebbles.

In the southern and eastern parts of Monument Valley, the Monitor Butte Member is generally similar to exposures of the member in the Defiance Plateau. The Monitor Butte Member forms very dusky red (10*R* 2/2) and light-greenish-gray mudstone-siltstone slopes that are interrupted by ledges of yellowish-gray (5*Y* 8/1) to light-brown (5*YR* 6/4) sandstone. The sandstone beds, however, are not as coarse in Monument Valley as are the sandstone beds in the Defiance Plateau and Zuni Mountains. Parts containing coarse-grained sandstone commonly grade into very fine grained to fine-grained sandstone that displays pseudocrossbedding. Limestone-conglomerate beds consisting of an assortment of sandstone fragments, limestone nodules and pebbles, bone fragments, and teeth of amphibians and reptiles occur as lenses in the member. Some of the lenses grade laterally into crossbedded and ripple-laminated sandstone.

Between southern Monument Valley and the San Juan River, there seems to be a progressive decrease northwestward in the amount of sandstone and a decrease southeastward in the amount of claystone-mudstone beds now assigned to the Monitor Butte Member. In places along the flanks of Skeleton Mesa, Witkind and Thaden (1963, p. 27) stated that the member consists "predominantly of dark-purple claystone and siltstone beds." Farther west in Nokai Canyon and northwest in San Juan Canyon, sandstone beds similar to those in the member in southern Monument Valley occur only at scattered localities and were not recognized by Cooley in 1958 north of San Juan Canyon. In San Juan and Nokai Canyons, these sandstone beds intertongue with purplish and greenish-yellow muddy units that contain lenses of sandstone (see section entitled "Petrified Forest and Monitor Butte Members Undifferentiated"). The tracing of these muddy units northward along Clay Hills indicates that in the White Canyon area they underlie the Moss Back Member of the Chinle Formation; southeastward from San Juan Canyon, extensive muddy units are not recognized beyond Skeleton Mesa. Stewart and others (1959) assigned the muddy units between the Moss Back and Shinarump Members to the Monitor Butte Member, although later Stewart (written commun., 1965) reported that he considers this muddy sequence to include strata of the Petrified Forest and Monitor Butte Members.

Because of the distribution of the sandstone beds and the muddy units, there has been considerable disagreement among geologists on the stratigraphic placement of the upper and lower contacts of the Monitor Butte Member in the area near San Juan Canyon. This problem is particularly acute at the type section of the member at Monitor Butte and in the nearby surrounding area. In this area, the stratigraphic interval between strata generally agreed by geologists to belong to the Petrified Forest or Shinarump Members consists of as much as 100 feet of alternating sandstone, claystone, and siltstone beds that are overlain by the muddy units, which are about 200 feet thick. The type section of the Monitor Butte Member, described by Witkind and Thaden (1963, p. 28), includes only 8 feet of siltstone and claystone above the highest sandstone bed of the alternating sandstone, siltstone, and claystone sequence, which they recorded as 99 feet thick. In a section measured about a quarter of a mile southeast of the type section, most of the alternating sandstone, siltstone, and claystone sequence was assigned to the Shinarump Member, and the muddy units, 184 feet thick and similar to deposits of the member north of the San Juan Canyon, were considered to be the Monitor Butte Member. The boundaries of the Monitor Butte Member need to be clarified by additional investigation, which is beyond the scope of this report. In this report, strata containing sandstone beds similar to those of the Monitor Butte Member in southern Monument Valley are included as the Monitor Butte Member, and the muddy units are assigned to the Petrified Forest and Monitor Butte Members undifferentiated.

In all areas, the Monitor Butte Member shows slumpage, which is probably diagenetic, and in the northern part of the Defiance Plateau this slumping is on such a large scale that it seems to be the result of tectonic deformation. The bedding of the underlying Shinarump Member, however, is not affected, and the distorted and folded beds are beveled and overlain by undisturbed sediments of the Petrified Forest Member. The slumpage in the Monitor Butte Member may be the result of unstable conditions that caused movement prior to consolidation. The intraformational folding, however, may have been related to local uplift or other tectonic activity because the Chinle Formation thins abruptly along a northeast-trending axis in this area. The Monitor Butte Member and the lower part of the Petrified Forest Member are about 100 feet thinner in this area than at Lukachukai. Slight differential upwarping during the deposition of the Chinle could have caused such thinning. Diagenetic slumpage is common in the Monitor Butte Member and in other sedimentary rocks in the lower part of the Chinle Formation south of the reservations.

The Monitor Butte Member intertongues everywhere with the Shinarump and Petrified Forest Members and locally with the Mesa Redondo Member (pl. 2). The Monitor Butte Member is thickest in the Defiance Plateau and Zuni Mountains, where it is 200–350 feet thick. It thins gradually westward and is about 100 feet thick in the central part of Monument Valley and less than 50 feet thick near Holbrook.

The Monitor Butte Member is one of the minor water-bearing units in the southeastern part of the Navajo country. It yields some water to wells on the Defiance Plateau, mainly in the valley of Black Creek and along the northeast flank of the Zuni Mountains. In the plateau, sandstone beds in the member are relatively coarse grained and extensive and allow free movement of water.

PETRIFIED FOREST AND MONITOR BUTTE MEMBERS UNDIFFERENTIATED

Light-greenish-gray to purplish-gray muddy units in the lower part of the Chinle Formation, referred to in this report as the Petrified Forest and Monitor Butte Members undifferentiated (table 1), extend only a short distance into the Navajo Indian Reservation from the north (fig. 7). These rocks are exposed in the western Monument Valley area and in San Juan and Nokai Canyons, and perhaps some discontinuous exposures occur in the Lees Ferry area.

In western Monument Valley, the lower contact of the Petrified Forest and Monitor Butte Members undifferentiated is placed at the highest sandstone bed of the Shinarump Member. In most of the area, the upper contact is placed at the top of a siltstone and silty sandstone sequence that shows considerable color banding of grayish white to purplish and reddish gray. The sequence of sediments showing the color banding seems to be persistent throughout the western Monument Valley area and in the area to the north.

Siltstone, sandy mudstone, sandy siltstone, and claystone form more than 60 percent of the Petrified Forest and Monitor Butte Members undifferentiated in exposures in San Juan Canyon west of Monitor Butte. The rest of this unit is composed of fine- to coarse-grained sandstone, which commonly is ripple laminated. The silty layers are lenticular and are 1–30 feet thick. Most layers extend laterally for 50 feet to a quarter of a mile. Extremely lenticular silty sandstone beds consisting of a series of ripple-laminated units that fill channels are interspersed in the finer grained units. Single channels, filled with mixtures of silty sandstone and siltstone, are less than one to more than 50 feet deep. One channel, exposed on the east side of Monitor Butte, is a quarter of a mile wide. Other channels in the same area have cut out part of the conglomerate beds of the Shinarump Member. Some of the mudstone and siltstone is not bedded, although a certain amount of color banding is present.

In most exposures the unit is weakly cemented by calcareous, argillaceous, and gypsiferous materials. Limestone nodules cover many of the exposures, and thin slabs and veins of selenite are present in many of the mudstone beds. Concentrations of carbonized wood fragments are associated with the selenite, and particles of carbon are disseminated throughout the mudstone. Secondary quartz was noted in many of the sandstone units, and calcite crystals, filling very thin veins and small vugs, are present nearly everywhere.

The Petrified Forest and Monitor Butte Members undifferentiated are 184 feet thick at Monitor Butte and thin southwestward to between 60 and 125 feet in Piute Canyon. The unit also thins generally northward from Monitor Butte where it underlies the Moss Back Member of the Chinle (Stewart, 1957, p. 453).

The Petrified Forest and Monitor Butte Members undifferentiated are nearly impermeable because of the fine-grained texture of the unit. The unit is not known to yield ground water in the reservations or in the area to the north between the San Juan and Colorado Rivers.

PETRIFIED FOREST MEMBER

The Petrified Forest Member is the most widespread member of the Chinle Formation. It is more than 450 feet thick at Monitor Butte, 500 feet thick at Lees Ferry, and as much as 1,000 feet thick on the Defiance Plateau. In the eastern part of the reservations and in adjoining areas, the Petrified Forest Member is divided into an upper part and a lower part by the Sonsela Sandstone Bed (Akers and others, 1958, p. 93). The Sonsela Sandstone Bed and the upper part of the Petrified Forest Member are not recognized in exposures in the valley of the Little Colorado River west of Leupp or in the area between Cameron and Lees Ferry (pl. 2). Where the Sonsela Sandstone Bed is absent, the Petrified Forest Member can be divided into ill-defined units based on slight lithologic and color differences.

EASTERN AREA

In the eastern area the Sonsela Sandstone Bed separates the thick sequence of strata forming the Petrified Forest Member into an upper part and a lower part. The Sonsela is an excellent datum for mapping, tracing, and correlating the units of the Chinle Formation. In most exposures the light-gray Sonsela Sandstone Bed caps prominent benches and cuestas and stands out in contrast to the brownish-red and grayish-purple mudstone units, which erode into badlands and rolling slopes.

LOWER PART

The lower part of the Petrified Forest Member is slate blue and gray white and erodes into badlands and low buttes, which make up the rugged and colorful topography of parts of Chinle Valley, Defiance Plateau, and the valley of the Puerco River (pl. 1).

This part of the Petrified Forest Member is composed mainly of mudstone containing varying amounts of tuffaceous siltstone and sandstone. Single units are rarely more than 20 feet thick, and they generally wedge out laterally within 300 feet. The units are thin bedded and have very large scale crossbeds deposited at very low and low angles; the units seem to have been deposited in broad channels. Channels filled with sandy material are better defined than the ones filled with silty material and contain medium- to large-scale crossbeds deposited at medium angles. In the finer grained units, much of the bedding is obscured by "puffy" weathering and slumping of the tuffaceous materials. The composition of the mudstone units is similar throughout the area, but there are more sandstone and tuffaceous beds near the Puerco River.

Contrasting colors accentuate the bedding and help to identify the large channel fillings and the more extensive shallow lakebed deposits. Color bands in well-exposed outcrops reveal bedding planes, which are gently concave upward and follow the outlines of old channels. In places, a well-defined steep-sided fairly symmetrical channel filled with coarse-grained material has truncated banded channel structures formed of finer grained materials. Thick sequences of mudstone having parallel and continuous color bands suggest shallow lakebeds. The whole sequence seems to consist of fluvial and lacustrine deposits laid down on broad flood plains having gentle gradients.

Generally, the lower part of the Petrified Forest Member is between 200 and 300 feet thick because of intertonguing with the Monitor Butte Member. North and south of the Defiance Plateau, the thickness is fairly constant, but southeastward to the Zuni Mountains, the unit decreases in thickness and is only about 100 feet thick at Bluewater Lake.

The lower part of the Petrified Forest Member yields water to only a few small springs in the Defiance Plateau area. Its chief hydrologic function is to act as a confining bed to water in the Sonsela Sandstone Bed and in the Monitor Butte Member. At no place does the lower part yield enough water for well development.

SONSELA SANDSTONE BED

The Sonsela Sandstone Bed of the Petrified Forest Member is composed of two conglomeratic sandstone units separated by a siltstone unit at its type section 3½ miles north of the Sonsela Buttes on the east flank of the Defiance Plateau (Cooley and others, 1964a, p. 132). The lower sandstone is 28 feet thick and consists of frosted, clear, and stained quartz grains that are very light gray (*N* 8), very fine to very coarse, and subrounded to subangular; feldspar and mica are common to abundant as accessory minerals, and argillaceous material is also abundant. A few quartz, chert, and limestone pebbles averaging three-eighths of an inch in diameter are concentrated along bedding planes. Quartz-granule lenses less than a foot thick are scattered in the unit. Bedding is irregular and lenticular, and crossbedding is of the trough type and is composed of small- to medium-scale crossbeds deposited at low and medium angles. A light-bluish-gray (5*B* 7/1) siltstone bed, 25 feet thick, separates the two sandstone units and weathers to a steep slope. The upper sandstone unit is 61 feet thick and forms a prominent irregular ledge. It is similar in composition to the lower sandstone unit except that it contains more coarse-grained sand.

The divisions of the Sonsela Sandstone Bed at its type section are not characteristic of the unit everywhere; in most places the Sonsela consists of a main sandstone bed and several minor sandstone beds separated by intervening mudstone and siltstone beds. Consequently, the thickness ranges from 50 to 200 feet and depends on the number and thickness of the sandstone beds. The Sonsela ranges in thickness from 120 to 200 feet along the east side of the Defiance Plateau and is a 60-foot ledge-forming conglomeratic sandstone in the northern part of the Petrified Forest National Park. North of Holbrook and in Chinle Valley west of Nazlini, the Sonsela Sandstone Bed is represented by a poorly defined unit of banded red and gray sandy siltstone and silty sandstone.

The Sonsela Sandstone Bed is more conglomeratic south of the Puerco River and in the Zuni Mountains than it is on the Defiance Plateau. At Lupton more than 25 percent of the bed is conglomerate, but near Round Rock Trading Post only a few exposures show sufficient pebbles to be called conglomerate. The gravel also decreases in size northward to the Defiance Plateau. Pebbles have a maximum diameter of 5 inches in the Petrified Forest National Park and near Thoreau, but in the northern part of the Defiance Plateau, they have a maximum diameter of only 2 inches. The gravel is composed mainly of well-rounded to subrounded pebbles of silicified limestone, white chert, and dark jasper and contains small amounts of quartz, quartzite, and porphyritic rhyolite and andesite.

The streams that deposited the Sonsela Sandstone Bed had a southern source (fig. 8), as evidenced by the northward dip of the crossbeds (Poole, 1961), the increasing amount of conglomerate to the south, and the Permian Kaibab Limestone fossils (McKee, 1937) in the conglomerate pebbles. The distribution of the conglomerate indicates that three main stream arteries deposited most of the Sonsela Sandstone Bed (Cooley, 1959a, p. 71); these main streams were near the Petrified Forest National Park, Lupton, and Thoreau.

The distribution of the conglomerate is one of the principal controls on the occurrence and yield of ground water in the Sonsela. Wells penetrating the Sonsela have higher yields or specific capacities in areas containing conglomerate, such as near Zuni Pueblo, on the northeast flank of the Zuni Mountains, and in the Lupton-Sanders area (fig. 8). The Sonsela also yields some water to wells drilled in the upturned rocks of the East Defiance monocline and to a few springs on the Defiance Plateau.

UPPER PART

The upper part of the Petrified Forest Member is composed of a series of banded moderate-grayish-red (10*R* 4/4), pale-reddish-brown (10*R* 5/4), and pale-red-purple (5*RP* 6/2) mudstone, siltstone, and sandy siltstone beds. The beds are flat and lenticular and generally are more than 50 feet thick and more than a quarter of a mile long. Some beds show low to very low angle very large scale crossbeds. The units of the upper part of the Petrified Forest Member are more flat

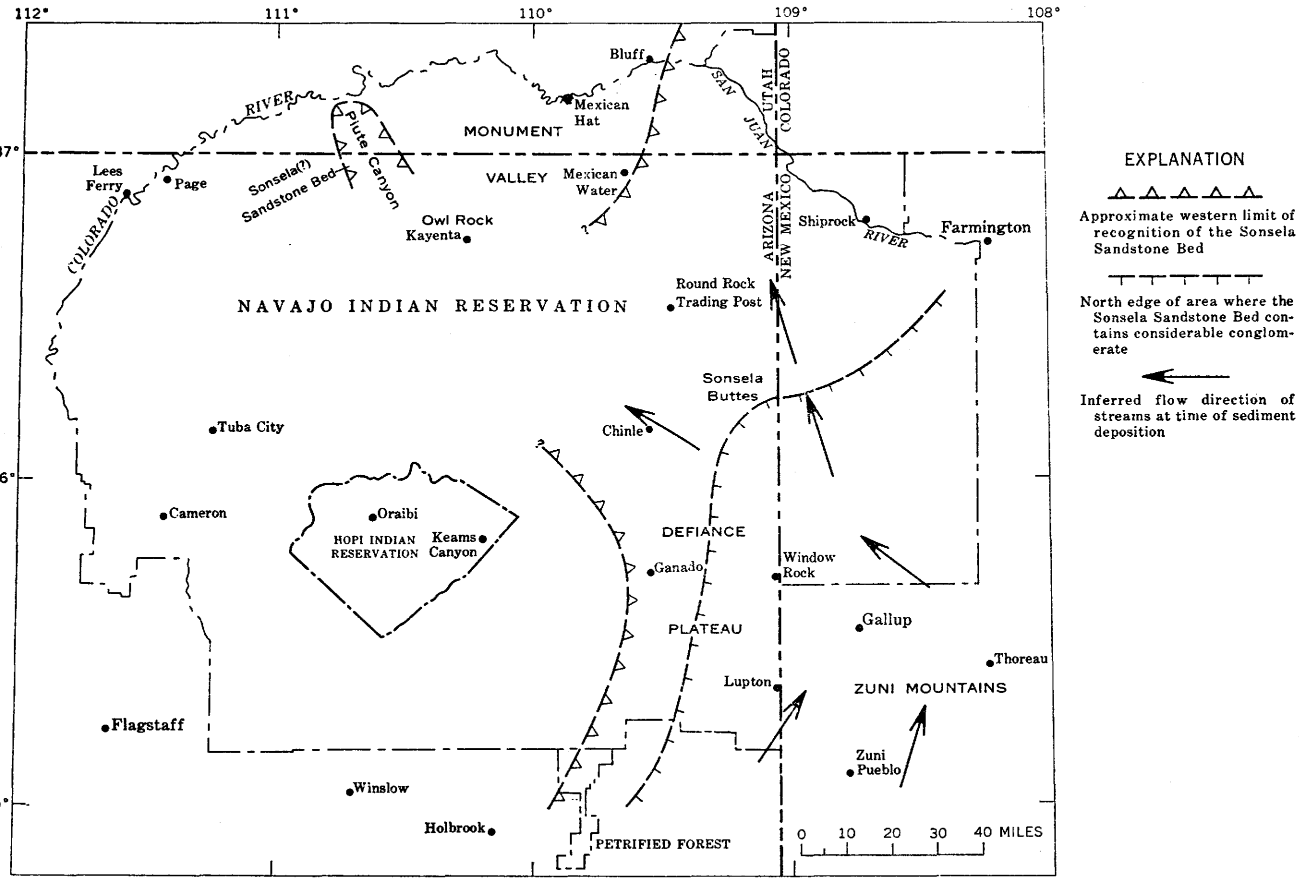

FIGURE 8.—Distribution of the Sonsela Sandstone Bed and hypothetical drainage during the time of its deposition.

bedded, can be traced farther laterally, and have fewer well defined channels than units of the lower part.

The upper part of the Petrified Forest Member is as much as 1,100 feet thick near Thoreau. It thins westward, is nearly 800 feet thick at Fort Wingate, is 400–500 feet thick in the northern part of the Defiance Plateau, and tongues and grades into the red and gray unit and gray unit undifferentiated in the western part of the reservations (pl. 2).

The sandstone beds, which are common in the lower 250 feet of the upper part of the Petrified Forest Member and in the upper 400 feet of the upper part near Thoreau, probably were deposited by northward-flowing streams (fig. 9). Many of the beds can be traced for about 5 miles. The sandstone beds have similar lithologic characteristics and are composed generally of pale-red (10*R* 6/2) and grayish-red (10*R* 4/2) very fine to medium quartz grains. The sandstone beds commonly contain small- to medium-scale crossbeds deposited at low and medium angles. Smith (1954, p. 10) considered one of these sandstone beds, which is stratigraphically 364 feet below the top of the Petrified Forest Member at Thoreau, to be correlative with the Correo Sandstone Member (Kelley and Wood, 1946) in north-central New Mexico.

The sandstone beds in the upper part of the Petrified Forest Member yield water to a few wells in the southeastern part of the Navajo country. The well yields are small, and some of the water is highly saline. Most of the water in the upper part of the Petrified Forest Member is from the sandstone beds in the lower 250 feet of the unit. In the Thoreau area, one well tapping only the upper sandstone beds yields water containing an excessive amount of chloride.

WESTERN AREA

The upper and lower parts of the Petrified Forest Member cannot be differentiated where the Sonsela Sandstone Bed is absent; therefore, in the western area—near Cameron and along Echo Cliffs—the Petrified Forest Member is divided into three units on the basis of slight lithologic and color differences (Akers and others, 1958, p. 93). These units are, in ascending order: a blue unit consisting of about 200 feet of mudstone, a gray unit consisting of about 400 feet of mudstone and sandstone, and a red unit consisting of about 250 feet of sandstone and mudstone (table 1; pl. 2).

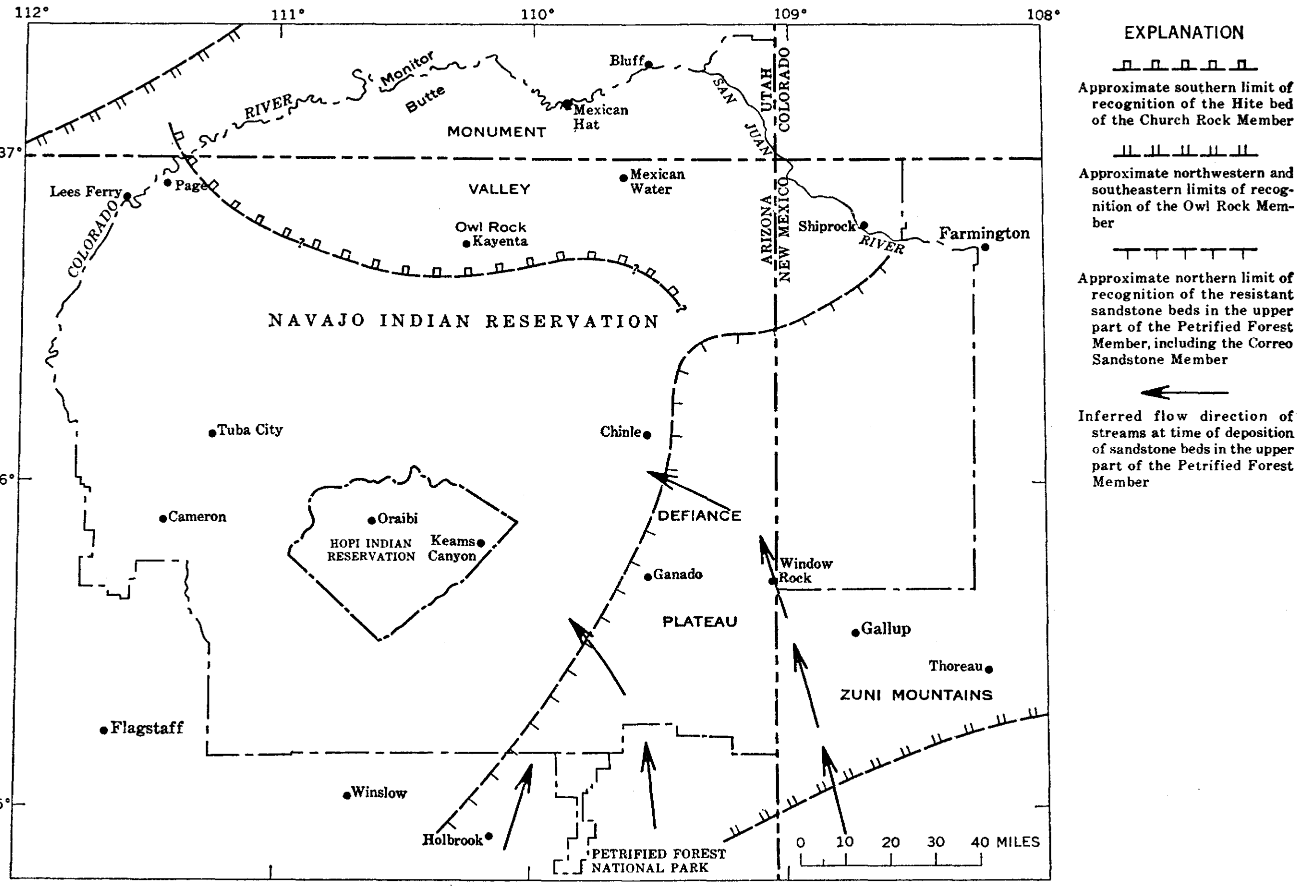

FIGURE 9.—Distribution of the Hite bed of the Church Rock Member, the Owl Rock Member, and the sandstone beds in the upper part of the Petrified Forest Member and hypothetical drainage during the time of their deposition.

In the western area the relations of units in the Petrified Forest Member are not fully understood: the question is whether they resulted from overlapping wedges of deposits, which originated from multiple source areas to the southwest, south, and southeast, or from advances and retreats of fluvial facies receiving deposits from one principal source direction. The blue mudstone unit is continuous with the lower part of the Petrified Forest Member, and the two overlying units seem to thin eastward and grade into the interval occupied by the Sonsela Sandstone Bed and the upper part of the Petrified Forest Member (pl. 2).

The Petrified Forest Member contains only a small amount of ground water in the western area, and the only water found is in the lower blue mudstone unit near Cameron. Here, pits for uranium ore exploration were filled by several feet of ground water, which probably moved upward along fractures in the blue mudstone unit from the underlying Shinarump Member (P. B. Blakemore, oral commun., 1959). The water is very blue green and is highly saline.

MONUMENT VALLEY AREA

In most of Monument Valley the Petrified Forest Member is mainly grayish red (5*R* 4/2) to pinkish gray (5*YR* 8/1) and light gray (*N* 7), but some beds are pale reddish brown and pale red. It is composed predominantly of siltstone and claystone but contains some mudstone, silty sandstone, and silty limestone. In the lower part of San Juan Canyon, the upper 100–200 feet of the Petrified Forest Member contains many thin- to thick-bedded nodular limestone and limestone conglomerate beds. A light-colored sandstone bed similar to, and perhaps correlative with, the Sonsela Sandstone Bed of the Petrified Forest Member is exposed in the walls of Piute Canyon (Cooley, 1965, p. 46–47, 53–54; pl. 2; fig. 8). The light-colored Sonsela(?) Sandstone Bed grades laterally into a series of bluish-gray and light-gray sandy siltstone and siltstone beds north of the San Juan River (observation by Cooley, 1958).

The preponderance of mudstone and siltstone prohibits any appreciable movement of ground water through the Petrified Forest Member in the Monument Valley area. The sandstone bed that may be an extension of the Sonsela Sandstone Bed is thin and silty and probably would not yield water to wells.

OWL ROCK MEMBER

The Owl Rock Member of the Chinle Formation consists of interbedded limestone and calcareous siltstone in its type section at Owl Rock in Monument Valley (Witkind and Thaden, 1963). The limestone beds are very resistant to erosion, form many thin ledges interrupting the slopes weathered from the dominant siltstone interbeds, or cap benches and cuestas. Strata of the Owl Rock Member are recognized easily in the Navajo country. In this report, the lower contact (pl. 2) is placed between horizontally bedded limestone and calcareous pastel-pale-red mudstone and siltstone units, which are included in the Owl Rock Member, and lenticular varicolored mudstone and silty sandstone beds of the Petrified Forest Member. Where the beds of either unit are not well defined, the placement of the contact has led to differences in thickness measurements made by different investigators, particularly in the northern part of the Navajo country. The upper contact of the Owl Rock Member is sharp and easy to recognize where it is overlain by the Wingate Sandstone or the Moenave Formation in most parts of the reservations (Harshbarger and others, 1957, p. 5). In Monument Valley, however, where it contains some reddish-brown silty sandstone similar to that of the overlying units, particularly the reddish-orange siltstone unit, the contact is difficult to determine precisely.

The limestone is mottled very pale blue (5*B* 8/2) and grayish pink (5*R* 8/2). It contains abundant chert nodules, mud pellets, and lenses of lime-pellet conglomerate; in some places it is rather silty and has concretionary structures. The limestone beds are 1–20 feet thick, and many can be traced for several miles. One limestone bed was traced by exposures for 20 miles in the Chinle area, and another was traced more than 40 miles by Smith (1957).

The siltstone consists of moderate-orange-pink (10*R* 7/4) flat and lenticular beds firmly to weakly bonded by calcareous cement. The siltstone beds are 1–30 feet thick. Calcareous nodules and impure limy zones are common in the siltstone.

Lithologic differences in the Owl Rock Member are slight in the Navajo country; however, some differences were noted near Cove (pl. 1), Thoreau, in the valley of the Little Colorado River, and in the lower part of San Juan Canyon. Near Cove the Owl Rock Member contains a few silty sandstone beds and seems to be slightly coarser than in the valley of the Little Colorado River. The limestone and silty limestone are grayish red (10*R* 4/2) and pale red (10*R* 6/2); the siltstone is pale reddish brown (10*R* 5/4); the silty sandstone is moderate reddish brown (10*R* 4/6). The silty sandstone is very fine grained and is rather similar to the overlying Upper Triassic Rock Point Member of the Wingate Sandstone. Near Thoreau, the Owl Rock Member includes some thin-bedded silty sandstone, and medium-grained sand is scattered in some of the limestone and siltstone beds.

In the valley of the Little Colorado River, siltstone and calcareous siltstone make up most of the Owl Rock Member. Limestone beds, although extensive, form less than 25 percent of the total member. Most of the siltstone is calcareous and contains nodular masses and concretions of limestone. Between Leupp and Holbrook the amount of calcium carbonate in the limestone beds ranges from 40 to 60 percent, and the insoluble material probably is mostly silica and silicified clay and silt (Smith, 1957). Along a roadcut about 8 miles southwest of Tuba City, the Owl Rock Member consists of one limestone bed 19 feet thick and 166 feet of limy siltstone containing an abundance of limestone nodules.

In the San Juan Canyon area, the limestone beds in the Owl Rock Member seem to be more lenticular than in other parts of the Navajo country, and the member is mostly siltstone and silty sandstone. Most of the sandstone beds are grayish red (10*R* 4/2) and are mottled with spots of light greenish gray (5*G* 8/1); they are composed of very fine grained to fine-grained sand and contain muscovite, biotite, and dark accessory minerals. The beds are thin to thick and have small-scale crossbeds of the trough and planar type. In a few places, channels filled with ripple-laminated layers and conglomerate composed of sandstone fragments are present in the sandstone.

The Owl Rock Member was deposited throughout the Navajo country (fig. 10), but thicknesses of the member vary considerably because of the intertonguing nature of its contacts with some of the overlying deposits, notably the reddish-orange siltstone unit, and the underlying Petrified Forest Member. The Owl Rock Member is about 300 feet thick along a line trending northeast between Winslow and Shiprock. The member thins northwestward and southeastward from this line; it is 270 feet thick near Cameron, 130 feet thick at Lees Ferry, and wedges out along the west side of the Paria Plateau (Akers, 1960). The member is 200 feet thick at Lupton and is absent south of Zuni Pueblo (Cooley, 1959a, fig. 8).

The flat-bedded nature of the Owl Rock Member and the extensive thin limestone beds indicate that the Chinle stream system was sluggish and contained many

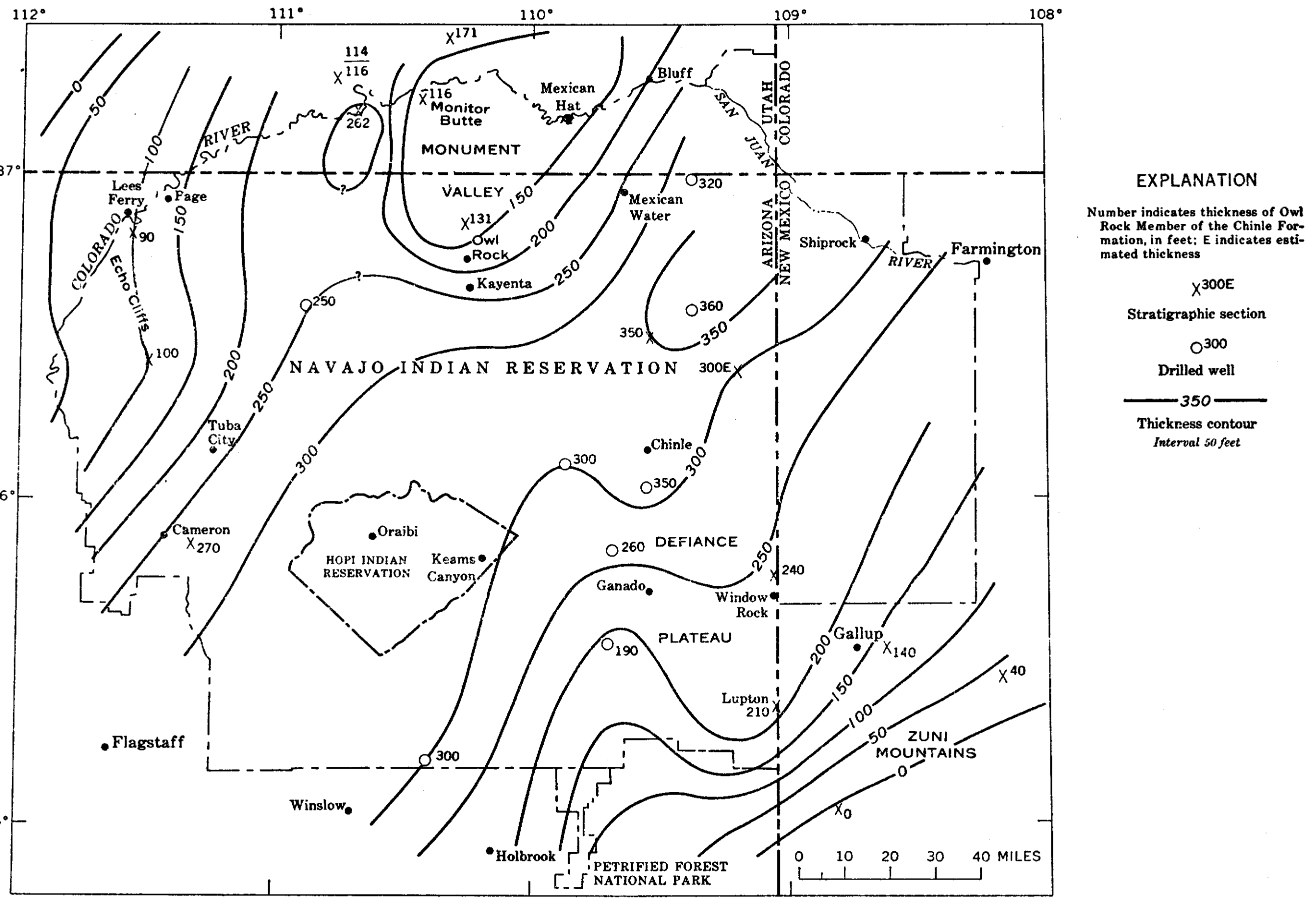

FIGURE 10.—Thickness of the Owl Rock Member.

lakes at the time the member was deposited. Lakes probably were more common in the southern part of the reservations, where their presence is indicated by the distribution of limestone and limy siltstone. In the northern and eastern parts of the Navajo country, the sandstone beds in the member indicate greater fluvial deposition and also indicate that the stream system, during the deposition of the Owl Rock Member, flowed generally southwestward. Due to the gradual decrease of limestone beds and an increase in siltstone and sandstone beds northward from the reservations, a more or less distinct unit of the Chinle is recognizable intertonguing with the Owl Rock Member. The unit is the reddish-orange siltstone unit, which has been referred to as the Church Rock Member by Stewart and others (1959, fig. 73), and it is recognizable above the typical Owl Rock Member as far south as Moses Rock in Monument Valley. It thickens northward in proportion to thinning of the Owl Rock Member.

Small amounts of water are available to wells in the Owl Rock Member of the Chinle Formation in scattered areas in the Navajo country. At least one well near Red Rock Trading Post obtains water from this member. Dug wells and springs furnish small but dependable supplies of water in the Hopi Buttes, valley of the Little Colorado River, along Echo Cliffs, and in the Defiance Plateau. The wells and springs yield less than 1 gallon per minute, but this is probably the only water available.

UPPERMOST UNITS OF THE CHINLE FORMATION IN THE MONUMENT VALLEY AREA

In Monument Valley, the strata between the Owl Rock Member of the Chinle Formation and the Lukachukai Member of the Wingate Sandstone include several units that form a sequence of red beds showing at least one unconformity. These beds have been considered to be part of the Chinle Formation in this area, but some of them have been assigned to the Rock Point Member of the Wingate Sandstone elsewhere in the reservations. Discrimination of the units in this sequence by R. B. O'Sullivan (written commun., 1965), who traced them along Comb Ridge, has tentatively suggested revised interpretations of the relation between the Owl Rock and Church Rock Members of the Chinle.

The Church Rock Member is divided into two parts: the upper Hite bed, composed mainly of sandstone, and the lower silty part, principally a reddish-brown siltstone to silty sandstone. The lower silty part of the Church Rock Member occurs only in the part of Monument Valley south of Moses Rock. The Hite bed of Stewart and others (1959, p. 518–519) is now considered to extend over most of the Monument Valley area. The rocks assigned to the Church Rock Member in Utah (Stewart and others, 1959; Cooley, 1965), having somewhat different lithologies and stratigraphic relations from those of southern Monument Valley, are termed the "reddish-orange siltstone unit" in this report. An additional sandstone bed, called the "lower ledge" by R. B. O'Sullivan (written commun., 1965), lies between the Owl Rock Member or reddish-orange siltstone unit and the Hite bed in the part of Comb Ridge north of Moses Rock. In southern Piute and Nokai Canyons, rocks shown on maps by Cooley and others (1964b, fig. 3) as the Rock Point Member of the Wingate Sandstone are now assigned in part to the Church Rock Member and in part to the Owl Rock Member.

Although the stratigraphic relationships are not clearly defined throughout all the area, the stratigraphic succession, in ascending order, seems to be as follows: reddish-orange siltstone unit, lower ledge, and Church Rock Member. The field relations and description of these units are presented briefly in this report.

REDDISH-ORANGE SILTSTONE UNIT

The reddish-orange siltstone unit consists principally of pale-reddish-brown (10*R* 5/4) to grayish-red (5*R* 4/2) mudstone to silty sandstone beds where it is exposed in San Juan Canyon, in isolated outcrops near Navajo Mountain, and along Comb Ridge near the San Juan River. Siltstone, however, makes up most of the unit in most exposures in the Navajo country. These beds form an alternating ledge-and-slope topography that in many places is similar to the Owl Rock Member. Individual units are lenticular, flat, thin to thick bedded, and are weakly bonded by calcareous and argillaceous cement. Locally, small channels are filled with silty very fine grained to medium-grained sandstone.

The reddish-orange siltstone unit, referred to as the Church Rock Member by Stewart and others (1959, fig. 73), thins generally southward. It is recognized only along the northern boundary of the reservations, where it is generally less than 50 feet thick. Most of the thinning is caused by the intertonguing of the unit southward with the Owl Rock Member.

LOWER LEDGE

A reddish-orange sandstone, termed the "lower ledge" by R. B. O'Sullivan (written commun., 1965), overlies the Owl Rock Member or reddish-orange siltstone unit in the part of Comb Ridge extending northward from Moses Rock. The sandstone is called the lower ledge because in this part of Comb Ridge there is also an upper ledge, which is formed by the Hite bed. The sandstone generally is fine grained and is not conspicuously crossbedded. The unit has a firm calcareous cement, which makes it sufficiently resistant to erosion to form a generally smooth vertical cliff. The lower ledge is 63 feet thick 2 miles north of the San Juan River and 92 feet thick 9 miles south of the San Juan River. Within a mile to the south of Moses Rock, the lower ledge was beveled out by erosion, which preceded the deposition of the Hite bed.

CHURCH ROCK MEMBER

The Church Rock Member of the Chinle Formation was named by Witkind and Thaden (1963, p. 32–34) and applied to Gregory's (1917) division A of the Chinle Formation in southern Monument Valley. In this area, the member consists of two parts—the Hite bed and a lower silty part that is lithologically similar to and continuous with the Rock Point Member of the Wingate Sandstone south of Comb Ridge. The Rock Point Member of the Wingate also was called division A of the Chinle Formation by Gregory (1917) south of Monument Valley. The lower silty part of the Church Rock Member does not extend northward along Comb Ridge beyond Moses Rock, and in western Monument Valley it wedges out between Skeleton Mesa and Monitor Butte. Rocks similar to the lower silty part of the Church Rock Member of the Chinle and the Rock Point Member of the Wingate are recognized in the upper reaches of Navajo, in Laguna, and in the southern part of Piute Canyons. The Hite bed is recognized in much of southeastern Utah and parts of northeastern Arizona.

LOWER SILTY PART

The lower silty part of the Church Rock Member consists of thin to thick parallel-bedded generally moderate-reddish-orange (10R 6/6) siltstone to silty sandstone. The lithology is typical of the member in all exposures and perhaps represents deposition in a subaqueous environment that was part of the Rock Point Lagoon described by Harshbarger and others (1957, fig. 18) as covering much of the Navajo country during the deposition of the Rock Point Member of the Wingate Sandstone. The member is weakly to firmly bonded by argillaceous and calcareous cement. Differences in the amount of cementation cause the units to form an irregular slope and to erode into hoodoolike features.

In southern Monument Valley the lower silty part of the Church Rock Member was deposited on the Owl Rock Member. The contact between both members does not show conspicuous irregularities caused by channeling or intertonguing. Along Comb Ridge between Cane Valley and Moses Rock, the lower silty part of the Church Rock Member thins rapidly and may grade into the two tongues of the Hite bed that coalesce near Moses Rock.

The maximum thickness of the lower silty part of the Church Rock Member is in southern Monument Valley, where it is 199 feet thick—not including the Hite bed—at the type section along Comb Ridge near Kayenta (Witkind and Thaden, 1963, p. 33). It is 191 feet thick—not including the Hite bed—at Owl Rock and 166 feet thick along Comb Ridge near the Arizona-Utah State line (R. B. O'Sullivan, written commun., 1966). South of Monument Valley, strata assigned to the Rock Point Member of the Wingate Sandstone that are probably lateral equivalents of the Church Rock Member have a thickness of 344 feet at the type section at Little Round Rock in Chinle Valley (Harshbarger and others, 1957, p. 9).

HITE BED

The Hite bed of Stewart and others (1959) forms the upper part of the Church Rock Member and is recognized throughout Monument Valley. It usually forms prominent reddish-brown cliffs or irregular ledges. In the western part of the area, it is represented chiefly by fills of large channels cut into the underlying reddish-orange siltstone unit or Owl Rock Member. In the other parts of Monument Valley, the bed is generally a continuous unit that overlies the Owl Rock Member, lower ledge, or the lower silty part of the Church Rock Member. Along Comb Ridge between Moses Rock and Cane Valley the Hite bed splits into two sandstone tongues that are separated by the lower silty part of the Church Rock Member. The Hite bed is not recognized in the nearest exposures in the Navajo country southeast or south of Monument Valley. However, a 4-foot bed of conglomerate at the top of the Rock Point Member reported in a section measured in Navajo Canyon (Cooley and others, 1964a, p. 96) may indicate a southwestward extension of the Hite bed. More or less isolated beds of fluvial deposits in the top of the Rock Point Member between Lukachukai and Lupton also may represent deposition comparable to, but probably not continuous with, the Hite bed.

The Hite bed is dominantly sandstone but includes some siltstone and conglomerate. All units are lenticular, and most show trough crossbedding. Most of the crossbeds are medium scale and were deposited at medium and low angles, but some are large scale and dip at low angles. At any locality, the Hite bed may consist of overlapping fills of channels or may represent the fill of a single channel. The sandstone ranges from pale red (10*R* 6/2) to grayish red (10*R* 4/2). It commonly is composed of poorly sorted subrounded to subangular very fine to medium grains of quartz and feldspar. In many places, lenses of conglomerate are interbedded with the sandstone. The conglomerate is made up of sandstone, limestone, chert, and siltstone pebbles. Both the conglomerate and sandstone are rather firmly cemented by calcareous materials.

The Hite bed has not been recognized previously in strata that are assigned to the Church Rock Member of the Chinle Formation in Monument Valley or to rocks that have been correlated with the Rock Point Member of the Wingate Sandstone. At the type section of the Church Rock Member (Witkind and Thaden, 1963, p. 33), the uppermost 47 feet of sandstone and siltstone is lithologically similar to the Hite bed farther north. In sections measured at Monitor Butte, 11+ feet of strata assigned to the Rock Point Member of the Wingate Sandstone (Cooley and others, 1964a, p. 114) and the topmost sandstone, 38 feet thick, of the Chinle Formation (Mullens, 1960, p. 320) are considered to be the Hite bed in this report. In another section measured at Owl Rock (Cooley and others, 1964a, p. 118), the upper 42.5 feet of the "Rock Point Member" is assigned here to the Hite bed and the lower 191 feet is assigned to the lower silty part of the Church Rock Member. In a section measured near San Juan Canyon near the mouth of Piute Canyon (Cooley, 1965, p. 50–51), 68.5 feet of strata correlated as the Church Rock Member are the Hite bed. The maximum recorded thickness of the Hite bed in Monument Valley is about 200 feet 4 miles south of Moses Rock, which includes both tongues of the Hite bed and some interbedded strata of the lower silty part of the Church Rock Member (R. B. O'Sullivan, written commun., 1966).

SUMMARY OF RELATIONS

The reddish-orange siltstone unit and the Owl Rock Member intertongue and apparently are closely related depositionally. According to R. B. O'Sullivan (written commun., 1966), the lower ledge passes laterally into sandstone and siltstone of the reddish-orange siltstone unit north of the San Juan River. Because the lower silty part of the Church Rock Member wedges out between two tongues of the Hite bed, deposits of the lower silty part of the Church Rock Member and the Hite bed also seem to be related depositionally. Within the red-bed sequence at the top of the Chinle, the only major break in deposition is represented by the channeled surface that underlies the Hite bed and is cut principally into the lower ledge and Owl Rock Member. The erosion that formed this surface has removed the lower ledge and an unknown amount of the Owl Rock Member south of Moses Rock. This erosion surface must extend some distance southward beyond the point of wedge out of the lower tongue of the Hite bed into the area where the lower silty part of the Church Rock Member overlies the Owl Rock Member.

In the Monument Valley area, the upper contact of the red-bed sequence, which is principally the upper contact of the Hite bed, is marked by a lithologic contrast between the well-sorted highly crossbedded Lukachukai Member of the Wingate Sandstone above and the poorly sorted channel-type deposits of the Hite bed below. The Lukachukai Member was deposited on a sharply defined flat surface that has a local relief of generally less than a foot. This may be the same surface that Stewart and others (1959, p. 523) suggested as representing a disconformity formed as a result of erosion caused by slight upwarping. Some removal of sediments in the San Juan Canyon area must have taken place because the surface truncates the bedding of the red-bed sequence (Hite bed) (Cooley, 1965, p. 50, 56). Some doubt exists, however, as to the nature of the red-bed sequence–Wingate Sandstone (Lukachukai Member) contact because it has been described as being conformable in the Clay Hills (Mullens, 1960, p. 290) and in southern Monument Valley (Witkind and Thaden, 1963, p. 35).

All units of the red-bed sequence are too fine grained or too tightly cemented to allow appreciable movement of water through them. They are not known to yield any ground water in the eastern and southern parts of Monument Valley. In a few places in western Monument Valley, some water from the overlying Lukachukai Member of the Wingate Sandstone percolates downward by means of openings formed along fractures in the upper few feet of the Hite bed. This water discharges as springs and seeps, but usually the flow is masked by the considerably larger spring flow that discharges from the Lukachukai Member in the same area.

AGE ASSIGNMENT AND FOSSIL OCCURRENCES OF THE CHINLE FORMATION

The Chinle Formation has been designated as Late Triassic in age, based on vertebrate and invertebrate remains and fossil plants collected by many workers. Von Huene (1926) considered the lower part of the Chinle to have Middle and Late Triassic faunas, and Branson (1927) and Branson and Mehl (1929, p. 17–18) suggested a Middle Triassic age but also felt that the fossils are of little use in correlation. Camp (1930, p. 4), Colbert (1950, p. 64), and others studied the vertebrate fauna of the Chinle and considered it to be unquestionably Late Triassic in age and equivalent to the Keuper faunas of Europe. This age is indicated also by the floral studies of Daugherty (1941, p. 42), and both Daugherty (1941, p. 40–41) and Camp (1930, table 1) concluded that the youngest Triassic rocks of Germany (Rhaetian) have no equivalents in the Chinle, a conclusion confirmed in part by the occurrence of Late Triassic fossils in the overlying Wingate Sandstone and by Triassic(?) fossils in the Moenave and Kayenta Formations (Harshbarger and others, 1957, p. 25–31; Lewis and others, 1961).

Most of the vertebrate fauna of the Chinle, with the exception of isolated fish scales and teeth, is from large animals. Because the remains of smaller animals that must have existed are missing, the picture of life existing during deposition of the Chinle Formation is somewhat distorted (Colbert, 1952, p. 591). The lack of fossils of smaller animals and the scarcity of smaller bones of larger animals probably are the result of the generally abrasive nature of the fluvial environment of the Chinle, the tendency of bone in the Chinle to be replaced and "rotted" by gypsum, and the destructive nature of the bentonitic clays that swell and tend to break even the largest bones into small pieces.

Vertebrate remains have been found in most places in the Chinle Formation in the Navajo country but are most common in the lower part of the Petrified Forest Member in the eastern area and in the blue mudstone unit at the base of the member in the western area. The most conspicuous fossil localities in these units are the Ward bone bed southeast of Cameron, near the Petrified Forest National Park, and at Lukachukai. North of the Red Rock Trading Post, fragmental phytosaur remains have been found in the Chinle in the upper part of the Owl Rock Member as well as in the base of the overlying Rock Point Member of the Wingate Sandstone. These were identified by D. H. Dunkle (in Harshbarger and others, 1957, p. 29) as the genus *Machaeroprosopus*, a genus typical of the Chinle Formation. Gregory (1962, p. 680) indicated that this should be considered a genus of *Phytosaurus*, which is known from Europe, India, and eastern and western North America.

The Chinle Formation contains only a few varieties of locally abundant invertebrate fossils. In the Petrified Forest Member, particularly in the Sonsela Sandstone Bed, many coquinalike beds of pelecypods, usually assigned to several species of the genus *Unio*, are present. Similar mollusks also were found in the Owl Rock Member near Kayenta, and concentrations of silicified gastropods are common near Kayenta, along Ward Terrace, and in San Juan Canyon. Yen (1951) identified five species of fresh-water gastropods in collections from the Owl Rock Member near Cedar Ridge Trading Post.

REFERENCES CITED

Akers, J. P., 1960, The Chinle Formation of the Paria Plateau area, Arizona and Utah: unpub. M.S. thesis, 83 p. Tucson, Arizona Univ.

Akers, J. P., Cooley, M. E., and Repenning, C. A., 1958, Moenkopi and Chinle Formations of Black Mesa basin and adjacent areas, *in* New Mexico Geol. Soc. Guidebook 9th Field Conf., Black Mesa basin, northeastern Arizona, 1958: p. 88–94.

Averitt, Paul, Detterman, J. S., Harshbarger, J. W., Repenning, C. A., and Wilson, R. F., 1955, Revisions in correlation and nomenclature of Triassic and Jurassic formations in southwestern Utah and northern Arizona: Am. Assoc. Petroleum Geologists Bull., v. 39, no. 12, p. 2515–2524.

Baker, A. A., 1936, Geology of the Monument Valley-Navajo Mountain region, San Juan County, Utah: U.S. Geol. Survey Bull. 865, 106 p.

Baker, A. A., and Reeside, J. B., Jr., 1929, Correlation of the Permian of southern Utah, northern Arizona, northwestern New Mexico, and southwestern Colorado: Am. Assoc. Petroleum Geologists Bull., v. 13, no. 11, p. 1413–1448.

Brady, L. F., 1935, The Moencopi Sandstone, Part 2 *of* Notes on the geology of northern Arizona: Mus. Northern Arizona Mus. Notes, v. 8, no. 2, p. 8–12.

Branson, E. B., 1927, Triassic-Jurassic "red beds" of the Rocky Mountain region: Jour. Geology, v. 35, no. 7, p. 607–630.

Branson, E. B., and Mehl, M. G., 1929, Triassic amphibians from the Rocky Mountain region: Univ. Missouri Studies, v. 4, no. 2, 87 p.

Brown, Barnum, 1933, An ancestral crocodile: Am. Mus. Novitates 638, 4 p.

Camp, C. L., 1930, A study of the phytosaurs with description of new material from western North America: California Univ. Mem., v. 10, 174 p.

Camp, C. L., Colbert, E. H., McKee, E. D., and Welles, S. P., 1947, A guide to the continental Triassic of northern Arizona: Plateau, v. 20, no. 1, p. 1–9.

Colbert, E. H., 1950, Mesozoic vertebrate faunas and formations of northern New Mexico, *in* Soc. Vertebrate Paleontology Guidebook 4th Field Conf., northwestern New Mexico, 1950: p. 57–73.

———1952, A pseudosuchian reptile from Arizona: Am. Mus. Nat. History Bull., v. 99, p. 561–592.

Cooley, M. E., 1957, Geology of the Chinle Formation in the upper Little Colorado drainage area, Arizona and New Mexico: Tucson, Arizona Univ., unpub. M.S. thesis, 317 p.

——— 1958, The Mesa Redondo Member of the Chinle Formation, Apache and Navajo Counties, Arizona: Plateau, v. 31, no. 1, p. 7–15.

——— 1959a, Triassic stratigraphy in the State line region of west-central New Mexico and east-central Arizona, *in* New Mexico Geol. Soc. Guidebook 10th Field Conf., west-central New Mexico, 1959: p. 66–73.

——— 1959b, Ancient cave deposit near Thoreau, New Mexico: Plateau, v. 31, no. 4, p. 89.

——— 1965, Stratigraphic sections and records of springs in the Glen Canyon region of Utah and Arizona: Mus. Northern Arizona Tech. Ser. 6, Glen Canyon ser. 6, 140 p.

Cooley, M. E., Akers, J. P., and Stevens, P. R., 1964a, Selected lithologic logs, drillers' logs, and stratigraphic sections, pt. 3, *of* Geohydrologic data in the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah: Arizona State Land Dept. Water-Resources Rept. 12–C, 157 p.

Cooley, M. E., Harshbarger, J. W., Akers, J. P., and Hardt, W. F., 1964b, Regional hydrogeology of the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah, *with a section on* Vegetation, by O. N. Hicks: U.S. Geol. Survey open-file rept., 245 p.

Cooley, M. E., Harshbarger, J. W., Akers, J. P., and Hardt, W. F., 1968, Regional hydrogeology of the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah, *with a section on* Vegetation, by O. N. Hicks: U.S. Geol. Survey Prof. Paper 521–A (in press).

Cooley, M. E., and others, 1966, Maps showing locations of wells, springs, and stratigraphic sections, pt. 4 *of* Geohydrologic data in the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah: Arizona State Land Dept. Water-Resources Rept. 12–D, 2 sheets.

Daugherty, L. H., 1941, The Upper Triassic flora of Arizona, *with* A discussion of its geologic occurrence, by H. R. Stagner: Carnegie Inst. Washington Pub. 526, Contr. Paleontology, 108 p.

Davis, G. E., Hardt, W. F., Thompson, L. K., and Cooley, M. E., 1963, Records of ground-water supplies, pt. 1 *of* Geohydrologic data in the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah: Arizona State Land Dept. Water-Resources Rept. 12–A, 159 P.

Evensen, C. G., 1953, A comparison of the Shinarump Conglomerate on Hoskinnini Mesa with that in other selected areas in Arizona and Utah: Tucson, Arizona Univ., unpub. M.S. thesis, 88 p.

——— 1958, The Shinarump Member of the Chinle Formation, *in* New Mexico Geol. Soc. Guidebook 9th Field Conf., Black Mesa basin, northeastern Arizona, 1958: p. 95–97.

Gilbert, G. K., 1875, Report on the geology of portions of Nevada. Utah, California, and Arizona: U.S. Geog. and Geol. Surveys W. 100th Meridian, v. 3, p. 17–187.

Goddard, E. N., chm., an dothers, 1948, Rock-color chart: Washington, Natl. Research Council (repub. by Geol. Soc. America, 1951), 6 p.

Gregory, H. E., 1917, Geology of the Navajo country: U.S. Geol. Survey Prof. Paper 93, 161 p.

——— 1948, Geology and geography of central Kane County, Utah: Geol. Soc. America Bull., v. 59, no. 3, p. 211–247.

——— 1950, Geology and geography of the Zion Park region, Utah and Arizona: U.S. Geol. Survey Prof. Paper 220, 200 p.

Gregory, J. T., 1962, The genera of phytosaurs: Am. Jour. Sci., v. 260, no. 9, p. 652–690.

Grundy, W. D., 1953, Geology and uranium deposits of the Shinarump Conglomerate of Nokai Mesa, Arizona and Utah; Tucson, Arizona Univ. unpub. M.S. thesis, 88 p

Hager, Dorsey, 1922, The Holbrook area, Arizona: Mineral and Oil Bull., v. 8, no. 9, p. 523.

Harshbarger, J. W., Repenning, C. A., and Irwin, J. H., 1957, Stratigraphy of the uppermost Triassic and the Jurassic rocks of the Navajo country: U.S. Geol. Survey Prof. Paper 291, 74 p.

Hunting, Ellsworth, and Goldthwait, J. W., 1903, The Hurricane fault in southwestern Utah: Jour. Geology, v. 11, p. 46–63.

Kelley, V. C., and Wood, G. H., Jr., 1946, Lucero uplift, Valencia, Socorro, and Bernalillo Counties, New Mexico: U.S. Geol. Survey Oil and Gas Inv. Prelim. Map OM–47.

Kister, L. R., and Hatchett, J. L., 1963, Selected chemical analyses of the ground water, pt. 2 *of* Geohydrologic data in the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah: Arizona State Land Dept. Water-Resources Rept. 12–B, 58 p.

Lewis, G. E., Irwin, J. H., and Wilson, R. F., 1961, Age of the Glen Canyon Group (Triassic and Jurassic) on the Colorado Plateau: Geol. Soc. America Bull., v. 72, no. 9, p. 1437–1440.

McGavock, E. H., Edmonds, R. J., Gillespie, E. L., and Halpenny, P. C., 1966, Supplemental records of ground-water supplies, pt. 1–A *of* Geohydrologic data in the Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah: Arizona State Land Dept. Water-Resources Rept. 12–E, 55 p.

McKee, E. D., 1937, Triassic pebbles in northern Arizona containing invertebrate fossils: Am. Jour. Sci., 5th ser., v. 33, no. 196, p. 260–263.

——— 1939, Some types of bedding in the Colorado River delta: Jour. Geology, v. 47, no. 1, p. 64–81.

——— 1954, Stratigraphy and history of the Moenkopi Formation of Triassic age: Geol. Soc. America Mem. 61, 133 p.

Mullens, T. E., 1960, Geology of the Clay Hills area, San Juan County, Utah: U.S. Geol. Survey Bull. 1087–H, p. 259–336.

Peabody, F. E., 1948, Reptile and amphibian trackways from the Lower Triassic Moenkopi Formation of Arizona and Utah: California Univ. Dept. Geol. Sci. Bull., v. 27, p. 295–467.

Phoenix, D. A., 1963, Geology of the Lees Ferry area, Coconino County, Arizona: U.S. Geol. Survey Bull. 1137, 86 p.

Poborski, S. J., 1954, Virgin Formation (Triassic) of the St. George, Utah, area: Geol. Soc. America Bull., v. 65, no. 10, p. 971–1006.

Poole, F. G., 1961, Stream directions in Triassic rocks of the Colorado Plateau, *in* Geological Survey research 1961: U.S. Geol. Survey Prof. Paper 424–C, p. C139–C141.

Reeside, J. B., Jr., chm., 1957, Correlation of the Triassic formations of North America, exclusive of Canada, *with a section on* Correlation of continental Triassic sediments by vertebrate fossils, by E. H. Colbert and J. T. Gregory: Geol. Soc. America Bull., v. 68, no. 11, p. 1451–1513.

Reeside, J. B., Jr., and Bassler, Harvey, 1922, Stratigraphic section in southwestern Utah and northwestern Arizona: U.S. Geol. Survey Prof. Paper 129, p. 53–77.

Repenning, C. A., Cooley, M. E., and Akers, J. P., 1965, Stratigraphy of the Chinle and Moenkopi Formations, Navajo and Hopi Indian Reservations, Arizona, New Mexico, and Utah: U.S. Geol. Survey open-file rept., 146 p.

Shimer, H. W., 1919, Permo-Triassic of northwestern Arizona: Geol. Soc. America Bull., v. 30, no. 4, p. 471–497.

Smith, C. T., 1954, Geology of the Thoreau quadrangle, McKinley and Valencia Counties, New Mexico: New Mexico Bur. Mines and Mineral Res. Bull. 31, 36 p.

Smith, R. S., 1957, A study of the (Triassic) Chinle-Shinarump beds in the Leupp-Holbrook area, Arizona: Tucson, Arizona Univ. unpub. Ph. D. thesis, 170 p.

Stewart, J. H., 1957, Proposed nomenclature of part of Upper Triassic strata in southeastern Utah: Am. Assoc. Petroleum Geologists Bull., v. 41, no. 3, p. 441–465.

——— 1959, Stratigraphic relations of Hoskinnini Member (Triassic?) of Moenkopi Formation on Colorado Plateau: Am. Assoc. Petroleum Geologists Bull., v. 43, no. 8, p. 1852–1868.

Stewart, J. H., Williams, G. A., Albee, H. F., and Raup, O. B., 1959, Stratigraphy of Triassic and associated formations in part of the Colorado Plateau region, *with a section on* Sedimentary petrology, by R. A. Cadigan: U.S. Geol. Survey Bull. 1046–Q, p. 487–576.

Thaden, R. E., Trites, A. F., Jr., and Finnell, T. L., 1964, Geology and ore deposits of the White Canyon area, San Juan and Garfield Counties, Utah: U.S. Geol. Survey Bull. 1125, 166 p.

Von Huene, F. R., 1926, Notes on the age of the continental Triassic beds in North America, *with* Remarks on some fossil vertebrates: U.S. Nat. Museum Proc., v. 69, art. 18, p. 1–10.

Ward, L. F., 1901, Geology of the Little Colorado Valley: Am. Jour. Sci., 4th ser., v. 12, no. 72, p. 401–413.

——— 1905, Status of the Mesozoic floras of the United States: U.S. Geol. Survey Mon. 48, 616 p.

Welles, S. P., 1947, Vertebrates from the upper Moenkopi Formation of northern Arizona: California Univ. Dept. Geol. Sci. Bull., v. 27, no. 7, p. 241–294.

Welles, S. P., and Cosgriff, John, 1965, A revision of the labyrinthodont family Capitosauridae and a description of *Parotosaurus peabodyi*, n. sp. from the Wupatki Member of the Moenkopi Formation of northern Arizona: California Univ. Pubs. Geol. Sci., v. 54, p. 1–148.

Witkind, I. J., 1956, Channels and related swales at the base of the Shinarump Conglomerate, Monument Valley, Arizona, *in* Page, L. R., Stocking, H. E., Smith, H. B., compilers, 1956, Contributions to the geology of uranium and thorium by the United States Geological Survey and Atomic Energy Commission for the United Nations International Conference on Peaceful Uses of Atomic Energy, Geneva, Switzerland, 1955: U.S. Geol. Survey Prof. Paper 300, p. 233–237.

Witkind, I. J., and Thaden, R. E., 1963, Geology and uranium-vanadium deposits of the Monument Valley area, Apache and Navajo Counties, Arizona: U.S. Geol. Survey Bull. 1103, 171 p.

Yen, T.–C., 1951, Some Triassic fresh-water gastropods from northern Arizona: Am. Jour. Sci., v. 249, no. 9, p. 671–675.

INDEX

[Italic page numbers indicate major references]

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