Stratigraphy of Triassic and Associated Formations in Part of the Colorado Plateau Region

GEOLOGICAL SURVEY BULLETIN 1046-Q

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By JOHN H. STEWART, GEORGE A. WILLIAMS, HOWARD F. ALBEE, *and* OMER B. RAUP

With a section on

SEDIMENTARY PETROLOGY

By ROBERT A. CADIGAN

CONTRIBUTIONS TO THE GEOLOGY OF URANIUM

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CONTENTS

ILLUSTRATIONS

TABLES

CONTRIBUTIONS TO THE GEOLOGY OF URANIUM

STRATIGRAPHY OF TRIASSIC AND ASSOCIATED FORMATIONS IN PART OF THF COLORADO PLATEAU REGION

By JOHN H. STEWART, GEORGE A. WILLIAMS, HOWARD F. ALBEE, and OMER B. RAUP

ABSTRACT

Stratigraphic studies of the Triassic and associated formations were made in southeastern Utah and adjoining parts of Colorado and Arizona. Five principal lines of investigation were followed: regional stratigraphy, sedimentary petrology, pebble studies, sedimentary-structure studies, and lithofacies studies.

The formations studied are the Cutler formation, Coconino sandstone, and Kaibab limestone of Permian age; the Moenkopi formation, Chinle formation, and Wingate sandstone of Triassic age; the Kayenta formation of Jurassic(?) age; and the Navajo sandstone of Jurassic and Jurassic(?) age.

The Cutler formation grades from a conglomeratic facies in southwestern Colorado to a unit containing alternating reddish siltstone and yellowish-gray sandstone members in southeastern Utah. The reddish siltstone members comprise the Halgaito, Organ Rock, and Hoskinnini tongues. These alternate with the yellowish-gray sandstone members—the Cedar Mesa, White Rim, and De Chelly sandstone members.

The conglomeratic facies of the Cutler is classified as an arkose that was deposited by streams flowing westward from a rising granitic area in southwestern Colorado. The reddish siltstone members were deposited by quiet water in basins of accumulation on a slowly sinking continental margin, and they, also, were derived from a source area in southwestern Colorado. The Organ Rock tongue is part graywacke and part arkose, whereas the Hoskinnini tongue is arkose. The yellowish-gray sandstone members were deposited by winds blowing toward the southeast, and the materials probably were derived from a source area to the northwest. The Cedar Mesa sandstone member is feldspathic orthoquartzite, and the De Chelly sandstone member is tuffaceous feldspathic orthoquartzite.

The Coconino sandstone and Kaibab limestone crop out in the western part of southeastern Utah. The Coconino is laterally equivalent to part of the Cutler formation and is an eolian deposit formed by southeastward-blowing winds. The Kaibab is a marine deposit.

The Moenkopi formation of Triassic age consists of reddish horizontally and ripple-laminated siltstone that is classified as arkose and some cross-stratified sandstone of moderately well sorted sand that is classified as feldspathic orthoquartzite. The Sinbad limestone member crops out in central and south-central Utah and to the south overlaps the underlying part of the Moenkopi.

The Moenkopi is 900 feet thick in the Capitol Reef area and thins to a depositional margin along the Utah-Colorado boundary.

The Moenkopi formation in southeastern Utah is predominantly a tidal-flat deposit containing some stream-deposited material. The streams flowed westward from a highland in southwestern Colorado. The Sinbad limestone member is a marine deposit. The sea of Moenkopi time transgressed southeastward and eastward across Utah.

The Chinle formation in southeastern Utah and in Monument Valley, Ariz., is divided into seven members, which are, in ascending order, the Temple Mountain, Shinarump, Monitor Butte, Moss Back, Petrified Forest, Owl Rock, and Church Rock members.

The Temple Mountain member is composed of mottled purple and white siltstone and claystone and minor amounts of yellowish-gray sandstone and conglomerate. It averages about 20 feet in thickness and is restricted to the San Rafael Swell area, in central Utah.

The Shinarump member is fine- to coarse-grained sandstone, composed of poorly to moderately well sorted sand, and conglomeratic lenses composed dominantly of siliceous pebbles. The Shinarump is feldspathic orthoquartzite with regional and local variations ranging from tuffaceous feldspathic orthoquartzite to arkose. It ranges in thickness from 0 to about 250 feet.

The Monitor Butte member consists of greenish bentonitic claystone and interstratified grayish sandstone, which is composed of very fine poorly sorted materials, and ranges in thickness from 0 to 250 feet. The sandstone in the Monitor Butte member is feldspathic orthoquartzite with local and regional variations that range from tuffaceous feldspathic orthoquartzite to arkose.

The Moss Back member is composed of grayish sandstone that consists of very fine- to medium-size poorly sorted sand and averages about 60 feet in thickness. The Moss Back ranges in composition from orthoquartzite to arkose and contains some graywacke.

The Petrified Forest member consists of variegated bentonitic claystone and clayey sandstone composed of poorly sorted sand and ranges in thickness from 0 to 700 feet. The sandstone in the Petrified Forest member is orthoquartzitic tuff.

The Owl Rock member is composed of reddish siltstone and limy sandstone of moderately well sorted material interstratified with thin limestone beds and ranges in thickness from 0 to 450 feet. The detrital units in the Owl Rock are tuffaceous arkose.

The Church Rock member consists of reddish siltstone and minor reddish sandstone composed of moderately well sorted sand and ranges in thickness from 0 to 350 feet. The Church Rock member has two compositional classifications: the sandstone is arkose and the siltstone is graywacke.

The Chinle formation is a continental deposit formed under alluvial-plain and lake or lagoonal environments. The Shinarump, Monitor Butte, Moss Back, and Petrified Forest members contain much volcanic debris. Cross-stratification studies indicate that the sandstone strata of the Chinle of southeastern Utah were derived from a source to the south and southeast.

The Glen Canyon group in southeastern Utah consists of the Wingate sandstone, Kayenta formation, and Navajo sandstone. Preliminary studies indicate that the sedimentary structures dip southeast to southwest in this area. The Wingate sandstone is composed of moderately to well sorted very fine grained sand and ranges in composition from tuffaceous arkose to feldspathic orthoquartzite. The sandstone of the Kayenta formation consists of well sorted very fine grained material and is feldspathic orthoquartzite or arkose, depending on the amount of kaolin present. The Navajo sandstone is well sorted very fine grained feldspathic orthoquartzite.

Most of the uranium deposits in the Triassic rocks are in the Shinarump, Monitor Butte, and Moss Back members of the Chinle formation, and in the base of undifferentiated Chinle. The deposits are generally near the base of the Chinle, regardless of which unit of the formation lies in that position. The deposits lie in broad northwestward-trending belts near the north limit of the respective units.

Many determinations have been made of the types of clay minerals in the sandstones in the Triassic and associated formations. Evidence supports the hypothesis that much of the hydromica in the Chinle is the result of alteration of montmorillonite in the presence of soluble potassium salts.

Thin-section studies of ore-bearing sandstone and barren sandstone in the Shinarump and Moss Back members of the Chinle formation suggest that uranium ore occurs predominantly in sandstone that contains 20 percent or more kaolin, and that strata containing 15 to 35 percent kaolin should be considered more favorable for the occurrence of uranium than strata containing less than 15 percent kaolin.

INTRODUCTION

Stratigraphic studies of the ore-bearing Chinle formation and associated formations of the Colorado Plateau region are being made to obtain information regarding the areal distribution, local and regional differences in lithologic character, sources and character of constituent material, and conditions of deposition of the formations. Because of the regional variations in lithologic character, it has been necessary to study many sections to analyze the stratigraphic relation of the Chinle formation to associated formations. This report is based on work done on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission.

The work is designed to help, both directly and indirectly, in the search for uranium deposits. Local sedimentary features such as channel fills and lenticular sandstone units in many areas appear to have controlled the deposition of ore, and evaluation of these controls is an essential part of the project. Areas where these features are prominent are considered favorable for the occurrence of ore deposits. Thus, broad areas or belts that are relatively favorable for finding new ore deposits can be outlined by study of the stratigraphic and geographic distribution of known ore deposits. Without a regional appraisal of the stratigraphic occurrences of the deposits, the significance of individual deposits or groups of deposits in the regional geologic setting is obscure. Indirectly, the study helps in the search for uranium deposits by providing basic knowledge that can be used by geologists engaged in exploration for uranium deposits on the Colorado Plateau.

Fieldwork was virtually completed in the northern part of the Monument Valley area (fig. 70) in 1951; in the Circle Cliffs, Capitol Reef, White Canyon, and Red House Cliffs areas in 1952; and in the

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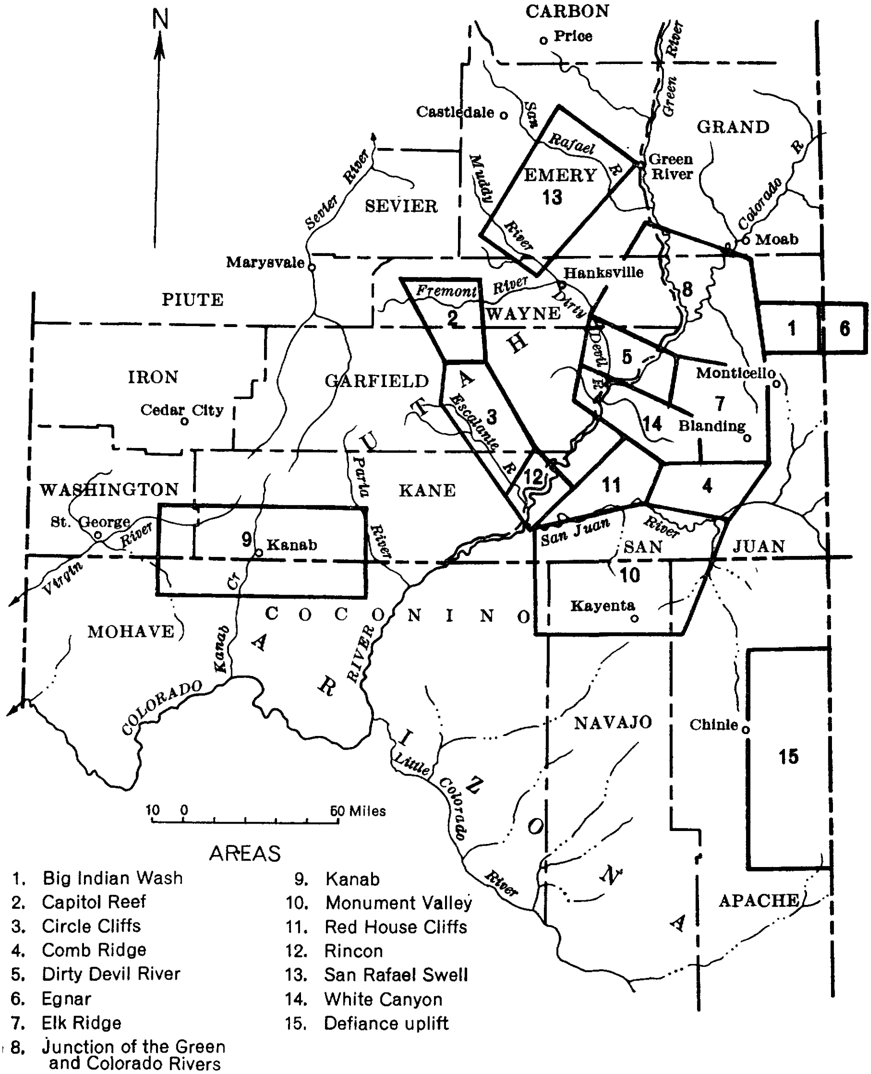

FIGURE 70.—Index map of part of the Colorado Plateau showing areas of stratigraphic studies.

Comb Ridge, Dirty Devil River, San Rafael Swell, Elk Ridge, and junction of the Green and Colorado River areas in 1953. Preliminary work has been done in the Big Indian Wash, Egnar, and Kanab areas. Although compilation and evaluation of field data collected in these areas are almost finished, results of laboratory studies are preliminary.

The rock units studied are the Cutler formation, Coconino sandstone and Kaibab limestone, of Permian age; the Moenkopi formation, Chinle formation, and Wingate sandstone of Triassic age; the Kayenta formation of Jurassic(?) age; and the Navajo sandstone of

Jurassic and Jurassic(?) age. The rocks studied represent as much as 7,000 feet of strata (plate 49).

The stratigraphy of the Triassic formations and associated units in southeastern Utah and adjoining parts of Arizona and Colorado, as well as the stratigraphy of the Chinle formation in the Kanab area, is summarized in this report. Correlations are not made beyond the areas in which work has been done, and the paleontology of the units is not discussed in detail.

SCOPE

Five principal lines of investigation are followed: regional stratigraphy, sedimentary petrology, pebble studies, sedimentary-structure studies, and lithofacies studies.

The study of regional stratigraphy establishes a background in the interpretation of the stratigraphic sequence. Regional correlation of stratigraphic units is based on physical continuity and primary and secondary lithologic characteristics.

Sedimentary-petrology studies reveal regional differences in composition and texture of the formations by means of statistical analyses of grain-size distributions, heavy-mineral studies, and thin-section studies.

Pebble studies of composition, average and maximum size, color, roundness, and sphericity show the regional and stratigraphic differences of pebble suites from conglomeratic units. Fossiliferous pebbles also aid in identification of possible source beds.

Sedimentary-structure studies of the orientation of cross-stratification, ripple marks, and current lineation indicate direction of movement of the depositing agent. These studies lead to interpretations of regional drainage patterns, of possible source areas, and of the validity of stratigraphic correlations.

The lithofacies study of the lower part of the Chinle formation has two general objectives: to determine regional variations of lithologic character and thickness, and to compare uranium-bearing parts with barren parts.

TERMINOLOGY AND METHODS USED IN SEDIMENTARY-ROCK CLASSIFICATION

Two methods of sedimentary-rock classification are used: a field textural classification and a laboratory petrographic classification. In the field, classification is based on the estimated average grain size of the detrital components of a rock. The Wentworth (1922) size classification is used (table 1) in conjunction with the rock names given on page 492. The petrographic classification is discussed in the sedimentary-petrology section of this report.

TABLE 1.—*Grain-size classification, modified after Wentworth (1922)*

Rock type	Constituent	Grade limit (diameter, in mm)
Conglomerate	Gravel:	
	Boulder	>256
	Cobble	256–64
	Pebble	64–4
	Granule	4–2
Sandstone	Sand:	
	Very coarse	2–1
	Coarse	1–½
	Medium	½–¼
	Fine	¼–⅛
	Very fine	⅛–1/16
Siltstone	Silt	1/16–1/256
Claystone	Clay	<1/256

The methods of determining average grain size in the field and in the laboratory often produce different results. Field determinations are visual, and the most abundant, or modal, grain size is the average grain size. Laboratory determinations are made with the aid of graduated sieves and pipettes, and the computed mean grain diameter is used as the average grain size. In most detrital sediments, the modal grain size is larger than the mean grain size. The difference may be 1 or 2 Wentworth grade sizes in a poorly sorted sediment or less than half a grade size in a well-sorted sediment. Thus, average grain sizes based on field observations are generally larger than those based on laboratory determinations.

For purposes of field classification, the fragments in a detrital sedimentary rock are divided into four constituents—clay, silt, sand, and gravel. The constituent with the largest percentage is the major constituent and the constituents with smaller percentages are minor constituents.

Type 1. No minor constituent greater than 20 percent.
Classification: Named after major constituent.
Example: 85 percent sand, 10 percent silt, and 5 percent clay; designated as sandstone.

Type 2. One minor constituent greater than 20 percent.
Classification: Major constituent name modified by minor constituent name.
Example: 75 percent silt, 25 percent sand; designated as sandy siltstone.

Type 3. Two or more constituents greater than 20 percent.
Classification: Double modification of major constituent name, with second largest minor constituent as first modifier and largest minor constituent as second modifier.
Example: 40 percent gravel, 35 percent sand, 25 percent silt; designated as silty sandy conglomerate.

Type 4. Gravel comprises 10 to 20 percent.
Classification: Modification of major and minor constituent names with one of the modifiers "granular," "pebbly," "cobbly," or "bouldery." The modifier is the largest class size in the gravel and precedes all other modifiers.
Example: 60 percent sand, 9 percent pebbles, 6 percent granules, 25 percent silt; designated as pebbly silty sandstone.

TERMINOLOGY AND METHODS USED IN SEDIMENTARY-STRUCTURE STUDIES

The methods used in sedimentary-structure studies are slightly modified from those developed by Reiche (1938). Descriptive terms are those proposed by McKee and Weir (1952).

The amount and direction of dip is measured on a number of individual cross-strata in the unit being studied. The number of measurements necessary for adequate sampling depends on the diversity in dip directions of the cross-stratification. The results of many field tests show that 150 measurements are adequate in sedimentary rocks such as the Shinarump member of the Chinle, which contains medium-scale cross-stratification. Fifty measurements are sufficient in sedimentary rocks such as the Navajo sandstone, which contains large-scale cross-stratification. Only one measurement is made on a single set of cross-strata.

A basic assumption in the study of the orientation of cross-stratification is that a component of the dip direction of the cross-strata is in the down-current direction. If each dip-direction reading is considered a vector, a resultant of the readings can be obtained by mathematical or graphical methods. This resultant is the average down-current direction, from which a transportation direction and a source direction can be inferred.

The spread of the readings in a study is measured in terms of a consistency factor which is expressed numerically from 0 to 1. If all the readings are in the same direction the consistency factor would be 1, whereas if the readings are equally distributed through 360°, the consistency factor would be 0. A consistency factor below 0.20 indicates an insignificant trend.

STRATIGRAPHY

PERMIAN ROCKS

The Permian rocks in southeastern Utah consist of the Coconino sandstone, Kaibab limestone, and Cutler formation. The Rico formation is considered to be of Pennsylvanian and Permian (?) age and is not described here. The Coconino sandstone, Kaibab limestone, and Cutler formation are all closely related and are marked by abrupt and prominent facies changes. The interrelations of these formations and of members within the Cutler are too complex to describe in detail here, and an outline of only the major stratigraphic features of the Permian rocks is presented.

COCONINO SANDSTONE

In southeastern Utah, the Coconino sandstone of Permian age (named by Darton, 1910, p. 21, 27) is exposed in the Capitol Reef and

San Rafael Swell areas. It overlies the Hermosa formation of Pennsylvanian age and underlies the Kaibab limestone of Permian age. Most, if not all, of the Coconino is equivalent to the Cutler formation in the areas south and east of the Capitol Reef and San Rafael Swell areas. In southeastern Utah, the practice of geologists has been to use the term Cutler in areas where the Permian sequence contains reddish siltstone members and to use the term Coconino in areas where there are no reddish siltstone members. A recent drill hole in the Circle Cliffs area shows the presence of a thick reddish siltstone unit in the Permian sequence (Steed, 1954) that has led to a reassignment to the Cutler of rocks formerly assigned to the Coconino sandstone by Gregory and Moore (1931).

McKee (1954a) has suggested that the Coconino of the type area of northern Arizona may not be physically continuous with the Coconino sandstone of southeastern Utah. Further work might show that the term Coconino is not appropriate in southeastern Utah.

The Coconino sandstone is yellowish-gray fine-grained sandstone composed of well-sorted rounded clear quartz and rare black accessory minerals. It is composed of thick to very thick trough sets of medium- to large-scale cross-strata. The Coconino attains a thickness of 685 feet in the San Rafael Swell area (Baker, 1946, p. 49), and at least 550 feet is exposed in the Capitol Reef area. The Coconino is interpreted to be an eolian deposit. The cross-strata in the Coconino dip dominantly southeast, indicating that the winds that deposited the Coconino blew southeastward.

KAIBAB LIMESTONE

In southeastern Utah, the Kaibab limestone of Permian age (named by Darton, 1910, p. 21, 28, 32) crops out in the San Rafael Swell, Capitol Reef, and Circle Cliffs areas. Between these areas and outcrops of Permian rocks along the Colorado River to the east the Kaibab either pinches out or grades laterally into the White Rim sandstone member of the Cutler formation. The Kaibab overlies the Coconino sandstone of Permian age in the San Rafael Swell and Capitol Reef areas and the Cutler formation of Permian age in the Circle Cliffs area. It underlies the Moenkopi formation of Early and Middle(?) Triassic age.

The Kaibab is composed of yellowish-gray and light-greenish-gray thin to thick horizontally bedded limestone and dolomite. Abundant gray and brown chert occurs as beds and nodules in the limestone and dolomite. Thick sets of yellowish-gray fine-grained cross-stratified sandstone are interstratified with the limestone in some places. The Kaibab ranges in thickness from 0 to 360 feet. Invertebrate fossils such as brachiopods, pelecypods, and gastropods are common, and the Kaibab limestone is interpreted to be a marine deposit.

CUTLER FORMATION

The Cutler formation of Permian age (named by Cross and Howe, 1905, p. 5) extends over all of west-central and southwestern Colorado, east-central and southeastern Utah, and in the Monument Valley area of Arizona. It is absent in the San Rafael Swell and Capitol Reef areas, but the Coconino sandstone of Permian age in these areas is probably equivalent to part or all of the Cutler. The Cutler is underlain by the Rico formation of Pennsylvanian and Permian(?) age and is overlain by the Moenkopi formation of Early and Middle(?) Triassic age or by the Chinle formation of Late Triassic age in extreme east-central Utah.

The Cutler formation in southwestern Colorado and east-central Utah is composed of grayish-red and pale-reddish-brown arkosic sandstone, conglomeratic sandstone, and minor quantities of sandy siltstone and is referred to in this report as the conglomeratic facies of the Cutler. The sandstone is very fine to coarse grained and locally includes conglomeratic sandstone lenses containing granitic pebbles. The sandstone is cross-stratified but may contain horizontal laminae and thin beds. The sandy siltstone units commonly contain minor amounts of very fine grained sand and are composed of horizontal laminae to thin beds.

The conglomeratic facies of the Cutler extends throughout southwestern Colorado and into east-central Utah. In southeastern Utah and in Monument Valley, Ariz., the Cutler is composed of alternating reddish siltstone members and yellowish-gray sandstone members. The members are, in ascending order, the Halgaito tongue, Cedar Mesa sandstone member, Organ Rock tongue, De Chelly sandstone member, White Rim sandstone member, and Hoskinnini tongue. Not all these members are found in the same area.

The Organ Rock tongue and possibly the Halgaito tongue, both reddish siltstone members, are finer grained westward-extending tongues of the conglomeratic facies of the Cutler. The Hoskinnini tongue, also a reddish siltstone member, has recently been found to be present in a large part of southeastern Utah and west-central Colorado (Stewart, and others, written communication, 1954) and is not a tongue of the conglomeratic facies of the Cutler. The Cedar Mesa sandstone member and White Rim sandstone member are lithologically similar to the Coconino sandstone and are probably tongues of the Coconino extending east and south of the San Rafael Swell and Capitol Reef areas, where the Coconino is exposed. The Cedar Mesa and White Rim members grade to the east across southeastern Utah into the reddish siltstone members and eventually pinch out to the east in the conglomeratic facies of the Cutler. The De Chelly sandstone member is also lithologically similar to the Coconino sandstone and may be equivalent to the White Rim sandstone member.

The Halgaito, Organ Rock, and Hoskinnini tongues are composed mainly of pale-reddish-brown horizontally laminated and bedded sandy siltstone and siltstone. The Cedar Mesa sandstone, White Rim sandstone, and De Chelly sandstone members are composed of very-pale-orange and yellowish-gray very fine- to fine-grained sandstone which is cross-stratified on a large scale.

More detailed descriptions of the lithologic character, distribution, and interrelations of the members of the Cutler are given by Baker and Reeside (1929), Baker (1933, 1936, and 1946), and Hunt and others (1953).

The rocks in the conglomeratic facies of the Cutler probably were deposited in streams. Field evidence indicates that this facies of the Cutler was derived from a rising granitic area in southwestern Colorado—the Uncompahgre highland—and that the streams flowed westward from this highland.

The rocks in the reddish siltstone members and light-colored sandstone members of the Cutler are interpreted as having been deposited in two main environments. The reddish siltstone members—the Halgaito, Organ Rock, and Hoskinnini tongues—were probably deposited in quiet water in a slowly sinking marginal continental basin. The yellowish-gray sandstone units—the Cedar Mesa, White Rim, and De Chelly sandstone members—are probably eolian deposits formed under quiescent conditions in subaerial basins. The cross-strata in the yellowish-gray sandstone members dip dominantly southeast, indicating southeastward-blowing winds and a source area lying northwest of southeastern Utah.

TRIASSIC ROCKS

MOENKOPI FORMATION

The Moenkopi formation of Early and Middle(?) Triassic age was named by Ward (1901, p. 403) for exposures in northeastern Arizona. It extends over most of southeastern Utah and all of Monument Valley, Ariz. (fig. 71). The east limit of the Moenkopi in southeastern Utah is covered by younger rocks, but further study of drill-hole information may locate the limit. The Moenkopi and equivalents are absent in the Big Indian Wash and Egnar areas. These areas may be east of the margin of the Moenkopi or they may be areas where the Moenkopi pinches out locally because of movement of salt in anticlines during Moenkopi time.

The Moenkopi formation overlies the Cutler formation in most of southeastern Utah, the Kaibab limestone in the San Rafael Swell and Capitol Reef areas, and locally the Coconino sandstone in the San Rafael Swell. The Moenkopi is overlain by the Chinle formation.

The Moenkopi formation in southeastern Utah is composed of

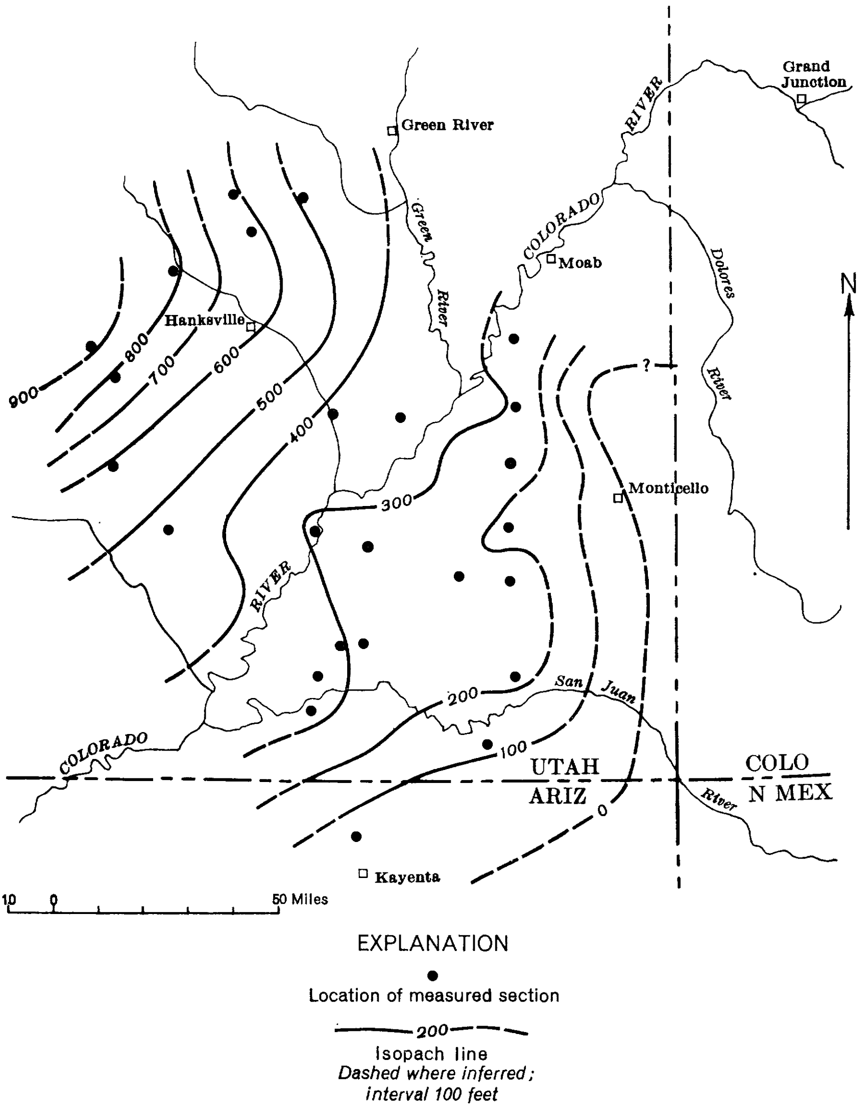

FIGURE 71.—Isopach map of the Moenkopi formation of Triassic age in southeastern Utah and Monument Valley area of Arizona.

pale-reddish-brown micaceous ripple- and horizontally laminated siltstone and sandy siltstone and minor pale-reddish-brown and yellowish-gray very fine grained cross-stratified sandstone. The trend of the ripple marks as developed in the siltstone is northeast-southwest, with steep southeast sides. The cross-stratified sandstone, less than 10 percent of the Moenkopi, occurs in channel-filling beds about 5 to 40 feet thick that weather to form ledges. The cross-strata in these sandstones dip northwest.

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In the San Rafael Swell, Capitol Reef, and Dirty Devil River areas, and in the western part of the White Canyon area, the basal part of the Moenkopi consists of conglomeratic sandstone ranging in thickness from 0 to 30 feet. The rock is light gray and yellowish gray and is composed of white and gray earthy angular rough-surfaced nonfossiliferous granules, pebbles, and cobbles of chert in a medium-grained sand matrix. This conglomerate at the base of the Moenkopi is composed of small-scale cross-strata that in places fill channels. The granules, pebbles, and cobbles closely resemble the chert pebbles found in the Hoskinnini tongue of the Cutler formation and may have the same source.

The Moenkopi formation is unconformable on the underlying rocks in some areas of southeastern Utah. The unconformity is well developed in the San Rafael Swell where Baker (1946, p. 51) reported that pre-Moenkopi erosion removed the Kaibab limestone over large areas, and that the pre-Moenkopi surface probably had a relief of 100 feet or more. The Moenkopi conglomerate that fills channels cut into the underlying units suggests an unconformity in the areas where the conglomerate is present. In the eastern part of White Canyon and to the south in the Monument Valley area, however, the boundary between the Permian and Triassic rocks exhibits no significant break in deposition.

The Moenkopi formation is more than 900 feet thick in the Capitol Reef area and thins to 0 in southeastern Utah (fig. 71). Locally, the Moenkopi may be anomalously thin due to deep channels cut into it that are filled with the Shinarump member of the Chinle. It is difficult to subdivide the Moenkopi formation in southeastern Utah except in the areas where the Sinbad limestone member is present. However, there is a poorly defined interval of as much as a few hundred feet near the middle of the Moenkopi in southeastern Utah in which the rocks are commonly more resistant and more cross-stratified than the rest of the Moenkopi.

The Sinbad limestone member of the Moenkopi formation crops out in the San Rafael Swell, Capitol Reef, and the northern part of the Circle Cliffs areas. In addition, thin limestone beds with a lithologic character and stratigraphic position similar to those of the Sinbad limestone member have been found at two localities near the junction of the Green and Colorado Rivers. Limestone at one of these localities contains *Meekoceras?* sp. (McKnight, 1940, p. 58). In southeastern Utah *Meekoceras* is restricted to the Sinbad limestone member. The fossil evidence and the similarity of the lithologic character and stratigraphic position suggest that these thin limestone beds are correlative with the Sinbad limestone member.

The Sinbad limestone member is composed of limestone and minor amounts of siltstone. The limestone is yellowish gray, pale yellowish orange, or light olive gray. It is dense but may be partly composed of medium to large oölites, and is horizontally laminated to thinly bedded. Minor amounts of thin trough sets of low-angle small-scale cross-laminae occur in the limestone. Siltstone in the Sinbad limestone member comprises 5 to 20 percent of the unit. The siltstone generally has the same color as the limestone and appears as thin to very thick horizontally laminated sets interstratified with the limestone. The Sinbad limestone member weathers to form a vertical cliff.

The Sinbad limestone member in the San Rafael Swell and the Capitol Reef areas ranges in thickness from about 12 feet (Baker, 1946, p. 55) to 150 feet. In the northernmost part of Circle Cliffs, the Sinbad is about 40 feet thick. In the southern part of Circle Cliffs, the Sinbad is thin and locally absent (E. S. Davidson, oral communication, 1956) and is inferred to be near a border of deposition.

The Sinbad limestone member becomes nearer to the base of the Moenkopi, although irregularly, south from the San Rafael Swell and finally overlaps that part of the Moenkopi formation underlying the Sinbad. The part of the Moenkopi underlying the Sinbad ranges in thickness from 90 to 200 feet (Gilluly, 1929, p. 83; Baker, 1946, p. 55) in the San Rafael Swell and from 50 to 100 feet in the Capitol Reef area. At one place in the northern part of the Circle Cliffs area, this part of the Moenkopi is only 8 feet thick. A few miles south of this place the part of the Moenkopi underlying the Sinbad pinches out and the Sinbad limestone member rests directly on the Kaibab limestone.

The Moenkopi formation is interpreted as dominantly a tidal-flat deposit. The interpretation is based on the abundance of ripple-mark laminae, shrinkage cracks, casts of salt cubes, and reptile tracks. The cross-stratified sandstone beds are interpreted to be stream deposits. The direction of dip of the cross-strata in these sandstone cosets indicates that streams during Moenkopi time flowed westward. The Moenkopi formation in western Colorado contains arkosic coarse-grained and conglomeratic sandstone which suggests that the Moenkopi was derived from the granitic Uncompahgre highland of southwestern Colorado and partly from the conglomeratic facies of the underlying Cutler formation. The chert granules, pebbles, and cobbles that are found in the conglomerate at the base of the Moenkopi in the White Canyon, Dirty Devil River, and San Rafael Swell areas probably were derived from nearby western sources as indicated by their angularity and rough surfaces. Probably these pebbles resulted from reworking of the chert nodules of the Kaibab limestone.

The fossil evidence in the Sinbad limestone member indicates that it is a marine deposit. The seas in which parts of the Moenkopi were deposited probably transgressed southeastward and eastward across

Utah as is shown by the thinning of the Moenkopi to the east, by the onlapping of the Sinbad limestone on older rocks to the southeast, and by the easterly asymmetry of the ripple marks. In addition, the Sinbad limestone, which is about 90 to 200 feet above the base of the Triassic rocks in the San Rafael Swell, contains the *Meekoceras* faunal zone which lies 1,000 feet above the base of the Triassic rocks in northern Utah (Newell and Kummel, 1942, p. 938). Considerable Triassic deposition may have taken place in northern Utah before deposition started in the San Rafael Swell. McKee (1954b) has described the transgression of the Moenkopi sea in detail.

At the end of Moenkopi deposition a regional emergence occurred, as shown by the erosion that preceded the deposition of the Shinarump member of the Chinle formation.

CHINLE FORMATION

The Chinle formation (named by Gregory, 1917, p. 42) of Late Triassic age is present in outcrops throughout southeastern Utah. It unconformably overlies the Moenkopi formation or the Cutler formation in extreme east-central Utah where the Moenkopi is absent. The unconformity at the base of the Chinle is the most conspicuous and widespread break in the sequence of the Permian and Triassic rocks and is marked by many channels that cut a few feet to several tens of feet into the Moenkopi surface. The Chinle is unconformably overlain, or perhaps conformably overlain in some areas, by the Wingate sandstone. The Chinle is composed of variegated claystone and siltstone, sandstone and conglomerate, and minor amounts of limestone and limestone-pebble conglomerate.

In southeastern Utah and in the Monument Valley area of Arizona, the Chinle is divided into seven members, which are, in ascending order, the Temple Mountain, Shinarump, Monitor Butte, Moss Back, Petrified Forest, Owl Rock, and Church Rock members. The Temple Mountain member is a thin unit composed largely of siltstone and is restricted to the San Rafael Swell. The Shinarump and Moss Back members are widespread sandstone and conglomerate units. The Monitor Butte and Petrified Forest members are mostly bentonitic claystone and clayey sandstone. The Monitor Butte member contains some lenses of sandstone. The Owl Rock and Church Rock members are largely reddish siltstone. Minor amounts of limestone are present in the Owl Rock member.

In most areas, the Shinarump and Moss Back members are distinctive units. The differences between the Monitor Butte, Petrified Forest, Owl Rock, and Church Rock members, however, are slight in some areas, and, locally, differentiation is extremely difficult. These members of the Chinle intertongue and intergrade, so that in some places defined contacts are as much as 100 feet higher or lower in a

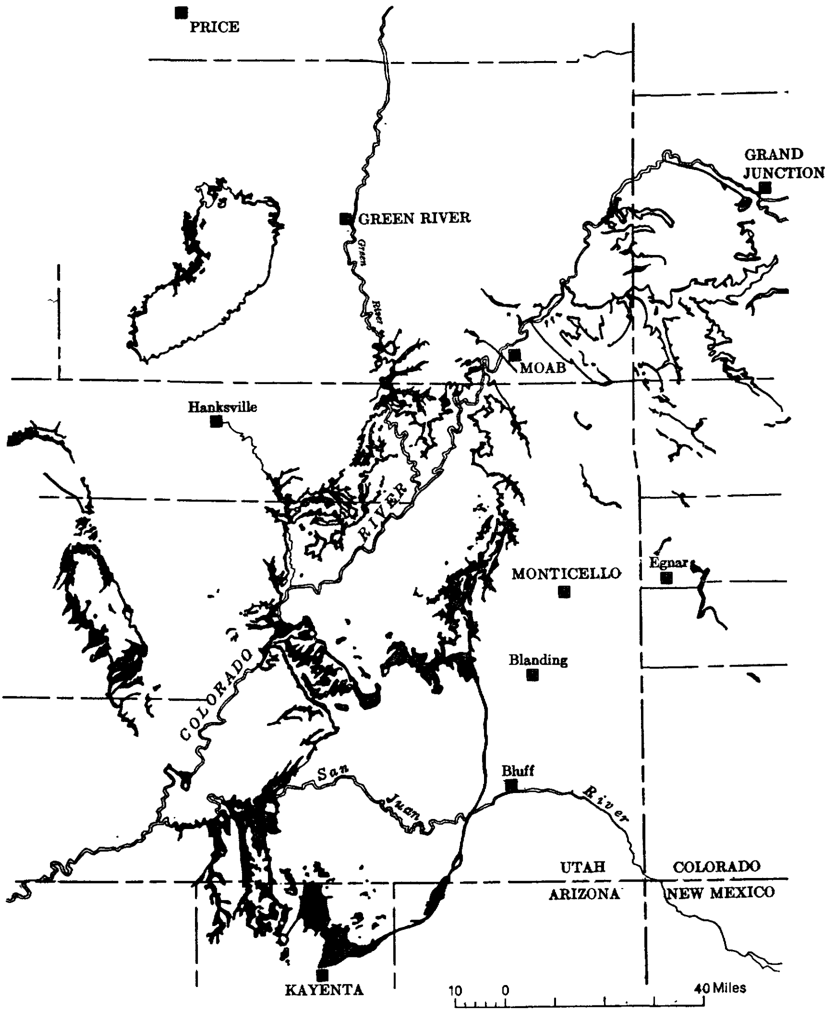

FIGURE 72.—Index map of part of the Colorado Plateau showing outcrops of the Chinle formation of Triassic age.

lateral distance of a few thousand feet. Because of these large local vertical variations in the contacts, an individual measurement of thickness may not be typical for a restricted area.

The outcrop pattern of the Chinle formation in southeastern Utah and adjoining areas is shown in figure 72. Some of the gaps between outcrops are large and correlations are correspondingly less certain.

TEMPLE MOUNTAIN MEMBER

The Temple Mountain member of the Chinle formation has been named and defined by Robeck (1956) in the San Rafael Swell and is restricted by the authors to that area. The member is a thin unit that unconformably overlies the Moenkopi formation. It underlies the Monitor Butte member in the southern part of the San Rafael Swell and the Moss Back in the northern part of the San Rafael Swell beyond the limit of the Monitor Butte (fig. 73). The upper contact is considered by some geologists to be an unconformity. The authors believe, however, that the depositional break may be minor and that the contact may not be an unconformity.

The Temple Mountain member consists mostly of mottled purple, reddish-brown, and white structureless siltstone. The siltstone generally contains some scattered well-rounded medium to coarse size quartz grains. In places, mottled purple and white claystone interfingers and intergrades with the siltstone. Locally, light-gray, light-greenish-gray, or, rarely, reddish-purple sandstone is present in the Temple Mountain member. The sandstone is generally medium to very coarse grained, although it is very fine grained in places. It locally contains conglomeratic lenses with granules and pebbles, mostly of quartz, and is cross-stratified. The sandstone is most commonly present at the base of the Temple Mountain member but may occupy any position in the member. Lenses of jasper and carbonaceous plant material are commonly present in the member.

Some of the sandstone lenses in the Temple Mountain member are lithologically similar to the Shinarump member, and possibly they are outlying lenses of the Shinarump. The term Shinarump, however, is not used in the San Rafael Swell because of uncertainties of correlation and because these lenses form an integral part of the thicker, more inclusive, Temple Mountain member that is lithologically unrelated to the Shinarump.

The Temple Mountain member is distinguished from the overlying and underlying strata by several lithologic characteristics, including the distinctive mottled purple and white coloration, medium- to coarse-grained quartz sand disseminated in the siltstone, sandstone containing large quartz pebbles, iron oxide pebbles, carbonaceous material, and lenses of jasper (Robeck, 1956). The lower contact of the member is located in many places at the change from siltstone of the Moenkopi to sandstone of the Temple Mountain member. Where siltstone of the Temple Mountain member rests on siltstone of the Moenkopi formation, the contact is difficult to locate but generally can be selected by the distinctive coloration and presence of medium- to coarse-grained sand in the siltstone of the Temple Mountain member. The upper contact in most areas is at the change from the mottled siltstone or claystone of the Temple Mountain member to the very fine- to fine-grained sandstone at the base of the Monitor Butte member or the fine- to medium-grained sandstone of the Moss

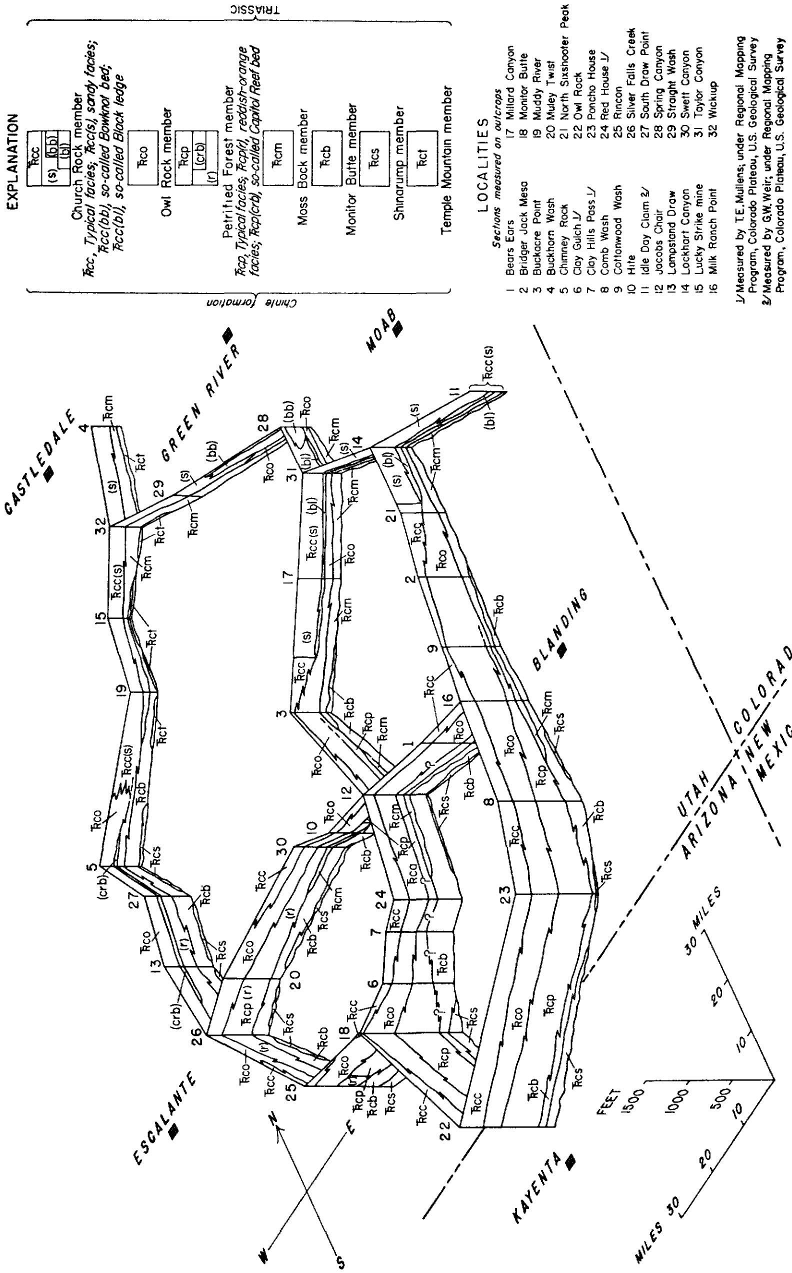

FIGURE 73.—Correlations of the Chinle formation of Triassic age.

Back member. Locally, siltstone and claystone of the Monitor Butte rest directly on the siltstone and claystone of the Temple Mountain, and in these places the Temple Mountain can be distinguished from the Monitor Butte by the presence in the Temple Mountain of the purple and white color, jasper, and pebbles of quartz and iron oxide (Robeck, 1956).

The Temple Mountain member averages about 5 feet in thickness in the southwest third of the San Rafael Swell, although it is not present in several exposures. The member averages about 20 feet in thickness in the central parts of the San Rafael Swell and about 30 feet in thickness in the northern part. Locally in the northern part of the San Rafael Swell the member attains a maximum thickness of 101 feet in a channel fill (Robeck, 1956).

A mottled purple and white siltstone unit lithologically similar to the Temple Mountain member is found in other parts of southeastern Utah and perhaps correlates with the Temple Mountain member. The strata rest directly on the Moenkopi formation and are overlain by the Shinarump, Monitor Butte, Moss Back, or some other part of the Chinle formation, whichever is present. The unit is present in parts of many areas throughout southeastern Utah, but its distribution is extremely spotty and perhaps the unit originally covered less than 10 percent of southeastern Utah. In most places the unit is less than 20 feet thick. The spotty distribution and thinness of these strata and the presence of lithologically similar mottled siltstone higher in the Chinle make precise correlation difficult. Possibly the mottled siltstone strata represent a deposit formed by a repetition of similar environments in different areas at different times rather than one widespread unit representing one time of deposition. In places, the mottled colors of the unit extend down into the top part of the Moenkopi formation, and part, or perhaps all, of the mottled siltstone strata in some areas is an altered zone at the top of the Moenkopi. In most areas, however, the unit probably represents reworked and altered sedimentary rocks from the Moenkopi at the base of the Chinle.

SHINARUMP MEMBER

GENERAL CHARACTERISTICS

The unit that constituted what has previously been called the Shinarump conglomerate was first noted by Powell (1873, p. 458). Powell selected the type locality and applied the name Shinarump Cliffs to the topographic feature of the unit, but Gilbert (1875, p. 176) was the first to use the name Shinarump conglomerate. Stewart (1957) has redefined the Shinarump as the Shinarump member of the Chinle formation and restricted the Shinarump to strata correlative to the type Shinarump of southwestern Utah.

The restriction of the Shinarump to strata correlative to the type Shinarump has led to a new classification of units previously included in the Shinarump conglomerate in southeastern Utah. The strata, previously called Shinarump conglomerate, included part or all of the Temple Mountain, Shinarump, Monitor Butte, and Moss Back members of the Chinle formation. In the Monument Valley, Circle Cliffs, and Capitol Reef areas the Shinarump member of this report is the same as the Shinarump conglomerate of Gregory and Moore (1931), Baker (1936), and Gregory and Anderson (1939). In most of the White Canyon and Elk Ridge areas, and in the area near the junction of the Dirty Devil and Colorado Rivers, the Monitor Butte and Moss Back members, and the Shinarump member where it is present, collectively form what was previously mapped as Shinarump conglomerate by Gregory (1938) and Hunt and others (1953). In the area near the junction of the Green and Colorado Rivers, the Shinarump and Monitor Butte members are absent, and the unit mapped as Shinarump conglomerate by Baker (1933 and 1946) and McKnight (1940) is the Moss Back member. In the San Rafael Swell, the Shinarump conglomerate of Gilluly (1929), Baker (1946), and Hunt and others (1953) consists mostly of the Moss Back and Monitor Butte members, or of the Moss Back member where the Monitor Butte is absent. In some places in the San Rafael Swell, these authors included the Temple Mountain member in their Shinarump; in other places, they included it partly in their Shinarump and partly in their Moenkopi; and in still other places, included it entirely in their Moenkopi.

The northeast limit of the Shinarump member is shown in figure 74. The limit is difficult to locate, as the strata correlative to the Shinarump form thin, small scattered lenses near the north limit and detailed work may reveal lenses north of those now known.

The Shinarump member is composed typically of yellowish-gray and pale-yellowish-orange medium- to coarse-grained sandstone composed of subangular clear quartz. Lenses of conglomeratic sandstone and conglomerate containing granules and pebbles predominantly of quartz, quartzite, and chert are common. The Shinarump consists of thin trough sets of medium-scale cross-strata and contains abundant silicified and carbonized wood. It forms vertical cliffs.

The Shinarump member can be differentiated in many places from other sandstone units in the Chinle formation on the basis of the range of grain sizes. The sandstone units in the Shinarump generally range from medium to coarse grained, whereas the sandstone units in the overlying part of the Chinle generally are very fine to medium grained. In addition, the proportions of pebble types in the Shinarump differ from those in the rest of the Chinle.

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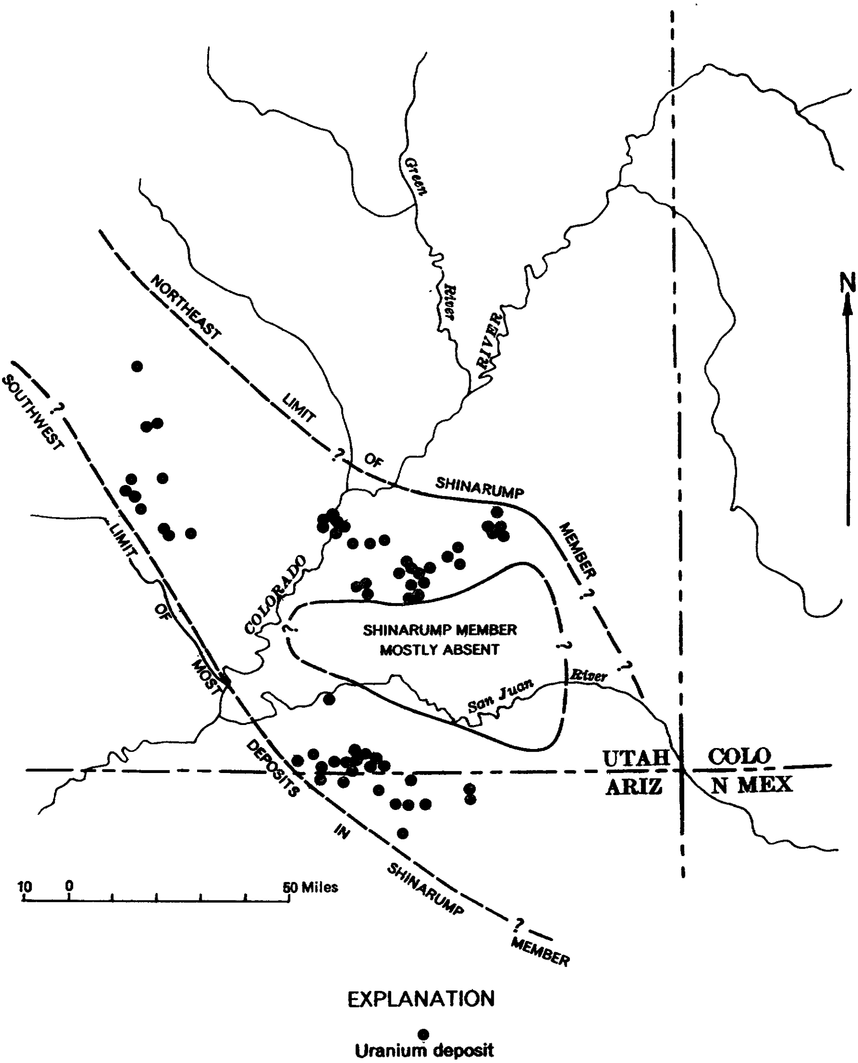

FIGURE 74.—Distribution of the Shinarump member of the Chinle formation of Triassic age and location of uranium deposits in this member in southeastern Utah and northeastern Arizona.

The contact of the Shinarump member and the Moenkopi formation is sharp and unconformable and is at the change from the reddish-brown micaceous ripple-laminated siltstone of the Moenkopi to the yellowish-gray cross-stratified medium- to coarse-grained sandstone of the Shinarump.

The contact of the Shinarump member and the Monitor Butte member is conformable and is at the change from the generally medium- to coarse-grained cross-stratified sandstone beds of the Shinarump to the ripple-laminated sandstone or the structureless claystone of the Monitor Butte.

The Shinarump member ranges in thickness from a maximum of about 250 feet to 0, and at many places in southeastern Utah and northeastern Arizona the Shinarump is locally absent within the depositional basin. These gaps in the Shinarump extend a few thousand feet to a few miles along the outcrops. In a fairly large area, including the Red House Cliffs and outcrops to the east, the Shinarump is absent (fig. 74) except for a few very thin conglomeratic sandstone lenses.

The general thickness, depth of channels, and continuity of the Shinarump vary from area to area in southern Utah and northern Arizona. In the Kanab area, the Shinarump is continuous and consistently 50 to 100 feet thick, and fills channels cut only a few feet into the underlying Moenkopi. In the Monument Valley, Circle Cliffs, and Capitol Reef areas, the Shinarump is discontinuous, ranges in thickness from 0 to 200 feet, and fills deep channels. In the White Canyon and Elk Ridge areas, the Shinarump is discontinuous and generally less than 20 feet thick, and fills channels cut only a few feet into the underlying Moenkopi.

PEBBLE STUDIES

The pebbles in the Shinarump are composed almost entirely of quartz, quartzite, and chert (table 2). Types of quartz pebbles differ

TABLE 2.—*Composition of pebbles, in percent, in the Shinarump member of the Chinle formation of southern Utah*

Area	Vitreous quartz	Quartzite	Chert	Other
Kanab	17	47	36	--------
Rincon	30	36	33	1
Circle Cliffs	41	20	35	4
Capitol Reef	60	16	13	11
Red House Cliffs	84	14	2	--------
White Canyon	89	9	1+	--------

markedly among the areas. In the Kanab area, the quartz is mostly either transparent or translucent white. In the Circle Cliffs and Capitol Reef areas, the quartz pebbles are dominantly transparent; pink and smoky quartz are common. In the White Canyon area, transparent quartz and a distinctive pink variety are dominant, and smoky varieties of quartz pebbles are common.

A pronounced change in the color of the chert pebbles occurs eastward from the Kanab area. In the Kanab area about 10 percent of the chert pebbles are red, pink, and orange, and the balance are gray, brown, black, and white. In the Capitol Reef area, gray chert is dominant; brown, black, and white chert are common; and red chert is rare.

A change in the color of the quartzite pebbles occurs northward and eastward from the Kanab area. In the Kanab area about 30 percent of the quartzite pebbles are red and pink. Most of the remaining 70 percent are gray, tan, and brown. In the Capitol Reef and White Canyon areas, the red and pink colors are uncommon; most of the pebbles are white, gray, and tan.

Silicified limestone constitutes about 5 percent of the pebbles in the Circle Cliffs and Capitol Reef areas. It was identified in only one other collection, from near Fredonia, Ariz., in the Kanab area.

The maximum size of the pebbles varies regionally. The maximum size decreases from about 4½ inches in the Kanab area to about 1½ inches in the Capitol Reef area and from about 8 inches in the Monument Valley area to about 4 inches in the White Canyon area.

Fossiliferous pebbles from the White Canyon area indicate a source in Mississippian, Pennsylvanian, and Permian rocks. Most of the fossil-bearing pebbles from the Kanab, Circle Cliffs, and Capitol Reef areas indicate a source in the Kaibab limestone of Permian age. The Kaibab or its lateral equivalents have not yielded fusulinids, which indicates that some pebbles containing fusulinids probably had another source. Areas that contain rocks of these ages surround the Colorado Plateau, and many of the areas could have been a source for the pebbles.

SEDIMENTARY-STRUCTURE STUDIES

The cross-strata in the Shinarump member, on the basis of the average resultant dip computed in 30 studies (fig. 75), dip N. 54° W. The consistency factors among readings in individual studies are quite variable and range from 0.46 to 0.95 and average 0.63.

MONITOR BUTTE MEMBER

The Monitor Butte member of the Chinle formation has been named and defined by I. J. Witkind and R. E. Thaden for exposures in the Monument Valley area of Arizona (written communication, 1954).

The Monitor Butte member is present in Chinle outcrops throughout the Monument Valley area of Arizona and most of southeastern Utah. Its limits in southeastern Utah are shown in figure 76. Recognition of the member is difficult in many areas and some of the correlations are tentative.

The Monitor Butte member consists dominantly of greenish-gray, with minor amounts of pale-reddish-brown, bentonitic claystone or clayey sandstone that weathers to form a "frothy" appearing slope. The clayey sandstone is fine grained and consists of milky, and minor orange and green, grains. The claystone and clayey sandstone com-

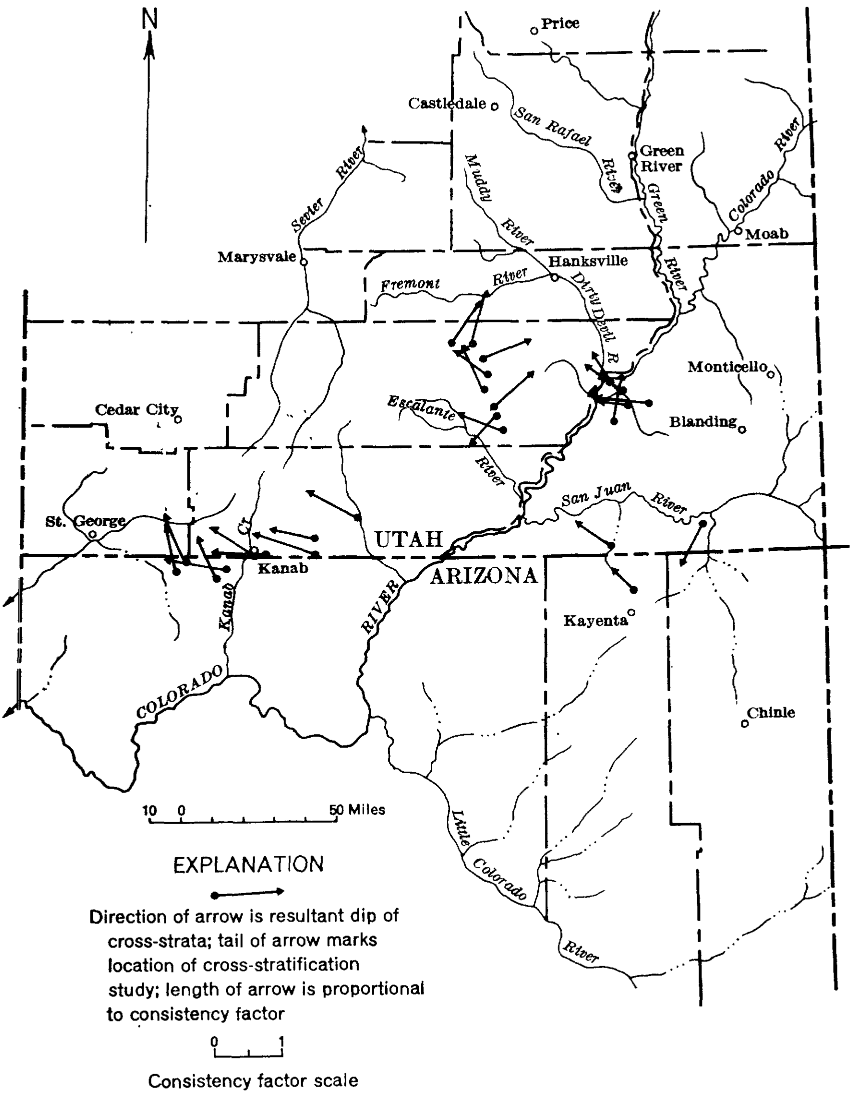

FIGURE 75.—Resultant-dip directions of cross-strata in the Shinarump member of the Chinle formation of Triassic age.

monly contain as much as 1 to 3 percent dark-green medium- to coarse-grained mica (probably biotite). Stratification is poorly exposed, but the rocks are either cross-stratified or structureless. Carbonized and silicified wood is common.

Interstratified with the claystone and clayey sandstone are sandstone lenses most of which are 1 to 10 feet thick and about 1,000 feet wide. The lenses form about 5 to 20 percent of the member. Locally these sandstone lenses may be absent. The sandstone is very fine grained,

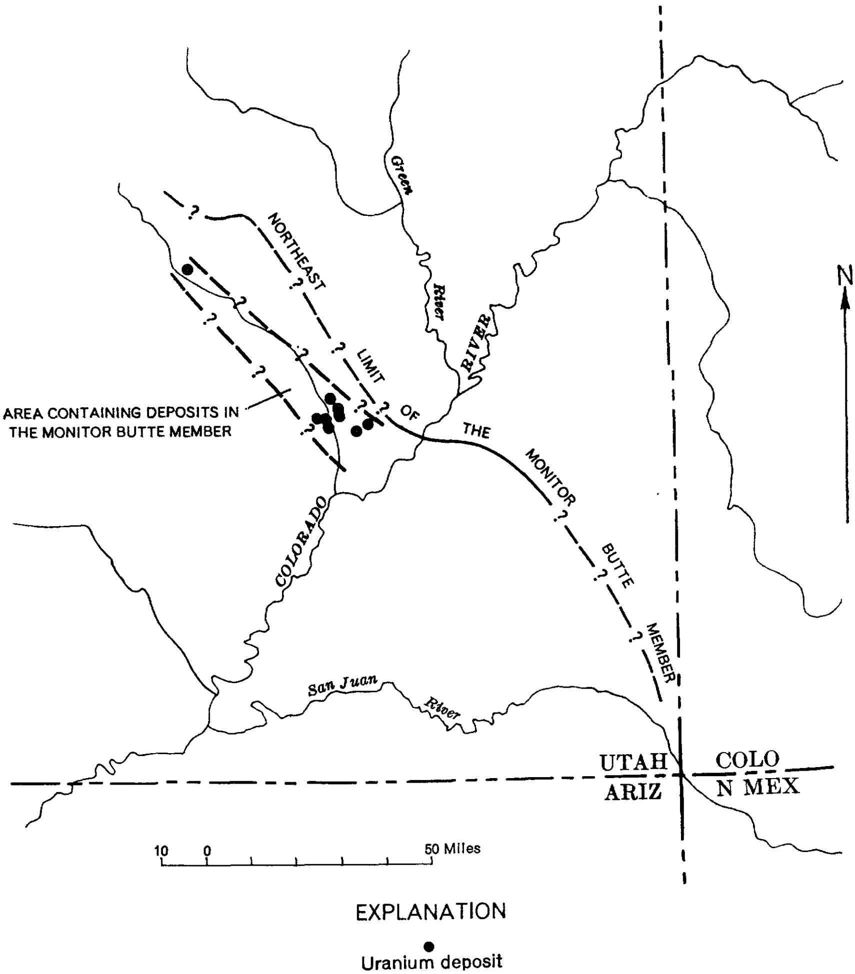

FIGURE 76.—Distribution of the Monitor Butte member of the Chinle formation of Triassic age and location of the uranium deposits in this member in southeastern Utah.

micaceous, well cemented, ripple-laminated or rarely cross-stratified, and platy splitting. A few of the sandstone lenses are conglomeratic, with pebbles of limestone, siltstone, and minor amounts of weathered chert pebbles. The sandstone lenses are commonly highly contorted by many small-scale folds and faults.

The Monitor Butte member has several lithologic characteristics that distinguish it from associated units. Lenses of greenish-gray micaceous well-cemented ripple-laminated sandstone are the main distinguishing characteristics of the member. Sandstone of this type is present in a few areas in other members of the Chinle, but these can be recognized as stratigraphically distinct from the Monitor Butte member. Although lenses of cross-stratified sandstone are to some extent diagnostic, similar sandstone lenses occur in the overlying Moss Back member. In many places, however, these lenses in the Monitor Butte member do not contain quartzose pebbles, whereas quartzose pebbles are common in the Moss Back member. Other characteristic features of the member that in places distinguish it from overlying rocks are contorted stratification of sandstone lenses; greenish-gray clayey sandstone composed of milky, and minor orange and green, grains, with an abundance of coarse dark mica; and flakes of carbonaceous material in thick units of claystone or clayey sandstone.

The contact between the Monitor Butte and Shinarump members is conformable and is at the change from the generally medium- to coarse-grained cross-stratified sandstone beds of the Shinarump to the ripple-laminated sandstone or structureless claystone of the Monitor Butte member. The contact is well defined in some localities and transitional in others. Intertonguing of the Shinarump and Monitor Butte members has been noted in several places in southeastern Utah. Where the Monitor Butte member directly overlies the Moenkopi formation, the contact is sharp and unconformable and is at the change from the reddish-brown micaceous ripple-laminated siltstone beds of the Moenkopi to the greenish-gray bentonitic claystone or clayey sandstone and ripple-laminated sandstone beds of the Monitor Butte.

The upper contact of the Monitor Butte member in most areas is at the top of the highest unit in the Chinle formation containing distinguishing lithologic features of the Monitor Butte member, and is generally the top of the highest ripple-laminated or cross-stratified sandstone lens. The location of the contact changes abruptly, depending on local variations in the position of the lenses. Locally the sandstone lenses that are typical of the Monitor Butte are absent, and the Monitor Butte is distinguished from the rest of the Chinle by characteristics of the member other than the sandstone lenses. Where the sandstone lenses are absent, however, it is difficult or even impossible to distinguish the Monitor Butte from the rest of the Chinle.

The Monitor Butte member in southeastern Utah and in the Monument Valley area of Arizona ranges in thickness from 0 to 250 feet. It thins from 200 feet in White Canyon to a limit along an east-west line passing about 15 miles north of White Canyon. In the San Rafael Swell, it ranges in thickness from 0 to as much as 100 feet.

The Monitor Butte member is confined to the Monument Valley area and to southeastern Utah but may correlate with defined members of the Chinle in western Utah and northern Arizona. In the Defiance uplift area, Harshbarger (oral communication, 1954) has recognized a lower member of the Chinle. This member corresponds with a unit that Gregory (1917, p. 43) called the "D" division of the Chinle. This lower member of the Chinle is similar lithologically to the Monitor Butte member and is probably physically continuous with it. In the Zion Park region, Gregory (1950, p. 67) recognized a lower sandstone member of the Chinle formation which may be physically continuous with the Monitor Butte member.

MOSS BACK MEMBER

The name Moss Back member has been proposed by Stewart (1957) for exposures in the eastern part of White Canyon, San Juan County, Utah. The distribution of the Moss Back member is shown in figure 77. The northeast and southwest limits are probably limits of deposition. The extension of the Moss Back to the southeast into Colorado is tentative. The northwest and southeast limits of the Moss Back are not known.

The Moss Back member is typically yellowish-gray and very-pale-orange fine- to medium-grained sandstone. The sandstone is composed of well-sorted subround clear quartz and rare black accessory grains. The stratification is dominantly thin to thick trough to planar sets of medium-scale cross-strata, but horizontally stratified sets are common. Carbonaceous material and silicified wood are abundant. The Moss Back typically forms vertical cliffs.

Conglomerate and conglomeratic sandstone lenses are common. The pebbles in the conglomerate lenses generally occur in two suites—either light-brown and gray siltstone and limestone or vitreous quartz, quartzite, and chert. These two pebble assemblages are not always found in the same lens; however, different lenses containing the two are generally found in the same outcrop. Where the limestone and siltstone pebbles occur with the quartzose pebbles, they generally exceed the quartzose pebbles in number by as much as 15 or 20 times. Where they are the only pebbles present, they may form more than 50 percent of the rock by volume.

The Moss Back member has a different facies in a belt about 10 miles wide along its north limit in the areas near the junction of the Green and Colorado Rivers. This facies of the Moss Back contains abundant interstitial greenish silt and clay and interstratified thin lenses of greenish siltstone and claystone and contains few, if any, quartzose pebbles.

The Moss Back member can be distinguished lithologically from the Shinarump member and other sandstone units in the Chinle on the basis of grain size and pebble types. The Moss Back is generally fine to medium grained, whereas the Shinarump is medium to coarse grained and the other sandstone units in the Chinle are generally very fine to fine grained. In addition, the Moss Back contains a different pebble assemblage than the Shinarump member. A study of about 2,000 pebbles from the Moss Back at 5 localities shows quartz-

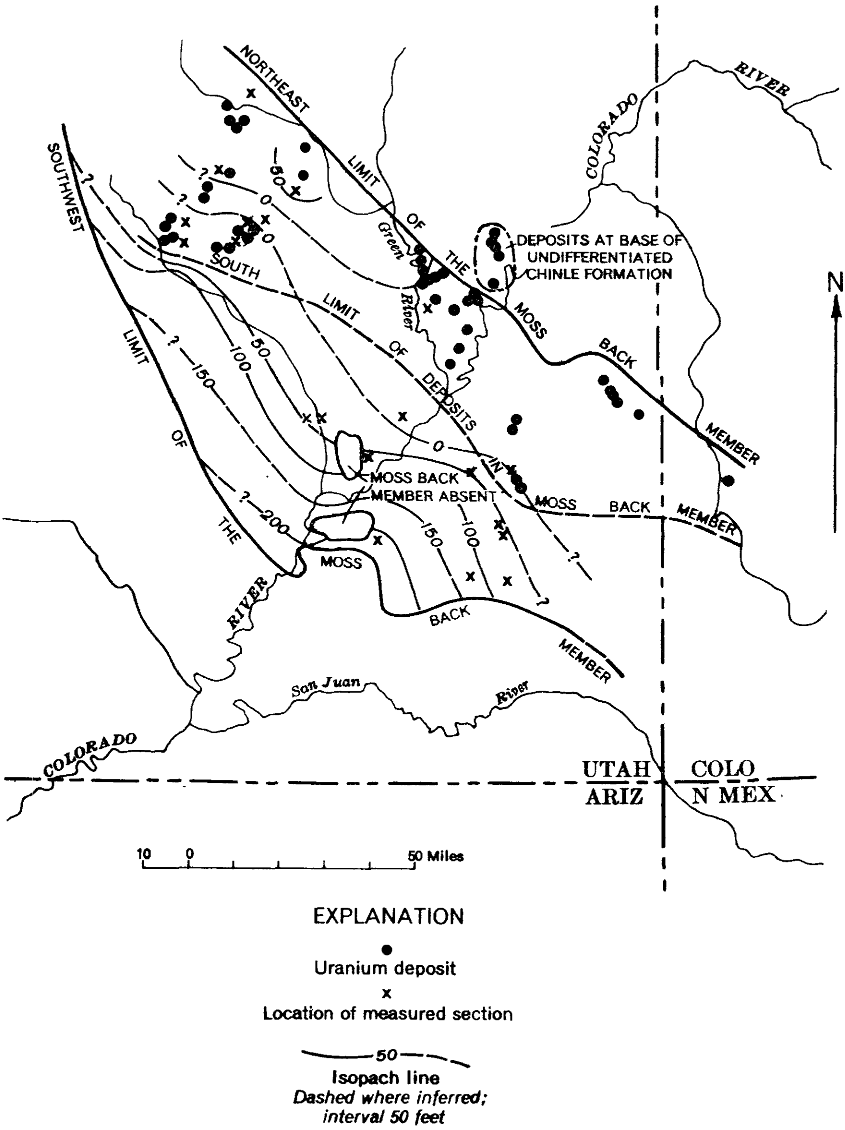

FIGURE 77.—Distribution of the Moss Back member of the Chinle formation of Triassic age; location of uranium deposits in the Moss Back and at the base of undifferentiated Chinle; and a generalized isopach map of that part of the Chinle formation underlying the Moss Back member.

ite to average 43 percent, chert 40 percent, quartz 13 percent, and other types 4 percent. In contrast, a study of about 1,000 pebbles from the Shinarump at 19 localities shows quartzite to average 25 percent, chert 18 percent, quartz 52 percent, and other types 3 percent. In addition, the Moss Back commonly contains conglomeratic sandstone lenses composed almost entirely of siltstone and limestone pebbles, whereas the Shinarump does not contain these conglomeratic lenses. The conglomerate in other parts of the Chinle formation contains few, if any, quartzose pebbles.

The lower contact of the Moss Back member is at the break between the channel-fill cross-stratified cliff-forming sandstone of the Moss Back and the siltstone and claystone of the underlying Chinle or the siltstone of the underlying Moenkopi.

The upper contact of the Moss Back is in most places well defined but in some places may be gradational with the overlying part of the Chinle. The top of the Moss Back is the top of the highest fine- to medium-grained cross-stratified sandstone. This contact marks the change from sandstone below to siltstone and claystone above. In places where the upper part of the Moss Back is gradational with the overlying part of the Chinle, the contact is arbitrarily placed at the most conspicuous change in the strata.

The Moss Back averages about 60 feet in thickness but may be as much as 150 feet thick where it fills channels. The Moss Back member overlaps the Monitor Butte member to the north in east-central Utah. In White Canyon, the Moss Back is about 200 feet above the base of the Chinle formation; north of White Canyon, the Moss Back is lower in the Chinle section; and north of a line trending northwest, about 15 miles north of White Canyon, the Moss Back is at the base of the Chinle (fig. 77).

TABLE 3.—*Composition of pebbles, in percent, in the Moss Back member of the Chinle formation in part of southeastern Utah*

Areas	Quartzite	Quartz	Chert	Other
White Canyon	46	9	41	4
San Rafael Swell:[1]				
Locality:				
1	22	13	63	2
2	31	9	60	0
3	56	19	17	8
4	62	15	18	5

[1] From south to north.

PEBBLE STUDIES

The percentage of quartzose pebble types in the Moss Back at various localities, based on detailed studies, is shown in table 3. Not enough information is available to determine any systematic regional variations.

SEDIMENTARY-STRUCTURE STUDIES

The cross-strata in the Moss Back member, on the basis of the average resultant dip as computed in 16 studies, dip N. 59° W. (fig. 78). The consistency factors among readings in individual studies are quite variable and range from 0.46 to 0.97 and average 0.58.

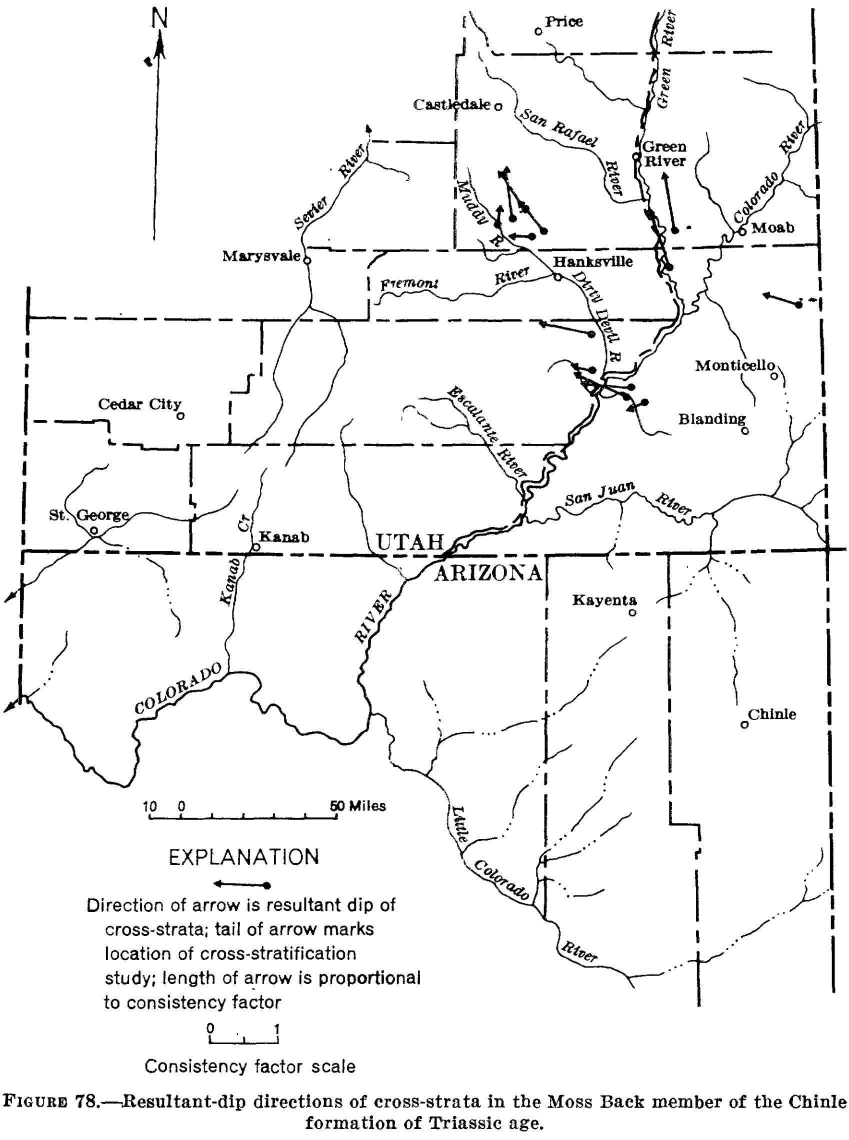

FIGURE 78.—Resultant-dip directions of cross-strata in the Moss Back member of the Chinle formation of Triassic age.

PETRIFIED FOREST MEMBER

Petrified Forest member of the Chinle formation was named by Gregory (1950, p. 67) in the Zion Park area although he derived the name from the Petrified Forest in northeastern Arizona. Strata in northeastern Arizona have been correlated with the Petrified Forest member in the Zion Park area by Gregory (1950, p. 68). The member is present throughout northeastern Arizona and extends north into southeastern Utah nearly as far as White Canyon. A reddish-orange facies of the Petrified Forest member extends into the Circle Cliffs and Capitol Reef areas but cannot be recognized in the San Rafael Swell area.

The Petrified Forest member typically consists of bentonitic claystone and clayey sandstone. The rocks are variegated with red, purple, green, and yellow. The sandy parts of the rocks are very fine to fine grained, are composed of milky grains and as much as 10 percent orange and green grains, and contain abundant very coarse flakes of dark mica (probably biotite). Most of the claystone and clayey sandstone beds in the Petrified Forest member are structureless, but a few cross-stratified units crop out. The member weathers to form a "frothy-surfaced" slope which results from the weathering of swelling clay. It contains some limestone-pebble conglomerate lenses.

The reddish-orange facies of the Petrified Forest member of the Chinle formation consists dominantly of pale-reddish-brown, light-brown, moderate-reddish-orange, and grayish-red siltstone and minor amounts of pale-red and light-greenish-gray sandstone. The sandstone is fine grained and is composed of clear and milky quartz, minor amounts of colored grains, and common amounts of dark-green mica. It is composed of trough sets of small- to medium-scale cross-strata. A persistent and conspicuous bed referred to locally as the so-called Capitol Reef bed is present at the top of the reddish-orange facies in the Capitol Reef area and the northern part of the Circle Cliffs area (fig. 73). This reddish-orange unit weathers to form characteristic reddish-orange slopes with conspicuous reddish ledges.

The basal contact of the Petrified Forest member is the top of the stratigraphically highest rocks that distinguish the Monitor Butte member or the Moss Back member where it is present. The top contact of the Petrified Forest member is at the base of the lowest dense limestone bed in most areas.

In the Monument Valley area, the Petrified Forest member ranges from about 500 to 700 feet in thickness. North from the Monument Valley area it thins to about 100 feet just south of the White Canyon area and the southernmost part of the Elk Ridge area. North of these areas it loses identity by intertonguing with the Owl Rock member.

The resultant-dip direction of the cross-strata in the so-called Capitol Reef bed, on the basis of four studies, is dominantly north to northwest.

OWL ROCK MEMBER

The name Owl Rock member has been proposed by I. J. Witkind and R. E. Thaden for exposures in the Monument Valley area, Navajo County, Ariz. (written communication, 1954). The Owl Rock member is present in most of southeastern Utah. J. W. Harshbarger (oral communication) has traced the Owl Rock member over most of northeastern Arizona. It grades laterally into the Church Rock member to the north in the area near the junction of the Green and Colorado Rivers. A similar lateral gradation probably takes place between the Capitol Reef and the San Rafael Swell areas. The Owl Rock member is the "B" division of Gregory (1917, p. 42).

The Owl Rock member typically is composed of pale-red and pale-reddish-brown structureless siltstone interstratified with thin to thick sets of limestone that form about 5 to 10 percent of the member. The limestone is pale red and light greenish gray, dense, and commonly grades to limy siltstone. The limestone occurs as horizontal beds which average about a foot in thickness and are in part horizontally laminated. Limestone-pebble conglomerate lenses are common. The member weathers to form steep slopes with alternating small ledges of limestone.

The only distinguishing feature of the Owl Rock member is dense limestone beds. At a few places limestone beds occur in other parts of the Chinle formation, but these limestone beds are in most places separated from those of the Owl Rock member by at least 100 feet of strata.

In most areas, the bottom contact of the Owl Rock member is the base of the lowest limestone unit and the top contact is the top of the highest limestone unit. Locally, however, the contacts are stratigraphically higher or lower in order to include strata that laterally contain limestone.

The base of the Owl Rock member marks the most significant break in the lithologic characteristics of the Chinle. This horizon is the change from variegated partly cross-stratified bentonitic claystone and clayey sandstone below to reddish horizontally stratified nonbentonitic siltstone above.

In southeastern Utah, the Owl Rock member is generally 150 to 250 feet thick. Intertonguing of the Owl Rock member with the overlying and underlying members causes it to vary greatly in thickness. The member shows an abnormal thickness in the White Canyon and Elk Ridge areas, where it is 350 to 450 feet thick. Near the northern limit the member is 50 to 100 feet thick (fig. 73).

CHURCH ROCK MEMBER

The Church Rock member has been named by I. J. Witkind and R. E. Thaden for exposures in the Monument Valley area, Navajo County, Ariz. (written communication, 1954). The Church Rock is present in most of southeastern Utah and all of the Monument Valley area of Arizona. It is absent in the Capitol Reef area and in most of the Circle Cliffs area, probably because of both internal thinning and intergrading of the Church Rock and the Owl Rock members.

Typically the Church Rock member is composed of pale-reddish-brown and light-brown very fine grained sandy siltstone. The sandy siltstone may be structureless, composed of thin to very thick horizontal beds, or, in a few places, ripple-laminated. The sandy siltstone fractures into pebble-sized angular fragments and forms slopes.

Over a large part of southeastern Utah the top 10 to 50 feet of the Chinle formation is cross-stratified sandstone. This sandstone is well developed on exposures about 2 miles south of Hite, San Juan County, Utah, and is referred to locally as the so-called Hite bed. This bed is tentatively assigned to the Church Rock member because of lithologic similarities to other units in the Church Rock member. It is composed of pale-red and light-greenish-gray very fine grained sandstone and of many lenses of pale-reddish-brown siltstone. The sandstone is composed of trough sets of medium-scale cross-strata and contains a few conglomeratic sandstone lenses of granules, pebbles, and a few cobbles and boulders of reddish siltstone. The siltstone is structureless but contains minor amounts of horizontally laminated or ripple-laminated rocks. The Hite bed weathers to form a vertical cliff that is continuous with the overlying cliff of the Wingate sandstone.

The so-called Hite bed is correlated over most of southeastern Utah north of the San Juan River. A sandstone bed that appears to be similar to the Hite bed is at the top of the Chinle formation in part of the Monument Valley area. Not enough detailed work has been done to correlate this bed definitely with the Hite bed of local usage. To the west the Hite bed has been tentatively correlated with a prominent local sandstone bed at the top of the Chinle in the southeastern part of the Circle Cliffs area. The Hite bed is absent in Capitol Reef and cannot be correlated through the area between the Green and Colorado Rivers.

The Church Rock member contains many sandstone units in the San Rafael Swell and in the areas near the junction of the Green and Colorado Rivers, and in these areas is referred to in this report as the sandy facies of the Church Rock member. The sandstone units form fairly thick and conspicuous ledges. They are generally interstratified with reddish sandy siltstone typical of the Church Rock member of the Monument Valley area. The sandstone is pale red and very fine grained and is composed of trough sets of low-angle medium-scale cross-laminae. The south limit of one of these units—referred to locally as the so-called Black ledge (fig. 73)—arbitrarily marks the south limit of the sandy facies of the Church Rock member. A unit referred to locally as the so-called Bowknot bed (fig. 73) forms a conspicuous sandstone unit in the northeastern part of the area near the junction of the Green and Colorado Rivers.

The contact between the Church Rock member and the Owl Rock member is at the top of the highest limestone or limy siltstone in the

Chinle in most areas. The contact of the Church Rock member and overlying rocks in most of southeastern Utah is between the so-called Hite bed and the Wingate sandstone. This contact is well defined and disconformable. The contact marks the change from pale-red and light-greenish-gray purplish-weathering sandstone in the Chinle to the light-brown brownish-weathering sandstone of the Wingate. The contact also marks the change from well-cemented sandstone in the Chinle formation that is composed dominantly of subangular milky minerals and clear quartz and that commonly contains clay galls and interstitial clay to the poorly cemented Wingate sandstone that is composed of subrounded grains of clear quartz and contains no clay galls or interstitial clay. A highly characteristic feature of the contact is the abundance of frosted and rounded medium-size to coarse grains in the basal part of the Wingate.

In places where the so-called Hite bed is not present, the contact between the Church Rock member and the Wingate sandstone is the disconformity between the reddish horizontally stratified siltstone of the Chinle and the light-brown cross-stratified sandstone of the Wingate.

The Church Rock member in most of southeastern Utah ranges in thickness from 50 to 350 feet. The Church Rock thickens north of the Elk Ridge area (figs. 70 and 72), probably by incorporating strata which are equivalent to the Owl Rock farther south.

The Church Rock member in Monument Valley is probably physically continuous with at least part of the Rock Point member (Harshbarger and others, 1957) of the Wingate sandstone in northeastern Arizona. The Rock Point member corresponds to Gregory's "A" division (Gregory, 1917, p. 42) of the Chinle. Harshbarger and others (1957) have placed the Rock Point member in the Wingate sandstone because of lithologic similarities and of intertonguing between the Rock Point and the overlying Wingate.

SEDIMENTARY-STRUCTURE STUDIES

Sedimentary-structure studies have been made in three units in the Church Rock member (fig. 79): the Bowknot bed of local usage, a prominent sandstone bed in the middle of the Church Rock member in the San Rafael Swell, and the Hite bed of local usage. The resultant-dip direction of the cross-strata in the so-called Bowknot bed, on the basis of one study, is N. 45° W. with a consistency among readings of 0.87. Three studies of a prominent sandstone bed in the middle of the Church Rock member in the San Rafael Swell area show an average resultant-dip direction of N. 85° W. and a consistency among the readings that ranges from 0.41 to 0.61. Three studies of the so-called Hite bed give an average resultant-dip direction of N. 60° E. and a consistency among readings that ranges from

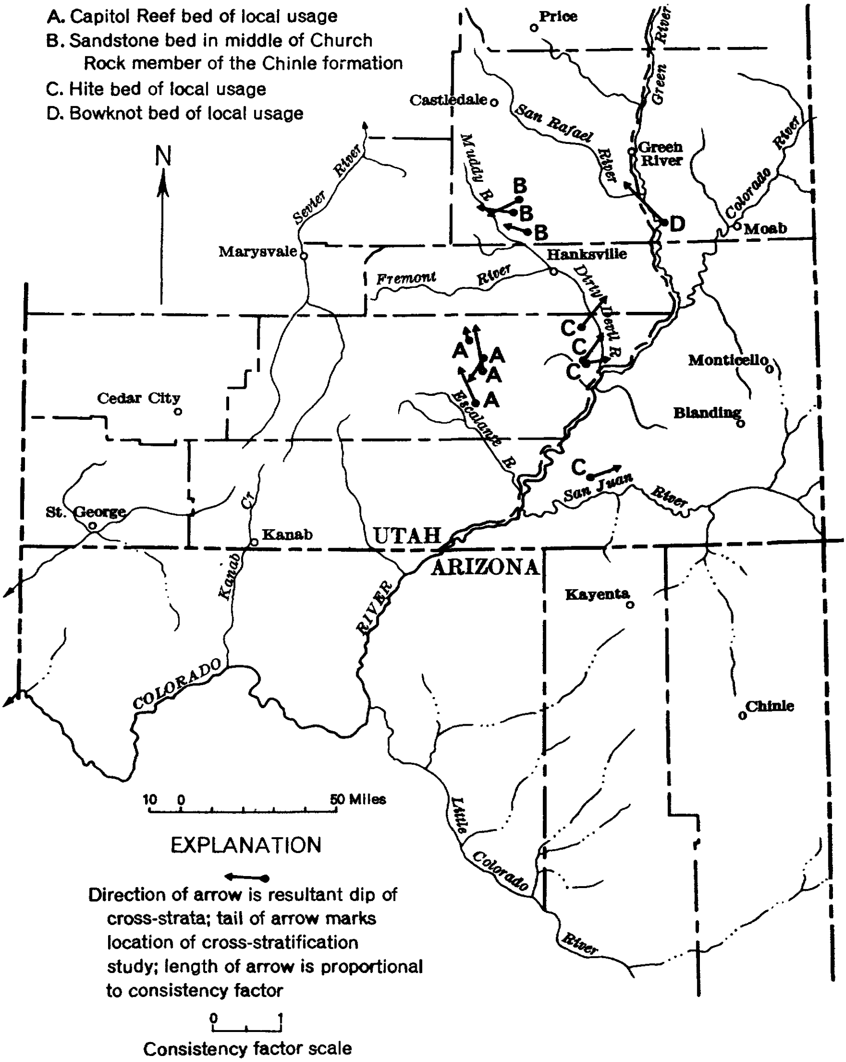

FIGURE 79.—Resultant-dip directions of cross-strata in various sandstone units in the Chinle formation of Triassic age.

0.34 to 0.55. The great difference in resultant-dip direction in the Hite bed as compared with those in the other two units suggests that the Hite bed may not be related to the other units and that it may not properly belong in the Church Rock member.

SOME CHARACTERISTICS OF THE CHINLE FORMATION

THICKNESS

The thickness of the Chinle formation in the areas studied is shown in figure 80. In three places in southeastern Utah—the Red House

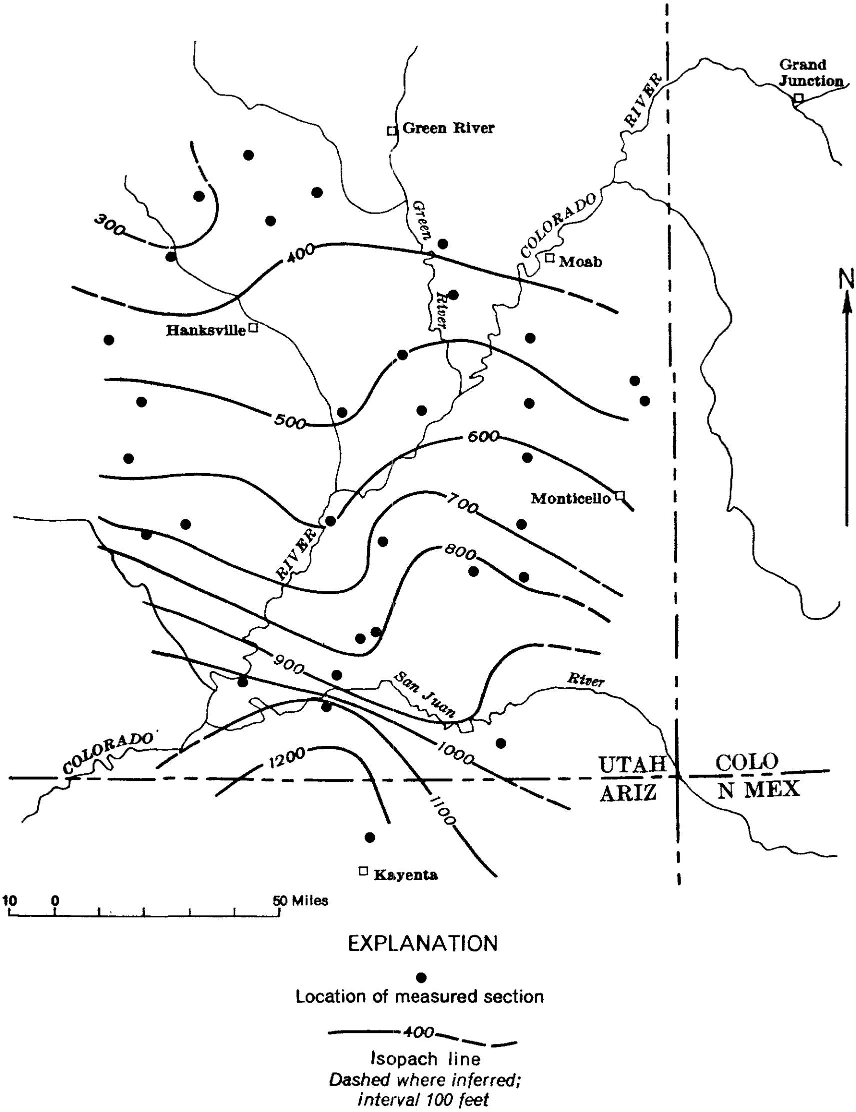

FIGURE 80.—Isopach map of the Chinle formation of Triassic age in southeastern Utah and Monument Valley area of Arizona.

Cliffs area, the central part of the Dirty Devil River area, and the southeastern part of the San Rafael Swell area—the Chinle is slightly thinner than in adjoining areas. In these same areas the Shinarump or Moss Back members are thin or mostly absent. Possibly these three areas were at a relatively high elevation in the continental basin in Late Triassic time and caused diversion of Shinarump and Chinle streams, resulting in thinner deposits than in adjoining areas.

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PALEONTOLOGY

Fossils in the Chinle formation consist of plants, pelecypods, gastropods, and vertebrates. The pelecypods are mostly fresh-water *Unios*, and the gastropods are small nonmarine forms. Vertebrate remains consist of amphibians, fish, and reptiles. Phytosaurs are the most numerous reptiles, particularly common in Arizona, and have been described in detail by Camp (1930). Assignment of the Chinle to the Upper Triassic is based on vertebrate-fossil evidence. Various types of fossil plants have been described by Daugherty (1941) from east-central Arizona.

INTERPRETATION

A continental environment of deposition is indicated for the Chinle formation by the type of sedimentary structures, the presence of nonmarine vertebrate and invertebrate fossils, and the presence of fossil wood. Both fluvial and lacustrine environments probably existed.

The Temple Mountain, Shinarump, Monitor Butte, Moss Back, and Petrified Forest members of the Chinle formation were probably deposited in an alluvial-plain environment including stream and flood-plain deposits. The Temple Mountain, Shinarump, and Moss Back members are interpreted to be stream deposits. The association of the cross-stratified conglomeratic sandstone, channels, and fossil wood as found in these members is similar to that found in present-day stream deposits.

The Monitor Butte and Petrified Forest members probably include both stream and flood-plain deposits. The cross-stratified sandstone lenses of the Monitor Butte and possibly some of the claystone and clayey sandstone of the Monitor Butte and Petrified Forest members are probably stream deposits. The crescentic ripple-laminated sandstone lenses in the Monitor Butte member indicate current action and, possibly, deposition on a flood plain. In addition, the structureless claystone of the Monitor Butte and Petrified Forest may be flood-plain deposits. Possibly the Monitor Butte and Petrified Forest members contain some swamp and lake deposits.

The Moss Back member is mostly cross-stratified channel-filling sandstone and conglomerate which contains carbonaceous material, indicating that it is a stream deposit. The scarcity of clay and the presence of moderately well sorted sandstone indicates considerable reworking of the sand during deposition. The persistency of the Moss Back in southeastern Utah suggests that it was deposited in a fairly quiescent time in the Chinle basin of deposition and on an alluvial plain with little relief, so that the streams could migrate freely.

The Owl Rock and Church Rock members are probably, in large part, lake or lagoonal deposits, as suggested by the limestone beds, horizontal stratification, and nonmarine gastropods. The limestone beds in the Owl Rock member represent times of slower deposition of clastic material than those of the overlying and underlying rocks, and clear-water conditions more favorable for the existence of animals and for the preservation of fossils. The type of cross-stratification and channels in the sandy facies of the Church Rock member suggests stream deposits. The limestone-pebble conglomerates in the Owl Rock and Petrified Forest members may have been produced during periods of slow deposition by wave action in a lake environment.

The Monitor Butte and Petrified Forest members contain a considerable amount of volcanic debris. This is suggested by the bentonitic clays, the reported presence of altered glass shards (Waters and Granger, 1953, p. 6) and the coarse flakes of dark mica (probably biotite). The claystone in these members may have been derived from volcanic ash by alteration and devitrification.

Studies of the orientation of cross-strata in the Chinle formation indicate the direction of stream currents. The cross-strata in all the units of the Chinle formation studied, except the so-called Hite bed, have a northwest resultant-dip direction, which indicates northwestward-flowing streams. The northeast resultant-dip direction in the Hite bed indicates northeastward-flowing streams. The consistency of most of the resultant-dip directions suggests that the units of the Chinle were deposited under similar conditions of regional slopes and had similar source areas.

The source areas for the Chinle, suggested by sedimentary-structure studies, lie southeast of southeastern Utah. A similar direction for the source area of the volcanic debris in the lower part of the Chinle is suggested by the thickening of the bentonitic units to the south and the reported presence of coarse volcanic debris (Allen, 1930) in the Chinle of east-central Arizona. Regional relations suggest that a source area may have been present in southern Arizona and New Mexico.

The disconformity at the top of the Chinle formation in most of southeastern Utah probably represents a period of erosion of varying intensity in different areas that resulted from slight upwarping of the region of Chinle deposition.

TRIASSIC AND JURASSIC ROCKS

GLEN CANYON GROUP

The Glen Canyon group in southeastern Utah consists of three formations which are, in ascending order, the Wingate sandstone of Triassic age, the Kayenta formation of Jurassic(?) age, and the Navajo sandstone of Jurassic and Jurassic(?) age. Study of these formations has been confined mostly to sedimentary-petrology and sedimentary-structure investigations.

WINGATE SANDSTONE

The Wingate sandstone was named and defined by Dutton (1885) for exposures near Fort Wingate, McKinley County, N. Mex. The Wingate was correlated with strata in southeastern Utah (Gregory, 1917), where the name was extensively used. Later work (Baker and others, 1947) showed that most of the Wingate sandstone at Fort Wingate correlated with the Entrada sandstone of Late Jurassic age and that the Wingate of Utah was for the most part not equivalent to the Wingate at Fort Wingate. The name Wingate sandstone, however, because of its extensive use, was retained for the unit in southeastern Utah, and the name Entrada sandstone was applied to most of the original Wingate sandstone at Fort Wingate.

The Wingate occurs in all of southeastern Utah and adjoining parts of Arizona and Colorado. It is composed of very-pale-orange and light-brown very fine- to fine-grained sandstone. The well-sorted sand grains are dominantly rounded to well-rounded quartz. The lower few feet, and in places as much as the lower third, of the Wingate contains abundant frosted and rounded medium- to coarse-size grains. The sedimentary structures of the Wingate are trough sets of large-scale cross-strata that are tangential to the lower contact of the set. These cross-strata, as is indicated by nine sedimentary-structure studies, dip dominantly southeast.

The basal contact of the Wingate in southeastern Utah is sharp, but the top part of the Wingate intertongues with the overlying Kayenta formation.

The Wingate in most of southeastern Utah ranges in thickness from 200 to 350 feet but is generally about 300 feet thick.

KAYENTA FORMATION

The Kayenta formation (Baker and others, 1947) extends throughout southeastern Utah but pinches out to the east in western Colorado and northeastern Arizona. It is composed of pale-red and very-pale-orange sandstone and some siltstone, and weathers with a purplish tinge. The sandstone is very fine to medium grained, fairly well to well sorted, and composed of subangular to rounded grains. Field observation suggests that most of the Kayenta in central and south-central Utah is composed of quartz grains but that to the east the content of feldspar in the Kayenta increases. In western Colorado, it may, in places, be arkose. The sandstone beds of the Kayenta are composed of interstratified cosets of horizontal laminae and cosets composed of thin trough sets of medium-scale, very low angle cross-strata. Six sedimentary-structure studies indicate that these cross-strata dip dominantly southwest. The sandstone commonly contains angular fragments of reddish siltstone that were undoubtedly derived from underlying siltstone lenses.

The Kayenta intertongues with both the overlying and underlying units. In many places a transition interval of as much 50 feet is present between the Kayenta and the overlying Navajo sandstone. The Kayenta is about 250 feet thick in southeastern Utah.

NAVAJO SANDSTONE

The Navajo sandstone (Gregory, 1915) occurs in most of southeastern Utah and adjoining parts of Arizona and Colorado. It pinches out to the east in western Colorado and northeastern Arizona. The Navajo is a very-pale-orange fine- to medium-grained sandstone composed dominantly of fairly well to well-sorted subround to round quartz grains. The structures are composed of thin to very thick trough sets of medium- to large-scale cross-strata. Twelve sedimentary-structure studies indicate that the cross-strata dip dominantly southeast.

The Navajo intertongues with the underlying Kayenta formation, and in places a transitional zone is present between the two units. The contact of the Navajo with the overlying Carmel formation of Middle and Late Jurassic age is disconformable at most places; a beveling surface overlain by reworked Navajo sandstone is characteristic of the contact. In some places, however, work by L. C. Craig (oral communication, 1954) indicates that strata included in the Carmel in some areas grade laterally into beds included in the Navajo in other areas. These relations suggest that deposition may have been continuous from the time of Navajo deposition into the time of the Carmel deposition in these areas.

INTERPRETATIONS

The formations in the Glen Canyon group are all of continental origin. Sedimentary structures indicate that the Wingate and Navajo sandstones are probably eolian deposits formed by southeastward-blowing winds and that the Kayenta formation is, in large part, a stream deposit formed by southwestward-flowing streams.

RELATION OF URANIUM DEPOSITS TO THE STRATIGRAPHY OF THE TRIASSIC AND ASSOCIATED FORMATIONS

Studies of the relations of uranium deposits to the stratigraphy of the Triassic and related formations permit broad generalizations which may not apply in detail to specific deposits. Most of the deposits in the Triassic and associated formations in southeastern Utah are found in five stratigraphic units: the conglomeratic facies of the Cutler formation, the Shinarump member of the Chinle formation, the Monitor Butte member of the Chinle formation, the Moss Back member of the Chinle formation, and strata near the base of undifferentiated Chinle. A few deposits have been found in the Moenkopi formation and the Wingate sandstone.

DISTRIBUTION OF ORE DEPOSITS

PERMIAN ROCKS

CUTLER FORMATION

A large number of small weakly mineralized uranium deposits in the Cutler formation occur in the area near the junction of the Green and Colorado Rivers. These deposits are in the conglomeratic facies of the Cutler and are near the area where the conglomeratic facies changes to the light-colored sandstone and reddish siltstone facies. The deposits may be related to this facies change, or to particular lithologic rock types associated with the margin of the conglomeratic facies.

The ore-bearing strata are light-colored arkose beds in contrast to the nonmineralized reddish arkose beds. The ore-bearing arkose is at different stratigraphic levels from place to place and always has well-developed cross-stratification and small channel fills.

TRIASSIC ROCKS

MOENKOPI FORMATION

Mineralized material in the Moenkopi formation is found in relatively few areas. The two known ore deposits are in the Capitol Reef and Elk Ridge areas. No relation is indicated between the ore deposits and regional stratigraphic features. In the middle of Moenkopi in many places is an interval of channel-filling cross-stratified conglomeratic sandstone lenses that may be favorable host rocks for uranium. Prospectors may tend to bypass the Moenkopi in favor of units that contain many known deposits, and the lack of systematic prospecting may account for the small amount of mineralized material reported.

CHINLE FORMATION

The distribution of the known deposits in the Shinarump member of the Chinle formation in southeastern Utah and an adjoining part of Arizona is shown in figure 74. The Shinarump contains a few occurrences of mineralized material in northwestern, central, and east-central Arizona and southwestern Utah, but most of the deposits and all of the important ones are in an area that lies near the north limit of the Shinarump. The limits of this area can be only crudely located because of large gaps between outcrops. This area appears to be more favorable for finding new ore deposits than other areas.

Uranium deposits in the Monitor Butte member of the Chinle formation (fig. 76) are known in two areas—the Dirty Devil and the San Rafael Swell (fig. 70). Between these two areas, across a gap in exposures, a belt of ground containing deposits is inferred. This belt is suggested by a similarly oriented belt of deposits in the Moss Back member.

The uranium deposits in the Moss Back member of the Chinle formation are present in a belt about 30 to 40 miles wide that parallels the north limit of the member (fig. 77). No deposits are known south of this belt. Deposits in the Moss Back occur where the Moss Back lies less than 50 feet above the base of the Chinle formation.

A few uranium deposits occur in the Chinle formation in southeastern Utah at or above the stratigraphic position of the Moss Back member. The most important of these deposits are in sandy siltstone or very fine grained sandstone that lie near the base of the undifferentiated Chinle formation (fig. 81). Several deposits are known

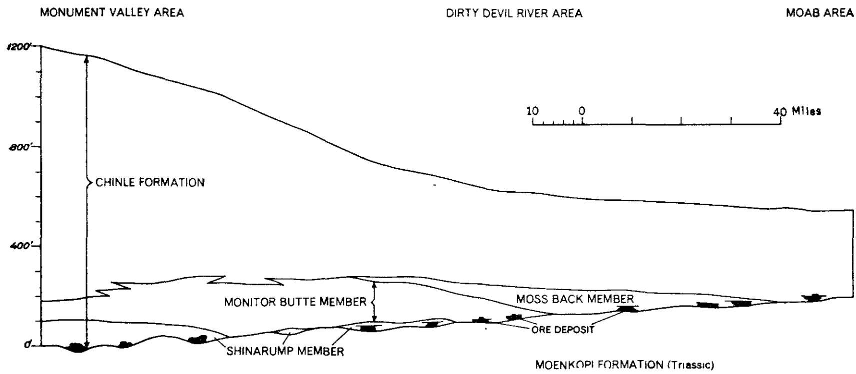

FIGURE 81.—Generalized cross section showing distribution of ore deposits in the Chinle formation of Triassic age.

in the area near the junction of the Colorado and Green Rivers in a unit that appears to be equivalent to the Black ledge of local usage.

The uranium deposits in the Chinle formation are near the base of the Chinle, regardless of the unit that is in that position (fig. 81). Northward across southeastern Utah, as various units onlap the Moenkopi and pinch out, the ore deposits occur in progressivly higher stratigraphic units. In progressing northward in southeastern Utah the deposits are in the Shinarump member, then, in order, the Monitor Butte member, the Moss Back member, and finally near the base of the undifferentiated Chinle formation.

The localization of the deposits near the base of the Chinle may have been caused by the damming of vertically rising ore-bearing solutions by the bentonitic rocks of the Chinle. Open fractures that provided passageways for solutions below the Chinle may not have continued through the Chinle because the bentonitic beds were either not strong enough to support open fractures or were closed by the swelling of the clay when the ore-bearing solutions arrived. Or, although at the present time the Chinle rocks appear to be less permeable than those of the Moenkopi, at some time in the past the Chinle formation may have been composed largely of beds of volcanic material such as glass shards. This volcanic material may have made the Chinle more permeable than the Moenkopi, so that vertically descending solutions were dammed and migrated laterally on top of the Moenkopi.

The distribution of the deposits appears to have some relation to pinchouts and to continuity of the ore-bearing unit. The deposits in the Shinarump member occur near its north limit where the Shinarump is discontinuous, but they are not as common to the south in Arizona and southwestern Utah where the Shinarump is more continuous. In addition, many of the deposits in the Moss Back member lie near its north boundary in an area where the Moss Back is discontinuous.

The relation of the ore deposits to pinchouts may result from the traps that the pinchouts formed for the ore-bearing solutions. Solutions passing laterally through the rocks would probably continue to a place close to a pinchout, where reduced permeability might cause precipitation of the uranium. In areas where the Shinarump member or basal sandstone of the Chinle formation is continuous, the ore-bearing solutions might have moved through without being confined or delayed enough to form a deposit.

WINGATE SANDSTONE

Only a few small deposits are known in the Wingate sandstone of southeastern Utah. No relation is apparent between these deposits and the regional stratigraphy. The deposits appear to be related to secondary structural features such as faults and collapse structures.

RELATION OF ORE DEPOSITS TO LOCAL SEDIMENTARY FEATURES

The ore deposits in the Chinle formation appear to be related to at least two local sedimentary features: channel fills and lithologic features.

CHANNEL FILLS

Almost all the ore deposits in the Chinle formation are related to channel fills (Finch, 1953; Witkind and others, written communications, 1953). Channel fills are probably the best guide to ore in these units. They range in size from 75 feet deep and several thousand feet wide to only minor scour fills less than a foot deep and only a few feet wide. The size of the channel fills does not seem to be related to the location of ore deposits, because deposits are found both in large and small channel fills.

LITHOLOGIC FEATURES

The ore deposits in the Chinle formation appear to be associated with a host rock of specific lithologic characteristics. Rock of this character is considered favorable for the occurrence of ore and is distinguished by three features: lenticular sandstone units that are bounded by mudstone lenses, conglomerate composed both of quartzose and of siltstone or claystone pebbles, and carbonaceous plant material.

In general, rock of this character occurs in channel fills or near pinchouts. It occurs near the bottom of channel fills and is associated with a more diversified direction of dip of the cross-strata than is usual in the unit (McKee and others, 1953).

The ore deposits can be related either to the physical presence of channels or pinchouts or to the presence of this rock type favorable for ore. As the channel fills, pinchouts, and this rock type are generally associated, an evaluation of their relative importance is difficult. Deposits are known in channel fills and near pinchouts that do not contain rocks with these favorable lithologic characteristics, but deposits are also known that occur in rocks of this favorable type but that do not appear to be related to channel fills or pinchouts. These relations suggest, therefore, that the channel fills, pinchouts, and these favorable lithologic characteristics acted independently in affecting the localization of ore.

SEDIMENTARY PETROLOGY

By R. A. Cadigan

This section of the report contains the results of the petrologic investigation of the Triassic and associated sedimentary rocks of the Colorado Plateau. Certain observed relations of petrographic features within uranium-ore samples are also reported with tentative interpretations. A discussion of petrographic terminology is included because it differs markedly from the field terminology used in the first part of the report.

Emphasis is placed on the fact that conclusions and interpretations presented here are based on incomplete data and are, therefore, subject to change.

OBJECTIVES

The petrologic study of the Triassic and associated sedimentary rocks has two general objectives: to obtain evidence which will support some logical conclusions regarding the paleotectonic background of the accumulation of sediments during the late Permian, Triassic, and Early Jurassic times, and to detect relations that may be present between the location of uranium-ore deposits and petrologic characteristics of the sedimentary host rocks.

METHODS

Outcrop samples were collected from the Cutler formation of Permian age, the Moenkopi formation, Chinle formation, and Wingate sandstone of Triassic age, the Kayenta formation of Jurassic(?) age, and the Navajo sandstone of Jurassic and Jurassic(?) age. The samples were analyzed for measurable characteristics of texture and composition.

Texture was studied by disaggregating the samples and making a statistical analysis of the grain-size distribution. Composition was studied by obtaining volumetric mineral-composition measurements of thin sections, separating representative loose mineral grains, concentrating samples of heavy minerals, and making X-ray spectrographic analyses of clay fractions.

TEXTURAL ANALYSIS

Fine sediments are difficult to study in thin section with ordinary equipment, and textural and compositional parameters of fine silt and clay raise many unresolved problems of interpretation. Thus, pertinent information can be obtained more easily from a study of sandstone and sandy siltstone than from claystone, shale, and fine-grained siltstone. Measured textural data presented in this report were arbitrarily restricted to sediments with a mean grain size of 33 microns or larger.

Samples weighing 100 grams each were crushed to pass through a U. S. No. 5 sieve, digested in 400 milliliters of boiling 20-percent-strength citric acid, cooled, acidified with 20 to 50 milliliters of concentrated hydrochloric acid, and washed at 24-hour intervals 4 to 6 times to remove dissolved salts. The silt and clay fractions were separated and analyzed for size distribution by the pipette method. The sand-size material was analyzed for size distribution by sieving through a set of graduated sieves.

Statistical analyses of grain-size distributions produce measurements of a number of properties of the texture. Some of the measurements are familiar in a geologic sense and some, though common in statistics, are unfamiliar in geologic discussion.

Four textural concepts are used in this investigation of sedimentary rocks: average or mean grain size, sorting, skewness, and kurtosis (or peakedness). These properties may be said to define a grain-size distribution. They are derived from the first four statistical moments of the phi grain-size distribution. The term "phi" refers to a conventional scale obtained by translating sizes in millimeters into their respective negative logarithms to the base of two ($-\log_2$) (Krumbein, 1934).

In order to define the mathematical terms so that they may be applied in geologic discussion, it is necessary to impose connotations which are not strictly precise from the mathematical point of view but which aid materially in their interpretation. Thus, the mean of the phi grain-size distribution may be interpreted as the average grain size of the rock material. When the phi mean is converted to millimeters it approximates the geometric mean of the arithmetic distribution.

Average grain size of the material of a rock is classified in terms of the Wentworth (1922) scale. Each size grade is represented by a range of mean grain sizes. Part of the Wentworth scale with the range of mean grain size for each grade is illustrated by table 4.

TABLE 4.—*Phi mean and Wentworth grain-size classification*

Wentworth grade	Phi mean	
	Millimeters	Phi units
Pebbles	64. 000–4. 000	−6. 00–−2. 00
Granules	4. 000–2. 000	−2. 00–−1. 00
Very coarse sand	2. 000–1. 000	−1. 00– . 00
Coarse sand	1. 000–0. 500	. 00– 1. 00
Medium sand	. 500– . 250	1. 00– 2. 00
Fine sand	. 250– . 125	2. 00– 3. 00
Very fine sand	. 125– . 062	3. 00– 4. 00
Silt	. 062– . 004	4. 00– 8. 00
Clay	. 004– . 000	8. 00– ∞

The standard deviation is the second important parameter for describing the phi grain-size distribution of sediments. The phi standard deviation may be interpreted as the measure of sorting. As no common sorting classification based on the standard deviation is in general use, the system illustrated in table 5 has been adopted for this investigation.

TABLE 5.—*Classification of sorting*

Sorting	Phi standard deviation
Very well sorted	0. 0–0. 500
Well sorted	. 500–1. 000
Moderately well sorted	1. 000–2. 000
Poorly sorted	2. 000–4. 000
Unsorted	4. 000–∞

The mean size and the standard deviation define a grain-size distribution if the distribution of sizes forms a symmetrical statistically normal bell-shaped frequency curve when plotted on a graph of which the ordinate is frequency and the abscissa is grain size. The mean locates the center of the curve over the size scale, and the standard deviation measures the spread or width of the curve.

Two other measurements—skewness and kurtosis—are used to define grain-size distributions which vary from the theoretical normal as defined by the mean size and standard deviation. Skewness is a measure of asymmetry of the distribution and is generally marked by a spread of the size range on one side of the mean that is out of proportion to the spread on the other side of the mean. To express skewness in terms of sorting, one end of the size distribution is less well sorted than the average sorting of the whole distribution. The distribution is said to be skewed toward the end with the poorer sorting. By convention, positive skewness in a grain-size distribution indicates a disproportional spread or poorer sorting in the finer sizes, which is illustrated by a stringing out of the right side of the frequency curve. Negative skewness indicates a disproportional spread or poorer sorting in the coarser sizes, which is illustrated by the stringing out of the left side of the frequency curve.

Kurtosis is a measure of the peakedness of the distribution. In terms of sorting, kurtosis measures the relative degree of sorting that the center of a distribution bears to the two ends. Sand with a grain-size distribution which is better sorted in the center than anywhere else has a positive kurtosis. If it is poorer sorted in the center, it has a negative kurtosis.

The basis for comparison of sorting in various parts of a distribution is the theoretical normal distribution; skewness and kurtosis represent measurements of average deviations from the particular theoretically normal distribution, defined by the mean and standard deviation. For comparative purposes certain ranges of values of skewness and kurtosis are given verbal classifications as shown in tables 6 and 7.

Textural parameters that are used to describe stratigraphic or lithologic units are generally reduced to a system of verbal classifica-

TABLE 6.—*Classification of skewness*

Skewness	Phi skewness coefficient
Slightly skewed	0. 50–1. 00
Moderately skewed	1. 00–2. 00
Highly skewed	≥2. 00
Negatively skewed	(1)

[1] All negative values.

TABLE 7.—*Classification of kurtosis*

Kurtosis	Phi kurtosis coefficient
Flattened	<−1. 00
Normal	−1. 00– 1. 00
Moderately peaked	1. 00–10. 00
Highly peaked	10. 00–20. 00
Very highly peaked	≥20. 00

tions. However, for regional comparisons or tabulations of data, numerical values are used.

COMPOSITIONAL ANALYSIS

Mineral composition was determined from the study of a thin section of a selected fragment of each sample. Each thin section was etched with hydrofluoric acid and stained with sodium cobaltinitrite in the method described by Chayes (1952); potassium feldspar and potassium-bearing clay were stained canary to golden yellow by this process. The thin section was then covered with a conventional cover glass set in cool rather tacky uncooked canada balsam. The slide was allowed to air-dry for 2 weeks or more before being trimmed. Xylol was used sparingly and only for cleaning.

The proportion of minerals was measured by means of a petrographic microscope equipped with a point-count stage, and a cell counter, similar to those described by Chayes (1949). Five hundred counts were made on each thin section to obtain a measure of the average proportional area of the thin section occupied by each mineral or mineral group counted. Some rapid estimates of composition were obtained for this report by making only 100 counts on certain selected thin sections.

In this study, it has been convenient to consolidate the minerals into 10 groups, and the descriptions of the composition of the rocks that follow are in terms of these groups. The mineral groups and their constituent minerals are listed below.

Group	*Minerals or rock fragments*
Quartz	Quartz, quartz overgrowths.
Hydromica	Illite, sericite, chlorite, heavy minerals, fragments of micaceous metamorphic rocks.
Potassium feldspar	Orthoclase, microcline.
Kaolin	Kaolinite group of clay minerals and kaolin mud—a mixture of kaolinite clays and ground-up quartz and feldspar with minor amounts of carbonate and of other clay.
Cement	Calcite, gypsum, chalcedony, dolomite, barite, iron oxides, interstitial ore minerals, other interstitial chemically deposited materials.
Quartzite	Quartzite and quartz schist fragments.
Tuffaceous material	Silicified tuff fragments, chert, montmorillonite, rhyolite fragments, other volcanic material.
Mica	Muscovite, biotite.
Plagioclase	Plagioclase feldspar group.
Miscellaneous	Minerals and mineral mixtures such as highly altered opaque heavy minerals or basic igneous rock fragments which are not readily identified or assigned to other mineral groups.

A sedimentary rock that contains more than 50 percent cement is classified as a chemically deposited rock. A rock that contains more than 50 percent detrital components is classified as a detrital rock, and the chemically deposited constituents are not considered in the classification of the rock.

For the classification of the detrital rocks, the detrital-mineral groups are consolidated further into four general groups as follows:

Quartz (quartz, quartzite).
Tuffaceous material.
Feldspar (potassium feldspar, kaolin, plagioclase).
Mica (hydromica, mica, miscellaneous).

Rocks are classified according to table 8 or as illustrated in figure 82. This consolidation of minerals into four general groups is patterned after that of Krynine (1948); however, the role of tuffaceous material is, as far as the authors know, unique to this paper. Tuffaceous material is combined with quartz in figure 82 for practical reasons. An isometric projection would be required to illustrate a four-dimensional classification; such a diagram is difficult to use and for most detrital sedimentary rocks would be unnecessarily complicated. In rocks where the separation of fragments of silicified tuff from chert is questionable, the chert may be added in with quartz as proposed by Krynine (1948). In rocks where fragmental tuff is identified, it modifies the classification made with the tuff counted as quartz.

TABLE 8.—*Petrologic classification of detrital sedimentary rocks based on percentage composition*

[After Pettijohn, 1949, and Krynine, oral communication, 1952. Ranges include termini]

Classification	Quartz and tuffaceous material	Feldspar	Mica
Orthoquartzite:			
Range	72–100	0– 9	0– 19
Typical	85	5	10
Feldspathic orthoquartzite:			
Range	57– 90	10– 24	0– 19
Typical	75	15	10
Graywacke:			
Range	0– 70	10– 80	20– 74
Typical	50	20	30
Subgraywacke:			
Range	17– 80	0– 9	20– 74
Typical	60	5	35
Arkose:			
Range	0– 75	25–100	0– 19
Typical	50	40	10
Pelite:			
Range	0– 25	0– 24	75–100
Typical	5	15	80

The amount of tuffaceous material present modifies the rock classification in the following manner:

1. If there is less than 10 percent tuffaceous material, the rock classification is not affected.

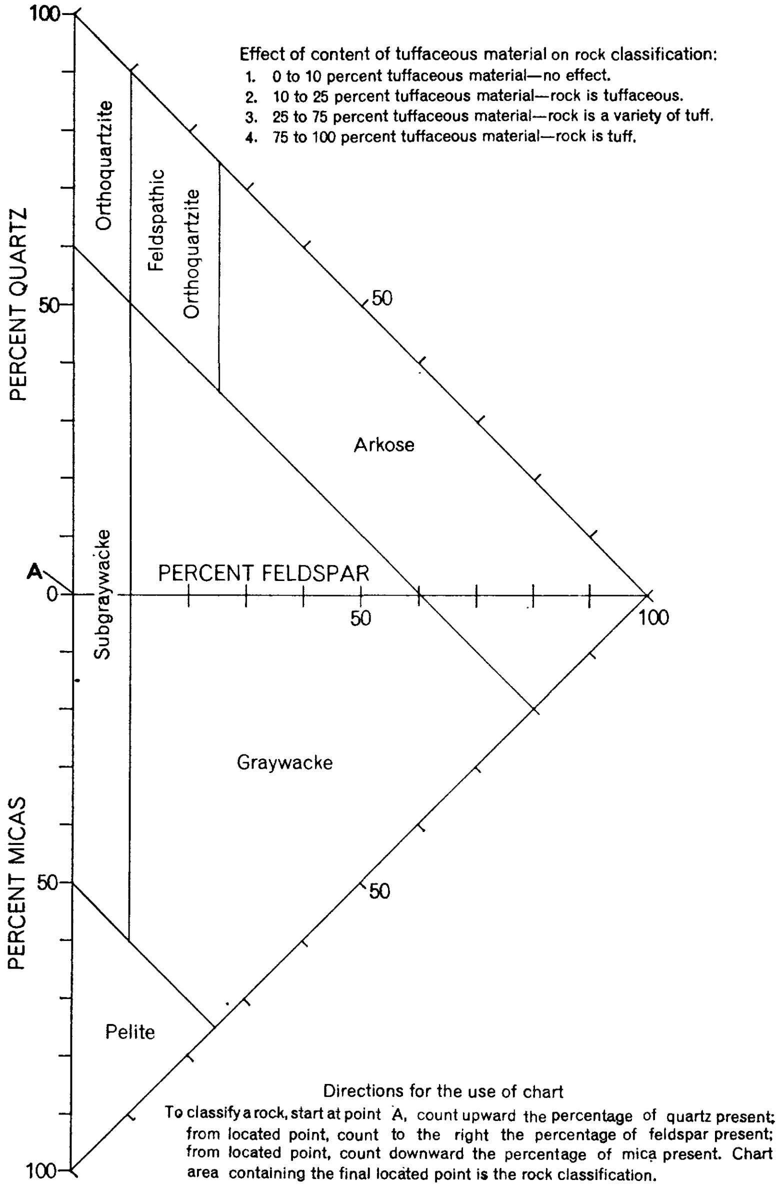

FIGURE 82.—Petrologic classification of detrital sedimentary rocks. (After Pettijohn, 1949, and Krynine, oral communication, 1952).

2. If there is 10 to 25 percent tuffaceous material, the rock name is modified by the word "tuffaceous"; for example, tuffaceous arkose.

3. If there is 25 percent to 75 percent tuffaceous material, the rock name designates a variety of tuff; for example, graywacke tuff.

4. If there is 75 percent or more tuffaceous material, the rock is unmodified tuff.

Heavy-mineral studies have not been completed and results are not presented in this report.

RESULTS

Preliminary estimates of the composition of some Permian and Jurassic formations were made by selecting thin sections of representative sandstone and siltstone, making a point count of mineral composition using 100 counts, and classifying rock units on the basis of the information obtained. The classification is adequate only for the location studied; a more thorough study using many more samples will be necessary to determine regional variations. The classification of a rock unit may change completely from one area to another; for example, arkose may grade into orthoquartzite. Data sufficiently complete to permit regional comparisons have been obtained for the Shinarump and other lower sandstones in the Chinle only.

The genetic interpretations associated with the terms "orthoquartzite," "graywacke," and "arkose" by Pettijohn (1949) and Krynine (oral communication, 1952) have been tested and found applicable, with slight modification, to the sediments of the Colorado Plateau.

The thick sequence of continental-basin or structural-trough sediments of Mesozoic and late Paleozoic age found in the Colorado Plateau region might be expected to contain sediments related to tectonic conditions that varied from extreme uplift to quiescence. Sediments of the type associated with deposition in deep marine basins would be expected to be rare. Genetically, then, the sediments should range from orthoquartzite to arkose. In contrast, graywacke which is related to subaqueous troughs or basins should be rare except in small localized deposits. Observations to date generally confirm this theoretical concept.

The presence of hydromica clay, which is characteristic of the graywacke series, as the dominant clay-mineral group in a sediment which otherwise appears to have been derived from a granitic igneous source or silicic-alkalic volcanic debris casts some doubt on the genetic interpretations associated with the system of classification. This problem is dealt with to some extent in the section on clay minerals, but the final answer must come from the clay mineralogists.

Several summary tables of grain-size analyses of the formations studied (table 14) and point-count analyses of sandstone samples of the Chinle formation (Shinarump member, table 14; Monitor Butte member, table 15; Moss Back member, table 16; Petrified Forest member, table 17) follow page 567.

PERMIAN ROCKS

CUTLER FORMATION

CEDAR MESA SANDSTONE MEMBER

The Cedar Mesa sandstone member, the lowest member of the Cutler formation of Permian age, is the oldest unit studied. The unit is reddish brown or yellowish-gray massive sandstone with conspicuous large-scale cross-strata. The Cedar Mesa was examined in the field and in thin section, and grain-size analyses were completed on seven samples.

The strata are composed typically of very fine moderately well sorted subangular to subround grains of quartz, feldspar, chert, and mica cemented with carbonate (predominantly calcite) cement. Variation in cohesion in the samples suggests that the Cedar Mesa has zones of both highly cemented and friable sandstone. On the average, the grain-size distributions are moderately skewed and highly peaked.

An estimate of the composition of sandstone (one thin section) from the Poncho House area in the northeast corner of the Monument Valley area (fig. 83) is as follows:

Mineral group	*Percent by volume*
Quartz	49
Potassium feldspar (orthoclase)	11
Quartzite fragments	1
Plagioclase (albite)	5
Mica (muscovite)	1
Cement (mostly calcite)	33

The classification of the rock is based on the following detrital components:

Component	*Percent by volume*
Quartz	75
Feldspar	24
Mica	1

The Cedar Mesa is feldspathic orthoquartzite in the Poncho House area (fig. 83).

ORGAN ROCK TONGUE

The Organ Rock tongue of the Cutler formation overlies the Cedar Mesa sandstone member. The unit is a dark-red earthy-weathering sequence of alternating nonresistant siltstone and slightly resistant sandstone strata. Thin sections of the Organ Rock were examined, and grain-size analyses were completed on 14 samples (table 13).

The coarser textured strata of the Organ Rock tongue are coarse sandy siltstone and very fine grained silty sandstone composed typically of moderately well sorted subangular to subround grains of quartz, feldspar, and heavy minerals and minor igneous- or metamorphic-rock

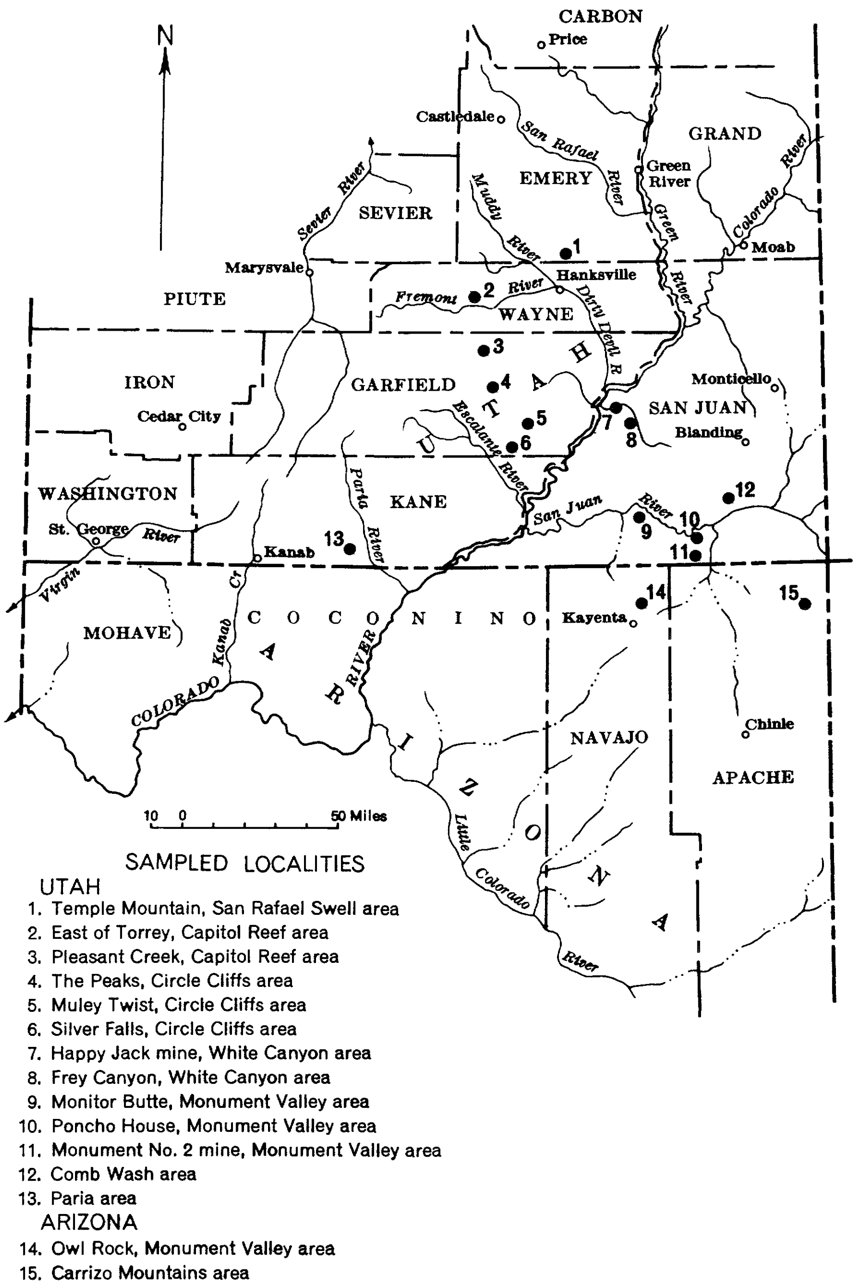

FIGURE 83.—Index map showing localities sampled for sedimentary-petrology studies in Arizona and Utah.

fragments. The constituents are tightly bound together by interstitial hydromica clay stained red by iron oxide, and isolated patches of carbonate (dominantly calcite) cement. The average grain-size distribution is moderately skewed and moderately peaked.

An estimate of the composition of representative sandy siltstone (one thin section) of the Organ Rock from the Poncho House area in the northeast corner of Monument Valley (fig. 83), is as follows:

Mineral group	*Percent by volume*
Quartz	48
Potassium feldspar (orthoclase)	16
Hydromica (stained red by iron oxide (?))	18
Quartzite	1
Plagioclase (albite)	10
Cement (mostly calcite)	4
Miscellaneous (leucoxene, opaque iron oxide pellets)	3

As an exception to the above, some strata of the Organ Rock contain interstitial kaolin as the dominant clay mineral.

The classification of the rock is based on the following detrital components:

Component	*Percent by volume*
Quartz	51
Feldspar	27
Mica	22

At most places, the Organ Rock is a graywacke, but at a few places it is an arkose. Its classification as a graywacke is due to the high proportion of hydromica clay. The significant amount of rock fragments considered essential by Pettijohn (1949) and others is not present; however, the hydromica might be considered by some petrographers as being derived from micaceous shale or phyllite.

DE CHELLY SANDSTONE MEMBER

The De Chelly sandstone member of the Cutler formation lies above the Organ Rock in parts of southeastern Utah and northeastern Arizona. The De Chelly sandstone member was examined in the field and in thin section, and grain-size analyses were completed on seven samples.

The unit is light-colored to reddish massive sandstone with conspicuous large-scale cross-strata. On the basis of the average grain-size-distribution measurements (table 14), the De Chelly is composed of well-sorted sand that is very fine grained and has slightly skewed and highly peaked grain-size distributions.

The De Chelly sandstone member is composed typically of very fine subround to subangular grains of quartz, feldspar, various heavy minerals, and grains of altered tuff loosely cemented by interstitial montmorillonite, hydromica or kaolin clay, reddish iron oxides, and isolated patches of carbonate cement.

An estimate of the composition in terms of mineral groups is based on 100 point-counts on a thin section of a representative De Chelly sandstone sample from the Monitor Butte area (fig. 83) and is shown below.

Mineral group	*Percent by volume*
Quartz	67
Potassium feldspar (orthoclase)	11
Hydromica	2
Tuffaceous material	10
Plagioclase (albite)	5
Cement	4
Miscellaneous	1

The De Chelly sandstone member of the Cutler formation is a tuffaceous feldspathic orthoquartzite in part, but examination of other thin sections indicates that the unit also includes feldspathic orthoquartzite and arkose in the Comb Wash area (fig. 83). The classification of the rock is based on the following detrital components:

Component	*Percent by volume*
Quartz	70
Feldspar	17
Mica	3
Tuffaceous material	10

HOSKINNINI TONGUE

The Hoskinnini tongue of the Cutler formation lies above the De Chelly or above the Organ Rock where the De Chelly is absent. The Hoskinnini is the uppermost member of the Cutler and forms the top unit of the rocks of Permian age. The Hoskinnini tongue was examined in the field and in thin section, and grain-size analyses were completed on 13 samples.

The unit is light-yellowish-gray to reddish-brown thin horizontally to irregularly bedded sandstone and siltstone strata. Some of the strata are strongly resistant to weathering and others are weakly resistant. Owing to the lack of conspicuous well-defined characteristics in the outcrop, recognition depends to a large extent upon the presence of medium-size or coarse sand grains anomalously present in the finer grained sandstone strata.

On the basis of the average grain-size-distribution measurements (table 13), the sandy strata of the Hoskinnini tongue are composed of moderately well sorted, very fine grained sand with slightly skewed and moderately peaked grain-size distributions.

The Hoskinnini is composed typically of very fine to coarse subround grains of quartz and feldspar. In some samples the grains of quartz and feldspar occur in a matrix of kaolin with isolated patches of carbonate (mostly calcite) cement; in other samples they occur in a continuous red carbonate cement stained by iron oxide, without matrix.

An estimate of the composition in terms of mineral groups is based on 100 point counts on each of three thin sections of representative sandstone of the Hoskinnini tongue in southeastern Utah and northeastern Arizona (Poncho House, Monitor Butte, and Comb Wash) (fig. 83) and is shown below.

Mineral group	*Percent by volume*
Quartz	59
Potassium feldspar (orthoclase, microcline)	8
Kaolin	10
Hydromica	1
Plagioclase (albite)	3
Cement	19

The classification of the rock is based on the following detrital components:

Component	*Percent by volume*
Quartz	73
Feldspar	26
Mica	1

Most of the Hoskinnini tongue of the Cutler formation is arkose, with some thin beds suggestive of what Pettijohn (1949, p. 259) refers to as a tectonic arkose, a coarse sediment derived from a rapidly eroding granitic land mass resulting from abrupt tectonic uplift.

CONGLOMERATIC FACIES

The conglomeratic facies of the Cutler formation, which is present chiefly along the flanks of the granitic and metamorphic crystalline rocks that comprise the Uncompahgre highland, has not been studied in thin section. The type Cutler has been observed in the field, however, and grain-size analyses have been completed on two samples of associated sandstone.

The unit consists of reddish to purplish thick-bedded sandstone, pebbly sandstone, conglomerate, and fanglomerate strata. On the basis of the average grain-size-distribution measurements (table 13), the sandstone is made up of moderately well sorted medium-grained sand with moderately skewed and moderately peaked grain-size distributions.

The composition has not been determined from point-count measurements, but field examination reveals the presence of coarse fragments of pink feldspar, quartz, mica, and a kaolinlike clay matrix; these features identify the Cutler as arkose.

TRIASSIC ROCKS

MOENKOPI FORMATION

The oldest of the Triassic sequence of sedimentary rocks in the Colorado Plateau region is the Moenkopi formation. The Moenkopi was studied in the field and in thin section. Grain-size analyses were completed on 21 samples of the sandstone or sandy siltstone facies.

The unit is generally uniform pale-reddish-brown silty sandstone and siltstone that weathers to "shaly" slopes which are littered with ripple-marked platy sandstone fragments. On the basis of the average grain-size-distribution measurements (table 14), the coarser strata of the formation consist of moderately well sorted very fine grained sand with moderately skewed and moderately peaked grain-size distributions.

The siltstone and sandstone strata of the Moenkopi formation are composed of subangular to subround grains of quartz and feldspar, round heavy-mineral grains, angular chert grains, and flakes of mica. The detrital grains are bound and cemented by an interstitial matrix of hydromica clay stained red by iron oxide and carbonate (dominantly calcite and dolomite) cement which occurs in isolated patches and as disseminated subhedral crystals. The siltstone strata vary from the sandstone mostly in the increased angularity of the grains in the siltstone, as well as in the increased difficulty of identification of minerals and mineral relations.

An estimate of the composition of the siltstone and the sandstone facies in terms of mineral groups is based on 100 point counts each on a thin section of representative siltstone of the Moenkopi formation in the Monitor Butte area (fig. 83) and a thin section of typical Moenkopi very fine grained sandstone in the Poncho House area in northeastern Arizona and is shown below:

Mineral groups	*Sandstone (percent by volume)*	*Siltstone (percent by volume)*
Quartz	47	40
Potassium feldspar	12	12
Kaolin	—	1
Hydromica	4	12
Plagioclase	8	12
Mica	—	1
Cement	29	21
Miscellaneous	—	1

The classification of the rocks is based on the following detrital components:

Component	*Sandstone (percent by volume)*	*Siltstone (percent by volume)*
Quartz	66	51
Feldspar	28	32
Mica	6	17

The typical very fine grained sandstone and the typical siltstone of the Moenkopi are classified as arkose.

CHINLE FORMATION

SHINARUMP MEMBER

The Chinle formation lies immediately above the Moenkopi in southeastern Utah, and the Shinarump member is the basal unit over much of the southern part of the plateau region. It has been studied in the field and in thin section in greater detail than any of the previously described units. Grain-size analyses were completed on 83 samples.

Thin sections from 28 of the samples were analyzed by the point-count method and 500 counts per section were made in 10 traverses of 50 counts each. Many of the slides were made from semifriable material, which resulted in loss of material from the section during preparation. Because of losses of material and other damage to the thin sections, voids were not counted and volume was calculated on the basis of the percentage of the mineral volume rather than the percentage of the rock volume. One constituent of which there probably is a disproportionate loss in the damaged thin sections is the kaolinite group of clay minerals.

The Shinarump member is typically light-colored sandstone, conglomeratic sandstone, or conglomerate. In outcrop it presents a strong color and texture contrast with the underlying dark-red siltstone of the Moenkopi, but may grade upward into overlying sandstone of the Chinle. On the basis of the average grain-size-distribution measurements (table 14), the Shinarump contains fine-grained sandstone strata with poorly sorted to moderately well sorted slightly skewed moderately peaked grain-size distributions.

The sandstone strata of the Shinarump member are composed of subround to subangular grains and granules of quartz and feldspar and some altered tuffaceous material bound in a matrix of kaolin mud. The sand is commonly very loosely cemented with isolated patches of carbonate (predominantly calcite) and iron oxide cement.

One or more samples from each of the numbered areas shown on figure 83, except 1, 14, and 15, were used in the composition analysis. An estimate of the regional average composition based on 28 thin sections is as follows:

Mineral groups	*Percent by volume*
Quartz	71.0
Potassium feldspar	4.6
Kaolin	12.5
Hydromica	1.5
Quartzite	.5
Tuffaceous materials	3.2
Plagioclase	.4
Mica	.3
Cement	6.0
Miscellaneous	.0

The classification of the rock is based on the following average amounts of detrital components:

Component	Percent by volume
Quartz	76
Feldspar	19
Mica	2
Tuffaceous materials	3

The average sandstone of the Shinarump member in the area sampled is feldspathic orthoquartzite, but the composition varies from bed to bed and between areas (table 15). Samples of the Shinarump member from the Paria River area (fig. 83) are tuffaceous feldspathic orthoquartzite and contain an average of 15 percent altered tuffaaceous material; this suggests a source of volcanic debris to the south or southwest. Samples of the Shinarump member from southern Monument Valley (fig. 83) are arkose, averaging 31 percent feldspar and kaolin; this suggests a granitic source to the southeast. Further work will be necessary to substantiate these regional variations as evidence of contributions from different source areas.

Table 9 summarizes the percentage composition of sandstone of the Shinarump in the areas sampled (fig. 83).

TABLE 9.—*Mineral components, in percent by volume, of the Shinarump member of the Chinle formation*

Area	Location (fig. 83)	Number of samples	Quartz	Feldspar	Mica	Tuffaceous materials	Classification
Paria River	13	2	70	14	1	15	Tuffaceous feldspathic orthoquartzite.
South Monument Valley.	14	3	66	31	3	0	Arkose.
North Monument Valley.	10, 11	7	81	14	4	1	Feldspathic orthoquartzite.
Monitor Butte	9	2	75	15	3	7	Do.
White Canyon	7	7	80	17	1	2	Do.
Capitol Reef	2, 3	2	73	22	1	4	Do.
Circle Cliffs	5, 6	5	73	22	1	4	Do.

MONITOR BUTTE MEMBER

In different areas various units of the Chinle formation lie just above the Shinarump member. These units range from claystone to pebbly sandstone. The contact may be marked by either an abrupt or a gradational lithologic change. The Monitor Butte member overlies the Shinarump member of the Chinle over a large area of the

Colorado Plateau region. Sandstone beds of the Monitor Butte have been examined in the field and in thin section. Grain-size analyses were completed on 12 samples of the sandstone or sandy siltstone facies.

The unit consists of greenish limy sandstone, siltstone, and claystone strata. The general appearance in outcrop is that of medium-bedded sandstone ledges separated by thicker strata of siltstone and claystone. The sandstone ledges show horizontal, irregular, or rippled lamination with paper-thin micaceous clay laminae between the sand laminae. The sandstone fractures in a rectangular pattern resembling the fracturing of limestone and splits easily along the horizontal laminae within each block.

On the basis of the average grain-size-distribution measurements (table 13), the sandstone of the Monitor Butte member is composed of very fine poorly sorted sand that has slightly skewed and moderately peaked grain-size distributions.

The sandstone and sandy siltstone of the Monitor Butte member are composed of subangular grains of quartz, feldspar, mica, and tuffaceous material. Hydromica clay or in some samples kaolinite or montmorillonite clay minerals are present as a sparse matrix or in pods or thin laminae. The sand is usually well cemented with carbonate and iron oxide cement. Two types of microscopic structure are seen in thin section: one is a quartz-grain and quartz-overgrowth mosaic (as seen with crossed nicols) interbedded with clay laminae; the other type is a heterogeneous arrangement of the components mentioned above, with the grains surrounded by matrix and cement and with irregular spacing between grains. The thin sections that show the mosaic structure contain much less feldspar than those that show the heterogeneous structure.

An estimate of the composition of the sandstone and sandy siltstone facies of the Monitor Butte member in terms of mineral groups is based on the average of the results of point-count analysis of 17 thin sections (table 15), and is as follows:

Mineral groups	*Percent by volume*
Quartz	62.5
Potassium feldspar	5.0
Kaolin	8.9
Hydromica	3.2
Quartzite fragments	.2
Tuffaceous material	5.3
Plagioclase	.6
Mica	.8
Cement	13.5
Miscellaneous	.0

The classification of the sandstone and sandy siltstone strata of the Monitor Butte member is based on the following average amounts of detrital components:

Component	*Percent by volume*
Quartz	74
Feldspar	16
Mica	4
Tuffaceous material	6

The average sandstone of the Monitor Butte member is feldspathic orthoquartzite, but the sandstone strata vary markedly both locally and regionally (table 15). Like the Shinarump, Monitor Butte samples from the Paria River area (fig. 83) are tuffaceous feldspathic orthoquartzite averaging 20 percent altered tuffaceous material. Samples from the Capitol Reef area (fig. 83) are arkose with an average feldspar and kaolin content of 34 percent by volume.

The composition of the sandstone of the Monitor Butte member in the Paria River area (fig. 83), like that of the Shinarump, supports the hypothesis of a source of volcanic material to the west or southwest. The changes in ratios of the detrital components may be interpreted as indicating the existence of multiple sources of sediment for the basal part of the Chinle. Table 10 is a summary of the composition of the Monitor Butte member in the areas sampled (fig. 83).

TABLE 10.—*Mineral components, in percent by volume, of the Monitor Butte member*

Area	Number of samples	Quartz	Feld-spar	Micas	Tuffa-ceous material	Classification
Paria River	2	56	21	3	20	Tuffaceous feldspathic orthoquartzite.
North Monument Valley.	2	85	7	6	2	Orthoquartzite.
White Canyon	5	87	7	3	3	Do.
Circle Cliffs	5	72	17	4	7	Feldspathic orthoquartzite.
Capitol Reef	3	57	34	6	3	Arkose.

MOSS BACK MEMBER

Another basal sandy unit of the Chinle formation is the Moss Back member, which may overlie either the Moenkopi formation or the Monitor Butte member of the Chinle formation (fig. 81). The sandstone strata of the Moss Back member have been examined in the field and in thin section. Grain-size analyses were completed on 13 samples.

The unit contains light-colored sandstone, pebbly sandstone, and conglomerate. Generally an exposure of the Moss Back consists of one or more very thick sandstone beds which form a resistant massive or compound ledge in the less resistant units near the base of the Chinle. Gray to greenish strata of claystone or clayey siltstone occur between beds in some localities but are not typical. The unit is generally conspicuously cross-stratified and in places fills channels at the base in the same manner as the Shinarump member.

On the basis of the average grain-size-distribution measurements (table 13), the sandstone of the Moss Back is very fine to fine grained with moderately to poorly sorted, moderately skewed and moderately peaked grain-size distributions.

The sandstone of the Moss Back is composed of detrital grains, matrix, and cement arranged heterogeneously in microscopic structure. The detrital components are subrounded to subangular grains of quartz, orthoclase, albite, chert, tuffaceous material, mica, and a few heavy-mineral grains. Other components are represented by subhedral carbonate (mostly calcite) crystals and reddish iron oxide-type cement interspersed with interstitial wads of kaolin, montmorillonite, or hydromica. Thin sections of only one of the sandstone strata showed a mosaic arrangement, with quartz and feldspar grains in a sparse interstitial montmorillonitic matrix. The heterogeneous arrangement of components is typical of the sandstone units of the Moss Back member.

An estimate of the composition of the sandstone of the Moss Back member in terms of mineral groups is based on the averages of point-count analyses of six thin sections (table 16) and is as follows:

Mineral groups	*Percent by volume*
Quartz	68.3
Potassium feldspar	3.9
Kaolin	9.7
Hydromica	6.0
Quartzite fragments	.1
Tuffaceous material	4.8
Plagioclase	1.2
Mica	.6
Cement	5.4
Miscellaneous	.0

The classification of the sandstone of the Moss Back member is based on the following average amounts of detrital components:

Component	*Percent by volume*
Quartz	72
Feldspar	16
Mica	7
Tuffaceous material	5

The average sandstone of the Moss Back member is feldspathic orthoquartzite; however, none of the individual samples are in this classification. Two samples of arkose are from the Temple Mountain area, and 3 of orthoquartzite and 1 of graywacke (hydromica type) are from the White Canyon area (fig. 83). Not enough samples of the Moss Back have been studied to be certain of regional differences, but the arkose of the Moss Back at Temple Mountain, the arkose of the Monitor Butte at Capitol Reef, and the high-feldspar feldspathic orthoquartzite of the Shinarump from Capitol Reef and Circle Cliffs suggest a high feldspar content for the Shinarump and other basal sandstone of the Chinle in the northwestern part of the Plateau area.

PETRIFIED FOREST MEMBER

The Petrified Forest member of the Chinle overlies the Moss Back member in many areas. The Chinle may be easily divided into an upper and lower part with the boundary at the top of the Petrified Forest member. Most of the lower part is dark-grayish-green siltstone and shale, variegated bentonitic shale and pale-brown sandstone. Most of the upper part is pale-reddish-brown siltstone and sandstone and grayish-green limestone and limy siltstone. The Petrified Forest member has been studied in the field and in thin section. Grain-size analyses were completed on four samples of sandstone. The Petrified Forest member is principally a bentonitic siltstone-claystone unit but contains scattered discontinuous thin- to thick-bedded moderately to poorly resistant sandstone beds, many of which are conspicuously cross-stratified.

On the basis of the average grain-size-distribution measurements (table 13), the sandstone strata of the Petrified Forest member consist of very fine poorly sorted material with moderately skewed and moderately peaked grain-size distributions.

The sandstone strata of the Petrified Forest member are composed of subangular to subround grains of quartz, feldspar, tuffaceous material, and a few scattered flakes of mica in a matrix of montmorillonite and hydromica clay minerals. They are slightly cemented by subhedral carbonate crystals, and much reddish to purplish iron(?) oxide stain is present. The microscopic structure of the sandstone as seen in thin section is heterogeneous.

An estimate of the composition of the sandstone facies of the Petrified Forest member of the Chinle in terms of mineral groups is based on the average of point-count analyses of two thin sections (table 17) from the Comb Wash area (fig. 83) and is as follows:

Mineral group	*Percent by volume*
Quartz	51.9
Potassium feldspar	7.3
Kaolin	.6
Hydromica	6.6
Quartzite fragments	.0
Tuffaceous material	32.1
Plagioclase	.4
Mica	.7
Cement	.4
Miscellaneous	.0

The classification of the Petrified Forest is based on the following average amounts of detrital components:

Component	*Percent by volume*
Quartz	52
Feldspar	8
Mica	7
Tuffaceous material	33

The average sandstone of the Petrified Forest member in the Comb Wash area is orthoquartzitic tuff. This conforms with the general impression of volcanic origin for much of the material making up the Petrified Forest member of the Chinle formation.

OWL ROCK MEMBER

The Owl Rock member of the Chinle formation overlies the Petrified Forest member. As discussed above, the boundary between the two members may also be used to divide the Chinle into an upper and lower part.

The Owl Rock member has been examined in the field and in thin section. Grain-size analyses were completed on four samples of sandstone or silty sandstone.

The unit is characteristically pale-dark-green and pale-reddish-brown siltstone, sandstone, and limestone. The general appearance in outcrop is that of several moderately to poorly resistant rounded rough-surfaced limestone ledges separated by intergraded poorly resistant units of limy siltstone; the unit forms a slope thinly covered with limestone pellets 1 mm to 10 mm in diameter.

On the basis of the average grain-size distribution measurements (table 13), the sandstone and silty sandstone of the Owl Rock member is composed of very fine moderately well sorted sand that has slightly skewed and moderately peaked grain-size distributions.

The rocks of the Owl Rock member are composed of calcite and dolomite pellets and crystalline masses which contain subangular to subround grains of quartz, orthoclase, albite, tuffaceous material, and, in some parts, biotite and muscovite, and a matrix of interstitial montmorillonite and chlorite types of clay minerals. The ratios of chemical material to detrital material (including carbonate pellets) probably form a series. Many of the "limestone" beds consist of carbonate-pellet conglomerate or calcarinites and appear as such in outcrops, as well as in thin section.

An estimate of the composition in terms of mineral groups is based on 100-point counts on a thin section of representative Owl Rock member sandstone (53 percent allogenic detrital minerals and 47 percent carbonate minerals) from the Monitor Butte area (fig. 83) and is as follows:

Mineral group	*Percent by volume*
Quartz	20
Potassium feldspar	13
Hydromica (mostly chlorite)	9
Tuffaceous material	8
Plagioclase	3
Cement (mostly calcite, dolomite, iron oxides)	47

The classification of sandstone of the Owl Rock is based on the following amounts of detrital components:

Component	*Percent by volume*
Quartz	38
Feldspar	30
Mica	17
Tuffaceous material	15

The average sandstone of the Owl Rock member in the Monitor Butte area has the detrital composition of tuffaceous arkose. The average "limestone" unit varies in composition within the same bed from true limestone to what would properly be called dolomite; this conclusion is based on field tests using 10-percent strength hydrochloric acid. No data are available on the proportion of total calcium to total magnesium in these beds.

CHURCH ROCK MEMBER

The Church Rock member of the Chinle overlies the Owl Rock member and forms the uppermost unit of the Chinle in southeastern Utah. The sandstone and sandy siltstone beds of the Church Rock have been examined in the field and in thin section. Grain-size analyses were completed on seven samples. The generally dark reddish-brown unit appears as a sequence of moderately resistant alternating thick sandstone and siltstone beds at the top of the Chinle. Some of the sandstone beds are cross-stratified.

On the basis of the average grain-size-distribution measurements (table 14), the sandstone and silty sandstone of the Church Rock are composed of very fine moderately well sorted sand with moderately skewed and moderately peaked grain-size distributions.

The sandstone and silty sandstone of the Church Rock are composed of subangular to subround grains of quartz, orthoclase, albite, some heavy minerals, flakes of mica, interstitial hydromica stained with iron oxide, disseminated subhedral crystals of carbonate (mostly calcite) cement, and interstitial blobs of iron oxides.

The composition in terms of mineral groups is based on 100 point-counts on thin sections of representative silty sandstone and of sandy siltstone of the Church Rock member from the Monitor Butte and Comb Wash areas (fig. 83), respectively, and is as follows:

Mineral group	*Percent by volume*	
	Sandstone	*Siltstone*
Quartz	44	33
Potasium feldspar	11	14
Hydromica	3	20
Tuffaceous material	0	0
Plagioclase	7	8
Mica	6	3
Cement	27	20
Miscellaneous	2	2

The classification of the silty sandstone and the sandy siltstone of the Church Rock member is based on the following amounts of detrital components:

Component	*Percent by volume*	
	Sandstone	*Siltstone*
Quartz	60	41
Feldspar	25	28
Mica	15	31
Tuffaceous material	0	0

The average fine-grained sandstone of the Church Rock member of the Chinle formation in the Monitor Butte area (fig. 83) is arkose, but the average siltstone is graywacke. The difference in classification between the two samples results from the increased amount of hydromica clay minerals in the siltstone.

The Chinle formation in southwestern Colorado resembles the Church Rock member superficially but may be better referred to as undifferentiated Chinle. Compositional data based on thin-section study have not been determined. Grain-size analyses were completed on seven samples of sandstone and coarse siltstone. The rocks were found to be, on the average (table 13), very fine grained silty sandstone composed of moderately well sorted sand with moderately skewed moderately peaked grain-size distributions.

TRIASSIC AND JURASSIC ROCKS

GLEN CANYON GROUP

WINGATE SANDSTONE

The Wingate sandstone lies above the Chinle formation and forms the uppermost part of the Triassic rocks in southeastern Utah.

The Wingate has been examined in the field and in thin section. Grain-size analyses were completed on 44 samples of sandstone or sandy siltstone.

The unit consists of light-colored very thick bedded massive cliff-forming sandstone strata. The general appearance of the unit in the outcrop is that of a high vertical cliff at the top of the dark-reddish slope formed by the Chinle formation. The Wingate contains conspicuous large-scale cross-strata.

On the basis of the average grain-size-distribution measurements (table 13), the sandstone and coarse siltstone of the Wingate are very fine grained with moderately to well-sorted sand that has moderately skewed highly peaked grain-size distributions.

The sandstone beds of the Wingate are composed of subround grains of quartz, orthoclase, microcline, albite, altered tuffaceous material, quartzite fragments, and some rounded heavy-mineral grains. The matrix consists of a small amount of kaolinite, hydromica, or montmorillonite clay. The cement consists of some subhedral interstitial carbonate crystals and reddish iron(?) oxides that stain the matrix. The base of the Wingate is often marked by coarse to very coarse spherical grains of quartz, feldspar, quartzite, and chert (silicified tuff?) in a matrix of very fine grained sand.

An estimate of the composition of the Wingate sandstone in terms of mineral groups is based on 100 point-counts in 2 thin sections of representative sandstone from the Poncho House and Carrizo areas, respectively, (fig. 83) and is as follows:

	Percent by volume		
Mineral groups	*Poncho House*	*Carrizo*	*Average*
Quartz	37	58	48
Potassium feldspar	17	11	14
Kaolin	1	0	1
Hydromica	6	10	8
Tuffaceous material	23	2	12
Plagioclase	16	11	13
Cement	0	6	3
Miscellaneous	0	2	1

The classification of the Wingate sandstone in extreme northeastern Arizona is based on the following amounts of detrital components:

	Percent by volume		
Component	*Poncho House*	*Carrizo*	*Average*
Quartz	37	63	49
Feldspar	34	23	29
Mica	6	12	9
Tuffaceous material	23	2	13

The Wingate sandstone in northeastern Arizona ranges from tuffaceous arkose to feldspathic orthoquartzite. More work must be done to obtain a significant mean composition and an idea of the distribution of components. From the inspection of several thin sections, the Poncho House sample appears to represent one extreme but is also one of many of the same general classification. The typical or more common sandstone is more similar in composition to the Carrizo sample.

The unexpected presence of tuffaceous material suggests either the reworking of old tuffaceous material (from the Chinle?) or volcanic activity contemporaneously with the deposition of the Wingate. The fact that the tuffaceous material is abundant in some strata and nearly absent in others supports the hypothesis of intermittent contemporaneous volcanism as the explanation. Additional work may reveal a regional distribution of the tuffaceous material in the Wingate.

KAYENTA FORMATION

The Kayenta formation of Jurassic(?) age overlies the Wingate sandstone in much of the Colorado Plateau area. The sandstone beds of the Kayenta have been examined in the field, but not in thin section. Grain-size analyses were completed on 19 samples.

The unit is generally light- to dark-red or brown medium- to thick-bedded sandstone which forms a moderately resistant slope above the massive vertical cliff of the Wingate sandstone. Some of the sandstone beds contain cross-strata.

On the basis of the average grain-size-distribution measurements (table 13), the sandstone of the Kayenta is composed of very fine moderately to well-sorted sand with moderately skewed and highly peaked grain-size distributions.

No thin-section data are available on the Kayenta formation. Previous work done on loose-grain mounts of disaggregated sand from 7 samples taken in southwestern Colorado indicated that the detrital grains in the Kayenta consist, on the average, of 16 percent potassium and sodium feldspar, 6 percent fragments of silicified tuff and chert, 78 percent quartz, and a trace of mica. The Kayenta would be classified as a feldspathic orthoquartzite or arkose, depending upon the amounts of kaolin clay and sodic-calcic feldspars present. The rock is composed on the average of 81 percent sand, 9 percent silt and clay, and 10 percent soluble cement.

NAVAJO SANDSTONE

The Navajo sandstone overlies the Kayenta in much of the Colorado Plateau region. The sandstone beds of the Navajo have been examined in the field, but not in thin section. Grain-size analyses were completed on 22 samples.

The unit is generally light-colored thick-bedded sandstone. The appearance in outcrop is that of massive light-colored sandstone with convex weathering surfaces and, in most localities, with conspicuous large-scale cross-strata that have been brought into relief by differential weathering along the contacts of the cross-strata.

On the basis of the average grain-size-distribution measurements (table 13), the sandstone of the Navajo is composed of very fine grained, well-sorted sand with moderately skewed and highly peaked grain-size distributions.

No thin-section data are available on the Navajo sandstone. Previous work done on loose-grain mounts of disaggregated sand from 9 samples taken about 30 miles north of the Temple Mountain area (fig. 83) indicates that the detrital grains consist, on the average, of 85 percent quartz, 12 percent potassium and sodium feldspar, and 3 percent chert and fragments of tuff. The rock is composed of 94 percent sand, 3 percent silt and clay, and 3 percent soluble cement. The Navajo is classified as feldspathic orthoquartzite.

STUDY OF THE CLAY-MINERAL GROUPS IN THE TRIASSIC AND ASSOCIATED FORMATIONS

Clay fractions obtained in the grain-size analyses of sandstones of Jurassic, Triassic, and Permian age were submitted to a U. S. Geological Survey laboratory for identification by X-ray spectrometer. Acknowledgment is made of the help and cooperation of Alice D. Weeks who expedited the service requests and Mary E. Thompson and Evelyn Cisney who made the clay-mineral identifications.

The results of the clay analyses are shown in tables 11 and 12. The percentages given in table 11 refer to the number of samples that contain the particular clay-mineral group as the major constituent in the clay fraction. In table 12, the percentages refer to samples that contain the particular mineral group as the minor constituent in the clay fraction.

As an example, in a group of 54 sandstone and siltstone samples from the Shinarump member of the Chinle formation (table 11), 85 percent of the samples have kaolinite as the major clay-mineral group, 11 percent have hydromica as the major clay-mineral group, and 4

TABLE 11.—*Units in which sandstone contains 1 of the 3 clay-mineral groups as the major clay mineral*

Unit	Number of samples	Clay mineral group (percent)		
		Kaolinite	Hydromica	Montmorillonite
Navajo sandstone	17	71	23	6
Kayenta formation	9	78	22	0
Wingate sandstone	28	50	29	21
Chinle formation:				
Exclusive of Shinarump member	25	11	81	8
Shinarump member	54	85	11	4
Moenkopi formation	18	28	72	0
Hoskinnini tongue of the Cutler formation	6	100	0	0
De Chelly sandstone member of the Cutler formation	4	50	25	25
Organ Rock tongue of the Cutler formation	7	43	57	0

TABLE 12.—*Units in which sandstone contains 1 of the 3 clay-mineral groups as the minor clay mineral*

Unit	Number of samples	Clay mineral group (percent)		
		Kaolinite	Hydro-mica	Montmor-illonite
Navajo sandstone	10	40	40	20
Kayenta formation	6	33	67	0
Wingate sandstone	19	32	63	5
Chinle formation:				
Exclusive of Shinarump member	13	85	15	0
Shinarump member	29	17	83	0
Moenkopi formation	14	64	29	7
Hoskinnini tongue of the Cutler formation	6	0	33	67
De Chelly sandstone member of the Cutler formation	3	33	67	0
Organ Rock tongue of the Cutler formation	8	38	62	0

percent have montmorillonite as the major clay-mineral group. Of the original 54 samples, 29 contain 2 or more detectable clay-mineral groups (table 12), of which 17 percent have kaolinite as the minor clay-mineral group and 83 percent have hydromica as the minor clay-mineral group.

The typical clay minerals in the sandstone and siltstone strata of the Shinarump member of the Chinle formation in order of abundance are kaolinite and hydromica. Study of thin sections of samples from these rocks indicates that the kaolinite is mostly allogenic and detrital and was probably derived from potassium and sodium feldspars during the weathering of granitic rocks or fanglomerates. The presence of kaolinite as the dominant clay supports other petrographic evidence that most of the Shinarump member is arkosic.

The hydromica may be allogenic detrital clay, but petrographic evidence suggests that the hydromica is authigenic and was derived from the alteration of montmorillonite or volcanic ash in the presence of soluble potassium salts. The potassium salts would originate from the breakdown of potassium feldspar or during the alteration of alkalic-silicic volcanic glass, and other tuffaceous debris.

The Chinle has long been noted as a formation which contains much altered volcanic debris, yet from table 11 it may be seen that 81 percent of a group of 25 sandstone and siltstone samples contain hydromica as the major clay mineral and only 8 percent contain montmorillonite as the major clay mineral. The minor clay minerals in the 13 samples which contain a second clay-mineral group are kaolinite in 85 percent of the samples and hydromica in 15 percent (table 12).

Microscopic study of the same samples on which clay analyses were run showed hydromica to occur as rims around grains even where the more conspicuous clay was kaolinite or montmorillonite. Hydromica also occurs interstitially or as wads or galls in which one part of the wad is montmorillonite and part is hydromica, with a mixed-layer transition between the two types.

Thus, evidence supports the hypothesis that much of the hydromica in the Shinarump member and in the Chinle formation generally is the result of the alteration of volcanic debris or montmorillonite in the presence of soluble potassium salts. Such an alteration is suggested by Grim (1953), with references to Noll (1936), and others. The confirmation of such a hypothesis would explain the anomaly of tuffaceous sandstone interbedded with hydromica-rich claystone in the Chinle formation.

The following diagrammatic arrangement of the materials involved illustrates the hypothesis of the formation of much of the hydromica.

```
Potassium or sodium feldspar                         Alkalic-silicic ash
            ↓                                                 ↓
Kaolinite or montmorillonite                          Montmorillonite
     /                                                        \
    /               +soluble potassium salts                    \
Kaolinite              \                  /              Montmorillonite
                        ↘                ↙
                            Hydromica
```

Many of the interpretations in this report are based on certain expected occurrences and associations of clay-mineral groups. Most of the kaolinite is assumed to be related to granitic source rocks and the formation of arkose; most of the montmorillonite is assumed to be related to sediments derived from alkalic-silicic source rocks of volcanic origin (ash, tuff, glass, felsite); most of the hydromica was originally assumed to be related to sediments derived from sericitic sedimentary and micaceous metamorphic rocks. As discussed above, the concept of the role of hydromica as an authigenic clay mineral has altered the original assumption.

PETROLOGIC FEATURES OBSERVED IN ORE-BEARING SANDSTONE

During the petrographic study of thin sections of sandstone samples from the Shinarump and the Moss Back members of the Chinle formation and the estimation of volumetric composition by the point-count method (based on 500 counts), 9 thin sections from uranium-mineralized locations were studied. These thin sections represent samples that may be classified as 1 sample of high-grade ore-bearing sandstone (L258, table 14) and 3 samples of medium- to low-grade ore-bearing sandstone (L260, L842, table 14; L252, table 16). Five samples can be classed as barren sandstone associated with ore-bearing sandstone (L261, L259, L883, L841, table 14; and L254, table 16).

Study of the thin section from the high-grade ore sample (L258) and the thin section from the associated barren-sandstone sample (L261) from the Happy Jack mine in White Canyon, San Juan County, Utah, suggests that kaolinite may have influenced the deposition of the ore minerals. Each of these thin sections contains quartz, potassium feldspar, quartzite, tuffaceous material, plagioclase, cement (calcite, iron oxides, barite, etc.), and kaolin. In addition, the ore-bearing sandstone contains unidentified uranium minerals, chalcopyrite, azurite, barite, covellite, malachite, and pyrite; these minerals occur interstitially and form about 30 percent of the volume of the rock. The mine face at the point where the sample was taken was reported by the owners to assay about 10 percent copper and 2 percent uranium.

Quartz grains in the associated barren thin section have euhedral authigenic overgrowths, whereas the quartz grains in the ore-bearing sandstone contain few overgrowths and these show corrosion by solution which apparently occurred before or during deposition of the sulfide minerals.

Kaolin occurs in the two thin sections primarily as detrital interstitial mud composed of ground-up quartz, potassium and sodium feldspars, kaolinite clay minerals, and minor amounts of carbonate minerals and micaceous clay minerals, and secondarily as an alteration product along cleavage planes in some of the potassium feldspar grains. A comparison of the two thin sections shows that they are similar in the proportions of all components, with the exception of kaolin mud and ore minerals.

The results of this comparison suggest that less kaolin mud is present in the ore-bearing sandstone because most of the original mud has been replaced or obscured by uranium and copper minerals, whereas most of the kaolin in the adjacent barren sandstone has been unaffected.

Other data indicate some possible significance in the relations between ore and kaolin. At the mine face where samples L258 and L261 were taken, the copper and uranium sulfide-bearing sandstone was surrounded by a halo of mineralized sandstone stained by azurite and malachite. A thin section from the halo (sample L260) contains euhedral crystals of azurite and malachite in an interstitial kaolin matrix.

A similar relation between ore sand and associated barren sand was studied in the Moss Back member of the Chinle at Temple Mountain, Emery County, Utah. The ore-bearing sandstone (L252) contained 19 percent interstitial kaolin and 5 percent asphaltoid residue containing ore minerals and pyrite in cryptocrystalline form. The associated barren sandstone (L254) contained 24 percent interstitial kaolin and 1 percent pyrite. It may be that the amounts of kaolin and of asphaltoid residue, ore, and pyrite are complementary, that the ore-bearing sandstone was originally of the same composition as the barren sandstone, and that the mineralization was effected at the expense of the interstitial kaolin.

To test this apparent relation further a comparison of kaolin content was made between the nine sandstone samples containing ore minerals or associated with known ore deposits, and the average for all the samples of the Shinarump and Moss Back studied. The ore minerals of high-grade sample L258 are combined with the kaolin to compensate for the supposed loss of kaolin by it and other ore-bearing samples.

The mean amount of kaolin for the ore-associated samples is 21 percent, with a range of from 5 to 35 percent. The mean amount of kaolinite in the barren samples is 9 percent, with a range from 0 to 26 percent. The mean amount of kaolin for all 34 samples is 12 percent, with a range from 0 to 35 percent.

The three barren samples with the highest kaolin content that were collected away from known ore deposits came from the Owl Rock section (table 14) in southern Monument Valley.

The results of the study suggest that ore is localized in the Shinarump and other lower sandstone units of the Chinle formation containing 20 percent or more interstitial kaolin mud. The effect of the kaolin may be physical or chemical, or both, or the effective agent may be something contained in the kaolin. Whatever the cause of localization, the recommendation is made that strata containing 15 to 35 percent interstitial kaolin be considered as more favorable for the occurrence of uranium ore than strata containing less than 15 percent kaolin.

INTERPRETATIONS

The final objectives of the petrographic study of the Triassic and associated sedimentary rocks have been achieved in part. More progress has been made on reconstruction of the paleogeography than on the problem of associating the occurrence of uranium ore with measurable properties of the sedimentary host rocks.

Thin-section study indicates that the source areas of the rocks studied were dominantly granitic, with minor areas of quartzite and quartz-mica schist or gneiss. At least three separate source areas were contributing sediments to the major continental basin of deposition when the Shinarump and other members of the lower part of the Chinle formation were being deposited. Some volcanic activity occurred in all periods, but the greatest contribution of volcanic material to the sediments occurred during the deposition of the lower part of the Chinle. The volcanic material appears to have had an alkalic-silicic composition. The main volcanic contribution now forms thick deposits of claystone and siltstone combined with a large volume of sand-size altered tuffaceous material. The main loci of deposition were in the extreme northeastern part of Arizona and southeastern to south-central Utah. Many thin concretionary or banded cherty lenses in the lower part of the Chinle may have derived their silica from the altering volcanic glass.

The chief uranium-bearing units, the Shinarump, Monitor Butte, Moss Back, and Petrified Forest members of the Chinle formation, are distinguished from the other units by both physical and chemical features. The uranium-bearing rocks are made up of generally coarser and generally more poorly sorted materials than the other rocks studied. The units contain large amounts of sand-, silt-, and clay-sized materials, which have been derived from alkalic-silicic volcanic material. Owing to the impervious nature of many of the montmorillonite and hydromica clay minerals, many of the more soluble products of decomposition of the volcanic materials have probably been retained in the clayey strata or are still being slowly leached, which makes possible a wide variety of chemical environments in the uranium-bearing units. Any one of these features mentioned, or a combination, may have been critical in localizing the uranium ore.

Conclusions resulting from petrographic study of these sedimentary rocks fall into two categories. In one category are direct comparisons based on microscopic or megascopic measurements; for instance, sandstone of the Moenkopi formation is finer grained on the average than sandstone of the Shinarump member of the Chinle formation. (See table 13 for comparison of mean grain size.) In the second category, hypotheses are put forward by the petrologist to explain why sand deposited during Moenkopi time was finer grained than sand deposited during Shinarump time.

Second-category conclusions are based on interpretations or assumptions which are open to question at all times, even when the assumptions are based on fairly well accepted and often well substantiated cause-and-effect relations. A logical course in presenting conclusions of the second category is to present the basic cause-and-effect relations that are assumed by the author to be true.

The assumption is made that the grain size and sorting of a sediment are determined by conditions in the source area, the basin of deposition, and the particular environment within the basin. It is assumed that the gross controlling causes are the degree of differential tectonic uplift in the source area, the degree of differential subsidence or uplift in the basin of deposition, and the degree of region-wide subsidence or uplift.

The effect of these multiple causes on the mean grain size and the sorting of the related sediments is assumed to be as follows:

1. With an increase in differential tectonic uplift in the source area, the mean grain size increases and the sorting becomes poorer (standard deviation increases).

2. With an increase in the differential subsidence of the basin of deposition, the mean grain size decreases and the sorting becomes poorer (standard deviation increases).

3. With region-wide uplift encompassing both source area and basin, grain size increases and sorting becomes better (standard deviation decreases). The effect is the same with an uplift of the basin of deposition.

4. With general quiescence, grain size is determined by the texture of the material available for reworking; sorting steadily improves until the sediment is finally buried. Eolian sand is a continental terrestrial sediment typical of this condition.

Any combination of the first three conditions is possible, with resulting modification of the sediments. When tectonic movements are relatively rapid the resulting sediments change characteristics abruptly. When tectonic movements are slow, but fast enough to change rates of erosion or deposition, the resulting sediments will indicate gradational change. Quiescence may result from a slight region-wide positive tectonic movement which tilts the lower end of the profile of equilibrium upward or may occur during a period when the basin is subsiding very slowly and erosion is proceeding at a diminishing rate in the source area.

If the above cause-and-effect relations may be assumed for the overall area and the minor modifications may be ignored, interpretation then becomes a matter of selecting a cause or causes for each effect.

Figure 84 is a graph showing mean grain size and sorting (as measured by the standard deviation of the phi grain-size distribution) for each formation and member studied. Plotted points are connected by lines to emphasize the sense and degree of change. Data for the points are listed in table 13.

Using figure 84 for reference, interpretations are made on the basis of changes that take place in the sequence. To interpret the texture of each unit without reference to adjacent units would be similar to taking phrases out of context—some would make sense, others would be unintelligible.

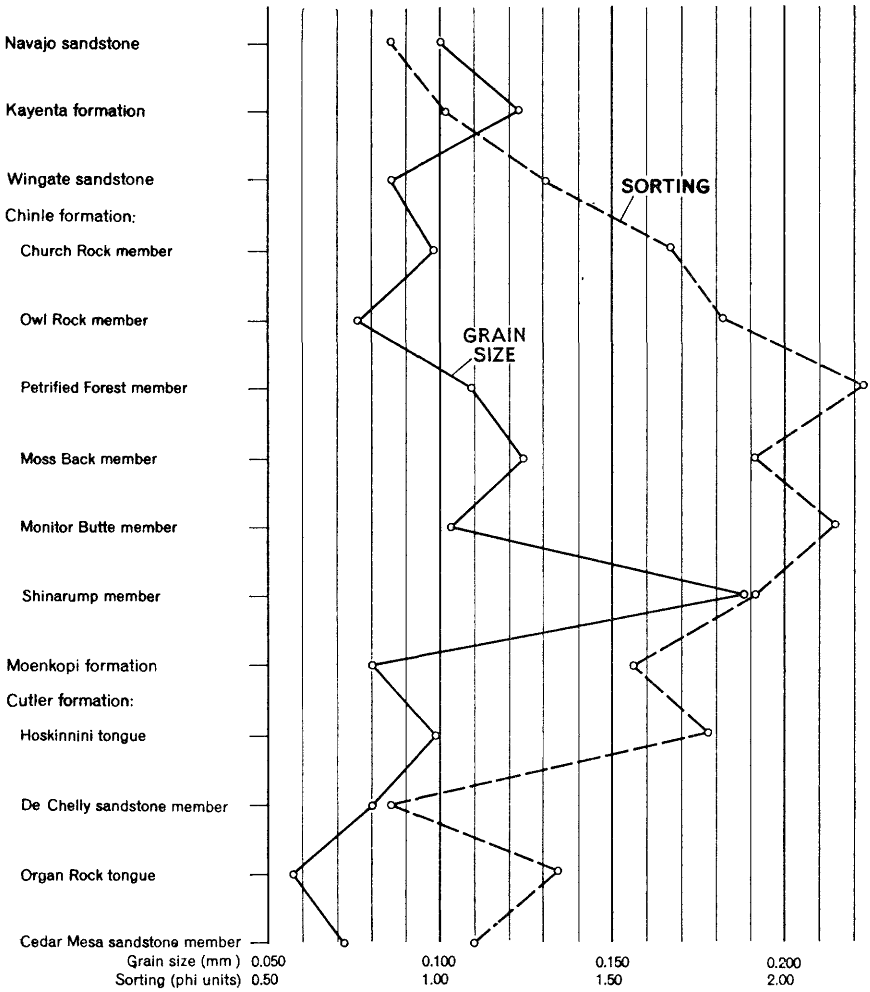

FIGURE 84.—Changes in average grain size and average sorting from Upper Permian to Lower Jurassic units in the central part of the Colorado Plateau.

The two curves present an interpretive summary of general tectonic activity during the period covered. The projection of the grain-size curve to the right may be read as an indication of movement of coarser material from the source areas into the basin of deposition. The projection of the sorting curve to the right is an indication of an increased rate of deposition, based on the assumption that the slower the rate of deposition is, the better sorted the sediments will be.

One other characteristic used in interpretation is the structure of the sedimentary unit as observed in the field. A massive thick-bedded sandstone unit with large-scale cross-strata and fairly extensive regional distribution is interpreted as eolian in origin, but it should be noted that even if the unit were of marine origin the tectonic significance would be the same. Units that have even, regular bedding suggest continuous deposition and little or no erosion or reworking. Units that have irregular bedding, cut-and-fill structure, or local erosional disconformities suggest discontinuous deposition accompanied by much erosion and reworking of deposits which in turn suggests deposition in a slowly subsiding basin where rate of burial is not fast enough to prevent reworking.

When interpreting change, certain reference points must be recognized. A reference point would be an interpretation attached to a particular type of sediment such as an eolian sandstone unit. An eolian sandstone unit or a unit resembling eolian sandstone would suggest or be interpreted as evidence of quiescence in the basin of deposition.

Interpreting the changes illustrated on figure 84, the Cedar Mesa sandstone member of the Cutler formation has many of the criteria of an eolian sandstone unit and represents conditions of quiescence in the basin area, and probably in the region, which resulted in an interval of decreased erosion in the source area and a very slowly subsiding basin of deposition. The unit is classified as a marginal terrestrial deposit.

The Organ Rock tongue of the Cutler formation is marked by a decrease in grain size and a decrease in the degree of sorting which, combined with the depositional structures, is interpreted as indicating more rapid deposition brought about by faster subsidence of the basin. The unit is classified as a marginal terrestrial deposit.

The De Chelly member of the Cutler is marked by an increase in grain size and an increase in the degree of sorting which, in view of the eolian characteristics of the unit, is interpreted as a return to quiescent conditions with continued, slow erosion in the source areas and decreased deposition in a very slowly subsiding basin. The De Chelly is classified as a marginal terrestrial deposit.

The Hoskinnini tongue of the Cutler formation is marked by an increase in grain size and a decrease in the degree of sorting. This change, combined with irregular bedding, suggests moderate tectonic uplift in the source area which resulted in increased erosion with some increase in deposition in a slowly subsiding basin. The Hoskinnini is classified as a marginal terrestrial deposit.

The Moenkopi formation, which has a decrease in grain size, slightly improved sorting, and regular bedding, is interpreted as representing a slightly decreased rate of erosion in the source area accompanied by deposition in a basin which was subsiding at an increased rate.

The Moenkopi is classified as a marginal terrestrial-marginal marine deposit.

The Shinarump member of the Chinle formation is marked by an abrupt increase in grain size and a decrease in the degree of sorting. These changes, in light of the irregular, discontinuous bedding features and large erosional cuts, are interpreted as indicating marked regional uplift, tectonic uplift in the source area—resulting in increased erosion—and little if any subsidence in the basin of deposition. The unit is classified as a terrestrial deposit. The occurrence of altered tuffaceous material in the unit indicates that the tectonic activity was accompanied by volcanic activity.

The Monitor Butte member of the Chinle formation is marked by a decrease in grain size and a decrease in the degree of sorting. These changes, combined with the more regular bedding and amount of clay present, are interpreted as indicating continued tectonic activity in the source areas, rapid erosion, and increased deposition in a subsiding basin. Volcanic activity continued. The unit is classified as a terrestrial deposit.

The Moss Back member of the Chinle is marked by an increase in grain size and an increase in the degree of sorting. These changes together with irregular bedding and erosional features of moderate relief within the deposit, are interpreted as indicating continued tectonic activity in the source areas and a decreased rate of subsidence in the basin. Volcanic activity continued. The unit is classified as a terrestrial deposit.

The Petrified Forest member of the Chinle is marked by a decrease in grain size and a decrease in the degree of sorting. These changes, combined with irregularly bedded sandstone and relatively thick bentonitic claystone and siltstone units, are interpreted as indicating continued volcanic activity, continued tectonic uplift, rapid erosion in the source areas, and moderate to rapid subsidence in the basin of deposition, with intervals, at least locally, when subsidence halted for short periods. The unit is classified as a terrestrial deposit.

The Owl Rock member of the Chinle formation is marked by a decrease in grain size and an increase in the degree of sorting. These changes viewed with respect to changes in lithologic character are interpreted as indicating a substantial decrease in tectonic activity in the source area, reduced erosion, minor volcanism, and slower subsidence of the basin of deposition. The unit is classified as a marginal terrestrial deposit.

The Church Rock member of the Chinle formation is marked by an increase in grain size and a further increase in the degree of sorting. These changes and the combination of regular and irregular bedding are interpreted as indicating almost no tectonic activity and continued slow erosion in the source areas, a decrease in deposition, and slower subsidence of the basin of deposition. The unit is classified as a terrestrial deposit.

The Wingate sandstone is marked by a decrease in grain size and a continued increase in the degree of sorting. These changes, the eolian structure of the Wingate, and the erosional contact at the base are interpreted as indicating regional quiescence brought about by minor uplift in the basin of deposition during a time of tectonic inactivity and slow erosion in the source areas. The Wingate was deposited under conditions of gradual subsidence in the basin following the uplift which preceded deposition. The unit is classified as a terrestrial deposit.

The Kayenta formation is marked by an increase in grain size and a continued increase in the degree of sorting. These changes, combined with irregular bedding and erosion surfaces in the unit, are interpreted as indicating minor uplift in the source areas, a resulting increase in erosion but a continued decrease in the rate of deposition, and little or no change in the slow subsidence of the basin of deposition. The unit is classified as a terrestrial deposit.

The Navajo sandstone is marked by a decrease in grain size and a continued increase in the degree of sorting. These changes, combined with the eolian structure, are interpreted as indicating general regional quiescence with very slow deposition and very slow subsidence in the basin of deposition. The unit is classified as a terrestrial deposit.

Such a scheme of interpretation explains the relatively thin, widespread, but discontinuous nature of the Shinarump member of the Chinle formation. The regional uplift with initial erosion of the Moenkopi plain followed by deposition of the Shinarump suggests that gravel, sand, and clay were deposited on a "high" if not rising surface with few of the opportunities of burial found in a subsiding basin. However, the sand is only moderately sorted, which suggests that reworking was not extensive. Reworking probably failed to improve sorting because of a huge sediment load being carried most of the time across the alluvial plain.

Other parameters resulting from statistical analysis of the grain-size distributions, such as the measure of peakedness, may eventually be usable in the interpretation of the petrology of Triassic and associated sediments, but sufficient data have not yet been accumulated, and further study is necessary.

SUMMARY OF STRATIGRAPHIC AND PETROLOGIC INTERPRETATIONS

Integration of the preliminary conclusions and interpretations derived from all lines of investigation in the stratigraphic and petrographic study provides an historical account of the paleogeology and tectonic background of the sediments deposited during part of the Permian and Triassic periods and the early part of the Jurassic period. The part of the continental area where sediments accumulated, as discussed in this summary, includes the southeastern quarter of the State of Utah and adjoining 50-mile overlap into Colorado, New Mexico, and Arizona.

In Permian time the area east and southeast of what is now the Colorado Plateau region was marked by extreme tectonic uplift of granitic and metamorphic terranes—possibly the Uncompahgre-San Luis highlands. The rising highlands contributed thick wedge-shaped deposits of arkosic sediments along their western flanks. These deposits form the conglomeratic facies of the Cutler formation of western Colorado and eastern Utah; simultaneous with deposition they were reworked and the finer material transported by streams into a continental area of sedimentary accumulation in southeastern Utah. Conditions in the basin alternated between slow subsidence and quiescence which resulted in the deposition of the reddish siltstone members and yellowish-gray sandstone members of the Cutler. Slow subsidence brought in arkosic material from the east that formed the reddish siltstone Halgaito, Organ Rock, and Hoskinnini tongues of the Cutler formation. Quiescence resulted in the slow accumulation of eolian sand derived from northwest of southeastern Utah that formed the light-colored sandstone Cedar Mesa, De Chelly, and White Rim members of the Cutler formation and the equivalent Coconino sandstone. Contemporaneous with the deposition of all or part of the reddish siltstone and yellowish-gray sandstone members, limestone units were being deposited in the sea to the west; these form the Kaibab limestone of central and north-central Utah and northern Arizona.

At the end of Cutler deposition adjustments in the level of parts of the basin resulted in erosion in some areas while deposition continued uninterrupted in other areas. Parts of the Kaibab limestone deposited in the western sea in central Utah were exposed to erosion and were redeposited as conglomerate at the base of sediments now assigned to the Moenkopi formation of Early and Middle(?) Triassic age.

Early Triassic time was marked by general subsidence and a gradual advance of the shallow sea from the west and northwest. Part of the sediments of the Moenkopi formation probably was derived from erosion of the conglomeratic facies of the underlying Cutler formation. Moderate uplift and erosion of the Uncompahgre-San Luis highlands may have continued to contribute sediments. Some coarse sediments accumulated along the flanks of the highland, and deposition of sediments of the Moenkopi formation occurred at a moderate rate in the subsiding basin. Tidal flats in advance of the shallow sea occupied the basin during much of Early Triassic time and resulted in widespread ripple marks in the sandy siltstone of the basal part of the Moenkopi. The advancing shallow sea deposited the Sinbad limestone member of the Moenkopi in central Utah. Following the deposition of the Sinbad limestone member the environment of deposition returned to predominantly that of a tidal flat. Minor adjustments in subsidence of the basin of accumulation or uplift in the source area resulted in the deposition of thick cross-stratified very fine grained sand units far out in the basin. Following the adjustment in middle Moenkopi time, deposition continued at a moderate rate in the subsiding basin in a dominantly tidal-flat environment.

At the end of Moenkopi time, regional uplift of the Triassic basin of deposition and associated highlands resulted in an interval of erosion which developed a stream-cut surface on the top of the Moenkopi sediments. Uplift of granitic and volcanic source areas, probably south of the Colorado Plateau started deposition of Chinle sediments of Late Triassic age. Chinle deposition probably took place on an alluvial plain of low relief. Some basal Chinle deposits included reworked Moenkopi sediments. The Temple Mountain member and lithologically similar strata may contain a high proportion of such reworked sediments.

After deposition of the initial reworked sediments, coarse material including granite wash, volcanic material, and quartzose pebbles spread out over the area and formed the widespread coarse-textured Shinarump member of the Chinle formation.

The sediments of the Monitor Butte member indicate conditions of continued rapid erosion in the source areas and an increase in deposition owing to the moderate increase in rate of subsidence of the basin. Ripple laminations and generally horizontal bedding in the sandstone units, plus an increase in the amount of mudstone, are evidence of gentler currents than those responsible for deposition of the Shinarump.

Interruption of the subsidence resulted in the deposition of slightly reworked coarser sediments with strong fluvial characteristics such as those that constitute the Moss Back sandstone and similar sandstone units in the lower part of the Chinle.

Volcanism increased in intensity, resulting in the deposition of great quantities of volcanic debris in the southern part of the basin to form the Petrified Forest member of the Chinle. Deposition in the subsiding basin was rapid with intervals of reduced subsidence which resulted in some reworking of the sediment under fluvial conditions to produce strata of coarser average texture.

The long period of deposition in an alluvial-plain environment ended in Late Triassic time as volcanism and uplift in the source areas decreased or ceased altogether. Subsidence in the basin continued at a reduced rate but was fast enough to keep the basin flooded with water. The decreased rate of deposition and a lake or lagoonal environment resulted in deposition of the limestone and limy-siltstone strata identified as the Owl Rock member.

Further decrease in the rate of subsidence of the basin, together with the slow rate of erosion in the source areas, changed the environment to an emerging plain with mixed low-velocity fluvial and shallow-water "mud-flat" conditions to produce the flat-bedded partly cross-stratified silty sandstone units of the Church Rock member of the Chinle formation.

The deposition of the last Chinle sediments was interrupted by a slight uplift of the basin which was followed by a period of moderate erosion and moderate reworking of the sediments on the emergent plain, resulting in some deposition in low or slightly subsiding areas and slight scouring in more positive areas. This short period of adjustment was followed by a quiescent period of considerable duration. Windblown sediments partly derived from underlying Chinle and from sources to the northwest accumulated to form the eolian strata of the Wingate sandstone.

This cycle of eolian deposition was interrupted by moderate uplift to the east, possibly in the Uncompahgre-San Luis highlands area, which resulted in a movement of some granitic material into the basin and a substantial amount of erosion and reworking of eolian sand by westward-flowing streams to form the Kayenta formation. Little or no change occurred in the rate of basin subsidence, so that with the cessation of the uplift the continued stability of the basin area rapidly reinstituted conditions of quiescence. Eolian deposition of sand from the northwest resulted in the accumulation of the strata assigned to the Navajo sandstone.

TABLE 13.—*Mean or average measures of the properties of the phi (grain-size) distribution of sediments in some Permian, Triassic, and Jurassic sandstone and coarse siltstone from the Colorado Plateau*

Formation	Location	Number of samples	Grain size (millimeters): Mean and range	Grain size (millimeters): Mode and range	Grain size (millimeters): Median and range	Standard deviation and range (phi units)	Skewness and range (phi units)	Kurtosis and range (phi units)
Navajo sandstone	Southeast Utah, northeast Arizona, southwest Colorado.	22	0.100 0.156– .072	0.099 0.138– .062	0.107 0.154– .075	0.854 1.440– .510	1.298 2.211– .059	12.883 30.500– .733
Kayenta formation	do	19	.123 .244– .067	.137 .258– .074	.140 .253– .082	1.005 1.521– .654	1.474 2.232– .621	13.506 28.704– 2.299
Wingate sandstone	do	44	.086 .175– .032	.093 .210– .044	.098 .208– .045	1.031 1.792– .523	1.404 2.301– .329	13.154 29.700– 4.714
Chinle formation (undifferentiated).	Western Colorado	7	.059 .116– .034	.078 .149– .044	.075 .151– .044	1.254 1.377– 1.099	1.114 1.493– .852	6.201 10.248– 2.781
Church Rock member	Southeast Utah	7	.098 .209– .039	.172 .353– .044	.145 .337– .046	1.668 2.507– 1.119	1.145 1.641– .607	6.737 12.386– .719
Owl Rock member	do	4	.076 .146– .035	.123 .210– .031	.105 .210– .044	1.822 2.287– 1.478	.862 1.359– .365	3.885 8.296– .170
Petrified Forest member	do	4	.089 .094– .048	.186 .250– .148	.168 .209– .151	2.225 2.723– 1.975	1.014 1.277– .613	3.604 5.976– .213
Moss Back member	do	13	.124 .260– .048	.228 .490– .098	.195 .402– .087	1.905 3.173– 1.113	1.075 1.678– .466	5.493 16.345– .413
Monitor Butte member	do	12	.103 .331– .050	.221 .557– .096	1.88 .461– .076	2.145 3.454– .995	.945 1.612– .531	4.119 15.026– .226
Shinarump member	Southeast Utah, northeast Arizona.	83	.188 .616– .034	.275 .593– .043	.251 .663– .045	1.914 3.568– 1.063	.959 2.051– .318	6.281 21.088– .940
Moenkopi formation	do	21	.080 .374– .036	.111 .590– .037	.109 .563– .042	1.560 2.242– .976	1.145 1.710– .433	7.140 17.097– 1.066
Cutler formation (undifferentiated).	Southwest Colorado	2	.367 .553– .181	.391 .553– .229	.421 .623– .218	1.611 1.962– 1.260	1.038 1.383– .693	7.580 11.302– 3.858
Hoskinnini tongue	Southeast Utah, northeast Arizona.	13	.098 .195– .033	.131 .241– .043	.124 .235– .044	1.777 2.224– 1.335	.921 1.370– .537	4.957 11.060– 1.033
De Chelly sandstone member	Southeast Utah	7	.080 .116– .057	.082 .139– .062	.084 .130– .062	.859 .990– .689	1.399 1.780– 1.000	13.190 17.747– 9.478
Organ Rock tongue	do	14	.057 .122– .033	.065 .109– .044	.066 .104– .044	1.342 1.703– .982	1.350 2.782– .783	10.356 28.279– 3.561
Cedar Mesa sandstone member.	do	7	.072 .098– .038	.076 .104– .045	.083 .114– .050	1.103 1.411– .725	1.533 2.022– .827	12.406 21.935– 3.243

TABLE 14.—*Mineralogic composition, in percent, of samples of the Shinarump member of the Chinle formation as determined by point-count analyses of thin sections*

Location	Sample	Detrital components								Rock components	
		Quartz	Potassium feldspar	Kaolin	Hydro-mica	Quartzite	Tuffaceous material	Plagioclase	Mica	Total detrital	Total chemical
Arizona											
Navajo County:											
Monument Valley area:											
Owl Rock section	L-660	60.4	8.1	25.9	2.4	0.0	0.0	1.8	1.4	99.0	1.0
	661	70.9	8.4	17.9	.8	.4	.2	1.0	.4	98.2	1.8
	662	63.7	8.8	20.1	3.4	1.4	.8	1.0	.8	95.4	4.6
Utah											
Garfield County:											
Circle Cliffs area:											
Muley Twist section	L-1012	88.5	3.6	4.7	0.2	0.0	2.6	0.2	0.2	94.0	6.0
The Peaks section	1017	70.9	10.9	13.1	.4	.0	2.7	1.6	.4	97.4	2.6
	1019	74.2	8.1	14.1	.0	.8	1.6	.8	.4	99.2	.8
Silver Falls, section B	1007	62.9	6.2	19.7	.2	.2	10.0	.4	.4	94.2	5.8
	1009	70.5	3.4	21.0	1.3	.0	3.4	.4	.0	95.0	5.0
Kane County:											
Paria area	CD-794	73.1	9.8	9.0	.2	.2	7.1	.0	.6	96.0	4.0
	L-1098	68.4	5.7	2.6	.0	.0	23.1	.0	.2	98.0	2.0
San Juan County:											
White Canyon area:											
Frey Canyon section	1049	57.7	11.2	13.3	2.4	.0	14.3	.7	.4	57.2	42.8
	1050	87.6	5.0	7.0	.2	.0	.2	.0	.0	99.6	.4
Happy Jack mine and area	258	90.2	2.1	3.7	.0	3.1	.0	.0	.9	65.6	34.4
	261	69.8	2.5	26.3	.0	1.2	.0	.2	.0	98.0	2.0
	259	82.1	1.0	13.9	.0	1.8	.6	.6	.0	99.6	.4
	260	64.7	4.4	29.4	.0	1.1	.4	.0	.0	94.8	5.2
	1043	98.6	.7	.0	.2	.0	.5	.0	.0	84.8	15.2
Monument Valley area:											
Monument No. 2 mine	841	75.1	2.8	11.8	4.9	1.0	1.4	1.4	1.6	98.6	1.4
	842	65.1	4.0	28.9	1.0	.2	.2	.6	.0	99.0	1.0
	871	78.1	.6	8.4	9.9	.8	2.0	.2	.0	99.6	.4
	872	93.2	.2	2.9	1.2	.8	1.7	.0	.0	97.2	2.8
	873	84.3	.4	11.6	2.5	.8	.0	.0	.4	98.4	1.6
	883	85.8	2.2	5.3	5.9	.2	.2	.0	.4	98.6	1.4
Monitor Butte section	906	76.3	7.2	5.2	.7	1.1	9.5	.0	.0	88.4	11.6
	907	71.7	4.7	13.1	3.2	.4	3.9	.2	2.8	99.0	1.0
Poncho House section	901	81.2	.2	13.5	.2	.0	4.8	.1	.0	99.2	.8
Wayne County:											
Capitol Reef area:											
Pleasant Creek section	1005	69.0	17.0	7.2	.0	.4	5.7	.7	.0	91.6	8.4
East of Torrey section	1027	76.4	8.3	11.3	.2	.6	2.2	.4	.6	99.0	1.0

TABLE 15.—*Mineralogic composition, in percent, of samples of the Monitor Butte member of the Chinle formation as determined by point-count analyses of thin sections*

Location	Sample	Detrital components								Rock components	
		Quartz	Potassium feldspar	Kaolin	Hydromica	Quartzite	Tuffaceous material	Plagio-clase	Mica	Total detrital	Total chemical
Utah											
Garfield County:											
Circle Cliffs area:											
Muley Twist section	L-1119	71.8	4.6	10.7	10.3	.0	0.8	1.0	0.8	95.6	4.4
	1120	72.0	5.1	14.5	.9	.2	3.1	1.3	2.9	89.6	10.4
The Peaks section	1126	57.2	10.9	10.1	1.7	.0	18.5	.4	1.2	97.2	2.8
	1128	73.4	8.6	9.6	.5	.7	6.7	.0	.5	83.4	16.6
Silver Falls section B	1118	84.4	4.0	4.0	2.3	.3	4.7	.0	.3	60.2	39.8
Kane County:											
Paria area	CD-796	49.2	7.5	9.7	.7	1.3	31.0	.2	.4	90.4	9.6
	798	61.3	9.4	15.5	2.6	.0	9.4	.4	1.4	98.2	1.8
San Juan County:											
White Canyon area:											
Frey Canyon section	L-1184	80.5	.0	8.6	7.4	.0	1.9	.8	.8	97.2	2.4
	1185	89.1	.0	3.8	3.1	.0	2.0	1.3	.7	89.2	10.8
Happy Jack mine and area	1106	83.0	5.5	2.1	.6	.3	7.0	.6	.9	65.6	34.4
	1181	91.8	5.7	1.1	.0	.0	1.4	.0	.0	55.8	44.2
	1182	91.5	1.5	2.9	2.9	.0	1.0	.0	.2	81.8	18.2
Monument Valley area:											
Monitor Butte section	908	84.1	.5	3.8	8.4	.2	1.4	1.6	.0	88.6	11.4
Poncho House section	900	86.9	.0	6.0	3.3	.0	2.5	1.3	.0	96.2	3.8
Wayne County:											
Capitol Reef area:											
Pleasant Creek section	1112	57.1	13.3	17.4	5.3	.0	2.3	2.0	2.5	97.4	2.6
	1113	65.5	11.2	13.8	1.4	.0	6.7	.2	1.2	98.2	1.8
	1114	47.8	9.6	32.9	8.1	.2	.2	.5	.7	85.8	14.2

TABLE 16.—*Mineralogic composition, in percent, of samples of the Moss Back member of the Chinle formation as determined by point-count analyses of thin sections*

Location	Sample	Detrital components								Rock components	
		Quartz	Potassium feldspar	Kaolin	Hydro-mica	Quartzite	Tuffaceous material	Plagioclase	Mica	Total detrital	Total chemical
Utah											
Emery County:											
San Rafael Swell area:											
Temple Mountain	L-252	67.4	7.8	20.2	0.0	0.0	0.8	3.4	0.4	95.2	4.8
	254	64.6	4.3	24.1	2.6	.4	.4	2.8	.8	98.8	1.2
San Juan County:											
White Canyon area:											
Frey Canyon section	1107	63.5	1.4	5.6	27.1	.0	1.0	.2	1.2	97.4	2.6
	1108	78.5	1.0	6.0	8.2	.0	4.6	.5	1.2	83.0	17.0
Happy Jack mine	1102	78.0	4.9	3.6	.2	.0	12.7	.2	.4	94.6	5.4
	1105	82.2	5.2	1.2	.1	.0	10.9	.4	.0	98.8	1.2

TABLE 17.—*Mineralogic composition, in percent, of samples of the Petrified Forest member of the Chinle formation as determined by point-count analyses of thin sections*

Location	Sample	Detrital components								Rock components	
		Quartz	Potassium feldspar	Kaolin	Hydro-mica	Quartzite	Tuffaceous material	Plagioclase	Mica	Total detrital	Total chemical
Utah											
San Juan County Comb Wash area	L-886	57.8	3.8	0.0	5.8	0.0	31.6	0.2	0.8	99.6	0.4
	945	46.4	10.9	1.2	7.4	.0	32.9	.6	.6	99.6	.4

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INDEX