Geology and Uranium-Vanadium Deposits of the Monument Valley Area Apache and Navajo Counties, Arizona

GEOLOGICAL SURVEY BULLETIN 1103

Prepared on behalf of the U.S. Atomic Energy Commission

Geology and Uranium-Vanadium Deposits of the Monument Valley Area Apache and Navajo Counties, Arizona

By IRVING J. WITKIND *and* ROBERT E. THADEN

With sections on SERPENTINE AT GARNET RIDGE

By HAROLD E. MALDE *and* ROBERT E. THADEN

and MINERALOGY AND PARAGENESIS OF THE ORE DEPOSIT AT THE MONUMENT NO. 2 AND CATO SELLS MINES

By DONALD H. JOHNSON

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GEOLOGY AND URANIUM-VANADIUM DEPOSITS OF THE MONUMENT VALLEY AREA, APACHE AND NAVAJO COUNTIES, ARIZONA

By Irving J. Witkind and Robert E. Thaden

ABSTRACT

In 1951 and 1952, the U.S. Geological Survey undertook, on behalf of the U.S. Atomic Energy Commission, a program of geologic mapping and uranium investigations in Apache and Navajo Counties, northeastern Arizona. The area studied encompasses the southern half of Monument Valley, and includes three 15-minute quadrangles covering about 700 square miles.

Exposed consolidated sedimentary strata range in age from the Halgaito tongue of the Cutler formation (Permian) to the Salt Wash member of the Morrison formation (Jurassic). Minettes and vogesites form volcanic plugs and dikes and are exemplified by Agathla Peak and the Porras Dikes. On Garnet Ridge are several rubble pipes filled with rounded cobbles and boulders in a matrix of serpentine.

Extensive surficial deposits, predominantly dune sand and alluvium, veneer mesa tops and valley floors.

The dominant structural element is the Monument upwarp, whose south end is in this area. On this major feature are superimposed (1) the Organ Rock anticline, (2) the Oljeto syncline, (3) the Agathla anticline, (4) the Tse Biyi syncline, and (5) the Gypsum Creek dome. Fractures cut all strata. Faults are rare but joints are common and widespread.

Uranium-vanadium ore deposits are in the Shinarump member of the Chinle formation (Late Triassic), a light-gray crossbedded conglomeratic sandstone. Commonly, conglomerate is at the base of the Shinarump and grades upward into finer sedimentary rocks, with a medium- to coarse-grained sandstone near the top. The Shinarump caps most of the isolated mesas and buttes and normally appears as a cliff about 50 feet thick. It rests unconformably on the top of the Moenkopi formation of Early and Middle(?) Triassic age. The unconformity is marked by elongate shallow depressions, termed "swales", cut in the top of the Moenkopi. These swales are as much as 3 miles wide and have a relief of about 50 feet. Local relief on the unconformity does not exceed 5 feet except where symmetric and asymmetric channels are scoured as much as 75 feet into the underlying strata. These channels range from about 15 feet to as much as 2,300 feet in width.

Sixty-two channels and channel segments were noted; of these, 18 have mineralized exposures. Nine of the channels are described, including the Monument No. 1 and Monument No. 2 channels, which have been and are being mined (1953).

The Monument No. 2 channel, one of the richest uranium-vanadium deposits in the Monument Valley area, is a short channel that strikes N. 18° W. and is about 1¾ miles long. It ranges in width in its central part from 400 to 700 feet and has been cut about 50 feet into the underlying strata. The major part of the channel is occupied by the Vanadium Corporation of America's Monument No. 2 mine. During mine mapping, four types of ore bodies were noted: rods, tabular ore bodies, corvusite-type ore bodies, and rolls. The rods are cylindroidal bodies about 3 to 5 feet wide, 2 to 3 feet high, and 15 to 20 feet long. These rods are found only in the Shinarump member of the Chinle formation. The tabular ore bodies are blanketlike masses composed of channel sediments impregnated with yellow uranium-vanadium minerals. These ore bodies are 40 to 50 feet long, range in width from 20 to 30 feet, and are 3 to 5 feet thick. The corvusite-type ore bodies are irregular-shaped masses within which the rock is thoroughly penetrated by vanadium minerals. Sedimentary rocks of both the Shinarump member of the Chinle formation and the De Chelly sandstone member of the Cutler deposits are mineralized in this type of ore body. The "rolls," the fourth type of ore body, are similar to those mined in the Morrison formation. Not all the channel strata that fill the Monument No. 2 channel contain ore; weakly mineralized ground alternatives at irregular intervals with richly mineralized ground, both laterally and vertically.

Swales and channels are important prospecting guides in the Monument Valley area. Other useful guides are (1) observable uranium minerals, (2) abnormal radioactivity, (3) channel fill, and (4) channel conglomerate containing carbonaceous matter. Guides of uncertain value are (1) limonitic impregnation of sandstone; (2) secondary copper minerals in channel fill; (3) abnormal thickness of an altered zone in the uppermost Moenkopi strata beneath channels; and (4) clay boulders, cobbles, and pebbles in channel fill.

Two tests for oil and gas have been drilled in the Monument Valley area. In 1924, the Midwest No. 1 Gypsum was completed to test the Gypsum Creek dome. It penetrated 2,083 feet to the Elbert formation of Late Devonian age, and although small shows of oil and gas were reported, the hole was abandoned. The most recent test, the Navajo A-1, was completed in 1953 on Hoskinnini Mesa, and was drilled to test the southern part of the Organ Rock anticline. The hole, which also bottomed in the Elbert formation, was abandoned as a dry hole after being drilled 4,523 feet. No oil or gas shows were reported. Other tests west and south of the Monument Valley area also have been unsuccessful. However, two recent Shell Oil Company tests about 50 miles to the northeast produce both oil and gas from anticlinal structures. As favorable strata and structures underlie the Monument Valley area, the area is deemed worthy of further investigation.

INTRODUCTION

PURPOSE OF WORK

In 1951 and 1952, the U.S. Geological Survey undertook, on behalf of the Division of Raw Materials of the U.S. Atomic Energy Commission, a program of uranium investigations and geologic mapping in the Monument Valley area, Apache and Navajo Counties, northeastern Arizona (fig. 1). The work had three major objectives: (1) to accumulate data basic to an understanding of the regional geology,

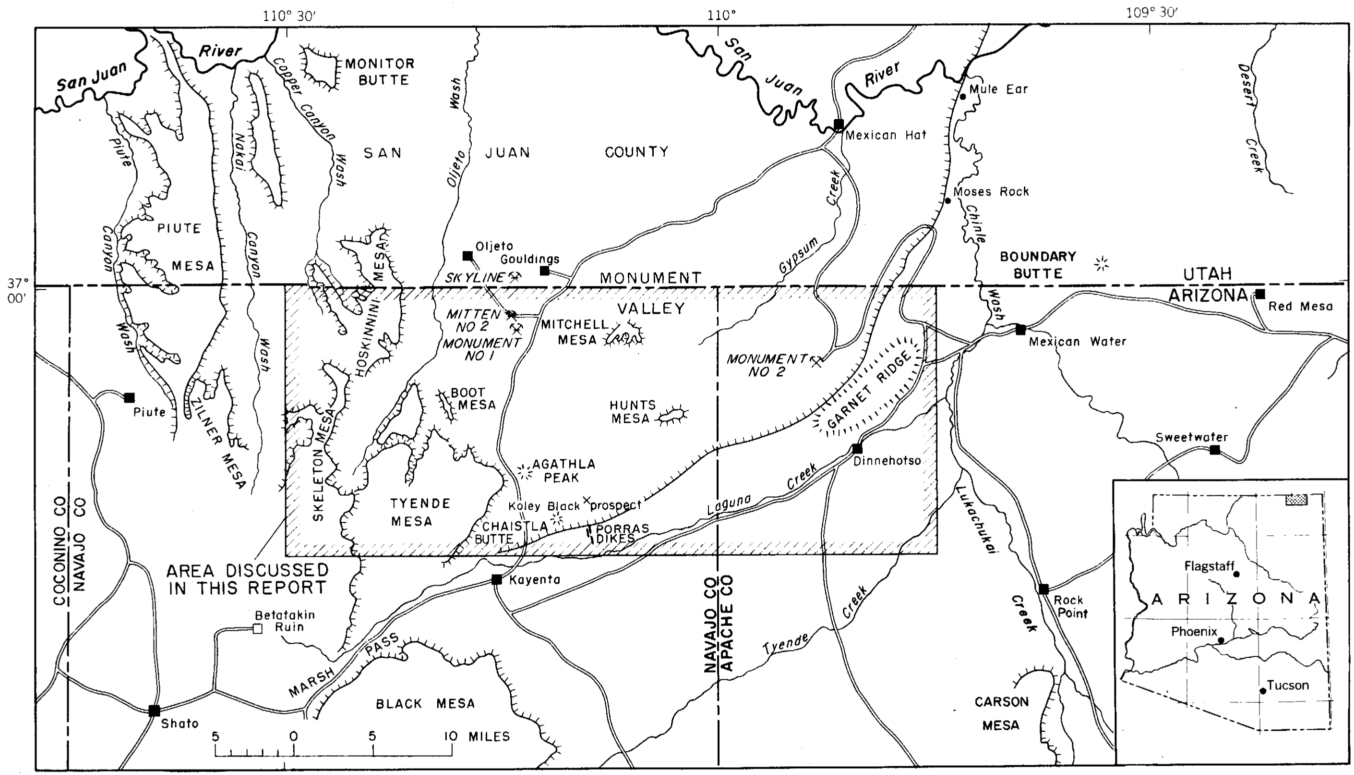

Figure 1.—Index map of parts of Apache and Navajo Counties, Ariz.

(2) to appraise the Triassic strata as host rocks for uranium deposits and to select areas favorable for exploration for concealed deposits, and (3) to study the controls that influence uranium deposition and from this study to establish guides useful in prospecting for uranium deposits.

FIELD METHODS

The geologic mapping was done on vertical aerial photographs at scales approximating 1:31,680, and 1:20,000. The geology was then transferred by inspection onto topographic maps at a scale of 1:48,000 to complete the geologist's final field copy.

A radioactivity survey in which areas of abnormal radioactivity were sampled was carried on concurrently with the mapping program.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the cooperation given by geologists of the U.S. Atomic Energy Commission, in particular, Ralph H. Wilpolt, John W. Chester, and John W. Hill.

Officials of the Vanadium Corporation of America kindly permitted us to map the workings of their Monument No. 2 mine. We are indebted for assistance to Mr. D. W. Viles, vice-president in charge of mining; Mr. Robert Anderson, former superintendent of the Monument No. 2 mine; and the late Mr. Carl Bell, mine foreman.

Among the many geologists who participated in the geologic mapping of the area were H. E. Malde, D. H. Johnson, T. L. Finnell, E. D. McKay, R. J. Claus, and C. F. Lough, all of the U.S. Geological Survey. Malde, Thaden, and Claus mapped the Garnet Ridge area (fig. 1) during a part of the summer of 1952. Finnell spent about 6 weeks at the Monument No. 2 mine in 1951, and while there developed hypotheses (Finnell, 1957) suggesting that fractures were instrumental in the introduction and localization of the ore. The local inhabitants advised and assisted in securing water and supplies.

GEOGRAPHY

LOCATION OF AREA

Monument Valley lacks clearly delineated geographic boundaries. It occupies parts of southeastern Utah and northeastern Arizona and is near the eastern border of these States. The northern part of the valley was studied by Baker (1936); the southern part is the area described in the present report. The Monument Valley area of this report extends from longitude 109°45′ W. to 110°30′ W., a distance of about 41 miles, and from near latitude 37°00′ N. to latitude 36°45′ N., about 17 miles. In all, the mapped area consists of three 15-

minute quadrangles and covers about 700 square miles (pl. 1). The three quadrangles occupy parts of Apache and Navajo Counties, Ariz., and a small part of San Juan County, Utah. The area is wholly within the Navajo Indian Reservation.

The Monument Valley area is within the central part of the Colorado Plateau and has much of the scenery, climate, and topography typical of that section of the country. The scenic features are due to pronounced differential erosion. The valley floor is marked by isolated mesas and ridges, castellated crags, fluted columns, and monuments, which give the valley its name (fig. 2). The altitude of the

FIGURE 2.—View northwest into Tse Biyi from crest of Hunts Mesa. Monuments rise about 800 feet above the valley floor.

area rises gradually from about 4,800 feet along the east edge to well over 7,000 feet along the west edge. The climate is arid and the region is a desert. Vegetation is sparse below 5,000 feet, but becomes more abundant and varied at higher altitudes. Most of the inhabitants are Navajo Indians whose principal occupations are grazing sheep and weaving rugs. All the white inhabitants live near trading posts at Kayenta and Dinnehotso, Ariz.; and Gouldings and Oljeto, Utah (fig. 1).

ROADS

Roads are poor and travel is difficult during or following severe sandstorms or rainstorms. Most automobile traffic is restricted to four principal roads, of which the most important is the Mexican

Hat-Kayenta road, known as Navajo Indian Reservation Route 1 (Utah Highway 47; fig. 1). It is the through route from Utah southward to Grand Canyon and Flagstaff, Ariz. Next in importance is the road that extends from the main uranium producer in this area, Vanadium Corporation of America's Monument No. 2 mine, to Mexican Water, Ariz. (fig. 1). The third road extends from the Monument No. 2 mine to Mexican Hat, Utah (fig. 1). Work during the summer of 1952 by both State and Federal highway agencies has so improved this road that the major part of it is suitable for all-weather traffic. The fourth road, passable during most of the year, extends northeastward from Kayenta to a junction southwest of Dinnehotso, and then turns southward to Chinle and Canyon de Chelly.

STRATIGRAPHY

Sedimentary units exposed range in age from Permian to Recent. In general the older rocks crop out in the north-central part of the report area, and younger rocks crop out on the east, west, and south sides. Scattered irregularly across all outcrops are deposits of dune sand, alluvium, and sand and gravel. Consolidated sedimentary rocks range in age from Permian to Jurassic and have an aggregate thickness of about 5,000 feet (pl. 2). Most of these strata consist of eolian and fluvial deposits which show some regularity in alternating one with another. In general, they range in color from light buff to deep reddish brown.

Many of the formations are made up of light-buff or reddish-brown massive or bedded sandstone. A prominent exception is the Chinle formation. The De Chelly sandstone member of the Cutler formation resembles the Wingate sandstone as well as the Navajo sandstone. The Organ Rock and Hoskinnini tongues of the Cutler formation are so alike that north of this area, in the vicinity of Monitor Butte (fig. 1), where the intervening De Chelly sandstone member pinches out, they are distinguished only with difficulty (Mullens, 1960, p. 277). Most of the units, however, are easily recognizable and the contacts are well exposed.

Wherever the massive sandstone beds are protected by a resistant caprock they form vertical cliffs; unprotected, they form rounded, steep-sided knolls alternating with deep narrow ravines.

PERMIAN SYSTEM

CUTLER FORMATION

The Cutler formation is exposed over a large area in the northern part of the Monument Valley area, Arizona. It crops out as far west as Copper Canyon and as far east as Comb Ridge. To the south, the Cutler dips below the surface just north of the Porras Dikes (fig. 1), due to the southward plunge of the Monument upwarp. Most of the mesas, buttes, and monuments are carved from the Cutler formation. The base of the formation is nowhere exposed in this area, although to the north Baker (1936, p. 28) reports extensive exposures of the entire formation.

The Cutler formation consists of five units; from oldest to youngest they are: the Halgaito tongue, the Cedar Mesa sandstone member, the Organ Rock tongue, the De Chelly sandstone member, and the Hoskinnini tongue. The De Chelly and Cedar Mesa are buff to gray massive cross-bedded sandstone. The Halgaito, Organ Rock, and Hoskinnini tongues are red fine-grained sandstone, siltstone, mudstone, and claystone. The Halgaito, Cedar Mesa, and Organ Rock maintain a uniform thickness over most of their area of exposure. The De Chelly thins northward and pinches out at Monitor Butte, but thickens both to the east and to the south. The Hoskinnini tongue thickens northward and thins eastward.

Diagnostic fossils were not found during the course of the present work, but Baker (1936, p. 29) reports that plant and vertebrate fossils from exposures of the Cutler formation in the Utah part of Monument Valley are of Permian age.

During most of Cutler time westward-flowing streams spread sediments across the area. The deposition of these beds was interrupted twice; once by the Cedar Mesa sandstone member which had a source area to the northwest, and the second time by the De Chelly sandstone member which came either from the southeast or northwest (Baker and Reeside, 1929, p. 1447). The Cutler is a thick series of red thin-bedded claystone, siltstone, and fine-grained sandstone into which two massive sandstone units interfinger. The lower sandstone, between the Halgaito and the Organ Rock tongues, is the Cedar Mesa, and the upper sandstone, separating the Organ Rock and the Hoskinnini tongues, is the De Chelly.

HALGAITO TONGUE

The Halgaito tongue, the basal member of the Cutler, is the oldest sedimentary rock exposed in the Monument Valley area, Arizona. It crops out in the core of Gypsum Creek dome (pl. 1), a small breached dome which straddles the Arizona-Utah State line just south of Mexican Hat, Utah.

The Halgaito forms a broad gentle dome in the central part of its outcrop area of about 8 square miles. The plain is bounded on all sides by beds of increasingly steep dip which form an annular pattern of cuestas and hogbacks, as much as 40 feet high.

The Halgaito characteristically weathers to a smooth dusty surface that is overlain by loose chips and flakes up to 3 inches in length.

In the Monument Valley area, Arizona, the Halgaito is a series of red shaly siltstone and fine-grained silty sandstone with a few small thin lenses of interbedded blue and gray limestone. Remarkably uniform in color, the rock is a moderate reddish brown with a gray cast (approximately 10*R* 4.5/3).[1] The major constituent of the Halgaito is poorly sorted subangular clear colorless polished quartz. Minor constituents are muscovite and a few grains of opaque minerals. The predominant grain size is about 0.02 mm, although many of the grains are as small as 0.003 mm and as large as 0.06 mm.

In any bed of the Halgaito tongue, the sequence of deposition is from coarse material at the base to fine material at the top. A shiny upper surface of clay, with glistening specks of muscovite, commonly represents the end of a sequence. Although most of the beds are from 1/16 to 1 inch thick, a few lenses of silt- pebble conglomerate are as thick as 8 feet. The well-rounded conglomerate pebbles are as much as 2 inches in long dimension. The conglomerate may extend several hundreds of feet, but invariably it grades laterally into typical thin-bedded Halgaito.

A thick iron-oxide stain on the grains gives the rock its brilliant color, but calcite, not iron oxide, is the principal cementing agent. The formation is limy to the extent that the local name for the Halgaito is the "red lime" (Gregory, 1938, p. 42).

Several lenticular limestone beds, not more than 8 inches thick, are in the upper part of the unit. They are blue, gray, or bluish gray and form small horizontal patches on a surface of low and gently rounded landforms. The limestone beds consist primarily of light-blue angular to rounded rough-surfaced concretionary limestone pellets, in a gray nearly lithographic limestone matrix. The pellets are as much as 2 inches in long dimension and give the limestone lenses a rubbly appearance.

The complete thickness of the Halgaito is not exposed in the Monument Valley area, Arizona. However, more than 300 feet of its upper part crop out and its base can be seen in Utah just north of the State line. It is reasonably certain that the Halgaito in the Monument Valley area is about the same thickness as the Halgaito section measured by Gregory (1938, p. 68) on the east flank of the Raplee anticline a few miles to the north. At that locality it is 402 feet thick.

The lower contact of the Halgaito, along the road near Mexican Hat, Utah, appears sharp and conformable with the underlying Rico formation of Pennsylvanian and Permian (?) age. Here the basal

[1] Numbers refer to the "Rock-Color Chart," distributed by the Geological Society of America in 1951 (Goddard and others, 1948.)

beds of the Halgaito are reddish-brown thin-bedded silty claystone or are gray to dark-brown lenticular rubbly limestone beds as much as 3 feet thick interbedded with the silty claystone. At none of the localities visited was a limestone in contact with the Rico.

The upper contact also appears conformable, although other workers (Prommel and Crum, 1927, p. 384; Gregory, 1938, p. 42) have noted local unconformities between the Halgaito and the overlying Cedar Mesa sandstone member in other areas. Typical Halgaito is terminated at the upper contact by light-green, light-blue, and nearly white limy siltstone beds of the basal Cedar Mesa which carry abundant nodules of brilliant red and white chalcedony. Except for this obvious lithologic change, nothing along the rather limited extent of exposed Halgaito-Cedar Mesa contact suggests unconformity between the two.

No fossils were discovered anywhere in the unit. Baker (1936, p. 30), however, reports vertebrate remains tentatively identified as either *Ephiacodon* or *Sphenacodon* from Halgaito exposures in the Utah part of Monument Valley, and Gregory (1938, p. 42) remarks that bone fragments found in the limestone lenses are diagnostic of a Permian age for the Halgaito.

The Halgaito represents the first sediments deposited by westward-flowing streams. East of the Monument Valley area, Cutler rocks are largely arkose. As these rocks are traced westward they become finer grained and pass into nonred beds west of the mapped area (Baker and Reeside, 1929, p. 1446). In the Monument Valley area the bedding and predominant silt size of the sediments imply deposition distant from the source area by relatively slow-moving streams. The thin interbedded blue and gray limestone and silt-pebble conglomerate suggest the presence of intermittent playa lakes. Dried chips and flakes formed when these playa lakes dried. These fragments were broken, rounded, and then incorporated into the next laid beds when the waters readvanced, forming conglomerate pebbles.

CEDAR MESA SANDSTONE MEMBER

The Cedar Mesa sandstone member of the Cutler formation crops out north of Meridian Butte (pl. 1) and flanks the Gypsum Creek dome on the east as low parallel hogbacks and on the west and southwest as low mesas and cliffs.

In the Monument Valley area, Arizona, the Cedar Mesa is predominantly a series of variegated sandstone, sandy siltstone, siltstone, limy siltstone, and limestone beds; a few beds are as thick as 30 feet. Lateral gradation of the strata of the Cedar Mesa with an accompanying change in color is well displayed.

Much of the Cedar Mesa is a moderate orangish-brown (5*YR* 5/5) well-sorted silty very fine grained quartz sandstone. The quartz grains are subround, covered by a faint iron-oxide stain, and average about 0.06 mm in diameter. The grains range in diameter from 0.03 to 0.09 mm. The only significant minor constituents are calcite and green grains of a chloritelike mineral. Calcite cement is abundant.

Another conspicuous lithic type in the Cedar Mesa is a light-brownish-gray (5*YR* 7/1) poorly cemented sandstone that has a pink cast. The quartz grains are subangular and average about 0.07 mm in diameter. The grains are clear, colorless, and are not stained. Sorting is only fair. Again, the only minor constituent of note is a green mineral of the chlorite group.

No good sites for measuring sections of the Cedar Mesa are available in the Monument Valley area, Arizona. However, several approximate measurements suggest an average thickness of about 315 feet. This thickness is much less than the 610 feet noted by Gregory (1938, p. 68) on the east flank of the Raplee anticline a few miles north of the mapped area.

The contact of the Cedar Mesa with the overlying Organ Rock tongue of the Cutler formation is poorly exposed. Where the contact is not covered by sand, it is concealed by a thick mantle of decomposed and disaggregated material. At the base of Meridian Butte (pl. 1), the contact is marked by an abrupt transition in color. The lower bed of the Organ Rock is a dark-reddish-brown micaceous siltstone with few sand grains. No evidence exists of an angular relationship between the units, nor is there any indication of an erosional surface. A disconformable surface with relief exceeding 15 feet is known in some areas north of the Arizona-Utah State line, but in the Monument Valley area the contact between the members is marked primarily by the color change.

The southward thinning of the Cedar Mesa and a change from sandstone in the north to thin-bedded interfingering sandstone and red shaly siltstone beds marks the first break in the deposition of red beds in the Cutler. The source of the Cedar Mesa is northwest of the area mapped (Baker and Reeside, 1929, p. 1447). Near its southern limit of deposition, south of the Monument Valley area, it loses its entity as a sandstone and becomes a transitional unit with sandstone beds (that is, Cedar Mesa) grading into typical red beds of the Cutler.

ORGAN ROCK TONGUE

The Organ Rock tongue of the Cutler formation is exposed throughout the northern half of the Monument Valley area, Arizona. It forms the floor of Copper Canyon (pl. 1) and comprises the pedestals upon which are perched the monuments for which Monument Valley is named.

Where the Organ Rock has no overlying protective rocks, it forms badlands characterized by steep concave slopes, shallow nearly vertical-walled gullies, flat-topped knobs, and sharp-ridged divides. Where capped by the De Chelly sandstone member, the Organ Rock stands as a gently concave slope that steepens near the top of the unit, and is nearly vertical at the contact.

The Organ Rock is predominantly a reddish-brown (10*R* 4/3) poorly sorted siltstone. Here and there, especially near the base of the unit, are a few white to buff very fine grained silty sandstone lenses a few inches thick. The grain size changes gradually in the upper 25 to 50 feet, becoming coarser near the contact. At the upper contact the Organ Rock is a fine-grained sandstone indistinguishable from basal De Chelly.

The silt grains are mostly angular to subangular clear colorless quartz with a pronounced iron-oxide stain. The average grain size is about 0.05 mm, but sorting is poor. Enough very small grains are included to make the member a clayey siltstone.

The cement appears to be a mixture of calcite and iron oxide. Splotches of clear calcite, up to several millimeters in diameter, are scattered throughout the member. This calcite has etched the quartz where they are in contact. Calcite also forms small bundles of subhedral crystals, each crystal being about the same size as the quartz grains. Other minor constituents include magnetite, gypsum, zircon, biotite, and muscovite.

The Organ Rock is dominantly even bedded, and the bedding is remarkably parallel throughout the unit, whether it be siltstone in beds 2 inches thick, or sandstone in beds 20 feet thick. Some of the siltstone and many of the sandstone beds show crossbedding gently inclined to the horizontal.

The Organ Rock is about 670 feet thick near the Monument No. 2 mine area (fig. 1). Baker (1936, p. 34) cites a thickness of 696 feet for the Organ Rock on the east side of Monument Pass, Utah. Gregory's measurements (Gregory, 1938, p. 46) in San Juan County, Utah, and measurements by Miser (1924a, p. 130–131) along the San Juan River demonstrate a southward thickening of the Organ Rock toward the Monument Valley area.

From a distance the contact between the Organ Rock and the overlying De Chelly appears sharp; the color changes from dark reddish brown to light brown, the slope changes from a steep angle to vertical, and bedding planes disappear. On the outcrop, however, these criteria are invalid. Upon close inspection it can be seen that the upper 25 to

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50 feet of the Organ Rock grades in color and in grain size to material that is megascopically identical to the De Chelly. The slope gradually steepens and approaches the vertical near, but not necessarily at, the contact. Nor can the lack of bedding planes be used to pick the contact, for the bedding planes, although closely spaced in the lower Organ Rock, are less closely spaced near the top of the member and persist into basal strata of the De Chelly for tens of feet. For mapping we selected a zone about 20 feet thick in which the bedding planes of the Organ Rock disappear, the steep slope of the Organ Rock gives way to the vertical cliff of the De Chelly, and the color changes from the dark reddish brown of the Organ Rock to the light tan of the De Chelly.

No fossils were found in the Organ Rock. Baker (1936, p. 35) reports the presence of two fossil plants of Permian age, as well as fragmental vertebrate remains that have also been identified as Permian in age.

At the close of Cedar Mesa deposition, westerly flowing streams began depositing another sequence of red beds which form the Organ Rock tongue. The even bedding and the fine grain of the red-bed sediments suggest that the streams were relatively sluggish. Near the close of Organ Rock deposition, light-colored sands from either the southeast or northwest (Baker and Reeside, 1929, p. 1447) gradually mingled with the red fluviatile sediments and eventually displaced them.

DE CHELLY SANDSTONE MEMBER

One of the most distinctive stratigraphic units in the Monument Valley area is the grayish-yellow to tan (5*Y* 8/4) massive crossbedded fine-grained De Chelly sandstone member of the Cutler formation. Commonly it is stained by wash from overlying units. The De Chelly sandstone member forms the main part of the monuments and larger mesas.

Wherever the De Chelly sandstone member is protected by overlying formations it forms unscalable vertical walls. The unit, however, is not extremely resistant and where unprotected weathers to round hummocky knolls. In places a great variety of alcoves, recesses, and tunnels have been formed at its base. These range in size from very small ones to great arched alcoves that are of a size sufficient to accommodate whole villages of cliff dwellings.

The De Chelly is a poorly sorted fine-grained sandstone with the grains ranging in size from 0.06 to 0.50 mm, although a bimodal grain-sized distribution exists. One grain size ranges from 0.25 to 0.50 mm (the average is about 0.30 mm) in diameter, the other ranges from about 0.06 to 0.12 mm (the average is about 0.10 mm). The grains range in shape from subround to round, but a few of the larger grains are overgrown by authigenic quartz and are angular. Most of the grains are of colorless quartz. However, small amounts of microcline, plagioclase feldspar, chalcedony, muscovite, biotite, and zircon are scattered at random throughout the sandstone. A thin brown film of iron oxide coats each grain, and it is this film that imparts color to the unit.

The sandstone is weakly cemented by chalcedony, calcium carbonate, and iron oxide; so the rock is friable.

The De Chelly ranges in thickness from 300 to 550 feet, and it thins and disappears to the north in the vicinity of Monitor Butte, about 15 miles north of the Utah-Arizona State line. In the western part of the Monument Valley area the De Chelly is about 300 feet thick and decreases rapidly in thickness northward to its pinchout. The De Chelly thickens in an easterly and southerly direction. In the center of Monument Valley, near Tse Biyi, it is about 450 feet thick. Farther east, near the Monument No. 2 mine (pl. 1), it is as much as 550 feet thick, and to the south, near Canyon de Chelly, beyond the limits of the mapped area, the De Chelly is well over 800 feet thick (McKee, 1934, p. 224).

A prominent and distinct disconformity unusually free of relief is at the top of the De Chelly (fig. 3). This disconformity is marked by

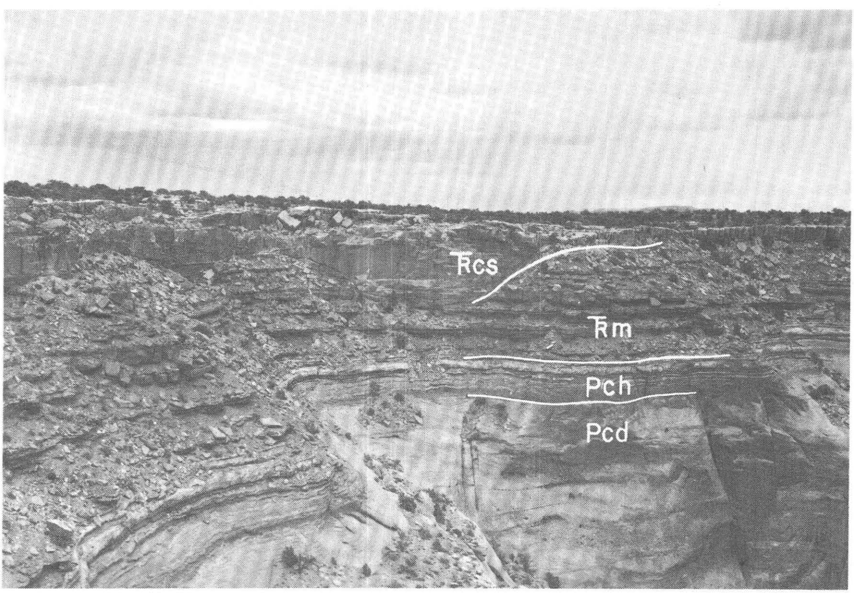

FIGURE 3.—Permian and Triassic formations showing relationship of a symmetrical channel (Mitchell Mesa No. 1) to other strata. Channel is scoured about 75 feet into underlying Moenkopi formation. Ꞧcs, Shinarump member of Chinle formation; Ꞧm, Moenkopi formation; Pch, Hoskinnini tongue of Cutler formation; and Pcd, De Chelly sandstone member of Cutler formation.

the abrupt change from the light-tan massive crossbedded De Chelly sandstone member to the dark-red even-bedded sandstone beds of the basal part of the Hoskinnini tongue of the Cutler formation. We consider these basal Hoskinnini strata to be a "reworked zone" composed partly of De Chelly sediments.

The top of the De Chelly, as here selected, differs from that chosen by Baker (1936). Baker recognized the disconformity but chose to include it and the "reworked zone" within the De Chelly. He indicates the boundary between the De Chelly and the overlying Hoskinnini as a gradational one marked by a series of beds 20 feet or more thick that show a gradual lithologic change from massive crossbedded sandstone to even-bedded red beds.

The disconformity, however, is so widespread and so persistent that we consider that it marks the boundary between two major stratigraphic units. The complete absence of fossils in the Hoskinnini prevents any conclusive determination as to the relative ages of the units involved; the base of the Hoskinnini may mark the rock-system break between the Permian and the Triassic. Lacking paleontologic evidence, the point of view expressed above is not followed on the map (pl. 1).

Fossils were not found in the De Chelly sandstone member although vertebrate and invertebrate footprints were noted in several localities. The best tracks have been discovered along the east edge of Todicheenie bench near the upper end of Adahchijiyahi Canyon (pl. 1). Baker (1936, p. 37) reports a lack of fossils in the De Chelly, although he found specimens of *Walchia piniformis* and *Yakia hetophylla* of known Permian age in the transitional beds that mark the change from the Organ Rock tongue to the De Chelly sandstone member.

The De Chelly is the uppermost of two sandstone beds that interfinger with typical red beds of the Cutler. The broad sweeping cross-laminae so typical of the De Chelly imply an eolian origin. The source of the sands that formed the De Chelly is unknown; however, the De Chelly interfingers with the red beds of the Cutler from the southeast and thickens in that direction. If the source area is considered to be near the greater thickness, it would appear that the De Chelly came from the southeast. Baker and Reeside (1929, p. 1447) note that the dominant dip of the crossbedding planes and the direction of thinning suggest a southeasterly source. They conclude, however, "It seems to the writers highly probable that all the light-colored sandstones came from the north or northwest."

HOSKINNINI TONGUE

The Hoskinnini tongue of the Cutler formation [2] is widespread in the Monument Valley area. Commonly, it crops out as a steep face but near the tops of many mesas and monuments, it weathers to a steep slope below the more gentle slopes formed by the shaly siltstone beds of the overlying Moenkopi formation. The extent of outcrop of the Hoskinnini is nearly coincident with that of the De Chelly. The type locality of the Hoskinnini is given by Baker and Reeside (1929, p. 1443) as the north face of Hoskinnini Mesa several miles west of Oljeto trading post on Moonlight Wash (that is, Oljeto Creek). The unit is so consistent in its makeup over such great distances that stratigraphic sections similar to the exposures at Hoskinnini Mesa can be found almost everywhere in the western part of the area.

The Hoskinnini tongue consists of a series of dark-red even-bedded nodular-weathering siltstone and fine-grained sandstone beds. In appearance the beds are similar to those of the Organ Rock tongue. In the Monitor Butte area, for instance, where the intervening De Chelly is absent, Baker (1936, p. 39) reports that the Hoskinnini is inseparable from the Organ Rock tongue of the Cutler formation. However, recent work by Thomas E. Mullens (1960, p. 277) of the U.S. Geological Survey in the Clay Hills area of Utah has suggested that the Hoskinnini can be differentiated from the Organ Rock tongue. Mullens has found that the Hoskinnini is a very fine grained sandstone containing abundant well-rounded medium-sized grains. This lithology, plus the smooth-surface weathering characteristic of the Hoskinnini in the Clay Hills area, Mullens contends, is adequate to separate the Hoskinnini from the underlying Organ Rock. Stewart and others (1959), using criteria established by Mullens, have traced the Hoskinnini northward from the Clay Hills area, where it is as much as 100 feet thick, to a pinchout in the middle of the White Canyon area, Utah.

In the Monument Valley area, Arizona, the Hoskinnini tongue can be divided into two units. Because of their thinness, however, these

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[2] Since this report was prepared, work by J. H. Stewart, of the U.S. Geological Survey, has suggested that the Hoskinnini is best assigned as the basal member of the Moenkopi formation (Stewart, 1959). The present report was prepared before the completion of Stewart's work, and to avoid further delays in the publication of this report the change in nomenclature proposed by Stewart and accepted by the Geological Survey has not been made. The Hoskinnini, therefore, both on the maps and in this report, is shown as the uppermost member of the Cutler formation.

divisions have been combined and mapped as one unit. The lower unit consists of an orange to dark-red massive sandstone which lies disconformably on the De Chelly, and the upper unit consists of the dark-red even-bedded sandstone of the type Hoskinnini. Locally, small discrete sandstone blocks of De Chelly are embedded in the lower sandstone of the Hoskinnini. Elsewhere, small tan whorls can be traced from the De Chelly into the basal few feet of the Hoskinnini. We consider this lower sandstone to be a reworked zone consisting in part of De Chelly, and in part of Hoskinnini sediments. In many places the reworked zone is missing and in these localities the dark-red even-bedded strata of the upper unit of the Hoskinnini tongue lie directly on the De Chelly.

Grains of two sizes are in the lower sandstone; some are distinctly coarse and average about 0.40 mm in diameter, although a few ellipsoidal grains are as much as 1.30 mm long. Smaller grains are dominant, and average about 0.06 mm in diameter. Much of the coarse material is within the small tan whorls that can be traced into the underlying De Chelly. The upper unit of the Hoskinnini consists of even-bedded fine-grained sandstone. In this unit, local lenses of siltstone and grit persist for lateral distances of 10 to 20 yards. Most of the grains range in shape from subangular to round with the coarser sediments slightly more angular, possibly as a result of authigenic quartz overgrowths.

The major constituent of the Hoskinnini is quartz; accessory minerals are plagioclase feldspar and chalcedony. Coating all grains is a thin film of iron oxide. Calcium carbonate is the principal cement.

The Hoskinnini thins eastward. Mullens (1960, p. 275) reports the Hoskinnini to be about 100 feet thick in the Red House Cliffs area. North of the Red House Cliffs it pinches out in the middle of the White Canyon area (Stewart and others, 1959). Baker (1936, p. 39) cites a thickness of 55 feet in the canyon of the San Juan River at the mouth of Nakai Creek, and about 50 feet near the northeast corner of Hoskinnini Mesa. In the Monument Valley area, Arizona, the Hoskinnini is about 45 feet thick along the flanks of Hoskinnini Mesa, but near the Monument No. 2 mine (pl. 1) it is only about 15 feet thick. It is missing from several of the monuments in the Utah part of Monument Valley (Baker, 1936, p. 39). However, at no place examined in the Arizona part of the Monument Valley area is the Hoskinnini absent.

The following section of the Hoskinnini tongue is characteristic:

Section of the Hoskinnini tongue of the Cutler formation measured at the southeast end of Hoskinnini Mesa, about 12 miles northwest of Agathla Peak.

Moenkopi formation.

Cutler formation, Hoskinnini tongue:

	Ft	in
Limestone, crinkly; contains mixture of calcite and pink quartz		3
Sandstone, even-bedded, dark-red	3	0
Limestone, crinkly; contains mixture of calcite and pink quartz		9
Siltstone, shaly, dark-red, thin-bedded, nodular-weathering	10	0
Sandstone, massive, dark-red, fine-grained, thin-bedded; weathers as rounded ledges	6	0
Sandstone, dark-red, massive, fine-grained	19	0
	39	0

Unconformity.

De Chelly sandstone member of Cutler formation.

Although the Moenkopi is reported (Longwell and others, 1923, p. 9), as unconformably overlying the Cutler formation, Baker (1936, p. 40–43) could find no evidence of the unconformity in the Utah part of Monument Valley. However, he cites several localities in the Arizona part of the Monument Valley area where this unconformity could be observed. We found no localities where the Moenkopi was unconformable on the Hoskinnini.

The upper contact of the Hoskinnini is gradational. Baker (1936, p. 40) selects the upper contact at a horizon 8 to 11 feet above two crinkly limestone beds. Both beds of limestone are unusually persistent in the western part of the Monument Valley area. They were not found, however, in the eastern part, possibly being replaced in that area by a persistent bed of white to gray fine-grained sandstone about 4 feet thick.

In most localities examined, the strata 8 to 11 feet above the crinkly limestone beds change from arenaceous even-bedded red beds to chocolate-colored beds composed of shaly siltstone. This change is expressed topographically by the transition from a steep slope formed by the red beds of the Hoskinnini to moderate slopes composed of the shaly siltstones of the Moenkopi formation.

Paleontologic evidence for the age of the Hoskinnini is lacking. Baker (1936, p. 40) suggests, on the basis of lithologic similarity to the sediments forming the Organ Rock tongue, that the Hoskinnini is Permian in age and represents the highest of the three red-bed tongues of the Cutler formation.

TRIASSIC SYSTEM

MOENKOPI FORMATION

Conformably overlying the Hoskinnini tongue of the Cutler formation are the chocolate-brown to dark reddish-brown (10*R* 3/4) easily eroded shaly siltstone and sandstone beds of the Moenkopi formation of Early and Middle(?) Triassic age. Where it is protected by a cap of the Shinarump member of the Chinle formation, the Moenkopi forms gentle to moderately steep talus-covered slopes; where unprotected, it is intricately dissected into a maze of canyons, ridges, low cliffs, benches, and isolated tables.

On weathered surfaces the Moenkopi is dark reddish brown (10*R* 5/4) with local areas of chocolate brown (10*R* 3/3). Its coloration is diagnostic and contrasts markedly with the light gray of the overlying Shinarump member of the Chinle formation and the light tan of the De Chelly. Fresh surfaces of the Moenkopi formation are light brown to pinkish brown. In places Moenkopi strata are a light yellowish gray (5*Y* 7/2) to a light olive gray (5*Y* 5/2). These have no great extent and laterally grade imperceptibly into the dark siltstone and sandstone beds of typical Moenkopi.

Distinctive features of the Moenkopi are many minor structures such as ripple marks, raindrop pits, and shrinkage cracks. Three main types of ripple marks were observed. The dominant type, confined principally to shaly siltstones, consists of even, asymmetrical, parallel crests and troughs, averaging about 1 inch from crest to crest. These current-type ripples have been called parallel ripple marks by McKee (1954, p. 57). The second type are cusplike and commonly appear as small basins about 3 inches in diameter. McKee (1954, p. 60) considers these as characteristic of stream deposits. In the Monument Valley area they are common in the sandstones. Interference ripples ("tadpole nests") are the third type and are relatively scarce. They resemble a honeycomb and appear as a series of small deep cells each about 1 inch in diameter, surrounded by sharp-crested walls. Raindrop pits and shrinkage cracks are found locally and are best preserved in the fine-grained sediments. In many places these shrinkage cracks ("mud-cracks") are filled with a fine-grained sand. Scattered throughout the siltstone are a few rounded quartz grains larger than silt size. The sandstone beds are fine grained with most of the grains ranging in diameter from about 0.1 mm to a maximum of about 0.3 mm. Most of the grains are angular to subangular. Colorless quartz is the major constituent, and accessory minerals are microcline, plagioclase feldspar, and mica. Zircon and garnet grains have been noted. All the grains are coated with a film of brown iron oxide. Calcium carbonate is the main binding agent, with both chalcedony and iron oxide cementing the grains.

Along the east and west flanks of Skeleton Mesa (pl. 1) lenticular beds of satin spar gypsum as much as 14 inches thick are intercalated in the shaly siltstone beds. Although gypsum in the Moenkopi is widespread in western Utah (McKee, 1954, p. 47), it is uncommon in the Monument Valley area.

Measured sections of the Moenkopi formation indicate a persistent and gradual thinning to the east. This conforms well to the regional pattern of the Moenkopi. McKee (1954, p. 76) reports that the Moenkopi is as much as 2,000 feet thick in western Utah and that it gradually thins eastward. In the Zion Park region the Moenkopi is more than 1,600 feet thick (Gregory, 1950, p. 59). Eastward the formation thins to about 900 feet in the Capitol Reef area (J. Fred Smith, Jr., E. Neal Hinrichs, and Robert G. Luedke, written communication, 1952), and near the western edge of the Monument Valley area it is only about 275 feet thick. As one traces the formation eastward in Monument Valley it continues to thin and is only about 65 feet thick near the eastern edge.

The following section is considered characteristic of the Moenkopi formation as developed in the western part of the Monument Valley area, Arizona:

Section of Moenkopi formation measured at southeast end of Hoskinnini Mesa, about 12 miles northwest of Agathla Peak

Shinarump member of Chinle formation.
Unconformity.

Moenkopi formation:	*Feet*
Siltstone, shaly, dark-reddish-brown; light-grayish-green zone 2 ft thick near top; thin-bedded, interleaved lenticular sandstone beds each about 2 ft thick throughout entire sequence	171
Sandstone, dark-reddish-brown, massive, fine-grained	3
Siltstone, shaly, reddish-brown; forms gentle slope	4
Sandstone, dark-red even bedded; forms cliff	27
Siltstone, shaly, dark-red, interbedded with platy ripple-marked sandstone	13
Sandstone, dark-reddish-brown crossbedded, fine- to medium-grained; locally alters to a light gray	5
Siltstone, shaly, dark-red to brown, ripple-marked	23
	246

Hoskinnini tongue of Cutler formation.

In several localities broad elongate shallow depressions, termed "swales," are cut in the top of the Moenkopi (p. 80). These swales range in width from half a mile to as much as 3 miles and extend in length for 3 to 4 miles. They have about 50 feet of relief.

The contact with the Hoskinnini tongue is gradational wherever observed in this area. In mapping, the contact used was the change from the massive nodular-weathering ledge-forming siltstones and fine-grained sandstones of the Hoskinnini to the thin-bedded shaly siltstones of the Moenkopi. This contact was emphasized in the western part of the area by the crinkly limestones, and in the eastern part by a bed of white to gray fine-grained sandstone (p. 17). Commonly this contact is marked by a topographic break between the clifflike escarpments of the Hoskinnini and the receding slopes formed by the Moenkopi. As selected, this contact is about 8 to 11 feet below the contact selected by Baker (1936, p. 40).

The upper contact is distinctly disconformable, for an undulatory erosional surface of wide extent bevels the top of the Moenkopi formation. No evidence of angular discordance was noted. This disconformity shows but slight relief when viewed in gross aspect although the swales referred to above cause it to be undulatory, and deep channel scours (p. 69) interrupt its smooth undulations. In general, relief along the disconformity, if one excepts the deep channel scours and the broad swales, does not exceed 3 to 5 feet.

McKee (1954, p. 37) reports as a common phenomenon hills or mounds of Moenkopi strata that stick up into the Shinarump member of the Chinle formation. Features of a similar nature were not noted in the Monument Valley area.

In the Monument Valley area a discoloration or bleaching of Moenkopi strata is nearly everywhere present below the disconformity. Generally this discoloration occurs as a 6-inch uninterrupted grayish-green zone which contrasts markedly with the reddish brown of underlying normal Moenkopi strata. Locally, however, especially below channels (p. 104), this light-grayish-green zone may increase in thickness to as much as 7 feet. The grayish-green discoloration is strongest in those strata directly below the disconformity. A few inches below the Shinarump member, the intensity of the grayish-green color diminishes through a transitional zone about 6 inches thick that consists of alternating bands of grayish green and reddish brown. Below this transition zone is the normal reddish-brown color of the Moenkopi.

Fossils were not found in the Moenkopi in the Monument Valley area of Arizona. An Early Triassic and possibly Middle(?) Triassic vertebrate fauna has been found in the general area of Meteor Crater, Ariz. (Welles, 1947).

The Moenkopi in the mapped area seems to have been deposited in a marginal marine area which was exposed to subaerial erosion at intermittent periods during its formation. Ripple marks imply a relatively shallow-water origin for some of the sediments. Raindrop impressions and shrinkage cracks suggest that Moenkopi sediments were exposed to the atmosphere. The presence of gypsum beds suggest local lagoons and playas. Many of the sandstones in the Monument Valley area are interpreted by McKee (1954, p. 78) to represent stream-laid deposits built along delta fronts.

Moenkopi rocks in the Monument Valley area probably can best be considered as near-shore mud flats on a broad plain sloping gently westward to the sea from higher lands in western Colorado (Baker, 1933, p. 36). On these mud flats, lagoons and playas formed, and locally deltalike deposits were built onto this sloping plain by westward flowing rivers (McKee, 1954, p. 79).

As the seas that deposited the silt and sand of the Moenkopi withdrew, a surface of low relief was exposed. McKee (1951a, p. 88) considers that this surface was dissected for a considerable period of time. In view of the complete absence of any deposits that can be definitely related to such an extensive period of dissection, we believe that the period of exposure was relatively short and that the deposition of the Shinarump member of the Chinle formation began shortly after the surface of the Moenkopi was exposed. We suggest that most of the channels, swales, and other features that mark the contact of the Moenkopi and Shinarump were formed by the streams that deposited sand and gravel of the Shinarump member. These clastic materials were deposited by northward-flowing streams from a newly raised highland mass in central and southern Arizona (McKee, 1951b, p. 493).

CHINLE FORMATION

The Chinle formation consists of conglomeratic sandstone, variegated siltstone, mudstone, and claystone beds in which light gray, gray, green, lavender, violet, black, and yellow are outstanding colors. In the Monument Valley area the predominant cast of the formation is a light greenish gray although the uppermost unit, the Church Rock member, is a contrasting reddish brown.

Badland topography is characteristic, due primarily to the easily eroded claystone and mudstone. A cliff about 50 feet high, formed by the Shinarump member, commonly marks the basal part of the unit. Locally, large masses of red sandstone and siltstone talus derived from the overlying strata form a protective cap over the Chinle claystone and mudstone. As the Chinle weathers back, these areas are dissected and preserved as demoiselles. Wherever exposed, the Chinle formation is marked by large landslide blocks. Blocks as much as a quarter of a mile on a side flank Skeleton Mesa and attest to the lack of internal strength of the Chinle.

In dry weather the claystone and siltstone beds are firm, compact, and well indurated, and their surfaces are marked by a spongy "popcorn" appearance. In wet weather, however, the strata become slick, sticky, and almost impassable.

Gregory (1917, p. 42) divided the Chinle formation into four divisions, each of which was designated by a letter of the alphabet, with Division A representing the youngest and Division D the oldest. Each of the members of Gregory's Chinle in the Monument Valley area, Arizona, has been given a geographic name, which is used in this report and is indicated below.

Gregory	*Current usage*
Chinle formation:	Chinle formation:
Division A	Church Rock member.
Division B	Owl Rock member.
Division C	Petrified Forest member.
Division D	Monitor Butte member.
Shinarump conglomerate	Shinarump member.

In many places contacts between the several members are gradational. Those contacts originally established by Gregory (1917, p. 42) have been used in the course of this work.

SHINARUMP MEMBER

In the Monument Valley area, where most of the formations are various shades of red and brown, the light-yellowish-gray (5*H* 7/1) Shinarump member of the Chinle formation stands out in sharp contrast. Since 1948, the presence of commercial quantities of uranium and vanadium minerals within the Shinarump has renewed interest in its extent, lithologic characteristics, and origin.

The outcrop belt of the Shinarump member in the Monument Valley area forms a broad W whose open end faces northeast. The Shinarump crops out as broad benches in the northwestern part of the area; forms isolated remnants capping mesas and buttes in the north-central part; and stands as a row of northeastward-trending cuestas across the northeastern part. Normally it is exposed as a broad uneven sheet from which all younger strata have been removed, but in a few localities it crops out as a narrow bench of low relief above which rise the dissected slopes and cliffs formed by the other members of the Chinle formation and the Glen Canyon group.

Where the Shinarump member is the caprock it forms a vertical cliff commonly about 50 feet high. Its surface is marked by irregular hummocks about 30 feet high and narrow gulches as much as 15 feet deep.

Cross-stratification is common in the Shinarump and is best represented by scour-and-fill deposits that are found at all horizons.

This type of crossbedding is one of the most characteristic features of the member and is of the type usually ascribed to fluvial deposits. Abrupt variations in structure and texture are common.

The Shinarump is a heterogeneous combination of conglomerate, sandstone, and mudstone beds. The proportion of each changes from locality to locality, but sedimentary studies at both Hoskinnini and Nakai Mesas (McKee and others, 1953) give the following average values: sandstone, 75 percent; conglomerate, 20 percent; and mudstone, 5 percent.

In places almost three-fourths of the formation may be conglomerate, and this may grade into medium-grained sandstone in a lateral distance of 200 to 300 feet. Conglomerate generally is at the base of the Shinarump, and this grades upward into a medium- to coarse-grained sandstone near the top of the formation. Lenticularity is common, and beds of sandstone and conglomerate may interfinger, wedge out, or grade laterally into other lenses of conglomerate, sandstone, siltstone, or claystone.

On weathered surfaces the Shinarump ranges in color from white to brown although commonly it is light tan to light gray.

The pebbles in the Shinarump are white, red, black, green, and yellow. Mixed with the pebbles are large quantities of fossil plant matter, principally silicified wood of all sizes and shapes. The smaller silicified wood fragments are abraded. This profusion of silicified wood is characteristic of the Shinarump everywhere, but probably more wood fragments are in rocks that fill channels than in the Shinarump away from channels.

The pebbles range in degree of roundness from subround to round but most are round. Measurements made by McKee, Evenson, and Grundy (1953) indicate roundness values between 0.53 and 0.60 and sphericity values between 0.68 and 0.73 on measurements of pebbles from samples collected at Hoskinnini and Nakai Mesas. Stewart and others (1959) reporting on a study of a much larger area in southern Utah and northern Arizona, state that "The pebbles in the Shinarump are composed almost entirely of quartz, quartzite, and chert."

Some cobbles are as much as 5 inches in diameter, although most of the clastic material is considerably smaller, the average pebble size being about ¾ to 1 inch. The pebbles are predominantly quartz with smaller amount of quartzite and chert. Less inert materials are present in extremely small quantities; in a few localities fragments of volcanic ash, limestone, schist, and granite are found.

Most of the formation is medium- to coarse-grained sandstone with the coarse-grained size predominating. Fine-grained sandstone beds are rare. The grains are subangular to subround, with considerable authigenic quartz overgrowth responsible for their angularity. The major constituent of the sandstone matrix is colorless vitreous quartz; minor constituents include small amounts of microcline, plagioclase feldspar, mica, zircon, and chalcedony. The main binding agent is silica; the subordinate cements are calcite and iron oxide, in a few small areas argillaceous material acts as a cement.

The Shinarump member maintains a relatively uniform thickness over large areas. Although it thickens in places, this seems to be more of a local phenomenon than a regional trend. In the Utah part of Monument Valley it is as much as 210 feet thick, although it averages between 100 and 140 feet in thickness (Baker, 1936, p. 45–46). In the Monument Valley area, Arizona, the Shinarump maintains a thickness of 50 to 75 feet that is constant for miles. Locally the Shinarump thins laterally and in a distance of as little as a fourth of a mile may pinch out. The maximum thickness measured was about 150 feet. Variations in thickness that have been observed can be attributed in part to the erosional unconformity at the base and in part to the gradational character of its contact with the overlying Monitor Butte member of the Chinle.

The following section of the Shinarump is characteristic:

Section of Shinarump member of Chinle formation about 2½ miles east of Agathla Peak

Chinle formation.	
Shinarump member:	*Feet*
Conglomerate, light-gray to yellowish-brown; rounded pebbles of quartz, quartzite, and chert, all varicolored, and with maximum diameter of about 2 in.; matrix of medium- to coarse-grained sand grains; locally grades laterally into conglomeratic sandstone; forms cliff	15
Sandstone, light-gray, massive, crossbedded, platy, medium- to coarse-grained; friable; small rounded pebbles of quartz, quartzite, and chert scattered at random throughout mass	41
	56
Disconformity.	
Moenkopi formation.	

In most places, the contact of the Shinarump member with the overlying Monitor Butte member of the Chinle is ill defined. Gregory (1913, p. 433) and Woodruff (1910, p. 87) both suggest that an unconformity may be at the top of the Shinarump in this region, but we have found no evidence to substantiate this. On the contrary, the Shinarump and the Monitor Butte members intertongue. Richard Q. Lewis, Sr., and Donald E. Trimble (1959, p. 111), studying the Utah part of Monument Valley, report an absence of unconformity and state that the Shinarump grades into the overlying member of the Chinle. Baker (1936, p. 46) reports the same and concludes that the Shinarump can be regarded as the basal conglomerate of the Chinle formation.

Wherever examined in the Monument Valley area, Arizona, the contact between the Shinarump member and the overlying rocks is gradational. The sandstone of the Shinarump grades into a series of alternating sandstone and claystone beds of the Monitor Butte member. At some places the upper contact of the Shinarump is arbitrarily selected at a zone that is marked by a concentration of black concretions, each about one thirty-second of an inch in diameter. Almost directly above this zone are the crossbedded sandstone and dark clay of the Monitor Butte member of the Chinle formation.

Vertebrate and invertebrate fossils are practically nonexistent in the Shinarump member, probably because they were destroyed by the coarse clastic sediments. McKee (1937, p. 261) collected some pebbles from the Shinarump that contained an invertebrate fauna typical of the marine facies of the Kaibab limestone of Permian age. These pebbles suggest to McKee a source for the Shinarump to the south and east of the Monument Valley area.

Large quantities of wood were buried during Shinarump time and are of value in dating the formation. Existing opinion is that these trees grew on the uplands and along the banks of the streams that deposited the Shinarump sediments. Their age, therefore, is the age of the enclosing sediments. All the logs that have been examined in the Shinarump have undergone some transportation. Daugherty (1941, p. 29) reports that although most of the logs he examined in the Shinarump had been rafted into their present location, some of the logs found in the Chinle strata exposed in the Petrified Forest National Monument were buried in place. In the Monument Valley area the fossil wood ranges from large silicified logs as much as 60 feet in length and 3 to 5 feet in diameter to tiny pieces of carbonized wood associated with uraniferous deposits. Species have not been identified. The form *Araucarioxylon arizonicum* has been identified to the south in the Petrified Forest National Monument as well as in other localities (Daugherty, 1941, p. 8). It has a widespread distribution and it seems likely that it may also be among the silicified logs exposed in the Monument Valley area.

Daugherty (1941) interprets the age of these fossil logs in the Chinle as Late Triassic. He believes that all the fossil plants in the Shinarump are identical with species found in the other members of the Chinle and that the area probably consisted of broad open-forest grass-covered uplands dissected by the tree-lined streams. He suggests that present-day savannahlike areas are the closest approach to conditions that existed during early Chinle (Shinarump) time. Daugherty contends that the climatic range was from tropical to subtropical.

Normally, rainfall was ample, but these periods of adequate moisture were interrupted by short periods of aridity.

A contrasting concept has been proposed by Stokes (1950) who considers the Shinarump to be a pediment deposit formed during a semiarid episode. In his view the channels were scoured and then filled by the coarse clastics carried by the streams that cut the pediment. In time these clastic rocks were spread laterally to form a broad pediment deposit of low relief.

In our opinion the Shinarump is best considered as a series of huge coalesced alluvial fans spread across a Moenkopi surface of low relief. Probably the Shinarump surface was also one of little relief marked here and there by northwestward-trending meandering and braided streams flowing in broad shallow valleys. The streams were tree lined, and as trees died and toppled many were rafted downstream until they came to rest against some obstruction. In time these were buried; other trees fell and were buried in place. The streams were constantly shifting their courses, chiefly during periods of flood. New channels were cut and old ones filled, the final result being a series of northwestward-trending meandering channels, some of which intersect. Many of these former stream courses now appear as channels, and their broad shallow valleys are the swales.

MONITOR BUTTE MEMBER

In the Monument Valley area, Arizona, the somber claystone, siltstone, sandstone, and conglomeratic sandstone beds of the Monitor Butte member commonly intertongue with the underlying Shinarump member.

The Monitor Butter member is well exposed along the northeast flank of Monitor Butte, its type locality. The butte is about 14 miles northwest of Oljeto, Utah.

In the Monument Valley area, Arizona, the Monitor Butte member is best exposed near the volcanic neck, Agathla Peak, and along the flanks and around the southern nose of the Agathla anticline (pl. 1). In these areas it consists predominantly of crossbedded conglomeratic sandstone beds interleaved with dark-gray claystones. It forms buttes, mesas, and badlands. In places dissection has developed narrow deep gullies which alternate at irregular intervals with steep-ridged interfluves. The Monitor Butte member also crops out along the flanks of Skeleton Mesa; in this locality it consists predominantly of dark-purple claystone and siltstone beds.

In places, the attitude of the beds forming the Monitor Butte member is extremely irregular and does not conform to the regional strike and dip. Folding, faulting, intraformational unconformities, and other evidence of deformation are present at most exposures. These phenomena, however, are not repeated in either the overlying or underlying strata, and probably are the result of slump and flowage of unconsolidated or partly consolidated sediments at time of deposition.

Many features common in the Shinarump member are duplicated in the Monitor Butte member. Crossbedding is extensive in both units, as is interfingering of the several beds. However, the Monitor Butte is marked by several distinctive features, among which are perfectly formed and extensive foreset beds. Locally these simulate bedding planes and the normal bedding is difficult to discern. Peculiar imbricating cusplike ripple marks are characteristic of the Monitor Butte member. Distinctive also are lenses of a brown conglomerate composed largely of angular to well-rounded dark-brown fragments of calcareous siltstone. The fragments are as large as 80 mm. Included with these are quartz, quartzite, and chert clastics similar in shape, size, and color to those of the Shinarump.

Much of the Monitor Butte member is dark-gray to grayish-orange crossbedded medium- to coarse-grained sandstone lenses. In these lenses the individual grains are angular to subround quartz with minor amounts of microcline, muscovite, chalcedony, and zircon. Much of the angularity of the quartz grains is attributable to authigenic quartz. Calcite is the dominant cement, with silica, iron oxide, and argillaceous matter important locally.

Because the upper and lower contacts of the Monitor Butte member are gradational, and because of the large amount of intraformational disturbance, thickness figures cannot be precise. In general, it is about 100 feet thick in the Monument Valley area of Arizona. At its type locality the Monitor Butte member is about 107 feet thick.

The position of the upper contact is arbitrary and differs from place to place. In those areas where the Monitor Butte member consists predominantly of sandstone and conglomeratic sandstone (that is, near Agathla Peak), the upper contact is selected as the last sandstone above which is an uninterrupted sequence of variegated siltstone and claystone beds. Elsewhere, as along the flanks of Skeleton Mesa, where the Monitor Butte member consists predominantly of dark-purple claystone and siltstone beds, the upper contact is selected as that horizon at which the sediments change in color from dark purple to light gray green.

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The following is presented as the type section of the Monitor Butte member of the Chinle formation:

Section of Monitor Butte member of the Chinle formation measured at north end of Monitor Butte in SE¼sec. 3, T. 41 S., R. 13 E., Utah, about a quarter of a mile southwest of the Whirlwind mine.

	Feet
Petrified Forest member of Chinle formation.	
Monitor Butte member of Chinle formation:	
Silstone and claystone, grayish-orange to moderate-yellowish-brown; contains beds of crossbedded conglomeratic sandstone, and fine- to coarse-grained sandstone lenses; weathers to form gentle scree-covered slopes	8
Sandstone, yellowish-gray, fine- to medium-grained, thin-bedded, platy; has cusplike ripple marks; grades laterally into dark-gray to light-gray siltstone	1
Claystone, grayish-yellow-green, fissile; weathers to form gentle scree-covered slope	9
Sandstone, dark-gray to pale-yellowish-brown, fine-grained, massive, dense, well-indurated; cemented by calcite	2
Sandstone, dusky-yellow, poorly consolidated; grades laterally into a siltstone facies; small fragments of silicified wood included	7
Sandstone, locally conglomeratic, grayish-orange to light-brown, fine- to coarse-grained though predominantly medium-grained, massive, crossbedded; cusplike ripple marks, forms cliff	25
Claystone, siltstone, and sandstone alternating with one another at irregular intervals; predominantly light gray to dark gray, thin-bedded in upper part, crossbedded, platy; forms broad gentle scree-covered slope	55
	107
Shinarump member of Chinle formation.	

No recognizable vertebrate or invertebrate fossils were found, although rare bone fragments are in the conglomerate beds. Fossilized wood resembles that in the Shinarump member and most likely represents the conifers *Araucarioxylon* and *Woodworthia.*

The northward-flowing streams that deposited the Shinarump continued uninterrupted during the beginning of Monitor Butte deposition. This is indicated by the similarity in materials and bedding, and by the extensive intertonguing between the two units. Near the end of Monitor Butte deposition the flow dwindled and the size of the material deposited decreased.

PETRIFIED FOREST MEMBER

Overlying the dark sandstone and mudstone beds of the Monitor Butte member are irregularly bedded variegated siltstone and claystone beds that form the Petrified Forest member of the Chinle formation. This unit was named by Gregory (1950, p. 67) for exposures in Zion Park, Utah. The thick uninterrupted sequence of fine-grained sedimentary rocks and the vivid hues distinguish this unit from the remainder of the Chinle.

This member of the Chinle is extremely weak and forms badland topography characterized by low round hillocks, immature mesas, deep intricately sculptured steep-walled ravines, and narrow ridges.

Because the Petrified Forest member is weak, landsliding is common and normally involves not only the Petrified Forest member itself but also the overlying strata.

Much of the Petrified Forest member is a massive uniform-textured well-indurated siltstone and mudstone in various tints and shades of pink, red, blue, gray, violet, and green. Locally small discontinuous lenses of mud pebbles form conglomerates which interrupt this sequence. In the massive facies the dominant grains are angular quartz about 0.006 mm long. Included with these small grains are individual quartz grains as much as 0.24 mm in size. Calcite is the principal cement with silica and clay as minor binding agents.

Dispersed throughout this member is light-gray claystone which swells notably when wet. In this, the dominant mineral has been identified as montmorillonite (Allen, 1930, p. 284). Other evidence of volcanic activity during Chinle time has been reported by Waters and Granger (1953) who noted fragments of altered volcanic glass and bits of microlite-filled lava in thin sections of rocks of the Chinle. Allen (1930, p. 286), commenting on the mottling in the Chinle, suggests that this peculiar type of coloration developed in bentonitic strata after deposition in response to environmental conditions under which the sediments accumulated.

The Petrified Forest member is about 620 feet thick at Tyende Mesa near Agathla Peak, and about 510 feet along the east flank of Skeleton Mesa. Stewart and others (1959) report the unit as about 500 to 700 feet thick in the Monument Valley area.

The following section of the Petrified Forest member, measured on the east flank of Tyende Mesa, (pl. 1) is characteristic:

Section of Petrified Forest member of Chinle formation measured at Owl Rock, about 7½ miles north of Kayenta, Ariz.

Owl Rock member of Chinle formation.	
Petrified Forest member of Chinle formation:	*Feet*
Claystone, mudstone, and siltstone, grayish-brown to red, mottled; interbedded platy lenses of well-rounded mud pebbles in a siltstone matrix; elsewhere nodules form conglomerate lenses containing pelecypod remains	472
Claystone, mudstone, and siltstone, variegated, generally light-greenish-gray to pale-red; spongy "popcornlike" surface weathers to form angular to rounded fragments; locally mudstone gives way laterally to siltstone with intercalated medium-grained sandstone lenses about 2 ft thick	148
	620
Monitor Butte member of Chinle formation.	

The upper contact is selected as the first limestone ledge below which is an unbroken series of variegated claystone, mudstone, and siltstone beds and above which is a series of cherty limestone beds alternating with claystone, mudstone, and siltstone beds. In several localities, the Petrified Forest member intertongues with the overlying Owl Rock member.

Petrified wood is sparsely distributed through the claystone and siltstone beds of this member, but elsewhere in northern Arizona the amount of fossil wood found in this member is in such quantities as to form fossil forests. Daugherty (1941, p. 9) reports such forests at Round Rock, Adamana, and Beautiful Valley, Ariz. Most of the logs (probably conifers) found in this member appear to have been rafted into place. Identifiable fossils were not found in the Monument Valley area, Arizona, but elsewhere in northern Arizona (Camp and others, 1947, p. 8) invertebrates such as mollusks are present, as well as vertebrates such as fish (pyctodonts, semionotids), amphibians (*Metoposaurus*), and reptiles (*Coelophysis*).

When the continued slackening of streamflow first became apparent during the later stages of Monitor Butte deposition, siltstone and claystone began to be deposited by relatively quiet waters. This depositional environment continued during the formation of the Petrified Forest member. Probably the climate was arid, and the landscape featureless and monotonous. Some volcanic activity is suggested by the presence of volcanic shards.

OWL ROCK MEMBER

The Owl Rock member of the Chinle formation is made up of cherty limestone and limestone conglomerate beds alternating with claystone, mudstone, and siltstone beds. Wherever this member crops out, the resistant limestone beds form a series of jutting ledges that serve partly to protect the underlying strata.

In the Monument Valley area, Arizona, the Owl Rock member is best exposed at its type locality near the base of Owl Rock.

Limestone conglomerate beds give way along the strike to massive cherty limestone beds which have subangular to angular nodules of black chert scattered irregularly throughout the beds. A light-bluish-gray (5*B* 7/1) color predominates, although locally greater concentrations of chert tend to darken the limestone beds to gray blue. The ledges formed by these limestone beds normally range from about 2 to 20 feet in thickness and are separated one from another by siltstone and mudstone masses as much as 30 feet thick. The cherty limestone beds weather to form nodular blocky well-jointed ledges. As many as six of these limestone ledges were noted in the Monument Valley area. Of these only five were persistent and could be traced with any degree of confidence.

The Owl Rock member ranges in thickness from about 120 to 166 feet. At Owl Rock the member is 166 feet thick; farther south along Comb Ridge near Chaistla Butte it is about 134 feet thick; to the west along the east flank of Skeleton Mesa it is about 128 feet thick. A comparable thickness for this unit is reported by Gregory (1917, p. 44–45) who cites a thickness of 152 feet for this member of the Chinle at the mouth of Segihatsosi Canyon near Boot Mesa (pl. 1).

The following is presented as the type section of the Owl Rock member of the Chinle formation:

Section of Owl Rock member of Chinle formation measured at Owl Rock about 7½ miles north of Kayenta, Ariz.

Church Rock member of Chinle formation.	
Owl Rock member of Chinle formation:	*Feet*
Limestone, pale-grayish-green, cherty; persistent cliff former; weathers to form blocky masses	7
Mudstone, pale-reddish-brown; some intercalated siltstone lenses; forms gentle slopes	11
Limestone, pale-grayish-green; includes black angular chert nodules; persistent cliff former	2
Mudstone, pale-reddish-brown; forms gentle slopes	2
Limestone, grayish-green; includes black angular chert nodules; cliff former	2
Siltstone, brown, massive, very slightly fissile; locally stands as vertical face	11
Mudstone; pale-reddish-brown to mottled appearance resulting from scattered small green specks; forms gentle slopes	26
Limestone, pale-gray; includes black angular chert nodules; persistent cliff former	10
Mudstone, pale-reddish-brown; locally grades into siltstone; forms gentle slopes	16
Limestone, light-gray, massive; includes black angular chert nodules; persistent cliff former	10
Mudstone, pale-red; locally altered to conglomeratic siltstone near top; lower part forms slopes, upper part stands as vertical face	33
Claystone, gray to purple, discontinuous; locally forms ledges	1
Mudstone, reddish-brown; forms gentle slopes	16
Limestone, light-gray; includes black angular chert nodules; weathers to form blocky masses	19
	166
Petrified Forest member of Chinle formation.	

In most places the upper contact is the uppermost limestone ledge in the mudstone and limestone sequence. Directly overlying the limestone bed is a sequence of reddish-brown parallel and crossbedded siltstone and sandstone beds (that is, Church Rock member) that contrast markedly with the underlying grayish-green mudstone, siltstone, and cherty limestone beds. In places the rocks of the Owl Rock member intertongue with the overlying Church Rock member. Along Comb Ridge in the area near the Monument No. 2 mine the mottled grayish-green siltstone beds of the Owl Rock member are replaced laterally by the reddish-brown siltstone and sandstone beds of the Church Rock member. Here, therefore, the distinctive limestone ledge selected as the top of the Owl Rock member is underlain by typical Church Rock strata. Similar intertonguing between these two units has been noted elsewhere in the Monument Valley area.

Invertebrates collected from a limestone conglomerate in the Owl Rock member have been identified by John B. Reeside, Jr. (written communication) as "*Unio* n. sp." He states, "Only one species appears to be present, but it does not match any of the dozen or so of described Upper Triassic species."

Although fossil wood has been found, it is in much smaller amounts than in the underlying Petrified Forest member. Fossil wood collected from this member elsewhere in Arizona has been assigned a Late Triassic age (Daugherty, 1941).

The Owl Rock member represents an episode marked by alternating lacustrine and fluviatile deposition. The fluviatile conditions that had continued uninterrupted since the beginning of deposition of the Shinarump member had slackened sufficiently by the close of Petrified Forest time to permit the formation of ephemeral fresh-water playa lakes. In these lakes, dense massive light-gray limestone of limited extent was deposited. These limestone beds in turn were soon buried by siltstone and claystone brought in by sporadic revivals of stream flow.

CHURCH ROCK MEMBER

Overlying the grayish-green limestone and claystone beds of the Owl Rock member are the reddish-brown (10*R* 4/3) parallel and cross-bedded siltstone and sandstone beds of the Church Rock member of the Chinle formation.

In detail the Church Rock member of the Chinle formation is marked by medium-scale trough-type cross-stratification (Stewart and others, 1959). The sorting is consistent and uniform. Most of the material is silt sized, although local lenses of sandstone are present. Grains are subangular and only a few show any rounding. The major mineral is colorless quartz with the grains coated by a thin film of brown iron oxide.

The Church Rock is remarkably uniform along most of its outcrop. The following section is considered typical:

Section of Church Rock member of Chinle formation measured on Comb Ridge about 6½ miles northeast of Kayenta, Ariz.

Wingate sandstone.

Church Rock member of Chinle formation:	Feet
Siltstone, reddish-brown, fissile, even-bedded; weathers to form nodular ledges	12
Siltstone, reddish-brown, crossbedded; locally interbedded lenses of fissile shaly siltstone	11
Sandstone, grayish-brown, crossbedded, coarse-grained; includes granules as much as a quarter of an inch in diameter; thin discontinuous seams of chocolate-brown siltstone along bedding planes	4
Siltstone, reddish-orange altering locally to light-gray; interbedded lenses of coarse-grained sandstone	20
Siltstone, reddish-orange, massive; weathers to form blocks about 2 ft on a side	3
Siltstone, reddish-orange, to reddish-brown, even-bedded, slightly fissile; mottled surface covered with light-gray spots about 2 in. across	75
Siltstone, reddish-brown, even-bedded; locally discontinuous; gray spots irregularly distributed over surface	5
Siltstone, reddish-orange, even-bedded, extremely fissile; locally interbedded with massive crossbedded siltstone beds	52
Siltstone, reddish-orange, fissile; locally discontinuous	6
Siltstone, reddish-brown, even-bedded although locally crossbedded; weathers as blocky ledges	52
Sandstone, light-tan to light-brown, thin-bedded, platy, faintly ripple-marked	6
	246

Owl Rock member of Chinle formation.

The Church Rock member differs in thickness at various localities. An average thickness for this member in the area west and south of Agathla Peak is about 150 feet.

In most places in the Monument Valley area a recognizable upper contact exists between the Church Rock member and the Wingate sandstone. In gross aspect the change is from a parallel and crossbedded deposit with depositional features typical of fluvial deposits, to a massive deposit marked by large sweeping cross-laminae commonly attributed to eolian deposits. In detail the contact is marked in many localities by distinctive well-rounded coarse quartz grains in the basal strata of the Wingate sandstone.

We interpret the intertonguing between the Owl Rock and Church Rock members (p. 32) as confirming the concept that the Church Rock is an integral part of the Chinle formation. J. W. Harshbarger and C. A. Repenning, of the U.S. Geological Survey, have studied the Chinle-Wingate relations south of the Monument Valley area. They noted an irregular erosional surface overlain by a thin granule and pebble conglomerate between divisions A and B (Church Rock and Owl Rock members) of the Chinle in several localities on the Navajo Indian Reservation (Harshbarger, Repenning, and Jackson, 1951, p. 96). Further, they cite intertonguing relationships in the Lukachukai Mountains, Ariz., between the Church Rock (Division A) and the overlying Wingate sandstone as evidence that the Church Rock (Division A) has closer affinities to the overlying Wingate than to the underlying Owl Rock member. On the basis of this intertonguing, the erosional surface, and the overlying granule and pebble conglomerate, Harshbarger and Repenning place the Chinle-Wingate contact below the Church Rock (Division A). This interpretation removes the Church Rock (Division A) from the Chinle and assigns it to the basal member of the Wingate sandstone.

We are unable to agree with this interpretation. Although Callahan (1951, p. 51) reports a pebble conglomerate between the Chinle formation and the Glen Canyon group in the vicinity of Kayenta, Ariz., we were unable to find such a zone. In the mapped area, we have not found a pebble and granule conglomerate at the base of the Church Rock member nor have we found an erosional surface. Moreover, we have not perceived any intertonguing relations between the Church Rock and the Wingate in the area we studied. Similar lack of intertonguing between Division A of the Chinle (Church Rock) and the Wingate sandstone was reported by Alfred F. Trites, Jr., for the White Canyon district, Utah; J. D. Sears for the San Juan River area, Utah; and Richard Q. Lewis, Sr., for the Monument Valley and Elk Ridge areas, Utah (all oral communications). The available paleontologic evidence affords little assistance in the solution of this problem.

North of Laguna Creek (pl. 1), Division A (of the Chinle) is known as the Church Rock member of the Chinle formation. South of Laguna Creek the same sequence of strata is to be known as the Rock Point member of the Wingate sandstone.

We are indebted to C. A. Repenning for the following information concerning the fossil content of strata (that is, Rock Point) stratigraphically equivalent to the Church Rock member of the Chinle formation. Only a few fossils have been found; these consist mainly of unidentifiable plant remains, petrified wood fragments, and a few fragmentary reptilian remains. The reptilian remains were identified as the phytosaur *Machaeroprosopus* by David H. Dunkle, of the U.S. National Museum. Camp (1930) assigns *Machaeroprosopus* to the Lettenkohle (Lower Keuper) of the German Triassic. Hence, on what fossil evidence exists, the age of the Rock Point (that is, Church Rock) is Triassic.

WINGATE SANDSTONE

Overlying the Church Rock member of the Chinle formation is the reddish-brown (10*R* 5/4) crossbedded massive fine-grained Wingate sandstone, the basal formation of the Glen Canyon group. The unit forms cliffs and commonly crops out in its full thickness. A close-spaced nearly vertical fracture system has been imposed on the Wingate and dissection along these vertical planes has resulted in perpendicular smooth-faced walls which in places are as much as 350 feet high. The imposing walls are an effective barrier for long distances and generally the only way across the cliff is by means of manmade trails.

On weathered surfaces the Wingate is a deep reddish brown, and dark surface stains give the formation a somber hue. On fresh surfaces the rock is lighter, ranging in color from pale pink to very light buff. Large-scale crossbedding is typical of the Wingate and can be observed wherever the formation crops out. Many of the beds show the broad curving tangential laminae typical of eolian deposits. The texture is unusually uniform. The Wingate is composed predominantly of subround to round fine-grained quartz sand with small amounts of well-rounded coarse quartz grains in the lower few feet. Authigenic quartz overgrowths give some grains an angular surface. Minor constituents include microcline, plagioclase feldspar, tourmaline, and chert. Among the heavy minerals are small quantities of zircon, magnetite(?), and garnet. The grains are cemented dominantly by calcium carbonate and to a lesser extent by secondary silica and iron oxide. Coating all the grains is a thin film of brown iron oxide.

The Wingate sandstone thins to the east and to the southeast from the Monument Valley area (Harshbarger, Repenning, and Jackson, 1951, p. 96). This progressive thinning, however, is interrupted by local erratic changes. Thus, the Wingate is between 310 and 320 feet thick along the west flank of Skeleton Mesa (pl. 1). At the northeast tip of Skeleton Mesa, however, we have measured a thickness of 360 feet. At Boot Mesa the Wingate is about 350 feet thick, and Harshbarger, Repenning, and Jackson, (1951, p. 96) give the thickness of the Wingate as 305 feet near Kayenta, Ariz. To the east, the progressive thinning is apparent along Comb Ridge north of Dinnehotso, Ariz., where the Wingate has thinned to 210 feet.

The contact with the underlying Church Rock member is conformable within the Monument Valley area of Arizona and no evidence of intertonguing between the Church Rock (Division A of the Chinle formation) and Wingate was observed. Farther south, in the Lukachukai area, Harshbarger and others (1951, p. 96) report such intertonguing relationships, and Baker (1936, p. 49) reports that in the Utah part of Monument Valley "irregularly bedded sandstones at the top of the Chinle formation grade into the Wingate sandstone."

The contact with the Kayenta formation is gradational and transitional. No break is apparent and, as far as is known, the contact is conformable.

No fossils were collected from the Wingate sandstone, and hence no evidence exists as to the age of this formation in the Monument Valley area, Arizona. Previous reports have tentatively classified the Wingate as Jurassic(?). However, in the Lukachukai area fossils of Late Triassic age (p. 34) have been found in sedimentary rocks (that is, Rock Point) that intertongue with the Wingate. On this basis a Late Triassic age has been assigned to the Wingate sandstone.

The tangential crossbedding that marks the Wingate sandstone of the Monument Valley area indicates that the unit was deposited by winds under terrestrial conditions of extreme aridity. Stewart and others (1959) suggest that most of the sediments came from the northwest. The Monument Valley area seems to be near the center of the Wingate's gross depositional area, which is in the form of a large shallow basin with one elongate protuberance to the east into New Mexico (Baker, Dane, and Reeside, 1936, p. 52). Near the margins of the basin, Baker, Dane, and Reeside (1936, p. 53) consider the Wingate to have been deposited by a commingling of water-worked and wind-worked material. They consider the sediments in the center of the basin, however, to be composed of eolian material.

JURASSIC(?) SYSTEM

KAYENTA FORMATION

The middle formation of the Glen Canyon group is the Kayenta formation, of Jurassic(?) age. The Kayenta is pale-reddish-brown (10*R* 5/5) to grayish-red (5*R* 5/2) irregularly bedded calcareous sandstone with intercalated layers of shale, arenaceous limestone, and conglomerate. Its type locality is along Comb Ridge about 1 mile northeast of the town of Kayenta, Ariz. (fig. 1).

Commonly, the basal part of the Kayenta forms a resistant ledge that protects the underlying Wingate sandstone. The upper part is less durable and weathers to a steep slope below the escarpment formed by the overlying Navajo sandstone. In detail, this steep slope is marked by a series of ledges and narrow platforms that are separated by short slopes.

Irregular bedding, which is characteristic of the Kayenta, is conspicuous, and was used in the course of mapping as a guide in delineating this formation from both the underlying and overlying massive crossbedded sandstones.

In detail, individual sandstone beds and lenses in the Kayenta formation cannot be differentiated either in color or lithologic character from similar appearing beds in either the Wingate or Navajo sandstones. Many of these sandstone lenses in the Kayenta are as much as 20 feet thick, are massive, and show good large-scale crossbedding. Lenticularity is typical of all the beds comprising the Keyenta whether they are of shale, sandstone, limestone, or conglomerate. Intertonguing between these units is common and results in rapid changes in lithologic character along the strike.

In gross aspect the Keyenta is reddish brown, and locally grayish red. The strata range in color from dark orangish brown, to dark greenish gray with individual beds colored buff, orange, pink, lavender, and purplish red.

In the sandstone beds the grains range in size from very fine grained (0.06–0.15 mm) to fine grained (0.20 mm). Most of the grains range in shape from subangular to round, but some are angular. Lime pellets and pebbles are common in the conglomerates as are angular nodules of black chert. Locally, a limestone conglomerate with included irregularly distributed red and gray shale fragments is present. The pebbles of the conglomerate range in shape and lithologic character from well-rounded quartz, quartzite, and chert pebbles to angular fragments of limestone and chert.

The major mineral in the sandstone units is colorless quartz, with microcline, plagioclase feldspar, chert, and tourmaline present in sparse amounts. Other accessory minerals are magnetite, zircon, and garnet. Most of the grains are coated with a thin film of brown iron oxide. The major cementing material is calcite, although secondary silica and iron oxide are important locally.

In general, the formation thins eastward, although this thinning is not uniform. The erratic thickening and thinning is well displayed in measured sections which extend from Skeleton Mesa on the west to Garnet Ridge on the east (pl. 1). At Skeleton Mesa the Kayenta maintains a thickness of about 165 feet. About 12 miles to the southeast, at its type locality near Kayenta, Ariz., the Kayenta is about 144 feet thick (Baker, Dane, and Reeside, 1936, p. 5). Still farther east along Comb Ridge, about 4 miles from its type locality, the formation has increased in thickness to 162 feet. Eastward, near the Porras Dikes, in a distance as short as 2 miles, the formation has dwindled to 146 feet again. Along Comb Ridge, west of Garnet Ridge, the Kayenta is about 68 feet thick, and near the very east edge of the mapped area the Kayenta is only about 45 feet thick.

The following section is characteristic of the Kayenta formation as developed on Tyende Mesa, Navajo County, Ariz.:

Section of Kayenta formation measured at west end of Adahchijiyahi Canyon about 9¼ miles west of Agathla Peak

Navajo sandstone.	
Kayenta formation:	*Feet*
Sandstone, reddish-brown, fine-grained, even-bedded; locally thin bedded to platy	40
Conglomerate, light-gray, lenticular; composed of angular to rounded pebbles of fine-grained sandstone, limestone, quartz, quartzite, and chert	3
Sandstone, reddish-brown, massive, even-bedded	3
Conglomerate, light-gray, lenticular; composed of angular to rounded pebbles of fine-grained sandstone, limestone, quartz, quartzite, and chert	6
Sandstone, reddish-brown, crossbedded; grain size ranges from fine to medium grained	5
Sandstone, light-gray to buff, platy, crossbedded, fine-grained, ledge-forming	5
Sandtone, reddish-brown, even-bedded, fine-grained; locally interbedded lenses of coarse-grained sandstone	10
Sandstone, dark-gray, crossbedded, fine-grained, dense and very well indurated	1
Sandstone, reddish-brown, massive, crossbedded, fine-grained; separated into layers about 6 ft. thick by local lenses of pebbles	29
	102
Wingate sandstone.	

The upper and lower contacts are arbitrary. We have included within the Kayenta all those units that show distinct irregular bedding planes. In many localities throughout the area we have selected a thin light-gray sandstone at the base of the Kayenta as marking the basal contact with the underlying Wingate. The upper contact was selected primarily on the presence or absence of bedding planes, for near its upper boundary the sandstone beds thicken and the bedding planes become less distinct. In several places the bedding planes at the top of the formation fade and disappear laterally and the sandstone beds grade smoothly and imperceptibly into the overlying Navajo sandstone. Many of these bedding planes reappear laterally some 200 yards distant at about the same horizon at which they disappeared.

The Kayenta is classified tentatively as Jurassic(?). No fossils were collected from the formation although previous workers (Baker, Dane, and Reeside, 1936, p. 5) report the presence of dinosaur tracks, unnamed species of the pelecypod *Unio*, and other fossils that are unidentified.

In 1953, vertebrate remains were discovered in the upper part of the Kayenta formation near Kayenta, Ariz., by B. C. Hoy, of the U.S. Department of the Interior, Bureau of Indian Affairs. G. E. Lewis, of the U.S. Geological Survey, quarried the remains and studied them. His report (written communication, 1955) follows:

The preliminary, incomplete identification and pertinent stratigraphic information are—

Class REPTILIA

Subclass SYNAPSIDA

Order ICTIDOSAURIA

Superfamily Tritylodontoidea near Bienotherium Young

The newly discovered skulls, represent the first new-world discovery of tritylodontoids. They seem to be close morphologically to *Tritylodon* of the Stormberg series of South Africa, and even closer to *Bienotherium* of the Lufeng series of Yunnan, China. These old-world vertebrates occur in rocks generally placed in Upper Triassic.

Most modern paleontologic opinion somewhat arbitrarily places the tritylodontoids in the Reptilia, but they are on the transitional morphologic boundary between reptiles and mammals.

The conglomerate, irregular bedding, channeling, and general coarseness of the rocks all indicate that the Kayenta is a stream deposit. Conditions of aridity prevailed and the shale lenses were probably deposited in pools of quiet water. Likely most of the sediments came from the north and northeast (Stewart and others, 1959). The Monument Valley area seems to be near the southern edge of the Kayenta basin of deposition (Baker, Dane, and Reeside, 1936, p. 46).

JURASSIC AND JURASSIC(?) SYSTEM

NAVAJO SANDSTONE

The Navajo sandstone, the uppermost formation of the Glen Canyon group, is a light-buff to pink (10*YR* 8/2) massive crossbedded sandstone. Where it is protected by a resistant caprock it forms high cliffs. Unprotected, the formation weathers to rounded steep-sided mammilary forms. Wherever it is exposed, its color, uniformity of grain size, and typical crossbedding easily identify it.

In the western part of the area, alcoves of all sizes are at the base of many of the steep cliffs formed by the Navajo sandstone. Most of the large cliff dwellings such as Betatakin, Keet Seel (fig. 4), and Inscription House are in the larger of these alcoves.

Although most of the Navajo consists of massive and crossbedded sandstone, lenticular sandy limestone beds are scattered irregularly throughout the upper part of the formation. These beds are extremely resistant and are composed of disseminated grains of quartz scattered through a limestone matrix. In the eastern part of the area these beds cap mesas.

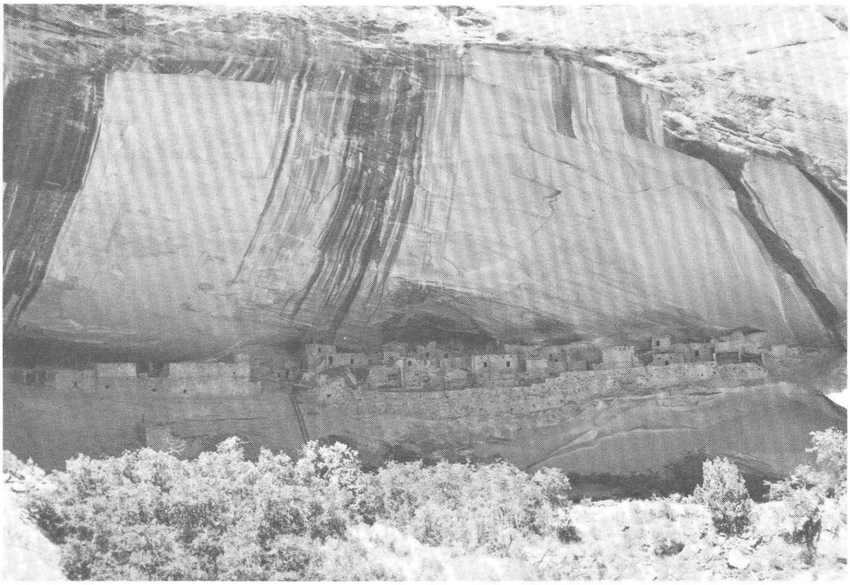

FIGURE 4.—One of the large alcoves formed near the base of the Navajo sandstone (ruins of Keet Seel in alcove). Note the massive nature of the sandstone and the long tangential crossbeds. Dark streaks are formed by rainwater.

The Navajo is light buff to pink, although in places it ranges in color from light gray to brownish tan. Most of the grains range in shape from subround to round, and only a very few are angular. In grain size, the sandstone ranges from very fine grained to fine grained with most of the grains ranging in diameter from 0.10 to 0.26 mm. The Navajo is predominantly a quartz sandstone with small amounts of microcline, plagioclase feldspar, chalcedony, magnetite, zircon, tourmaline, and garnet. The Navajo is weakly to firmly cemented by calcite, silica, and iron oxide. The cementation, however, is poor in most places and the Navajo is, in general, an extremely friable rock. A thin film of brown iron oxide coats each grain.

The top of the Navajo is exposed in only two places in the mapped area. Along Comb Ridge near Chaistla Butte, the Navajo is about 524 feet thick; farther to the east, also on Comb Ridge, north of Garnet Ridge (pl. 1), the Navajo is about 665 feet thick.

The contact between the light-buff crossbedded sandstone beds of the Navajo and the overlying dark-red even-bedded siltstone beds of the Carmel formation is marked by an unconformity of practically no relief. Angularity between the formations, if any, is too slight to measure within the limited area of contact exposed in the Monument Valley area.

No fossils were found in the Navajo sandstone during the course of the present work. However, a member of the Navajo Mountain-Monument Valley expedition of 1933, discovered a small "dinosaur about the size of a turkey" in the Navajo sandstone (Camp and VanderHoof, 1934, p. 385). The discovery site was about 1 mile north of the Keet Seel ruin on the west side of Keet Seel Canyon (pl. 1). The fossil was the first vertebrate skeleton to be recorded from the Navajo sandstone. It was about 500 feet above the top of the Wingate sandstone and lay parallel to the crossbedded sandstone in which it was found. The specimen was studied by Camp (1936) who named it *Segisaurus halli* n. gen. and sp. and deduced that it probably had a "bipedal ostrich-like mode of locomotion." Camp (1936) stated, regarding the age of the form, "It represents a single member of an unknown upland fauna and despite its primitive characters it could be placed in either the Triassic or Jurassic."

The Navajo represents an accumulation of wind-worked and wind-deposited sand that probably came from the west or northwest (Stewart and others, 1959). The local members of dark-gray dense unfossiliferous limestone in the upper part of the Navajo represent ephemeral playa lakes in what must have been a large desert. The Monument Valley area is near the eastern margin of a large northeastward-trending wedge-shaped mass of eolian sand (Baker, Dane, and Reeside, 1936, p. 44) that constitutes the Navajo sandstone.

JURASSIC SYSTEM

CARMEL FORMATION

The Carmel formation, basal formation of the San Rafael group, is exposed only in the southeastern and eastern parts of the Monument Valley area, Arizona (pl. 1). It is composed of alternating siltstone and sandstone beds with fissile siltstone beds predominating in the lower half and crossbedded sandstone beds in the upper half. Generally the siltstone beds form gentle slopes between the benches and ledges formed by the more resistant sandstone beds. From a distance the Carmel is dark reddish brown (10*R* 4/4), but in detail it ranges in color from light gray to orange brown to reddish brown. Commonly, the siltstone beds are reddish brown; the sandstone beds, however, are gray near the base of the formation, and are gray orangish gray, and brownish red near the top.

The siltstone beds are remarkably alike. They are reddish brown, fissile, and composed of poorly sorted clear colorless polished angular quartz heavily stained with iron oxide. Magnetite, feldspar, mica, and a chloritelike mineral are accessory minerals. The average grain size is about 0.06 mm, but many of the grains are as small as 0.04 mm and as large as 0.11 mm.

The sandstone beds are poorly sorted and are composed of clear colorless quartz with magnetite as an accessory mineral. The grains range in shape from subround to round and the larger grains are frosted and nearly spherical. Most of the grains range in size from 0.10 to 0.30 mm.

Both iron oxide and calcite are binding agents. The siltstone beds are held together by iron oxide, and the sandstone beds are cemented by calcite. A few of the grains have authigenic quartz overgrowths, but quartz apparently is not a major cement.

Ripple marks and small patches of polygonal networks are exposed on the surface of the sandstone beds. These polygons are as much as 8 feet across and are bounded by low rounded walls of sandstone as much as 8 inches high and 6 inches thick. The walls may represent mud cracks that were filled with sand and subsequently cemented. The walls now are more resistant to erosion than the surrounding rock.

The Carmel is about 118 feet thick at Garnet Ridge (pl. 1). It varies a few feet in thickness from place to place, probably because of variation in the thickness of the siltstone beds in the upper part of the formation.

The contact of the Carmel with the overlying Entrada sandstone of the San Rafael group is marked in most places by a color and grain size change from the dark-reddish-brown siltstone of the Carmel to the brilliant orangish-brown fine-grained sandstone of the Entrada.

No fossils were collected from the Carmel formation in the Monument Valley area, Arizona, although the formation is fossiliferous in other parts of the Colorado Plateau. Imlay (1948) reports an invertebrate fauna of Middle and Late Jurassic age from the San Rafael Swell.

The presence of exceptionally large frosted sand grains in the sandstone beds, the alternating beds of siltstone and sandstone, the polygonal networks, and the current-type crossbedding and ripple marks all imply that the Carmel was deposited during changing environmental conditions. These conditions probably ranged from periods of marginal marine inundation to periods of subaerial erosion.

According to Baker, Dane, and Reeside (1936, p. 54) the San Rafael group represents two invasions of a marine sea (that is, the Carmel sea) from the northwest, separated by a large eolian deposit. Deposits of the first advance of the sea are represented by the Carmel formation, and the Monument Valley area, Arizona, probably was at or near the southern margin of this sea. With the withdrawal of the sea, wind-worked material represented by the Entrada sandstone was deposited over the area. A readvance of the Carmel sea resulted in deposition of silt and sand that now form the Summerville formation. During this second advance, the area again was probably near or at the fluctuating southern margin of the sea.

ENTRADA SANDSTONE

The Entrada sandstone is part of the San Rafael group. It is an orange- to reddish-brown massive even to crossbedded fine-grained sandstone with intercalated thick siltstone beds in its upper part. Commonly the lower third to two-thirds of the formation crops out as a steep slope below a vertical wall that is formed by the upper part of the formation. On Garnet Ridge (pl. 1), the lower part is an extensive knobby tableland that encircles the ridge and which breaks away to form steep slopes at the edges. The upper part of the formation nearly everywhere weathers as hoodoos for which Baby Rocks point is named. These hoodoos develop, however, only where the formation is nearly horizontal and where the Entrada is protected by a resistant cap.

The lower part of the Entrada is a brilliant orange-red and reddish-brown massive tangentially crossbedded very fine grained quartz sandstone which is about 30 feet thick on the north side of Garnet Ridge and nearly twice that thick at the southwest end. Crossbedding in this basal unit is much like that of the Navajo except that it is more intricate and is on a smaller scale. The sand grains in the lower part of the Entrada are polished and well sorted, averaging about 0.1 mm in diameter. The orange-red and reddish-brown color is imparted by iron oxide stain on the quartz grains, and the iron oxide also is the bulk of the cementing material. Magnetite is the major accessory mineral.

The upper part of the Entrada is a dull-reddish-brown predominantly massive even-bedded very fine grained sandstone that is interbedded with several thick siltstone beds. The lithologic character of the whole formation changes abruptly from place to place; consequently, the massive even-bedded sandstone and siltstone beds of the upper part of the formation make up fully two-thirds of the thickness of the Entrada on the north side of Garnet Ridge, but less than one-third at the southwest end. Sorting is poor in the siltstone beds, and angular polished grains of quartz average about 0.06 mm in size. All grains are stained with iron oxide. Iron oxide is the principal cementing agent although calcite and authigenic silica are important locally. The siltstone beds range in thickness from one-tenth of an inch to several inches, but they weather as a unit to form hoodoos.

The upper 20 feet of the Entrada are very fine grained dark reddish-brown sandstone beds (fig. 5). The sandstone is even bedded and

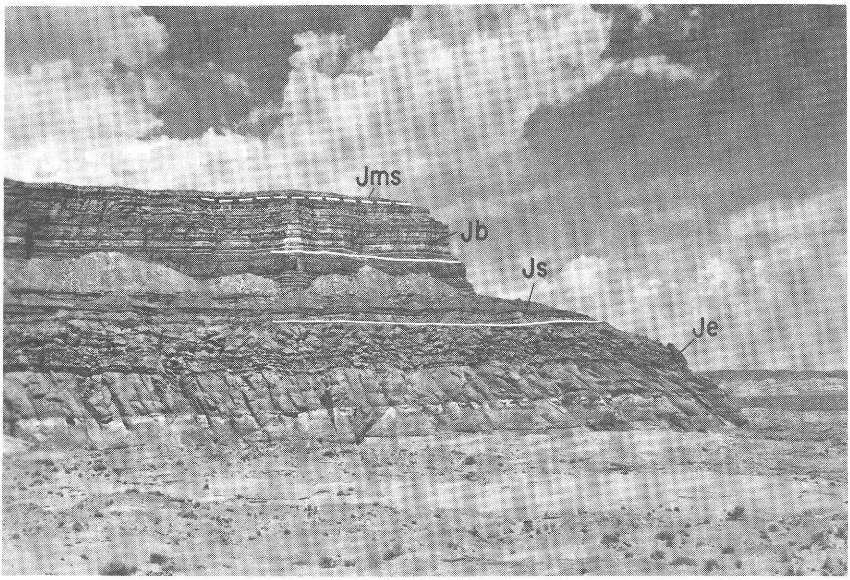

FIGURE 5.—Sedimentary strata forming Baby Rocks point. The point is capped by the Salt Wash member of the Morrison formation and has part of the Entrada sandstone exposed at its base. Bluff sandstone is about 45 feet thick. Jms, Salt Wash member of Morrison formation; Jb, Bluff sandstone; Js, Summerville formation; and Je, Entrada sandstone.

weathers as hoodoos. The upper part of this unit is contorted into open folds that are broken by high-angle faults of small throw. These structures may have developed as a result of disturbances before consolidation, or they may represent a collapse in beds from which soluble material was removed soon after deposition. It is certain that the disturbance of these beds was completed before deposition of the overlying Summerville formation, as the undeformed basal sandstone of the Summerville rests on the truncated edges of the folded uppermost beds of the Entrada (fig. 6).

The thickness of the Entrada, as measured on Garnet Ridge, is about 100 feet. The thickness differs only a foot or so from place to place even though the ratio of siltstone to sandstone becomes smaller from the northeast to southwest end of the ridge.

The contact between the Entrada and the overlying Summerville is sharp. The crests on the folds in the uppermost beds of the Entrada sandstone have been planed smooth and are overlain directly by about 5 feet of massive Summerville sandstone.

On the withdrawal of the Carmel sea following deposition of the Carmel formation (p. 42) a surface of low relief was exposed. On this surface wind-worked material was deposited, most of it derived

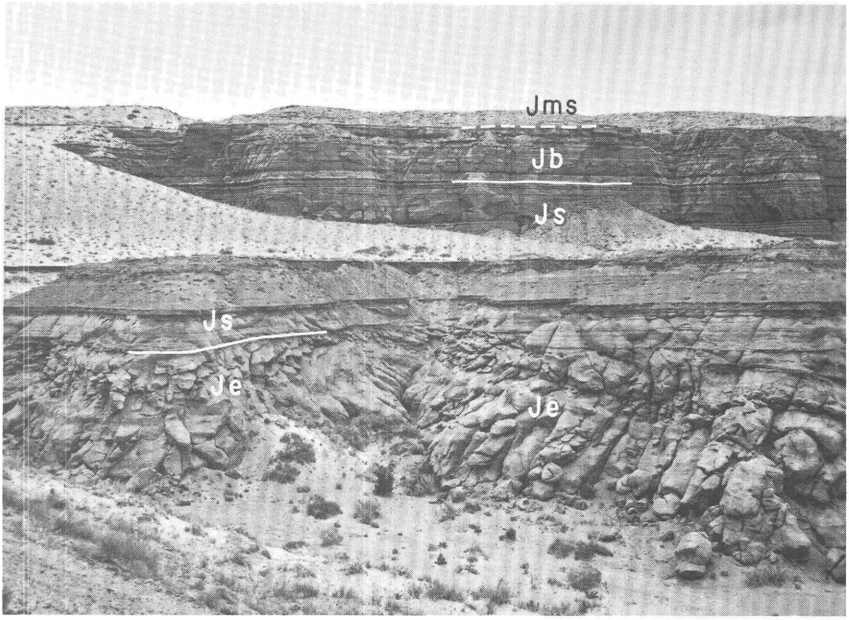

FIGURE 6.—Unconformity between the crumpled and distorted uppermost beds of the Entrada sandstone, Je, and the even-bedded overlying Summerville formation, Js, at Baby Rocks point. Jms, Salt Wash member of the Morrison formation; Jb, Bluff sandstone.

principally from the northwest (Baker, Dane, and Reeside, 1936, p. 46). Some of the material, however, probably came from the south, as a result of a renewed uplift of the Navajo highland (Smith, 1951, p. 100).

SUMMERVILLE FORMATION

The Summerville formation, part of the San Rafael group, is well exposed at Baby Rocks point, Red Point, and Garnet Ridge (pl. 1). Because of lithologic changes, outcrop characteristics at these localities differ. At Baby Rocks point and at Red Point the Summerville forms slopes, except for 5 feet of sandstone at the base, which forms a bench.

Lithologic characteristics of the Summerville at Baby Rocks point and Red Point are similar. In these localities it consists of quartz sandstone that is reddish brown, thin bedded, and fine grained, and that contains in its upper part, some sandstone beds that are white and silty. At Baby Rocks point the Summerville is about 35 feet thick (fig. 5). The following section is considered characteristic of the Summerville at that locality.

Section of Summerville formation measured on the west flank of Baby Rocks point, about 10 miles southwest of Dinnehotso, Ariz.

	Feet
Bluff sandstone.	
Summerville formation:	
Siltstone, brown to reddish-brown, even-bedded; weathers to rounded ledges, although unit as a whole forms a cliff	32
Sandstone, white, fine-grained; grades imperceptibly into siltstone above	1
	33
Entrada sandstone.	

Measurements of the thickness of the Summerville formation at Garnet Ridge range from 39 to 47 feet. The following section is selected as characteristic:

Section of Summerville formation measured on the northwest side of Garnet Ridge

	Feet
Bluff sandstone.	
Summerville formation:	
Siltstone, alternating white and moderate-red or white and pale-reddish-brown; thoroughly contorted	36
Sandstone, bright-orange-brown, very well sorted, fine-grained, cross-bedded; lower 18 in. bleached white or very pale green; the bleaching locally extends downward about an inch into the Entrada sandstone	5
	41
Entrada sandstone.	

The basal sandstone of the Summerville at Garnet Ridge consists of quartz grains that are well rounded, frosted, and exceptionally well sorted, averaging 0.13 mm in diameter. The grains are cemented by calcite and by some iron oxide. In most places the sandstone appears structureless, but differential weathering locally reveals gently inclined crossbedding. The bleached zone in the bottom of the sandstone is a conspicuous marker.

Overlying the sandstone is thin-bedded pale-red and white siltstone intricately contorted and faulted. Bedding is distinguishable by alternating colors and by minor variations in grain size. A few beds are fine-grained sandstone, but these cannot be traced far owing to the contorted bedding. The siltstone in the uppermost 12 inches is less deformed and is nearly flat lying at the top of the formation.

The contact of the Summerville formation with the overlying Bluff sandstone is marked by a change from contorted red and white siltstone to evenly bedded pale-green and grayish-red siltstone. The change occurs gradually in a zone a few inches to a foot thick and is found from 36 to 42 feet above the basal sandstone of the Summerville formation. Lack of definiteness of a contact plane suggests that the Bluff sandstone and the Summerville formation are conformable.

The uniformity and sorting of sand in the basal sandstone of the Summerville were perhaps caused by eolian or beach processes. The upper silty beds suggest nearshore marine deposition. A cause for the convoluted beds remains elusive, but they were perhaps deformed by collapse after removal of chemical precipitates.

The Summerville represents the second southward advance of the Carmel sea into this part of northeastern Arizona. Probably the Monument Valley area was at or near the fluctuating southern margin of the sea and was exposed intermittently to subaerial erosion.

BLUFF SANDSTONE

The Bluff sandstone is the uppermost unit of the San Rafael group in the Monument Valley area, Arizona. At Baby Rocks point, the Bluff stands as a reddish-brown banded vertical cliff below the capping Salt Wash sandstone member of the Morrison formation (fig. 6). At Garnet Ridge the lower half is a slope which becomes steep in the upper half where sandstone beds form ledges.

At Baby Rocks point and Red Point, the Bluff is a series of reddish-brown to chocolate-brown shale and sandstone beds. In general, the shale beds are even bedded, fissile, and intercalated with siltstone and sandstone beds. The sandstone beds are massive, even bedded, and range from fine to coarse grained. In these localities the Bluff is about 45 feet thick. The following section is characteristic of the Bluff:

Section of Bluff sandstone measured at Baby Rocks point about 10 miles southwest of Dinnehotso, Ariz.

Salt Wash member of Morrison formation.	
Bluff sandstone:	*Feet*
Sandstone, light-brown, massive, even-bedded, fine-grained, friable, weakly cemented; interbedded lenses of coarse-grained sandstone locally	27
Shale, chocolate-brown; bounded by a quarter of an inch of thick white siltstone seams	1
Sandstone, reddish-brown, massive, even-bedded, fine-grained	6
Shale, chocolate-brown; bounded by a quarter of an inch of thick white sandstone seams	1
Sandstone, reddish-brown, even-bedded, fine-grained	4
Shale, reddish-brown, even-bedded, fissile; intercalated white sandstone lenses	6
	45
Summerville formation.	

At Garnet Ridge the upper half of the Bluff sandstone resembles the beds exposed at Baby Rocks point and Red Point, but the lower half consists of fissile siltstone that is variegated pale green and grayish red. Where the siltstone merges with the upper beds, it becomes sandy and less green. The following section is representative:

Section of Bluff sandstone on the northwest side of Garnet Ridge

	Feet
Salt Wash member of Morrison formation.	
Bluff sandstone:	
Sandstone, friable, white to very light gray; grades upward into fissile dusky-red siltstone; immediately underlying unit weathers as hoodoos at southwest part of Garnet Ridge	4
Sandstone, silty, friable, light-brown to white; gradational with bed above	18
Sandstone, moderate-brown, massive to irregularly bedded; forms ledge	3
Siltstone, fissile, dusky-red; sandy at the top; gradational with bed above	4
Sandstone, fine-grained, white to very light gray, irregularly bedded; forms ledge	3
Siltstone, fissile, dusky-red, and sandstone, friable, light-brown, in alternating beds	18
Sandstone, fine-grained, friable, white to very light gray; forms ledge	2
Siltstone, fissile, variegated pale-green and grayish-red; more sandy near the top	48
	100
Summerville formation.	

Bedding in the lower siltstone of the Bluff at Garnet Ridge is even and flat lying at most places, but locally is tilted, folded, and cut by high-angle faults. The angles of dip of the deformed beds do not exceed 10° to bedding and the deformed zones, 20 to 30 feet above the base, are never more than 10 feet thick.

The upper half of the Bluff at Garnet Ridge is marked by three light-colored sandstone beds which form ledges. Although commonly massive, these sandstone beds are locally crossbedded. The grains are frosted, cemented by calcite, and range in diameter from 0.06 to 0.28 mm. Polygonal networks similar to those in sandstone beds in the Carmel formation (p. 42), but of smaller size, are common. Dusky-red siltstone between the sandstone beds forms slopes horizontally streaked with light-colored layers that contain sand. Ripple marks are common.

At the type locality at Bluff, Utah, the Bluff sandstone is virtually one massive bed of white crossbedded medium- to coarse-grained sandstone 200 to 350 feet thick. In the Monument Valley area, Arizona, however, it is thinner and finer grained. It thins southwestward to about 100 feet at Garnet Ridge and to 45 feet at Baby Rocks point.

The contact of the Bluff sandstone with the Salt Wash member of the Morrison formation is marked by an abrupt change to massive crossbedded coarse sandstone. An unconformity cannot be demonstrated because of the limited extent of the outcrop, but Stokes (1944, p. 974) suggests that the contact is unconformable.

Duplication in the Bluff of many of the sedimentary features of the Carmel, including ripple marks, crossbedding, and polygonal networks resembling mudcracks, suggests that the Bluff was deposited in a nearshore environment similar to that of the Carmel. Farther northeast, the massive crossbedded character of the Bluff suggests a more landward environment.

As the Carmel sea withdrew for the last time, the silt and sand of the Summerville were exposed as a surface of low relief (p. 43). On this surface eolian sands, represented by the Bluff sandstone, were deposited. The sand probably was derived from the northwest. This deposit of sand forms a southeastward-trending wedge of wind-worked material that reaches its maximum thickness near Bluff, Utah, and is almost pinched out near the Monument Valley area, Arizona.

MORRISON FORMATION

SALT WASH SANDSTONE MEMBER

Only the basal part of the Salt Wash sandstone member of the Morrison formation is preserved in the Monument Valley area, Arizona. On Baby Rocks point and Red Point (pl. 1) the basal 30 to 50 feet of the Salt Wash forms a generally flat-topped caprock (fig. 5). On Garnet Ridge only 32 feet of the Salt Wash is preserved.

The Salt Wash remnant on Garnet Ridge is predominantly yellowish-orange (10*YR* 7/2) massive crossbedded medium- to coarse-grained sandstone which contains some pebbles. The single exception is a 2-foot lens of maroon and bluish-gray shale about 2 feet below the crest of the ridge at the north end of the outcrop. Sorting is good in most sandstone beds, but some layers contain grains of coarse sand and even pebbles as much as 1 inch in diameter. Most of the grains average about 0.25 mm, and very few are less than 0.15 mm in diameter. The grains are subround to round, and consist primarily of quartz and minor amounts of chert.

The Salt Wash is very weakly cemented by authigenic quartz, and contains minor amounts of calcite, dark mineral grains, and iron oxide. A little iron stain streaks the coarse-grained layers, both in the flat-lying and inclined beds.

The principal source for the coarse clastics that form the Salt Wash member of the Morrison seems to have been a highland in west-central Arizona (Craig and others, 1955, p. 150). Streams spread northeastward from this highland mass and deposited the Salt Wash sediments on a surface of low relief.

QUATERNARY SYSTEM

Surficial deposits in the Monument Valley area, Arizona, include dune sand, alluvium, colluvium, talus, and landslide blocks, which mantle and veneer large areas of bedrock. Scattered across and buried in these deposits are archeological sites. Open sites are common and evidence of the former inhabitants is represented by a profusion of potsherds, arrowheads, spear points, remnants of one-room dwellings and foundations of ovens and cists. Hunt (1955) has made some attempts at dating the archeological sites in Cane Valley Wash (pl. 1) through a study of the surficial deposits.

Dune sand of two ages is in Cane Valley. These have been identified tentatively as "old dunes" (preoccupation age) and "new dunes" (postoccupation age). No attempt was made to separate these in the field, however, and they are shown on plate 1 as dune sand. The new dunes are postoccupation in age, unconsolidated, and subject to transport by the wind; they have not been stabilized. The older dunes are preoccupation in age, stabilized, dark brown, and contain fossil plant matter, principally as tree stumps of cottonwood, juniper, and pine (Hunt, 1955, p. 584).

Throughout the area, alluvium that is generally mantled by dune sand fills most of the stream washes. Data are not available as to the thickness of this alluvial fill, but resistivity investigations along Oljeto Creek have suggested a combined dune sand and alluvial thickness of between 80 and 100 feet. Three ages of alluvial fill exist. The oldest is a late Wisconsin alluvium, possibly correlative with the Jeddito formation of Hack (1942, p. 60). A second alluvium, known as the Tsegi formation (Hack, 1942, p. 62) rests upon the Jeddito(?) fill, and contains most of the artifacts of the ancient prepottery age inhabitants (Hunt, A. P., 1953, p. 21). The third alluvial fill is the most recent and is referred to as the Naha formation (Hack, 1942, p. 62, 67). It represents alluviation of postoccupation age.

A study by Hunt (1955) of the interrelationships between the alluvial fills, the two ages of dune sand, and the archeological sites in Cane Valley Wash (also known as Cane Valley or Little Capitan Valley) suggests the following sequence of events:

1. Deposition at the close of Pleistocene time of an extensive alluvial deposit (the Jeddito formation?) containing mammoth remains.
2. Onset of a very arid period (the Thermal maximum) when the "old dunes" formed.
3. Onset of a moist period when alluvial fill (Tsegi formation) and lakebeds developed. The area was inhabited by a prepottery-age people at this time.

4. Gradual diminution of water supply coupled with several severe drouths, resulting in a gradual exodus of the inhabitants (the Anasazi people) from the Navajo Country. The exodus occurred in the period A.D. 1275–1300.

5. Formation of a third alluvial fill (the Naha formation) in the period A.D. 1300–1700.

6. Covering of alluvial fills by dune sand of postoccupation age.

7. Onset of the present arroyo cutting, which began in the last two decades of the 19th century.

ERUPTIVE ROCKS

The sedimentary rocks of the Monument Valley area, Arizona, are disturbed in many places by materials that have been injected from below. Dikes, volcanic plugs, and other manifestations of eruptive activity are scattered irregularly through the area. They generally stand as topographic highs and their dark grayish-green color contrasts markedly with the buff to reddish brown of the sedimentary rocks through which they protrude.

Three types of eruptive structures can be distinguished: (1) volcanic plugs composed of lamprophyric intrusive breccia; (2) igneous dikes, also composed of lamprophyric rocks; and (3) rubble pipes composed of ultrabasic material with a heterogeneous mixture of sedimentary and crystalline inclusions.

The plugs and dikes are generally widely scattered throughout the eastern half of the mapped area. Structures of similar form, also of lamprophyric composition, are common elsewhere on the Navajo Indian Reservation (Williams, 1936). The rubble pipes, on the other hand, are rare. In this part of Arizona, they are in a narrow zone along Comb Ridge that extends from Garnet Ridge on the south to the San Juan River on the north (fig. 1). Many structures on the Colorado Plateau that have been mapped as diatremes (Williams, 1936) bear a superficial resemblance to the rubble pipes but differ from them in chemical composition and structure. The rubble pipes appear to be chemically and structurally similar to the diamond pipes of South Africa and to the kimberlitic tuff plugs described by Balk (1954, p. 381) at Buell Park and vicinity, northeastern Arizona.

IGNEOUS PLUGS AND DIKES

The denuded volcanic plugs are the most spectacular of the eruptive bodies. They are concentrated near the middle of the Monument Valley area in a crude line that trends somewhat west of north along the crest of the major structural feature of the region, the Monument upwarp. The most conspicuous plugs are Church Rock (just south

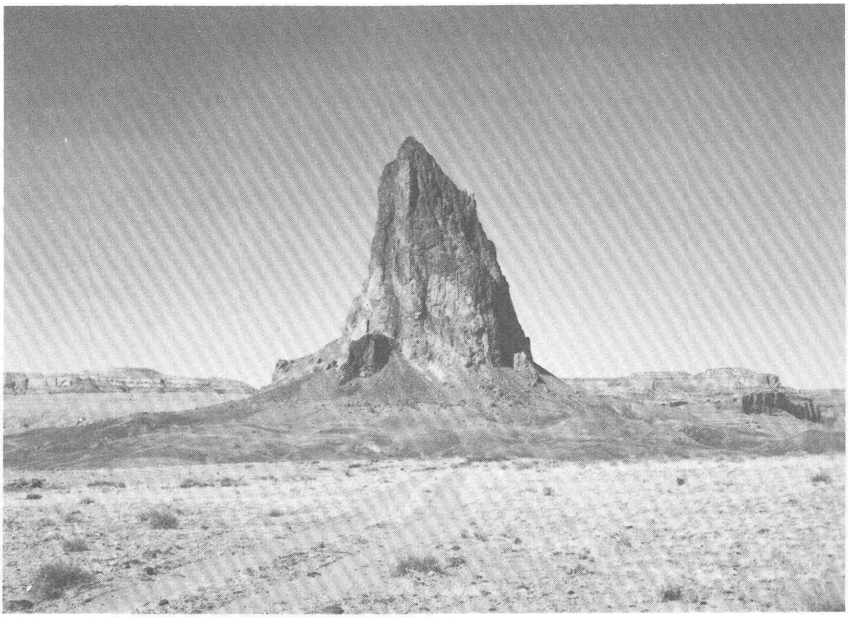

FIGURE 7.—Agathla Peak, a volcanic neck of nearly black lamprophyric rock that rises about 1,400 feet above the valley floor.

of the area), Chaistla Butte, and Agathla Peak (pl. 1 and fig. 7), the latter a tremendous monolith which rises over 1,400 feet above the surrounding plain and is visible for many miles.

All the volcanic plugs are a dark grayish green, all stand as cones surrounded by a flaring apron of sedimentary rocks, and all are nearly circular. Each is a chaotic mass of large angular to rounded fragments of lamprophyric volcanic rock and small amounts of sedimentary and crystalline xenoliths incorporated in a younger lamprophyric matrix. In some places the matrix is sheared, broken, and ground into fine particles. In other places the matrix is platy, foliate, and wrapped around the blocks by flowage. In still other places it is dense. The included blocks of lamprophyre range in size from pebbles and cobbles to huge boulders 20 to 30 feet on a side. Most of the foreign inclusions are not larger than cobbles. Pulverized sedimentary rock forms an appreciable part of the matrix at some places. Calcite has thoroughly cemented all of the material in the plugs, and it is largely this cement that gives them strength to stand as topographic highs. Williams (1936, p. 130) refers to the plugs as coarse tuff breccias, but we consider the term intrusive breccia more descriptive.

Alteration of the foreign inclusions in the breccia is rare. A few of the fragments of sedimentary rocks have weakly bleached surfaces. Most of the crystalline inclusions are acidic rocks of the granite family, and most appear unaltered. A few, principally those that contain much feldspar, have had their exposed surfaces, including fracture planes, altered to light-pink porous "rinds" of clayey material as much as a quarter of an inch thick.

Much of the material in the volcanic plugs is unsorted. A conspicuous exception to this lack of sorting is in the upper part of Agathla Peak where there is some sorting, partial alinement of the long axes of the inclusions, and a rudimentary layering.

All the volcanic plugs are cut by black dense dikes that trace irregular courses through the breccia. Most of the dikes are less than 12 feet wide, but several exceed 50 feet in width. Others pinch and swell as they branch and anastomose, or thin abruptly, as they pass around large sedimentary inclusions in the breccia. On Agathla Peak, a few of the dikes appear to have followed parting planes in the breccia blocks.

Mineralogically the matrix and cognate breccia blocks in the plugs, the dense black dikes in the plugs, and the dikes found elsewhere in the Monument Valley area are nearly alike; they differ mainly in color, grain size, structure, and texture. In general, the igneous intrusives are alkaline rocks characterized by a high potash content (Williams, 1936, p. 148). The plugs and dikes are largely biotite vogesite, but where biotite is abundant in zones, cavities, and pods, the rock is diopside minette.

The dikes, other than the late dikes that cut the plugs, are in elongate swarms that are confined principally to the eastern part of the area mapped. One extensive dike swarm occupies fractures along the crest of the Gypsum Creek dome (pl. 1) and trends parallel to the long axis of the dome. On the flank of Comb Ridge, dikes fill fractures that are radial to the Monument upwarp. Many of the dikes are less than 10 feet in width and less than half a mile long, although one is 1¼ miles in length. Some dikes merge to form plugs. Such is the case at the Porras Dikes (pl. 1), for example, where the plugs stand as towers 400 feet high. Commonly the dikes form low irregular ridges 2 to 30 feet high that protrude above the enclosing sedimentary rocks.

All the dikes contain inclusions, almost all of which are crystalline. Only a few sedimentary inclusions have been found, and these are but a few inches in long dimension. A few of the inclusions are slightly altered on exposed surfaces.

Most of the dikes are much more foliate near their walls, owing, primarily, to the parallel arrangement of biotite crystals. The platy structure is conformable to the contacts.

Other than the pronounced foliation near the contacts, the igneous intrusions are only slightly affected by the country rock. Poorly developed chilled zones are found locally, but the mineralogic composition of the igneous material apparently is not changed. The intruding masses have torn off and included small pieces of the country rock, many of which have bleached surfaces. Bleaching along fractures and for an inch or two into the wall rock also can be seen locally. At the Porras Dikes the wallrock is silicified locally, and the silicification extends laterally several inches from the dike contacts.

The intrusives, except for the late aphanitic dikes that cut the plugs, are sugary textured, medium purplish or greenish gray to black, and are spotted with clusters of biotite and diopside phenocrysts. The biotite phenocrysts occur as thin books and are distinctly of two generations: the older ones are as much as 4 mm in size and the younger ones as much as 2 mm. The largest diopside phenocrysts are about 1 by 3 mm in size. Small second generation crystals are disseminated throughout the groundmass.

The groundmass of the rocks forming the plugs and dikes is composed mostly of laths of subhedral orthoclase feldspar interspersed with small crystals of second generation biotite and diopside. No plagioclase was identified, but it is possible that small quantities are present. Minerals in the rocks forming both the intrusive breccias and the dikes are practically unaltered. A few biotite flakes show patches or rims of the green color that is characteristic of chlorite alteration, but the other constituents of the rocks are fresh.

Listed below are the results of Rosiwal counts that were made on lamprophyric rocks from four widely separated places in Monument Valley:

	Samples			
Composition	*1*	*2*	*3*	*4*
Groundmass (principally orthoclase)	58.1	75.9	72.6	67.1
Biotite	16.1	13.7	14.8	13.5
Diopside	21.5	8.4	12.6	19.4
Calcite	2.3	2.0	----	----
Quartz	2.0	----	----	----

The age of the volcanic disturbances in Monument Valley is unknown. Williams (1936, p. 148) suggests that the Navajo volcanoes were active during middle and late Pliocene, although he states that fossil evidence is lacking. We found fossils in several xenoliths of Mancos shale (Late Cretaceous), thus establishing a maximum age for the intrusions.

SERPENTINE AT GARNET RIDGE

By Harold E. Malde and Robert E. Thaden

Garnet Ridge was named from pyrope garnet that is in serpentine deposits which intrude rocks of Jurassic age about 35 miles northeast of Kayenta, Ariz. (fig. 1). The serpentine deposits are mainly in pipes choked with rock debris derived from a section more than 5,000 feet thick, ranging in age from Precambrian(?) to Cretaceous.

Garnets have been known from the Navajo Country since the Ives expedition (Newberry, 1861, p. 93), but were not seen by geologists until 1908 when D. B. Sterrett visited several localities, among them Garnet Ridge. Sterrett (1909, p. 824–825) described garnet-bearing unconsolidated deposits at Garnet Ridge which had the "general appearance * * * of a glacial deposit." A glacial origin was adopted, with doubt, by Woodruff (1910) for a similar deposit near Mule Ear, 18 miles north of Garnet Ridge. Gregory (1915; 1916; 1917, p. 102, 146–147), after examining the garnet-bearing deposits at Garnet Ridge and nearby Mule Ear and Moses Rock, concluded that a glacial origin is untenable because the deposits cut across bedding and are clearly intrusive. Later, Miser (1924a, pl. 15) mapped the Mule Ear deposit as a volcanic neck. Disrupted sandstones at Mule Ear were explained by Williams (1936, p. 134) as "the result of the upward-punching action of an igneous plug," and he endorsed an igneous cause for the disruption of beds and injection of garnet-bearing deposits at Garnet Ridge.

The general relations previously described are confirmed by the present work, but we find that volcanism is not conclusively demonstrated. The greenish matrix of the garnet-bearing deposits, previously assumed to be a finely comminuted minette—a conspicuous variety of basalt in the region—is largely serpentine. To attribute the serpentine to volcanism ignores consideration of nonmagmatic source rocks, although it is unquestionably intrusive. Some of the serpentine occurs in extrusive deposits, but these are so lithologically similar to the intrusive deposits that they can be distinguished only by their physiographic relations.

INTRUSIVE SERPENTINE DEPOSITS

DISTRIBUTION AND STRUCTURE

The intrusive serpentine deposits occur as pipe fillings and, rarely, as dikes and sills. The pipes are alined northeastward, parallel to the regional strike; but the dikes are parallel to joints which trend northwestward (pl. 3). Pipe 1 (pl. 3), at the ridge crest, measures about 1,000 feet across; three others (pipes 2, 3, and 4) about 2 miles northeast form a cluster 1,500 by 4,000 feet, which trends northwestward.

Garnet Ridge lies east of an upwarp which produces a bend in Comb Ridge (pl. 1). Where the rocks of Comb Ridge curve around the upwarp, they dip more steeply than elsewhere, coincidently with the anomalous occurrence of serpentine. A clearer suggestion of structural control is expressed by the line of pipes—Garnet Ridge, Moses Rock, and Mule Ear—which pierces Comb Ridge where the beds rise steeply in a monocline.

The pipes are steep walled and irregularly shaped. The southern wall of pipe 1 (pl. 3) is exposed in profile for a depth of more than 100 feet and is nearly a vertical plane, apparently corresponding to a joint face. Pipe 2 is bounded in part by nearly vertical walls that parallel northwestward-trending joints (pl. 4). A syncline with 180 feet of closure, deepest at this cluster of pipes, may have developed after the pipes were formed. Eruption of material would account for subsidence.

WALLROCK RELATIONS

Wallrocks of the serpentine pipes are commonly fresh country rock with large-scale fractures. On the other hand, wallrocks of the few dikes commonly contain secondary minerals.

Pipe walls are deformed or altered in two places: (1) beds of the Carmel formation on the north side of pipe 2 are deformed by small-scale folds and broken by reverse faults along which serpentine has been injected, and (2) Entrada sandstone at the southeast corner of pipe 2 is laced with fractures and bleached in a zone 20 feet wide.

Dike walls are altered in two places: (1) walls of a vertical dike that crosses the crest of Garnet Ridge are cemented by silica in a zone a foot or two wide, and (2) a dike northwest of pipe 2 is cemented by limonite which extends outward as an aureole from 3 to 50 feet wide in the enclosing Navajo sandstone (p. 61).

INTERNAL RELATIONS

Two kinds of material fill the pipes: (1) breccia blocks which subsided as much as 1,200 feet into the pipes, and (2) serpentine-bearing rubble, squeezed between the breccia blocks, containing crystalline rocks from more than 4,000 feet below.

The breccia blocks fill about two-thirds of the pipe and comprise a chaos of rock types originally far apart stratigraphically, now juxtaposed. Many are several hundred feet long. Most of them are angular; but faces, edges, and corners in contact with the serpentine rubble are smoothed, striated, and polished. Tabular blocks generally dip toward the center (pl. 4).

The serpentine-bearing rubble is no less chaotically mixed than the breccia blocks. Rocks from the crystalline basement and from strata of Paleozoic age are held in a fine-grained matrix rich in serpentine. The inclusions range in size from sand size to large boulders; most of them are of pebble size. The large inclusions are well rounded, but the smaller ones are angular; all are smoothed and polished. Fabric is expressed locally by oriented inclusions and schistosity of the serpentine matrix, but is not common.

Chemical alteration within the pipes is slight. Pieces of fossiliferous limestone show no recrystallization and lack thermal metamorphic minerals. Few inclusions of black shale and red sandstone are bleached. A few of the crystalline basement rocks have porous light-colored rinds as much as half an inch thick.

SOURCE OF BLOCKS AND RUBBLE

Nearly all the breccia blocks are from the Salt Wash member of the Morrison formation and the San Rafael group. Blocks from older beds are lacking. Pipe 2 includes a few blocks of dark-gray shale that contain species of pelagic Foraminifera [3] such as are found in the Mancos shale, stratigraphically about 1,200 feet higher.

Inclusions in the serpentine rubble apparently were all derived from considerable depth. About half are biotite granite gneiss and epidote granulite, in equal amounts. One-fourth are sedimentary rocks among which carbonate types containing fossils of Paleozoic age predominate. The remaining fourth is comprised of schistose garnet-tremolite amphibolite, foliated hornblendite, enstatite-cummingtonite amphibolite, and antigorite-tremolite-actinolite-calcite aggregates. Rare types include granite and fine-grained basic igneous rocks. The crystalline rocks were presumably brought up from a Precambrian terrane. Inclusions of limestone were derived from depths as shallow as 2,000 feet.

SERPENTINE MATRIX

The matrix of the serpentine rubble is pale grayish green, very fine grained, firm, and compact. It breaks apart into lumps and clods that remain coherent when wet. Pebbles break out leaving smooth, polished molds. When soaked with acid the matrix effervesces freely, but fails to distintegrate. In a few places, limonite is a cement or forms streaks which follow wavy partings. Associated with the limonite are carbonate veins faced with zeolites.

The serpentine matrix is mineralogically generally uniform. In approximate order of decreasing abundance, the predominant minerals are antigorite (altered from olivine), calcite, chlorite, white mica, melilite, clay, fresh biotite (perhaps exotic), chrome diopside, opaque oxides (probably ilmenite and chromite), and zeolites. Accessories (some of which may be exotic) include actinolite, hornblende, microcline, quartz, gypsum, chrysotile, and pyrope. No unaltered olivine

[3] Steven K. Fox, U.S. Geol. Survey (written communication, 1954), identified *Gümbelina globulosa* (Ehrenberg) and *Globigerina cretacea* d'Orbigny.

is present in the samples examined, although ghosts of former crystals, from 0.5 to 1.5 mm in diameter, are common. J. M. Axelrod, U.S. Geological Survey, made X-ray analyses of material in the serpentine matrix and identified minerals of the montmorillonite group (b=9.21 A), antigorite and chlorite.

Mineralogically, the serpentine matrix resembles the kimberlitic tuff plugs at Buell Park, Ariz., 100 miles southeast (Balk, 1954; Allen and Balk, 1954, p. 100–118). Charles Milton, U.S. Geological Survey, studied samples from Garnet Ridge and suggested (oral communication) that they are allied mineralogically with the chloritized-calcitized-serpentinized peridotite bodies of Kansas, Illinois, New York, and Virginia.

GARNET

The garnet that is not reworked and winnowed from the serpentine deposits is mostly in epidote granulite. The granulite is medium to coarse grained, and ranges from a massive type containing little garnet to a banded type rich in garnet (15 percent). Hornblende, extensively replaced by chlorite and less so by iron oxide and quartz, makes up from 25 to 50 percent of the granulite. The remainder consists of epidote laths enclosed in plagioclase crystals several times larger. The epidote laths are smaller and more tightly packed near hornblende than elsewhere. Distribution of garnet is irregular. Some garnet is in foliated amphibolite.

All the garnets are pyrope containing from 25 to 45 percent almandite (n, 1.74–1.76; sp gr, 3.67–3.89). Spectrographic analyses by G. W. Boyes, U.S. Geological Survey, show rather constant amounts of silicon, aluminum, iron, manganese, calcium, and magnesium, but variable amounts of chromium. The chromium content ranges from more than 1 percent to as little as a few hundredths of a percent.

EXTRUSIVE SERPENTINE DEPOSITS

The extrusive serpentine deposits are lithologically like the intrusive deposits. Physiographic relations show that their source was at the pipelike intrusive deposits. They form rounded mounds of surficial debris at two places: on a row of bedrock knobs leading from pipe 1, and on wallrock adjacent to pipe 2.

The mounds of serpentine rubble that cap knobs leading from pipe 1 define a curving line 2,000 feet long, descending 80 feet in altitude, and lying about 60 feet above the surrounding land (fig. 8). The rubble mounds decrease in thickness from 15 to 5 feet. Most rest on siltstone occurring low in the Bluff sandstone, but two are 20 or 30 feet lower on siltstone of the Summerville formation. The rubble mound farthest from the pipe is on a block of Bluff sandstone, 100 by 200 feet, displaced

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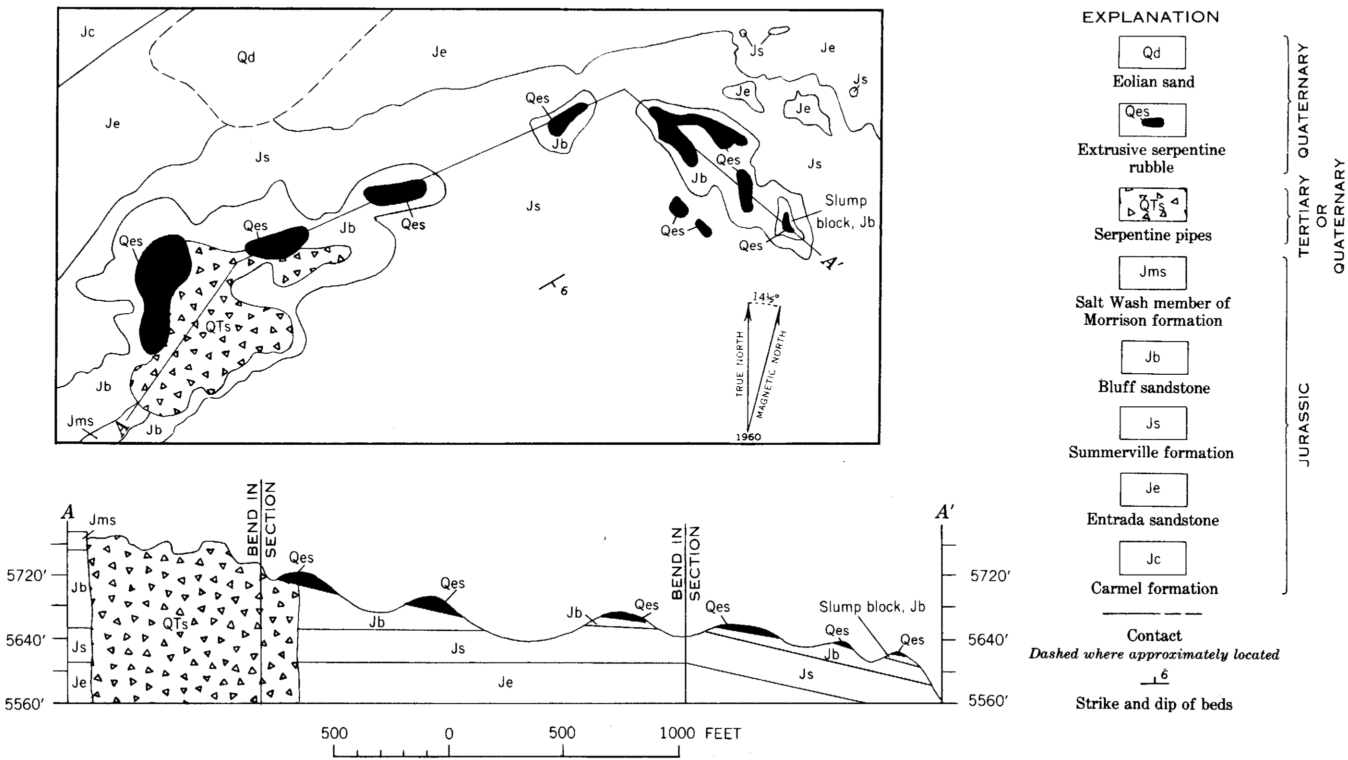

Figure 8.—Geologic map and cross section of the crest of Garnet Ridge, Arizona, showing location of pipe 1 and extrusive deposits of serpentine rubble.

50 feet or more below its normal stratigraphic position, but resting on undeformed beds. Mounds of serpentine rubble which overlap wall-rock at the pipe are regarded as extrusive, but are believed to be connected downward in the pipe with an intrusive source. Those on the knobs have no present connection with their only available source—the intrusive serpentine at pipe 1.

The mounds near pipe 1 appear to be remnants of a more extensive deposit spread either on an erosion surface about 60 feet above the surrounding land, or confined to a valley at that altitude, the topography becoming subsequently inverted. Movement of the rubble mass on the low gradient was probably aided by the structural weakness of serpentine, and was imperceptibly slow. It is assumed that movement was comparable to that observed in surface serpentine flows in California.

A mound of serpentine rubble overlaps the northwest wall of pipe 2 and lies from 20 to 30 feet above the level of erosion reached in surrounding country rock. The mound is about 100 feet above eroded debris in the pipe. Another mound of serpentine rubble northwest of the pipe is elongate parallel to the trend of a dike that lies farther northwest. A prospect trench 8½ feet deep in the mound failed to reach the base, but an extension of the dike possibly underlies it.

ORIGIN

The sequence of events at Garnet Ridge that seems to explain the field relations best is twofold. During Tertiary time there was an initial period of gaseous explosion, collapse, and rubble injection under a sedimentary cover that included the Mancos shale. In late Quaternary time there was reactivation of pressure from below, at which time the surface rubble was extruded.

It is unknown whether the rubble pipes are related to the volcanic plugs. Williams (1936, p. 131) classified all the eruptive features in Monument Valley as volcanoes and noted their resemblance to the diatremes of the Schwabian Alb. Shoemaker (1956, p. 180–183) similarly considers them diatremes and attributes their structural differences to differing stages of development and levels of exposure. We believe that two distinct and different types of eruptive bodies are found in the Monument Valley area. Most common are diatremelike features, such as the volcanic plugs, composed primarily of alkalic feldspar (orthoclase), biotite, and diopside, the olivine being only a very minor constituent. These are represented by Agathla Peak, Chaistla Butte, Church Rock, Alhambra Rock, and many others. Less common are rubble pipes such as those described here at Garnet Ridge.

It seems likely that other rubble pipes may form much of Buell Park, Ariz., for the description given by Balk (1954, p. 381) closely resembles that of the Garnet Ridge rubble pipes. In discussing the rocks that crop out at Buell Park, Balk states in part:

> . . . flatlying Paleozoic and Mesozoic sediments of the Colorado Plateau are pierced by at least three vertical plugs of kimberlite tuff * * *. Undisturbed vertical contacts are locally exposed, lacking any contact effects upon the sandstone wall rocks. Layers of tuff and xenoliths, vertical along contacts, flatten inward, and lie nearly horizontal in several places. Pale green and amber olivine, enstatite, pyrope garnet, chrome diopside, emerald-green actinolite, magnetite, titanoclinohumite, black spinel, ilmenite, and other mafics are the most important minerals, listed in order of decreasing abundance. Antigorite extensively replaces olivine, and constitutes a large volume of the tuff * * *.

In this connection Williams (1936, p. 143) notes the great dissimilarity between the rocks at Buell Park and those found elsewhere in the Navajo Country.

MINERALIZED STRATA AT GARNET RIDGE

A rubble dike associated with a vein at the northeast end of the ridge has been stained with iron oxide to a brownish-green color. The dike also contains veinlets of ankerite. The country rock adjacent to the dike is more friable than normal and contains small quantities of copper and uranium minerals. Three mineralized zones are roughly parallel to the dike walls and extend short distances along fractures in the country rock that intersect the dike. The zone closest to the dike is 1 to 3 inches wide and is bleached to a light buff. The middle zone, which is up to 2 inches wide and is absent in places, contains bluish-green copper minerals. The outer zone is 1 to 2 feet wide and is stained with limonite. This zone grades into normal Navajo sandstone away from the dike. Yellow uranium-bearing minerals are sparsely disseminated in all three zones but are most abundant in the copper-bearing zone. Tyuyamunite is the only uranium-bearing mineral that has been identified. The uranium and copper appear to be in specimen quantities only.

During the winter of 1951–52, the U.S. Atomic Energy Commission completed a drilling program at the Keith Francis claim, which includes this dike. Four inclined holes were drilled, all of which intersected the dike. Weakly mineralized ground was penetrated but the grade was considered inadequate to justify additional work.

STRUCTURE

FOLDS

In this part of northeastern Arizona the main structural element is the Monument upwarp, a broad flattened anticline whose crest is wrinkled by corrugations that are the structural elements within the Monument Valley area. The upwarp, which has a north-south axis, begins in the southern part of the Green River Desert—Cataract Canyon region (Baker, 1946, p. 94), and extends southward to terminate as a gently plunging nose in the southern part of Monument Valley. The east flank of the upwarp in this area is marked by Comb Ridge, a continuous escarpment of reddish-brown strata extending from Kayenta, Ariz., more than 90 miles northeastward into Utah. The west flank is less apparent and is probably marked by the folds which cross the plateaus far to the west of the Monument Valley area. Most of the strata dip gently away from the anticlinal crest, although locally, dips exceed 35°. Commonly, the steeply dipping strata flatten rapidly.

Structure contours of the Monument Valley area, Arizona, delineate five subordinate structural elements near the crest of the Monument upwarp (pl. 1). These are (1) the Organ Rock anticline, (2) the Oljeto syncline, (3) the Agathla anticline, (4) the Tse Biyi syncline, and (5) the Gypsum Creek dome. Two of these, the Organ Rock anticline and the Oljeto syncline, have been described by Baker in his report on the Utah part of Monument Valley (1936). In general, they are asymmetrical, with their axial planes dipping west. In addition to these previously described structural elements, three others have been noted and are here named. The first, and most prominent, is the Agathla anticline, a broad asymmetrical fold plunging to the southwest. The second is the Tse Biyi syncline, a northward-trending shallow basin. The third is the Gypsum Creek dome, an asymmetrical structure with steeper dips on the east flank than on the west.

ORGAN ROCK ANTICLINE

Baker (1936, p. 67) has traced the Organ Rock anticline southward from the San Juan River to the Utah-Arizona State line. From this point the well-developed anticline can be traced to the south along the east sides of Hoskinnini and Skeleton Mesas until it finally passes out of this area to end near Marsh Pass. Locally, small flexures and minor undulations are superimposed on the crest and flanks of the anticline. One of these is a small dome along the east edge of Hoskinnini Mesa.

The anticline is asymmetrical. It has a sinuous axial plane that dips westward. On the east flank, dips of 10° to 15° to the east have been measured near the Oljeto trading post (Baker, 1936, p. 67), and these steepen to a maximum of 35° in the Arizona part of the Monument Valley area. Dips on the west flank do not exceed 5° to the west and are marked by minor undulations. The west flank extends westward about 10 miles to the trough of the Nakai syncline (beyond the limits of the mapped area).

OLJETO SYNCLINE

Baker (1936, p. 67) traced the sinuous axis of the Oljeto syncline from the San Juan River southward to the Utah-Arizona State line. In both Utah and Arizona the axis of the syncline approximately follows the course of Oljeto Creek (pl. 1). South beyond the southern reaches of Oljeto Creek the synclinal axis is within the swale which marks the west edge of Tyende Mesa (pl. 1). The syncline is asymmetric. The steeply dipping east flank of the Organ Rock anticline forms the west flank of the Oljeto syncline, but the dips along the east flank of the syncline are low, generally averaging 3° to the west.

AGATHLA ANTICLINE

Of the structures not previously described, the Agathla anticline is the most prominent. It is named for the volcanic neck, Agathla Peak, which protrudes through the northwest flank of the anticlinal nose (pl. 1). The anticline is a broad asymmetrical southwestward-plunging feature whose southeast flank is Comb Ridge and whose northwest flank merges at its western end, with the east flank of the Oljeto syncline.

The anticlinal axis trends northeastward, although it gradually curves to the north and alines with the northward-trending synclinal axis that marks the Tse Biyi syncline (pl. 1). The axis of the Agathla anticline can be traced for about 16 miles. Dips are steepest on the northwest, where dips as high as 14° have been measured. Along the southwest nose and on the southeast flank the dips average 4°. The closure is about 400 feet.

TSE BIYI SYNCLINE

Within Tse Biyi (the valley between Mitchell and Hunts Mesas) the rocks are flexed downward into a northward-trending elongate irregular-shaped basin (pl. 1), here named the Tse Biyi syncline. Near the south end of the basin the synclinal axis, which is continuous with the Agathla anticlinal axis, trends slightly east of north. Northward, the axis curves and strikes north for the greater length of the basin. The extent of the syncline is unknown; in the Monument Valley area, however, it is about 7 miles long. On the south flank of the syncline the dips are between 9° and 10°. The dips along the west flank average 4°, although locally dips of 6° have been noted. Dips along the northeast flank of the basin do not exceed 1°.

GYPSUM CREEK DOME

The third structural element not previously described is named the Gypsum Creek dome (pl. 1). The axis of the dome forms a broad arc concave to the west. The 8-mile-long axis trends northeastward along the south edge of the dome; near the crest the trend is almost north; and at the north edge the axis strikes northwestward. The dome is asymmetrical with dips averaging 7° on the east flank, and 3° on the west flank. It plunges about 1° to both the north and south. Closure on the dome is about 400 feet. Dikes occupy a series of fractures along the crest of the Gypsum Creek dome and are parallel to the axial trend.

FRACTURES

Both faults and joints are exposed in the Monument Valley area, Arizona. In general the faults appear as small-scale normal and reverse faults involving displacements of only a few inches or feet. Intraformational faults are common in the Monitor Butte member of the Chinle (p. 27), and are present but not as extensive in the Moenkopi and Summerville formations.

Conspicuous joints are common and normally form a reticulate pattern on the surface. They include hairline breaks that can be traced only a few feet, as well as extensive cracks that extend for miles. All formations exposed are cut by joints, and these affect the mode of weathering of the unit.

At depth, in those mines where the workings permit examination of the joints, they commonly are clustered in zones 2 to 6 feet wide. Most are nearly vertical and are healed with fibrous quartz, calcium carbonate, and gypsum.

In the sandstone aquifers the joints serve as channelways. Many of the springs that issue from the base of the Navajo are along vertical joints that extend from the base of the sandstone to its top. Alteration of the strata along joints is common; the normal reddish-brown color of the strata has been altered near the joints to a light greenish gray.

The joints are expressed in the topography by sheer cliffs that are formed in many of the massive eolian sandstone beds. In many places the cliff face is parallel to the joints, and the great blocks that form the talus slopes have resulted from disintegration of rock slabs detached from the main rock mass along joint surfaces.

Several sets of joints have been observed. The dominant set ranges from N. 25° W. to N. 65° W.; a second set from north to N. 15° E.; and a third set strikes almost due east. All sets are vertical or nearly vertical.

GEOLOGIC HISTORY

The pertinent details of the geologic history of the Monument Valley area, Arizona, are summarized in the table below.

Outline of geologic history of the Monument Valley area, Arizona

System	Group	Formation	Member	Event
				POST-MORRISON INTERVAL As deposits of Eocene age are extensively exposed elsewhere on the Colorado Plateau, sedimentary deposition probably continued at least until the close of the Eocene. South of the Monument Valley area the Cretaceous rocks forming Black Mesa (fig. 1) have been folded. Evidence for the Late Cretaceous-early Tertiary age of this folding is the presence of undeformed Eocene strata which lie across eroded older folded rocks. Exposures of this nature are near Escalante, Utah (Gregory and Moore, 1931, p. 117–124), and at the north end of the Waterpocket fold (Dutton, 1880, p. 286–295). Hunt (1953, p. 209) suggests that the Monument upwarp was also formed at this time. The laccolithic mountains in Utah and Arizona may have been intruded in middle Tertiary time before great progress had been made in the dissection of their cover (Hunt, 1953, p. 212). Active dissection probably began at the close of the Eocene as a result of epeirogenic uplift and has continued uninterrupted to this day. All perennial streams of the region have been superimposed upon older strata. On the basis of included xenoliths, the igneous rocks exposed in the Monument Valley area were intruded at least after the Mancos shale of Late Cretaceous age was deposited. Intrusive relations elsewhere, however, have convinced Williams (1936, p. 148) that the age of these intrusions is Pliocene.
		—Unconformity—		
Jurassic	San Rafael group	Morrison formation	Brushy Basin shale	The major source area that produced most of the sediments that formed the Salt Wash member of the Morrison formation lay west of the Monument Valley area in west-central Arizona (Craig and others, 1955). Streams flowed northward and eastward from this source area and deposited clastic sediments in the shape of a broad thin alluvial fan. The Monument Valley area was covered by these sediments. As these streams lost velocity, a period of deposition by relatively quiet waters began and silts and clays were deposited to form the Brushy Basin member of the Morrison formation.
			Salt Wash sandstone	
		Bluff sandstone		On the final northward withdrawal of the Carmel sea, eolian sand and silt derived principally from a local source mingled with the uppermost red sediments of the Summerville. Gradually wind-worked sand prevailed and a large wedge-shaped mass of sand was deposited with its thickest part near Bluff, Utah, and its southern edge in the Monument Valley area, Arizona.
		Summerville formation		The second advance of the Carmel sea from the north into the Monument Valley area buried and truncated the eolian crossbedded sandstones of the Entrada (Baker, Dane, and Reeside, 1936, p. 54). Sediments deposited by these marine waters consist of orange- to reddish-brown thin-bedded sand with some intercalated silt lenses that together form the Summerville formation. The Monument Valley area once again was at or near the southern margin of this sea. Probably the Summerville was deposited under shallow quiet waters near an oscillating shoreline that locally withdrew and exposed small areas to subaerial deposition and erosion.
		Entrada sandstone		With the temporary withdrawal of this marine sea to the north, a surface of low relief was exposed upon which the basal sandstone of the Entrada was deposited. The sediments of the Entrada seem to have been deposited under arid climatic conditions, in part by eolian and in part by subaqueous action. The dominant source area of the material was to the northwest (Baker, Dane, and Reeside, 1936, p. 46), although the Navajo highland may have supplied some sediments from the south (Smith, C. T., 1951, p. 100).

Outline of geologic history of the Monument Valley area, Arizona—Continued

System	Group	Formation	Member	Event
Jurassic—Continued	San Rafael group—Con.	Carmel formation		The eolian deposition characteristic of the Navajo was ended by an extensive marine sea (that is, the Carmel sea) which invaded the Monument Valley area from the northwest and deposited the red silt and fine-grained sand of the Carmel (Baker, Dane, and Reeside, 1936, p. 54). The Monument Valley area was probably at or near the very southernmost extent of this sea. This is indicated by the alternating beds of sandstone and siltstone, the sand-filled mud cracks, and the current-type ripple marks, all of which suggest deposition in marginal marine waters that were locally exposed to subaerial erosion.
		Unconformity		
Jurassic and Jurassic(?)		Navajo sandstone		As the streams that deposited the Kayenta waned, eolian conditions prevailed and the tangentially crossbedded sands of the Navajo were deposited. The sediments apparently came from the northwest (Stewart and others, 1959), although Baker, Dane, and Reeside (1936, p. 53) suggest that the source of the Navajo was from the southwest. Near the end of this episode of eolian deposition, local lacustrine conditions prevailed and dense unfossiliferous gray limestone lenses in uppermost Navajo strata indicate the presence of ephemeral fresh water playa lakes.
Jurassic(?)		Kayenta formation		The eolian sandstones of the Wingate grade into the fluviatile deposits of the Kayenta. The Kayenta consists predominantly of conglomerate, coarse crossbedded conglomeratic sandstone, and lenses of mud-pebble conglomerate, all indicative of deposition by turbulent streams. Intercalated shale lenses suggest periods of relatively quiet deposition. The material was derived predominantly from the north and northeast (Stewart and others, 1959), although local variations in the direction of crossbedding in the sedimentary units suggest that stream directions were not constant.
	Glen Canyon group	Wingate sandstone		The Wingate is an eolian deposit near the center of its basin of deposition; near its margins, however, Baker, Dane, and Reeside (1936, p. 53) consider the deposits of the Wingate to represent the commingling of water-worked and wind-worked material. Near the close of Chinle time a new positive element, known as the Navajo highland, began to rise in central Arizona south of the Monument Valley area. This highland may have furnished some of the sediments for the Church Rock member of the Chinle, but apparently did not furnish any for the Glen Canyon group (Smith, C. T., 1951, p. 91). The highland served principally to confine deposition to the north. Continental conditions prevailed during formation of the Glen Canyon group and most of the sediments were derived from the northwest and probably from the same source area (Stewart and others, 1959). The Monument Valley area is at about the center of the basin in which Glen Canyon group sediments were deposited.
Triassic		Chinle formation	Church Rock member Owl Rock member Petrified Forest member Monitor Butte member Shinarump member	Northward-flowing streams heading in this newly uplifted highland began to deposit coarse clastic material in the form of a broad thin sheet of gravel over most of northeastern Arizona and southeastern Utah. This extensive gravel deposit is the Shinarump member of the Chinle formation. As the northward-flowing streams lost velocity, the depositional environment changed to one marked by nearly continuous quiet water sedimentation. The conglomerate and crossbedded sandstone of the Monitor Butte member represent the final stages of this episode of turbulent fluviatile deposition. The siltstone and claystone of the Petrified Forest member denote a long period of continuous deposition by quiet waters. Near the close of this episode of quiet fluviatile deposition, lacustrine conditions set in and local fresh water playa lakes were formed. Their sites are now marked by the limestones characteristic of the Owl Rock member. Arid conditions were dominant at the close of Chinle time and the red fluvially deposited siltstone of the Church Rock member was locally reworked by winds.

				The amount of time represented by the unconformity between the Moenkopi-Shinarump is difficult to determine. McKee (1951a, p. 88) suggests that the time involved was considerable. In the Monument Valley area, it would seem that the period was of relatively short duration, and that the streams flowed across a Moenkopi surface that was only partly indurated.
		—Unconformity—		
		Moenkopi formation		The shoreline of the western sea that truncated the De Chelly sandstone member changed continuously, locally inundating and then exposing certain areas (McKee, 1954, p. 78). Most of the sediments that form the Moenkopi were deposited under these shallow water conditions. In places, lagoons and playa lakes were formed (McKee, 1954, p. 79). Deltalike deposits were built on this sloping plain by westward-flowing rivers and in time these were buried by a renewed advance of the sea. With the complete westward withdrawal of the sea a period of subaerial erosion began. The surface of the Moenkopi was dissected into a series of broad shallow elongate swales and ridges. During this time, extensive uplift began in central and southern Arizona and probably continued throughout Late Triassic time (McKee, 1951b, p. 493).
Permian		Cutler formation	Hoskinnini tongue - - - - - - - - - - - - De Chelly sandstone member Organ Rock tongue Cedar Mesa sandstone member Halgaito tongue	According to Baker and Reeside (1929, p. 1446) the first red beds of the Cutler formation, represented by the Halgaito, were deposited by westward-flowing streams which headed in a highland mass in western Colorado. These sediments, deposited under arid climatic conditions, are coarse near their source and finer grained to the west. These red beds were displaced by the light-orange Cedar Mesa sediments which were probably brought in from the northwest by streams and then modified by eolian action. As the westward-flowing streams regained the initiative, a second period of red-bed deposition began, represented by the Organ Rock. These rapidly buried the Cedar Mesa sediments. This second sequence of red beds was interrupted by the sands that form the De Chelly. Probably these were also derived from the northwest and reworked by wind (Baker and Reeside, 1929, p. 1447). At the close of De Chelly deposition the Monument Valley area may have been subjected to subaerial erosion for a brief period. This was ended by the eastward advance of a western sea which truncated the partly indurated De Chelly sandstone member and deposited the red-bed sediments of the Hoskinnini (Baker and Reeside, 1929, p. 1448).
				Pre-Cutler

ORE DEPOSITS

Economic deposits in the Monument Valley area, Arizona, include uranium, vanadium, and oil. Elsewhere in the same general region small shows of gold, silver, and copper have excited interest, but no sizable deposits of commercial grade have been found. The great interest displayed in uranium-vanadium deposits since 1948 has furnished, in part, some basis for this report. In general, this part of the report discusses the history of the Monument Valley area, Arizona, in terms of uranium-vanadium production, and attempts to furnish some geologic concepts and prospecting guides that might assist prospectors in their search for commercially profitable deposits of uranium and vanadium.

Uranium-vanadium minerals have been reported from the Monument Valley area for many years. Gregory (1917, p. 149) mentions "carnotite" among pebbles of the Shinarump conglomerate, and Baker (written communication, 1936) noted the presence of "carnotite" associated with fossilized wood in the Shinarump conglomerate in the Utah part of Monument Valley.

The history of uranium- and vanadium-ore production from the Monument Valley area, Arizona, is in effect the history of two deposits: the Monument No. 1 and No. 2 mines (fig. 1). Both are in scour channels filled with Shinarump strata. In both places the Vanadium Corporation of America has been the major producer of uranium and vanadium ore. Relatively little is known concerning their early history, although both appear to have been active in the period 1942 to 1944. The Monument No. 2 mine assumed considerable importance as a producer of uranium and vanadium ore on the Colorado Plateau after 1948.

The Monument No. 1 mine began producing ore in 1942, and continued intermittently until 1950, at which time the Vanadium Corporation of America abandoned their mine. Production at no time was large. Since then, prospectors have examined the remnant of the Monument No. 1 channel and have made a few attempts at mining. In 1952, the Foutz Mining Co. (now the Industrial Uranium Co.) of Farmington, N. Mex., opened a small adit in the flank of the channel and began producing low-grade uranium and vanadium ore. They named their mine the Mitten No. 2 and produced small amounts of ore. No ore was produced from the Monument No. 1 mine in 1953. In 1954, the Foutz Mining Co. discovered and began to mine a sizable ore body in a previously unexplored part of the Monument No. 1 channel (Witkind, 1961).

In 1942, Luke Yazzie, a Navajo, staked a claim on mineralized strata southeast of Yazzie Mesa and then told one of the traders in the vicinity, Mr. Harry Goulding, of this exposure. Goulding contacted Mr. Denny W. Viles, an official of the Vanadium Corporation of America, and guided Viles to the area. As the news of the mineralized exposure spread, officials of other organizations examined the area. In 1942, the Vanadium Corporation of America leased the claim (Monument No. 2 mine) from the Navajo Tribal Council.

Mining in the Monument No. 2 mine was carried on during the period 1942–45, but production was small. In 1948, production began on a large scale after a bulldozer uncovered rich vanadium ore at the surface. At first, the ore was mined by stripping methods. By 1949, production had greatly increased and the Vanadium Corporation of America began underground mining operations. In 1950, underground mining was started at the West Red Oxide workings and the South workings (pl. 7*A*). Since then, the underground workings have been extended the entire length and width of the channel. In 1952, the company began to alter the operation gradually from underground to stripping methods, and in June 1953, both types of operations were being conducted concurrently in different parts of the mine.

Other companies and independent operators have mined from this channel adjacent to the Vanadium Corporation of America lease. The Climax Uranium Co. has mined along both flanks of the channel and at the southern end. The northern end of the channel has been mined by John M. Yazzie, a Navajo, and his associate Thomas Clani. Two Navajo Indians, Black and Blackwater, have also mined ore from the east flank of the channel. Their workings were leased, in 1953, to W. E. Pollock and B. N. Byler.

ORE-BEARING CHANNELS

APPEARANCE

The work in the Monument Valley area, Arizona and Utah, has repeatedly confirmed the fact that all the uranium-ore deposits are in symmetric and asymmetric troughs cut into the Moenkopi formation and the De Chelly sandstone member of the Cutler formation and are filled with sedimentary rocks of the Shinarump member of the Chinle formation (pl. 1). These troughs are known as channels and they accentuate the unconformity between the Shinarump member of the Chinle formation and the Moenkopi formation. Most channels are exposed along mesa edges and in valley walls as U-shaped depressions cut into the Moenkopi formation and filled with conglomeratic sandstone (fig. 9*A*). In this mode of outcrop the channels are buried beneath overlying beds of the Shinarump member. Where these upper beds of the Shinarump member have been removed, the channel strata appear as narrow elongate exposures of gray conglomeratic sandstone

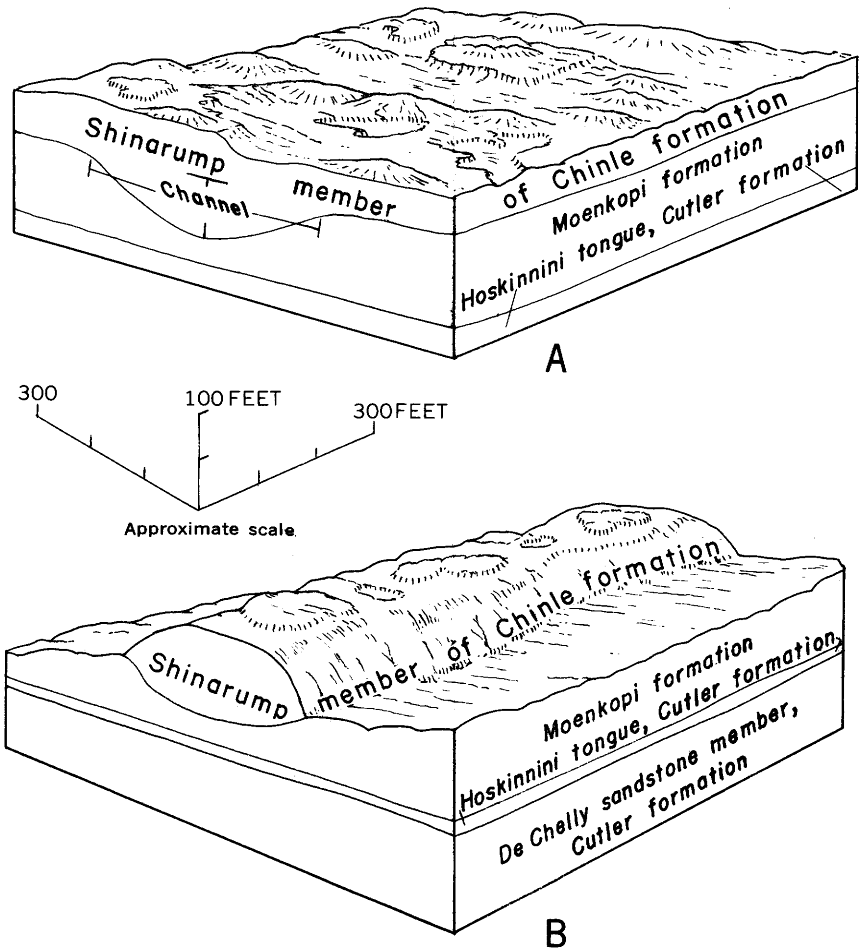

FIGURE 9.—Block diagrams illustrating modes of channel outcrop in the Monument Valley area, Arizona. *A*, Channel buried beneath overlying beds of the Shinarump member of the Chinle formation. *B*, Resistant channel strata standing as a ridge; erosion has removed overlying beds and adjacent shaly siltstone.

bounded by the red shaly siltstones of the Moenkopi formation or as ridges (fig. 9*B*) standing above the general level of the dissected Moenkopi surface. Cross sections of some typical channels of the Monument Valley area, Arizona, are shown in figure 10.

CLASSIFICATION

Commonly, the channels are difficult to trace, many because they are not well exposed, others because they differ greatly in length. A channel may crop out along a mesa rim, yet a projection of its trend fails to disclose it on the opposite rim or, for that matter, anywhere else along the rim. Other channels, however, are more continuous,

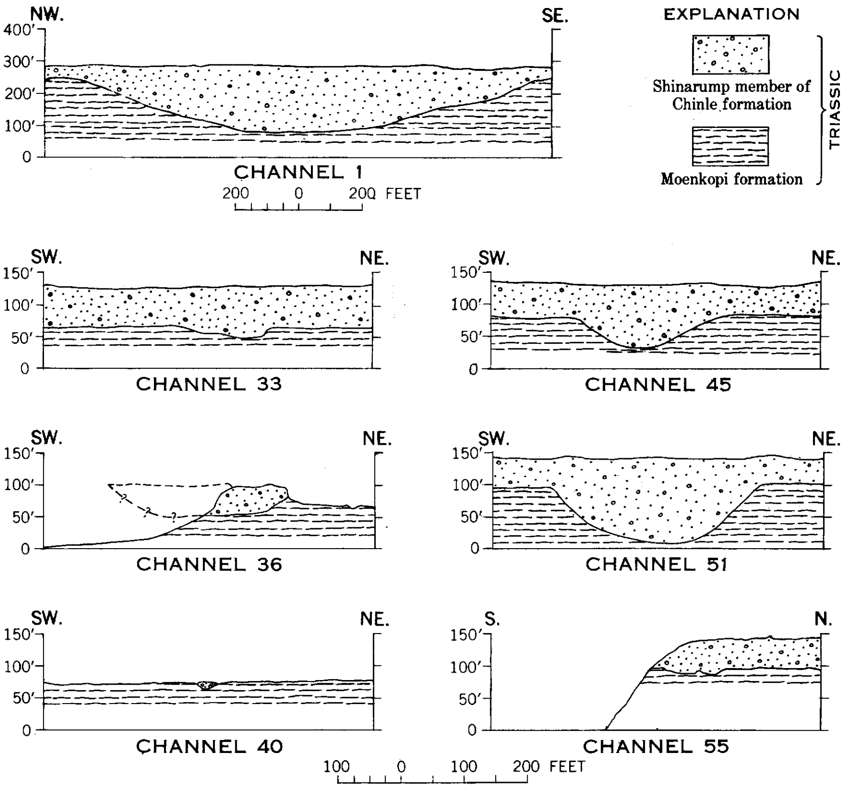

FIGURE 10.—Cross sections of typical channels in the Monument Valley area, Arizona. Locations of the channels are shown on plate 1. Channels 40 and 55 are narrow; channel 1 is broad; all others are of intermediate width.

and alined exposures of a channel can be projected across a mesa top. One channel was traced for 4 miles; others end within a mile or two.

A distance of 2 miles has been established arbitrarily as the division between the basinlike short channels and the long channels.

A drilling program completed by the U.S. Atomic Energy Commission (John W. Chester and Philip H. Donnerstag, written communication, 1953) in the Monument No. 2 channel established that these shorter channels terminate in curves, gently concave upward (pl. 7*B*). As of 1953, there had been no extensive drilling in long channels, so that how they terminate is unknown.

The channels have been divided into three classes based upon width (table 1). The first class includes channels as much as 50 feet in width. The second class comprises channels ranging in width from 50 to 350 feet. The third class includes channels more than 350 feet wide. Channel strata, sorting, and bedding seem identical in all three classes.

TABLE 1.—*Compilation of channel data, Monument Valley, Ariz.*

[Symbols for width of channels; (N), narrow (as much as 50 ft); I, intermediate (50–350 ft); and (B), broad (350–2300 ft)]

Channel No. on pl. 1	Name of channel		Latitude (north)	Longitude (west)	Trend	Width (feet)	Depth (feet)	Sedimentary rocks in channel		Width of bleached zone		Uranium minerals
	U.S. Geological Survey	U.S. Atomic Energy Commission						Rock type and structure	Texture	Near channel	Beneath channel	
1	Alfred Miles No. 1	Nokai Mesa	36°59.8′	110°28.1′	N. 50° E.	2150(B)	70	Massive sandstone.	Fine to medium grained.		2 ft 8 in.	Carnotite, torbernite, autunite(?).
2			36°59.2′	110°27.8′	N. 35° E.	(N)		do	do		2 ft	None.
3	Cutfinger Canyon		36°58.2′	110°28.7′		2300(B)		Lenticular sandstone.	Coarse grained and conglomeratic.		2½–3 ft	Do.
4			36°58.5′	110°28.4′		1500(B)		Crossbedded sandstone and siltation.	Conglomeratic		4–6 in.	Do.
5			36°57.9′	110°28.3′	N. 40° E.(?)	150(I)	10–15	Massive conglomeratic sandstone.	Conglomeratic, gritty.	30 in.		Do.
6	Double		36°59.8′	110°26.7′	E–W	1800(B)	50	Massive sandstone.	Medium to coarse grained.	6–8 in.	6–8 in.	Do.
7	Alfred Miles No. 2		36°59.6′	110°26.6′	E–W	900(B)	50	do	do	6–8 in.	2 ft	Do.
8	do		36°59.2′	110°25.0′	N. 80° W.	500(B)	75	do	Fine to medium grained.	6–8 in.	6–8 in.	Do.
9	do		36°59.2′	110°24.7′	N. 80° E.	250(I)	30	do	do	1 ft	1 ft	Do.
10			36°58.9′	110°24.5′		150(I)	10	do	Medium grained	1 ft	1 ft	Do.
11			36°58.7′	110°24.8′	N. 12° E.	150(I)	0	do	do	6 in.	6 in.	Do.
12	SW. Hoskinnini		36°58.1′	110°24.8′	N. 72° E.	600(B)	30	do	do	2 ft	3–4 in.	Do.
13			36°58.6′	110°25.8′	N. 55° E.	150(I)	10	do	do	1 ft	1½ ft	Do.
14			36°58.5′	110°25.8′	N. 80° E.	20(N)	6	do	do	1 ft	1½ ft	Do.
15			36°57.3′	110°28.7′	N. 70° E.(?)	50(I)	10–15	Lenticular sandstone.		6 in.		Do.
16	Checker		36°56.4′	110°28.5′	N. 20° E.	300(?)(I)	20–40	Massive sandstone.	Medium grained	4 in.	1 ft	Do.
17	Road		36°55.0′	110°29.8′	N. 25° W.	400(B)	50	do	do	1 ft	2 ft	Do.
18	Fish		36°54.3′	110°29.6′	N. 10° W.	400(B)	40	do	do	6 in.	1 ft	Do.
19	Re-entrant		36°53.9′	110°29.7′	N. 40° E.	600(B)	40	do	do	6 in.	1 ft	Do.
20			36°53.4′	110°24.8′	N. 50° E.	30(N)	10	Siltstone	Silty		4 in.	Do.
21	Cecil Todechenee		36°53.4′	110°24.8′	E–W	100(I)	20	Massive sandstone.	Coarse grained			Carnotite.
22	Ladder		36°51.9′	110°25.8′	N. 18° E.	45(N)	8	do	Medium grained		4 ft	None.
23			36°51.8′	110°25.7′	N. 35° E.	600(B)	30	do	do		4 ft	Do.
24			36°51.2′	110°25.9′	N. 25° E.	140(I)	20	do	do		6–8 in.	Do.
25			36°59.9′	110°23.2′	N. 30° W.	250(?)(I)	10	do	do		6–8 in.	Do.
26	E. Hoskinnini		36°59.4′	110°22.4′	N. 15° E.–N. 10° W.	300(I)	30	do	do	1 ft	1 ft, 2 in.	Do.
27		Hoskinnini No. 1.	36°57.8′	110°22.8′	N. 65° W.	250(I)	75	do	Coarse grained			Do.
28		Crescent	36°57.5′	110°22.2′	N. 45° W.	150(I)	50	Crossbedded sandstone.	Medium grained			Do.

29	Ramp		36°57.3′	110°21.4′	N. 10° W.	50(N)	20	do	do			Do.
30			36°56.7′	110°26.9′	N–S	175(I)	20	Lenticular sandstone.	Coarse grained	1 ft	2 in	None.
31			36°56.0′	110°26.1′	N–S	10(N)		Massive sandstone.	Medium grained		3 ft	Do.
32			36°59.9′	110°14.2′	N. 65° E.	25(N)	15	do	do		3 ft	Do.
33			36°59.9′	110°14.3′	N. 27° E.	15(N)	8	Lenticular sandstone.	do		1 ft	Do.
34		Triangle	36°59.3′	110°15.0′	N. 65° E.	200(I)	50	Massive sandstone.	do			Do.
35			36°58.9′	110°15.6′	N. 35° W.	250(I)	30	do	do	4 ft	4 ft?	Do.
36	Monument No. 1	Monument No. 1.	36°57.4′	110°14.0′	N.10°W.	250(I)	50	do	do	2 ft	5 ft	Carnotite.
37	Koley Black group		Center of group— 36°48.7′	110°09.3′	N.35°W.	80–100(I)	25	Lenticular sandstone.	Coarse grained		1 ft	None.
38	do		36°48.7′	110°09.3′	N.45°W.	80(I)		do	do		1 ft	Do.
39	do		36°48.7′	110°09.3′	N.44°W.	50(N)	5–10	do	do		1 ft	Do.
40	do		36°48.7′	110°09.3′	N.44°W.	50(N)	5–10	do	do		1 ft	Do.
41	do		36°48.7′	110°09.3′	N.44°W.	50(N)	5–10	do	do		1 ft	Do.
42	do		36°48.7′	110°09.3′	N.20°W.	35(N)	20	do	do		1 ft	Do.
43	do		36°48.7′	110°09.3′	N.45°W.	110(I)	30	do	do		1 ft	Do.
44	do	Sheep	36°48.7′	110°09.3′	N.45°W.	35(N)	25	Massive sandstone.	do		6 in	Do.
45	do	Cold (Cold Mesa.)	36°48.7′	110°09.3′	N.52°W.	270(I)	30	do	do	6 in	1 ft	Do.
46	do		36°48.7′	110°09.3′	N.20°W.	35(N)	20	do	do		1 ft	Do.
47	do		36°48.7′	110°09.3′	N.45°W.	110(I)	30	do	do		1 ft	Do.
48	Route No. 1	Dike	36°53.3′	110°14.8′	N–S	150(I)	30	do	do			Do.
49	Mystery Valley No. 1.		36°51.0′	110°11.7′	N.50°W.	150(I)	16	do	Medium to coarse grained.	1 ft	2–3 ft	Do.
50	Mitchell Mesa No. 2.		36°57.9′	110°06.9′	N.70°W.	350(?)(I)	50	do	do		1 ft	Do.
51	Mitchell Mesa No. 1.		36°57.8′	110°06.5′	N.55°W.	350(I)	75	do	Fine to medium grained.	1 ft	4 ft	Tyuyamunite.
52	Mitchell Mesa No. 3.		36°57.8′	110°07.8′	N.82°E.	300(I)	70	Crossbedded sandstone.	Medium grained	1 ft	3–6 ft	None.
53			36°51.8′	110°10.1′	N.85°W.	70–80(I)	15	Massive sandstone.	do			Do.
54	Mystery Valley No. 2.		36°51.7′	110°08.9′	N.75°E.(?)	50(N)	20	Lenticular sandstone.	Coarse grained			Do.
55	Jack Brodie	Brodie Nos. 4, 5.	36°51.4′	110°04.9′	N.85°E.	150(I)	20	do	Medium grained		1½ ft	Carnotite(?)
56	Hunts Mesa No. 2		36°53.9′	110°03.7′	N.82°E.	50(N)	20	Crossbedded sandstone.	do		2 ft	Carnotite.
57	Hunts Mesa No. 1		36°53.8′	110°02.8′	E–W	300(I)	50	Massive sandstone.	do		6 ft	Do.
58	Monument No. 2	Monument No. 2.	36°55.7′	109°53.1′	N.18°W.	400–700(B)	50	See text (p. 105–113.			2 ft	See text p. 105–113.
59	Cuesta		36°56.5′	109°52.9′	N.25°W.	300(I)	20	Crossbedded sandstone.		1½ ft	3 ft	None.
60			36°57.8′	110°21.0′	N.55°W.	150(I)	25	do	Conglomeratic	1 ft	2–3 ft	Do.
61			36°58.9′	110°16.4′	N.67°E.	300(I)	40	do	do	1 ft	3–4 ft	Do.
62			36°54.4′	110°07.8′	N.50°W.	300(I)	20	Lenticular sandstone.	Medium grained			Do.

TABLE 1.—*Compilation of channel data, Monument Valley, Ariz.*—Continued

Channel No. on pl. 1	Radioactivity anomaly		Metallic minerals	Inclusions in sedimentary rocks	Claim holder (1953)	Address	Remarks
	Airborne	Outcrop					
1	Positive	Positive	Malachite, azurite, limonite, jarosite.	Clay pebbles of Moenkopi, silicified wood.	Alfred Miles, F. Todechenee.	Oljeto, Utah	See text, p. 149, for drilling results.
2	None	None	Limonite	Plant matter	None		
3	do	do	Limonite, jarosite, manganese oxides.		do		
4	do	do	Limonite	Silicified wood	do		
5	do	do	Limonite, jarosite		do		
6	do	2 times background.	Malachite, limonite, jarosite	Clay pebbles, silicified wood	Alfred Miles	Oljeto, Utah	May be part of channel 7.
7	do	None	Malachite in bleached zone	do	do	do	May be part of channel 6.
8	do	do	Limonite		do	do	May be part of channels 7 and 9.
9	do	do	Limonite, jarosite	Silicified wood			May be part of channels 7 and 8.
10	do	do	Limonite				
11	do	do	do	Clay pebbles, plant matter, silicified wood.			
12	do	do	do				
13	do	do	do				
14	do	do	do				
15	do	do					
16	do	do	Jarosite				Only basal channel sediments preserved.
17	do	do	Malachite replacing wood	Silicified wood			Isolated remnant of channel.
18	do	do					Do.
19	do	do					
20	do	do		Sandstone blocks			
21	do	16 times background scintillometer.	Malachite, vanadium minerals, limonite.	Charred wood, silicified wood	C. and P. Todechenee.	Kayenta, Ariz	
22	do	None	Limonite		C. Todechenee	Kayenta, Ariz	
23	do	do	Limonite				
24	do	do		Clay stringers			
25	do	do					
26	do	do		Clay-pebble zones in basal sediments.			
27	Positive	None	Limonite	Silicified wood, hydromica			May aline with channel 28.
28	Positive	None	Malachite, limonite	Plant matter, silicified wood			May aline with channel 27.
29	None	None	Malachite, limonite	Silicified wood			
30	None	None					
31	do	do	Marcasite concretions, limonite, jarosite.	Charred wood			
32	do	do	Limonite	Silicified wood			
33	do	do		Silicified wood			

34	Positive	None	Secondary copper minerals, limonite.				
35	None	None	Limonite, jarosite	Silicified wood, plant matter			
36	Positive	Positive	Secondary copper minerals	Clay pebbles, silicified wood	Abandoned		See text p. 129–135.
37	None	10 times background.	do	Silicified wood			See text p. 142–144.
38	do	None	Limonite, jarosite				Do.
39	do	do					Do.
40	do	do					Do.
41	do	do					Do.
42	do	do					Alines with channel 46.
43	do	do					See text p. 143; alines with channel 47.
44	Positive	10 times background scintillometer.	Secondary copper minerals, limonite.	Silicified wood, charred wood	B. Maher	Kayenta, Ariz	See text.
45	Positive	10 times background scintillometer.	Malachite, azurite, limonite	do	do	do	See text p. 142–144.
46	None	None	Limonite				See text p. 142–144; alines with channel 42.
47	do	do					See text p. 142–144; alines with channel 43.
48	Positive	3 times background scintillometer.	Limonite				Anomaly due to igneous dike.
49	None	None					
50	do	do	Limonite, jarosite	Silicified wood, plant matter; hydromica.			May aline with channel 51.
51	do	10 times background Geiger counter.	Secondary copper minerals	Silicified wood, plant matter	H. Binoli	Gouldings, Utah	May aline with channel 50.
52	None	2 times background.	Vanadium minerals, limonite, malachite.	Silicified wood			
53	Positive	None	Limonite	Silicified wood			
54	None	do	Malachite, azurite				
55	do	2 times background, Geiger counter.	Secondary copper minerals	Silicified wood	R. C. Cutter	Grand Junction, Colo.	
56	Positive	Positive	See text	Silicified wood, clay pebbles, charred wood.	do	do	See text p. 136–139.
57	do	do	do	Silicified wood, plant matter	do	do	Do.
58	do	do	do	See text p. 105–113	See text p. 105–113		
59	None	None		Silicified wood			
60	do	2 times background.					
61	do	None	Limonite, jarosite	Silicified wood			
62	do	do	do	Asphaltic matter			

During the course of the fieldwork, 62 channels were noted. Of this number, 16 were included in the first class, 34 in the second class, and 12 in the third.

TRENDS

Many channels in the Monument Valley area trend northwestward (fig. 11), and it seems that a northwesterly trend is the preferred orientation. In an area as small as the Monument Valley area, Arizona, this northwesterly orientation is merely suggested by a diagram of the channel trends (fig. 11*A*). However, a diagram (fig. 11*C*) of all channels in a much larger area (the Utah and Arizona parts of Monument Valley) indicates clearly the dominant northwesterly orientation.

Geologic field data indicate that most channels are relatively straight. A few channels, however, such as the Monument No. 1 channel (fig. 22), apparently describe wide curves.

Confirmation of both the relative straightness and the short character of some channels stems from a geophysical investigation in the Koley Black area (fig. 12) by Rudolph A. Black and Wayne H. Jackson (written communication, 1954), of the U.S. Geological Survey. The fact that channel 45 (fig. 12) ends within 350 feet of the outcrop could not be foreseen from surface exposures.

Single channels are most common; but several bifurcate and, of these, at least one appears to divide into a series of subparallel smaller channels. This seems to be the case in the Koley Black area where a single large channel branches to form several minor channels (fig. 12). The Monument No. 2 channel also bifurcates, the two parts joining after several hundred feet to form again one large channel (pl. 7*B*).

FLOORS

Little is known about the configuration of channel floors. From mine workings in the Monument No. 2 and Monument No. 1 channels, the floors are known to be undulatory and locally extremely irregular, both in longitudinal extent and in cross section (pl. 7). Geophysical work in the Koley Black area (fig. 12) and along the Alfred Miles No. 1 channel (fig. 29) has also indicated that broad shallow depressions (scours) are in channel floors. The floors of the Monument No. 2 and the Monument No. 1 channels have similar scours. It has been suggested by some geologists of the U.S. Atomic Energy Commission (John W. Chester and Philip H. Donnerstag, written communication, 1953) that these basal depressions are important in localizing ore. They state, "In the majority of deposits the mineralized material is confined to the bottom or lower sides of the channel and most often in scours or potholes in the channel."

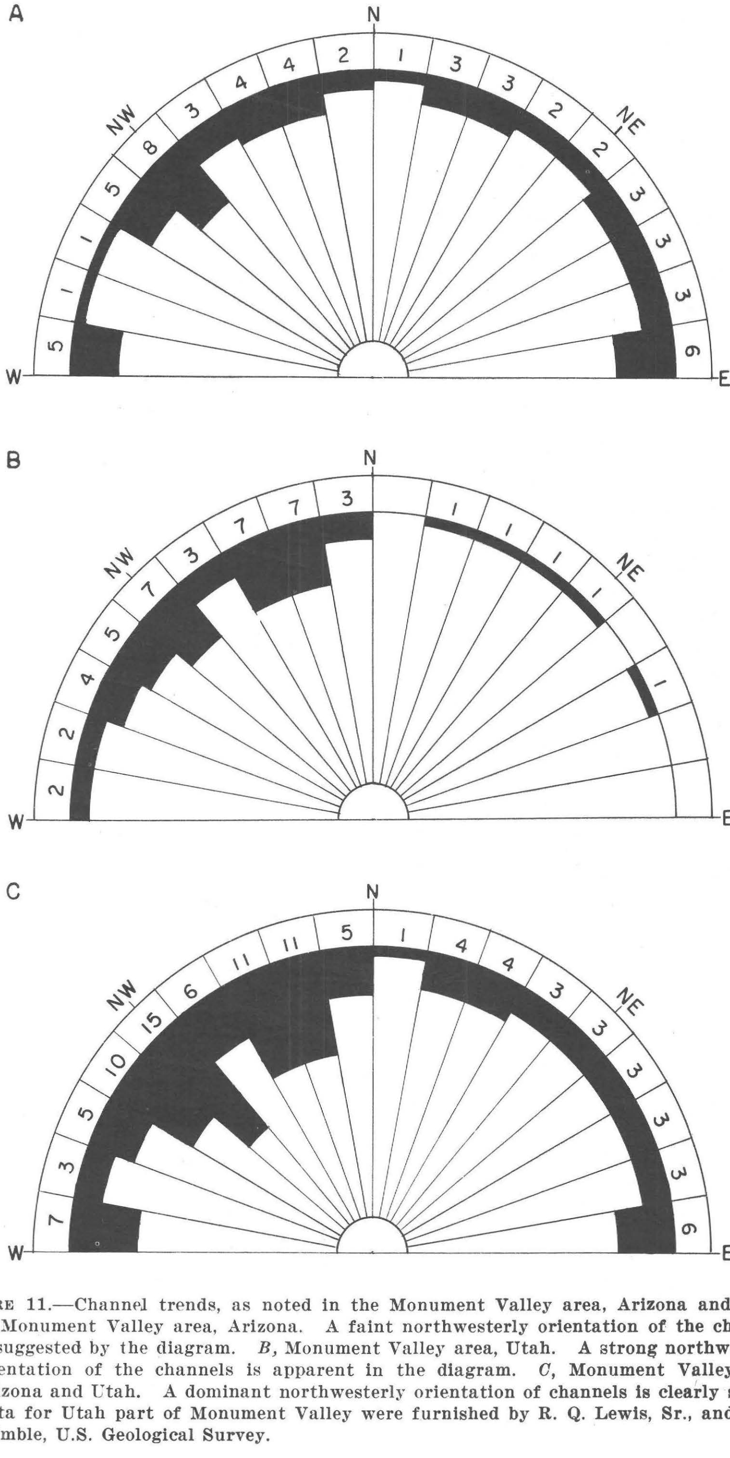

FIGURE 11.—Channel trends, as noted in the Monument Valley area, Arizona and Utah. *A*, Monument Valley area, Arizona. A faint northwesterly orientation of the channels is suggested by the diagram. *B*, Monument Valley area, Utah. A strong northwesterly orientation of the channels is apparent in the diagram. *C*, Monument Valley area, Arizona and Utah. A dominant northwesterly orientation of channels is clearly shown. Data for Utah part of Monument Valley were furnished by R. Q. Lewis, Sr., and D. E. Trimble, U.S. Geological Survey.

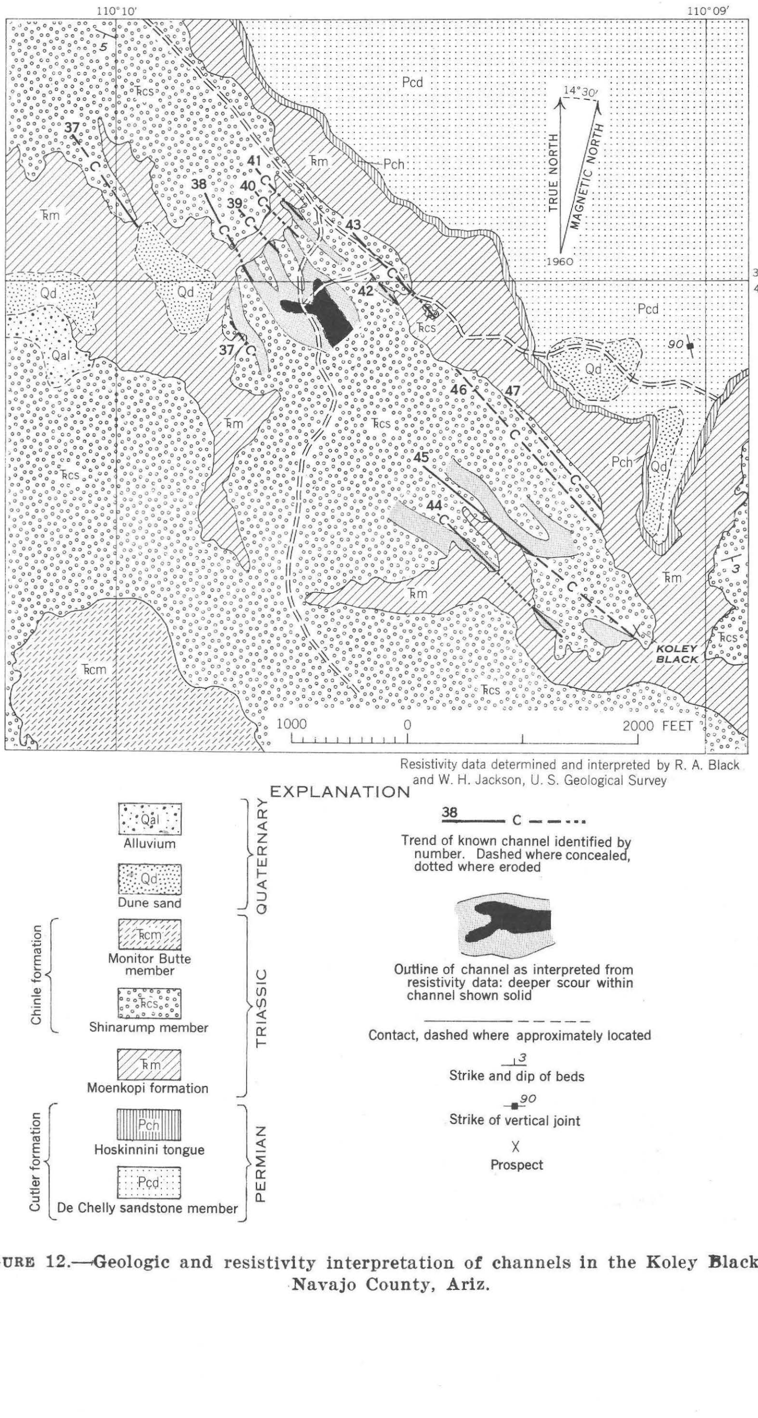

FIGURE 12.—Geologic and resistivity interpretation of channels in the Koley Black area, Navajo County, Ariz.

The mapping of the Vanadium Corporation of America's Monument No. 2 mine suggests that, although these depressions may be favorable localities for ore deposition, by no means are they the only ones. In general, the major deposits of uranium-vanadium ore are in basal channel fill. However, ore is found along the flanks, in the center, and in the uppermost channel strata (p. 108).

CHANNEL FILL

Sedimentary rocks filling the channels range from fine- and coarse-grained sandstone to conglomerate. Parts of channels are filled completely with a massive well-sorted uniform-textured medium-grained sandstone, totally devoid of pebbles or conglomerate lenses. Other parts contain conglomerate with minor amounts of interstitial coarse-grained sand.

Our impression is that the channels contain more fossil wood than the formation as a whole. Some of this wood is replaced by silica, some by copper carbonates and sulfides, some by uraninite, and some has been coalified. Flattened logs of black carbonaceous material (vitrain?) are associated with several ore deposits. Some of the rich ore bodies at the Monument No. 2 mine represent deposition of uranium minerals around logs (p. 87, 88). Pieces of wood partly replaced by secondary copper minerals (azurite, malachite) have been found in basal sediments of the Alfred Miles channels Nos. 1 and 2 and in Double channel (table 1).

At least two types of clay are included in sedimentary rocks of the Shinarump member of the Chinle formation. By far the most abundant are altered and unaltered clay fragments derived from the Moenkopi formation. Lesser amounts of clay are represented by altered volcanic ash which was included during original deposition of the Shinarump member.

Whether either type of clay fragment is instrumental in the localization of uranium ore is unknown. Conflicting evidence has been noted in mineralized rock at several localities. In the Monument No. 2 mine it is thought that clay has no significance in such localization, but at both the Monument No. 1 Annex and the Skyline mine clay pebbles appear to have acted as localizing agents for the accumulation of uranium minerals.

In the Skyline channel, San Juan County, Utah, clay fragments of unknown origin, as much as 4 feet on a side, are distributed profusely throughout the channel strata. Similar clay fragments are found in other channels. Preliminary X-ray work by Donald H. Johnson has indicated that most of these clay pebbles are composed of quartz, hydromica, and possibly a little montmorillonite (see table, p. 80).

Composition of some clay pebbles from the Monument Valley area, Arizona and Utah, as determined by X-ray diffractometer

[Identification by Donald H. Johnson, U.S. Geological Survey]

Sample	Location	Composition
	Navajo County, Ariz.:	
W-175A	Monument No. 1 mine.	Quartz, hydromica, and a little kaolinite.
W-175B	do	Quartz, hydromica, and carbonate apatite(?).
W-176A	Base of channel, Monument No. 1 mine.	Quartz, hydromica, and a little carbonate apatite(?).
W-176B	do	Quartz, hydromica, a little carbonate apatite(?), and kaolinite or chlorite.
W-180	Monument No. 1 mine.	Quartz, hydromica, a little kaolinite and possibly a little montmorillonite.
W-182	Monument No. 1 Annex.	Quartz, hydromica, and probably a little montmorillonite.
	San Juan County, Utah:	
W-186	Skyline mine	Quartz and hydromica.
W-187	do	Do.
W-188	do	Quartz, hydromica, and perhaps a little montmorillonite.

ASSOCIATED SWALES

Several channels are along the axes of broad shallow swales cut in the top of the Moenkopi formation. Whether all channels are so associated with swales is unknown; it seems likely that they are, for this channel-swale relation has been noted repeatedly at several widely separated localities in the Monument Valley area (Witkind, 1956a). Where the swales parallel the channels, they range in width from 2 to 3 miles, and have about 40 feet of relief. A few have been traced for distances as much as 4 miles. Because the swales are so wide in comparison to their depth they are difficult to perceive visually. Commonly they are readily apparent on maps of the base of the Shinarump member of the Chinle formation. Experience has indicated that such maps are compiled most easily and accurately in the Monument Valley area by isopaching the combined Hoskinnini tongue of the Cutler formation and Moenkopi formation (pl. 2). This interval is used because of the ease of recognizing the disconformity at the base of the Hoskinnini tongue, both on the ground and on aerial photographs. The disconformity is an excellent datum for isopachous work as it is remarkably free of relief.

This channel-swale relationship is best illustrated in the Monument No. 2 mine area (pl. 5). Isopach maps of the combined Hoskinnini tongue and Moenkopi formation in the Monument Valley area indicate a gradual thinning in an easterly direction (p. 19). In the Monument No. 2 mine area the regional thickness of the combined Hoskinnini tongue and Moenkopi has decreased to 80 feet. As the channel is approached laterally, the combined thickness dwindles to about 30 feet at the channel flank. Inasmuch as the datum used (disconformity between the Hoskinnini tongue and the De Chelly member of the Cutler formation) is nearly plane, this thinning reflects a swale in the top of the Moenkopi. The swale is about 3 miles wide, and its axis is marked by the Monument No. 2 channel. The channel has been scoured about 50 feet into the underlying strata. Thus, about 30 feet of the Hoskinnini tongue and Moenkopi are removed as well as the top 20 feet of the De Chelly sandstone member.

Swales similar to this one are associated with channels along both edges of Hoskinnini Mesa.

If each channel is associated with a swale, then a device may exist for the discovery of those channels that are buried beneath younger strata. Isopach maps of the combined thickness of the Hoskinnini tongue and Moenkopi formation could be prepared on the basis of surface exposures. Such maps would indicate the presence of the swales. Once parts of the swales are found, it may be possible to follow them beneath younger strata by geophysical techniques. If, as we believe, the channels do occupy a position near the axis of the swale, "fences" of holes drilled normal to the trend of the swale might help locate the channel more exactly.

ORIGIN

At least two hypotheses have been proposed to explain the origin of channels. The first suggests that the channels were formed during an episode of erosion subsequent to the formation of the Moenkopi formation but prior to the deposition of the Shinarump member of the Chinle. This viewpoint is exemplified by Gregory and Moore (1931, p. 52) who wrote:

> After Moenkopi time there was widespread erosion which partly beveled the soft Moenkopi strata and in places carved distinct erosion channels in them. The subsequently deposited Shinarump conglomerate constitutes a very widespread thin veneer which covers this erosion surface and fills its depressions.

Adherents of this viewpoint regard the unconformity and the channels as having formed probably during Middle Triassic, with the Shinarump member deposited much later in a second independent episode, most likely in Late Triassic time.

The second hypothesis suggests that the channels were cut by the streams that deposited the Shinarump member, and therefore, are contemporaneous in age with basal sedimentary rocks of the Shinarump.

There appears to be general agreement that the Shinarump member was deposited on a widespread surface of low relief, but no agreement exists as to when this surface was formed. Stokes (1950, p. 97) considers it to have formed synchronously with the deposition of the Shinarump, which represents a pediment deposit. McKee (1951a, p. 91), however, considers the surface to have been a flood plain, upon which the Shinarump was later deposited.

Apparently streams transported sand and gravel from a raised area to the south and gradually spread them northward as a thin blanket (p. 21). When one considers the coarse-grained and resistant materials that compose the Shinarump member, it seems unlikely that the formation could have been deposited without scouring the siltstone and shale of the underlying Moenkopi formation. It is suggested, therefore, that most of the scouring of channels occurred during deposition of the Shinarump member and not, to any large extent at least, in any period of erosion prior to this deposition.

Why one channel is continuous and another not is unknown. The short channels may represent scoured depressions within broad shallow stream valleys (that is swales). If these basinlike short channels do represent deep scours along the course of a former stream, it may be possible to project the trends and locate other short channels now concealed beneath overlying beds of the Shinarump member. As yet, such alinement of channels has not been found.

Bryan (1920, p. 191), in discussing present-day streams, suggests that scoured depressions are most likely to form near the outside bends of streams where the erosive force of the stream is at a maximum. If this concept is applied to the Shinarump member, it may be that a former meandering stream carrying sediments of the Shinarump member cut these depressions wherever it swung about. Monument No. 1 (p. 130–131), a gently curving short channel, might have formed in this manner.

Another possibility is that local variations in the hardness of the Moenkopi formation that once formed the banks of the former streams may have caused the formation of narrows. The subsequent increase in stream velocity together with an increase in gradient due to ponding upstream from the constriction may have increased downward erosion at the expense of lateral planation, resulting in the formation of short channels. Mathews (1917), referring to elongate scoured, depressions as much as 2,000 to 7,200 feet long, 200 to 300 feet wide, and 40 to 60 feet deep in the floor of the Susquehanna River, suggests that these "deeps," as he calls them, are the result of such constrictions.

TYPES OF ORE BODIES

The following four types of ore bodies can be differentiated in channel strata of the Shinarump member of the Chinle formation in the Monument Valley area, Arizona and Utah: rods, tabular ore bodies, corvusite-type ore bodies, and rolls. Of these, the most striking are cylindrical loglike masses of very rich tyuyamunite ore that have been called "rods" (Witkind, 1956b). Bodies similar to these have been noted in the Morrison formation and have been referred to as "cylindrical masses" (Coffin, 1921, p. 163). The second type of ore body consists of blanketlike deposits of uranium ore that are generally in the basal part of a channel and are elongated parallel to the channel trend. These are known as tabular ore bodies. These first two types comprise the major uranium-ore bodies. The third type of ore body has so far been found only in the Monument No. 2 mine and consists of irregular masses of rock that are thoroughly impregnated with vanadium minerals. This type, referred to as a corvusite-type ore body, has a highly irregular shape. It varies in thickness and length and locally includes sedimentary rocks of both the Shinarump member of the Chinle formation and the underlying De Chelly sandstone member of the Cutler formation. Rolls are the fourth type of ore body, and can be divided into two categories based on exposures in the Monument No. 2 mine. The first category includes rolls formed only in sedimentary rocks of the Shinarump member. These consist of channel strata impregnated with yellow uranium minerals that form curved bands which cut across bedding planes. The second type of roll is found only in sedimentary rocks of the De Chelly sandstone member and consists of curving laminae of concentrations of vanadium minerals that cross the bedding. These rolls seem to be related to the intersection of fractures and bedding planes.

RODS

The rods are exposed in the Monument No. 2 mine, where they appear in profusion and form richly mineralized bodies (fig. 13) apparently scattered at random throughout the channel fill. The channel strata surrounding the rods commonly contain only trace amounts of uranium. The uranium content about 1 foot away from the edge of a rod may be as low as 0.002 percent, whereas a sample from the edge of the rod will be as much as 14 percent or more uranium. Although present practice is to mine and ship the entire face, it is apparent that the bulk of the rock, even that part 1 foot or less from the rod, is essentially barren. The friable sandstone centers of the rods also are weakly mineralized. This difference in grade between rods and confining strata is repeated throughout the mine.

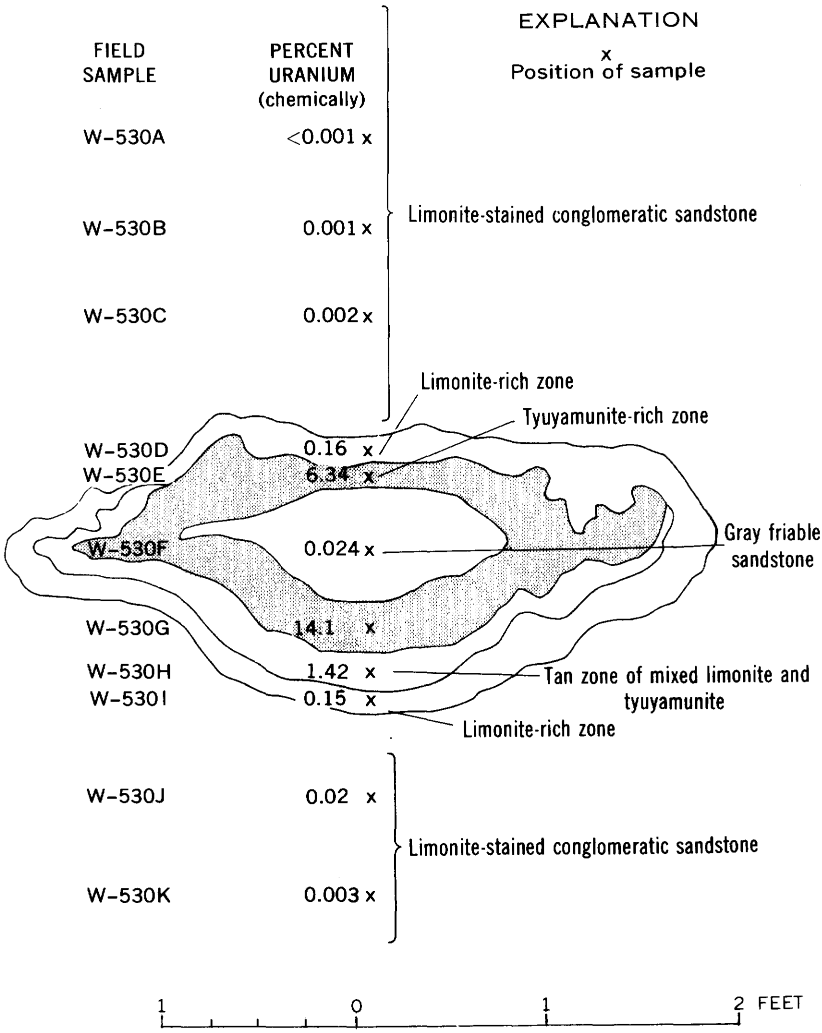

FIGURE 13.—Cross section of typical rod of the Monument No. 2 mine showing position of samples.

The origin of these rods is obscure. Some may result from chemical changes induced in the mineralizing solutions by organic matter; others may result from unusual conditions of permeability and porosity in the host rock.

The rods in the Shinarump member of the Chinle formation can be classified roughly into two categories: simple and complex. The simple rod is illustrated in figure 14*A*. It consists of an outer rim of sandstone impregnated with limonite within which is a rim of

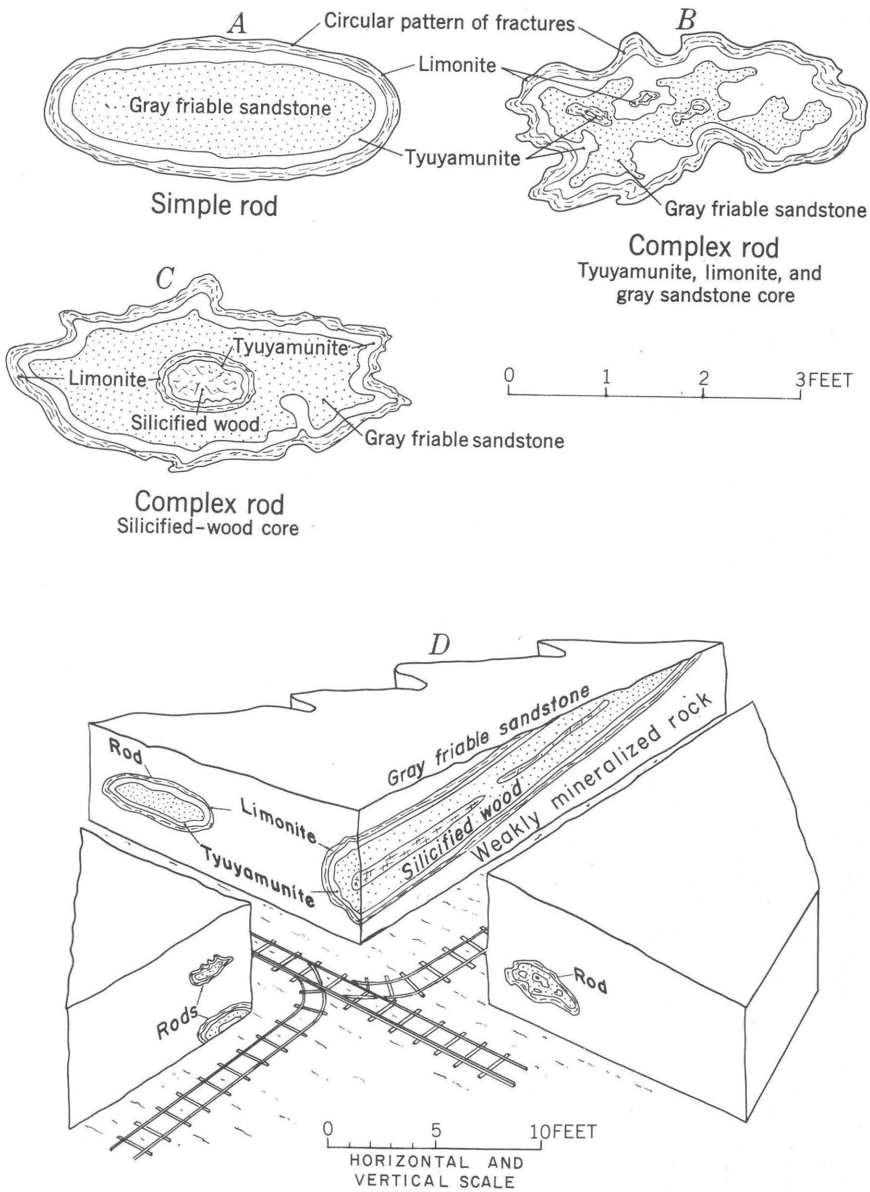

FIGURE 14.—*A–D*, Cross sections of simple and complex rods. *A*, Simple rod. *B*, Complex rod; core of tyuyamunite-limonite, gray sandstone. *C*, Complex rod; core of silicified wood. *D*, Idealized block diagram of mine workings in Monument No. 2 mine showing relationship of rods to one another and to mine drifts.

tyuyamunite-impregnated sandstone. The tyuyamunite, in turn, surrounds a core of extremely friable light-gray sandstone.

The complex rod is bounded similarly by an outer rim of limonite-impregnated sandstone within which is a rim of tyuyamunite-impregnated sandstone (fig. 14*B*, and *C*). These rims, however, are much more irregular than in the simple rod. There are two subtypes of the complex rod. One type contains irregular masses of mixed limonite and tyuyamunite randomly distributed throughout the gray sandstone center (figs. 14*B*, 15). The second type may have these irregular masses of limonite and tyuyamunite in the sandstone center, but in addition, it has a central core of silicified wood (figs. 14*C*, 16).

Near some of the rods the bedding of the confining strata is interrupted at the rims; elsewhere, the bedding arches over the rods. Grain side changes abruptly at the edges of some rods. Most rods are remarkably straight but a few taper and bifurcate. Many rods of the complex type are associated with silicified wood, and, invariably, where longitudinal exposures are available, the silicified wood is seen to be collinear with rods (fig. 14*D*). Exposures of several rods are large enough to permit longitudinal examination of the gray sandstone core filling the center. In these the direction of crossbedding is totally different from the direction of crossbedding of those sedimentary rocks outside the rods.

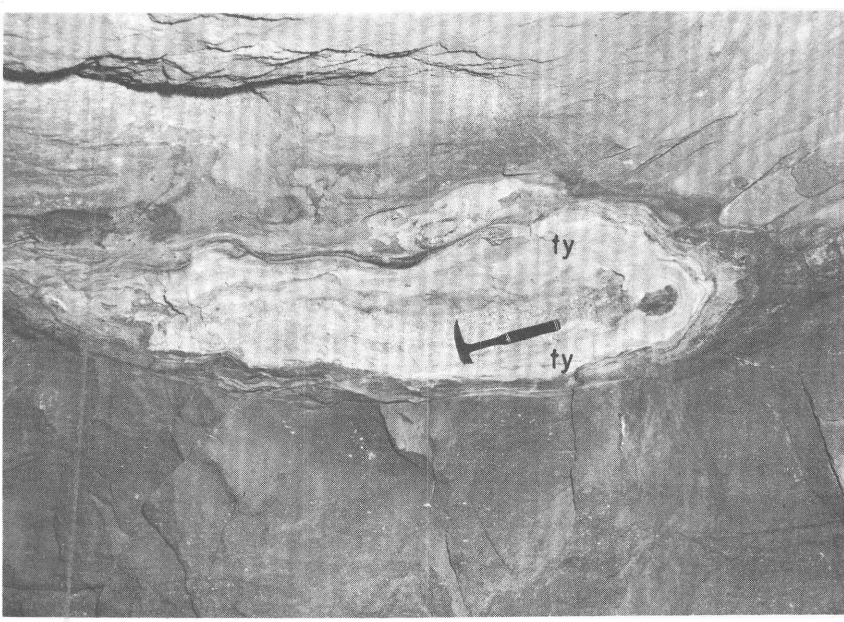

FIGURE 15.—Cross section of a richly mineralized rod. Light area is tyuyamunite-rich sandstone (ty) that may contain more than 20 percent U_3O_8. Darker areas are weakly mineralized rock that contains only trace amounts of U_3O_8.

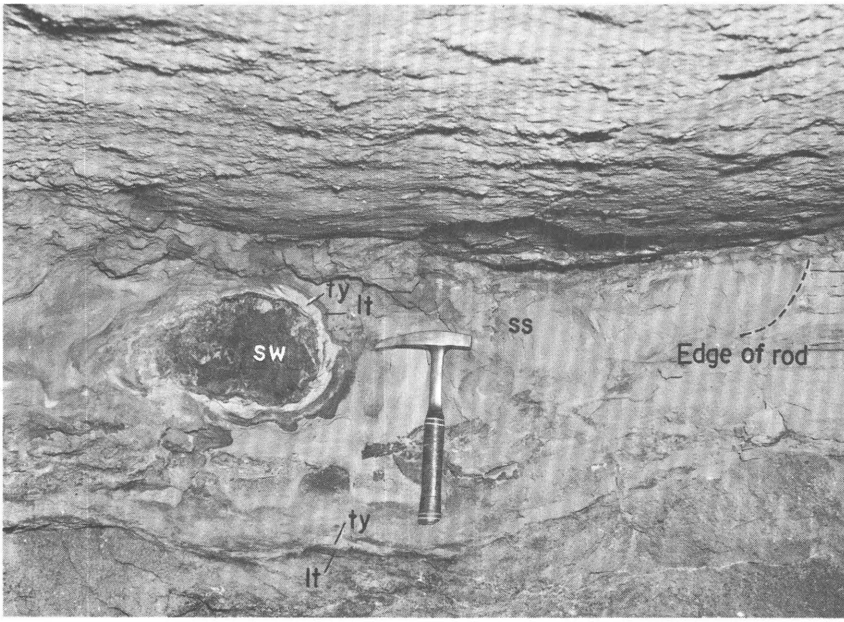

FIGURE 16.—Cross section of complex rod containing core of silicified wood (sw). Core is rimmed by thin band of tyuyamunite (ty) and limonite-impregnated sandstone (lt). Bulk of rod is composed of gray friable sandstone (ss) with mixed limonite and tyuyamunite. Edge of rod is marked by thin tyuyamunite and limonite bands.

Many of the rods were interpreted by the senior author to represent supplantation of logs by sand, silt, and clay. It was thought that the logs were partly buried in alluvial fill, and only parts of them were exposed. As the streams reworked the alluvial fill, the logs were covered and uncovered repeatedly by the shifting sediments, and minute fragments of decayed organic matter were removed. The voids were filled by clay, silt, and sand. In time most of the rims of the logs were replaced by more stable materials. To test this concept six samples were sent to James M. Schopf, of the U.S. Geological Survey for identification. Five of the samples were collected from the rims of the rods, and the sixth was collected from silicified wood in the core of a rod. Of the 6 samples submitted, Schopf identified only 1 as fossil wood, and that was the one collected from the silicified wood core of the rod; the others contained no trace of organic matter. It seems, therefore, that although parts of some rods may represent replacement of some form of former plant matter, the mineralized rims of the rods do not.

The distribution of the rods (fig. 19 and pl. 6), however, and the collinearity apparent between many rods and silicified remnants of logs (figs. 14*C*, 16) suggest that some relationship does exist between buried former logs and the rods. Possibly the shape, size, and distribution of the rods were determined by the buried logs. During or shortly after burial the original organic matter of the buried logs may have been removed and other, more stable, materials deposited much in the manner described above. Another hypothesis to explain the formation of the rods would involve the infiltration of parts of the buried logs by amorphous silica. In time the amorphous silicia crystallized to create the impression of a log composed of clastic material. What organic matter remained may have been removed during the passage of the ore-bearing solutions. Possibly during this episode porosity and permeability conditions changed sufficiently to localize the ore-bearing solutions.

Other rods may have been formed by mineralizing solutions in response to halos of decomposition products such as humic colloids, organic resins, and various other hydrocarbons spreading outward from buried logs. Possible examples of this type are those rods that contain silicified wood at their centers.

Still another possibility is that these rods may have formed completely independent of plant matter and may merely reflect fracture patterns formed during processes of compaction and authigenic crystal growth. It may be that no single concept alone will explain how rods formed. Perhaps combinations of the concepts mentioned above are involved. For instance, the shape, size, and distribution of the rods may have been determined by the presence of buried logs. After the logs were buried, their rims may have been partly replaced by more stable materials. If, at this time, compaction and authigenic crystal growth began, fracturing involving slight movement may have occurred along the zones represented by the former edges of the log. In the voids formed as a result of this movement and fracturing, the ore solutions may have deposited their minerals.

Fischer (1947, p. 455), in discussing the vanadium deposits of the Colorado Plateau, implies that an affinity may exist between vanadium deposits, channel fill, and organic matter in the Morrison formation of Jurassic age. Still referring to the Morrison formation Fischer and Hilpert (1952, p. 12) indicate that, although fossil plants are erratically distributed, most of the carnotite deposits are in parts of the sandstone that contain fairly abundant plant remains. In the Monument Valley area a close spatial relationship also exists between pockets of uranium ore, channel fill, and former plant matter.

The channels apparently were places where plant matter was concentrated. Trees growing along the flanks of these ancient streams may have fallen into them and then been buried by the stream sediments. Other plant material may have been rafted into the channels and buried. Subsequently, when mineralizing solutions moved through the Shinarump member, favorable physical and chemical conditions, resulting primarily from the former presence of buried logs, may have been responsible for the formation of rods.

FRACTURES AS RELATED TO RODS

Small fractures cut the sand grains that form the rim of the rods (figs. 17, 18). In consequence, a crudely circular pattern of fractures delineates each rod (fig. 14). These fractures, restricted to the rims of the rods, invariably follow the crenulations that form the edges of the complex rods, and persist for the entire length of the rods. The fractures are not apparent in those grains that fill the cores of the rods nor in the grains beyond the boundaries of the rods (fig. 18*B*). The fracturing is restricted to the limonite-impregnated sandstone zone and the tyuyamunite-impregnated sandstone zone, both of which form the rims of the rods. Moreover, the fracturing stops along very definite boundaries (fig. 17*A*); the separation between fractured and unfractured grains may be a zone not more than 1 mm wide.

Two systems of fractures were noted in thin sections; one consists of a set of parallel fractures (fig. 17*B*) with a subsidiary set trending approximately at right angles; the other is a plexus of fractures that lacks orientation (fig. 18*A*). Each fracture of the parallel set is about 0.2 mm away from adjacent fractures, and each fracture can be traced for as much as 5 to 10 mm in a relatively straight line as it continues uninterrupted through sand grains. In places, this parallel set of fractures is cut by a subsidiary set that is at right angles to the main set. The subsidiary set offsets the main fractures slightly. Those fractures that have no determinable pattern are less common. The fractures are jagged and end at the grain boundaries. The gross appearance of this fracture system is that of an interlacing network.

Filling the fractures, interstices, and other voids are secondary uranium and vanadium minerals, calcite, and authigenic quartz. The depositional sequence seems to be authigenic quartz first; secondary uranium and vanadium minerals second; and emplacement of calcite last.

The annular pattern formed by the fractures that outline the rods is distinctive and has been found in the Monument No. 2 mine as well as elsewhere on the Colorado Plateau (Alice D. Weeks, written communication). How these circular fracture patterns developed is unknown. One answer may involve factors of selective cementation. Perhaps those grains in the fractured zones were once tightly cemented. When stress was applied, the cemented grains may have fractured, but the uncemented grains may have merely rolled and readjusted themselves to the forces applied.

The effect of linear fractures (that is, joints) in localizing the uranium deposits is unknown, and in an attempt to resolve this ques-

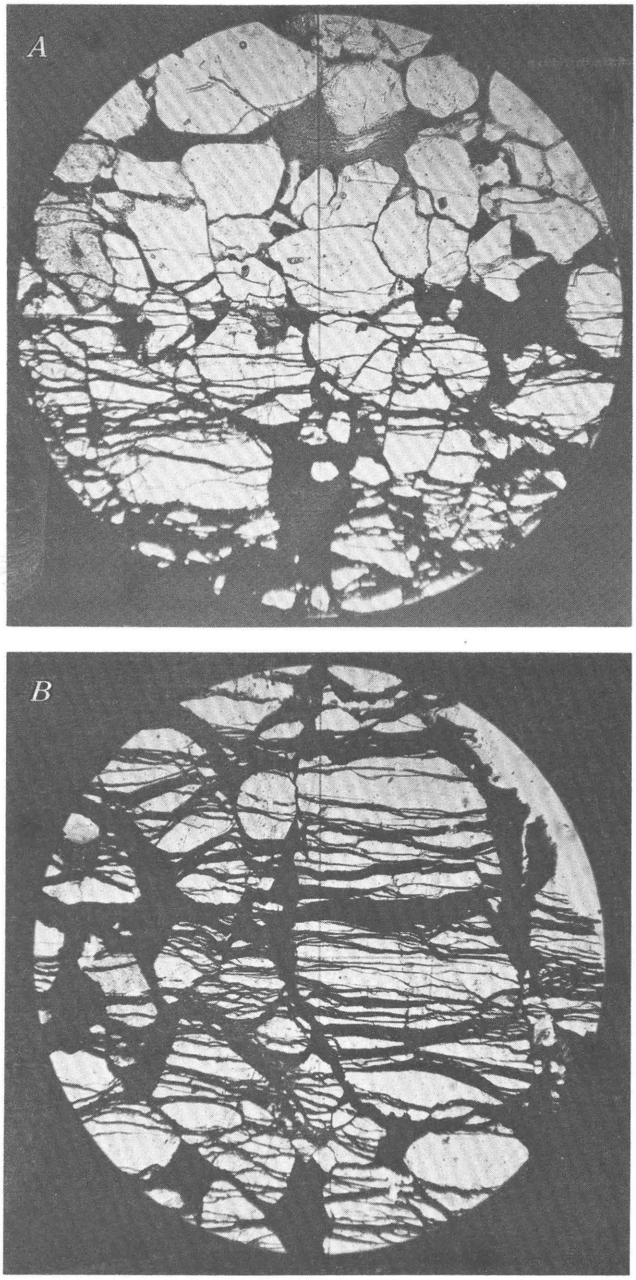

FIGURE 17.—Photomicrographs of thin sections prepared from specimens collected in the Monument No. 2 mine, Monument Valley, Ariz., showing uranium and vanadium minerals in fractures and interstices. *A,* Specimen from upper edge of rod showing sharp boundary between fractured and unfractured grains. Ordinary light. Enlarged 22 diameters. *B,* Specimen from lower edge of rod showing parallel fractures. Ordinary light. Enlarged 22 diameters.

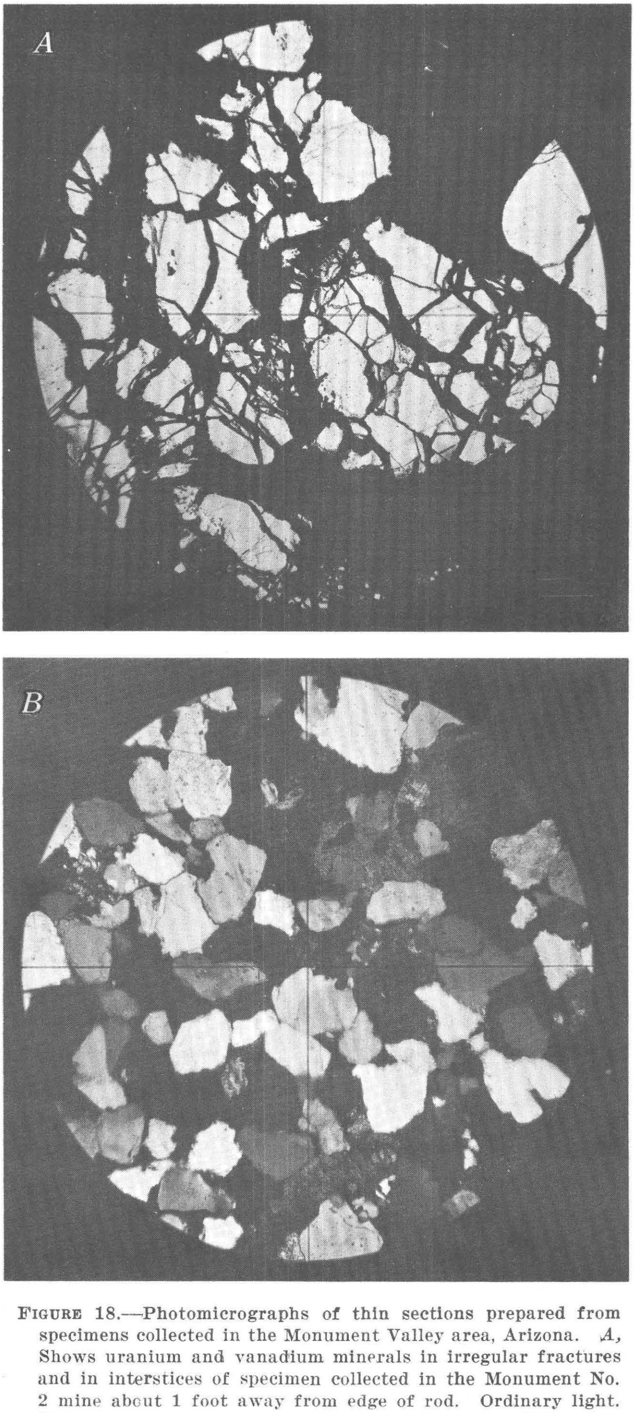

FIGURE 18.—Photomicrographs of thin sections prepared from specimens collected in the Monument Valley area, Arizona. *A*, Shows uranium and vanadium minerals in irregular fractures and in interstices of specimen collected in the Monument No. 2 mine about 1 foot away from edge of rod. Ordinary light. Enlarged 22 diameters. *B*, Specimen from the Shinarump member about a quarter of a mile from channel. Crossed nicols. Enlarged 22 diameters.

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tion three diagrams were prepared. The first shows the orientation of fractures mapped in the Monument No. 2 mine (fig. 19*A*) and indicates a northwesterly trend. The second diagram (fig. 19*B*) shows the orientation of all the rods on which strikes were taken and indicates a random trend. The third diagram shows the trend of silicified logs noted in the mine workings (fig. 19*C*) and again a random orientation is apparent. If fractures were a controlling influence, one would expect a northwesterly orientation of the major ore bodies (that is, rods) comparable to that shown by the fractures. As the diagram of the rods lacks this orientation, there seems to be some evidence against fracture control. The similarity between the random orientation apparent in the diagrams of the rods and the silicified wood suggests that some relationship, as yet unestablished, exists between the rods and silicified wood. Parallelism between fossil logs and rolls of ore is reported by Fischer and Hilpert (1952, p. 5) in discussing the Uravan mineral belt.

TABULAR ORE BODIES

As of June 1953, tabular ore bodies had been found in the Monument No. 2 mine, and in the Monument No. 1-Mitten No. 2 mine (pl. 1). The tabular ore bodies in the Monument No. 2 mine consist of conglomeratic sandstone containing scattered fragments of fossil plant matter and large amounts of yellow uranium minerals. The bodies are irregular in shape and outline, but commonly are elongate parallel to the channel's trend. They are biconvex in both longitudinal and transverse section; they range in width from 20 to 40 feet, and they are about 60 feet long and as much as 6 feet thick. They thicken downward into small depressions in the channel floor, where locally the richest uranium-vanadium ore seems to be concentrated.

The tabular ore body is best exemplified in the Monument No. 1-Mitten No. 2 mine (Witkind, 1961) (pl. 1). Those ore bodies found in the Mitten No. 1 and Skyline mines on Oljeto Mesa, Utah, and in the Whirlwind mine on Monitor Butte, Utah, probably are tabular ore bodies. Drilling by the U.S. Atomic Energy Commission on Holiday Mesa, Utah, has disclosed a similar type of ore body there. Three lithologic units form the Monument No. 1-Mitten No. 2 ore body. A trash-pocket conglomerate composed of angular claystone fragments, rounded pebbles of quartz, chert, and quartzite, and fossil plant matter, all in a matrix of coarse-grained sandstone, generally forms the upper part of the ore body. The lower part is composed of a coarse-grained silica-cemented sandstone. Intercalated between these units are lenses of barren hard calcite-cemented sandstone. The ore body is biconvex or planoconvex, about 650 feet long, extends in

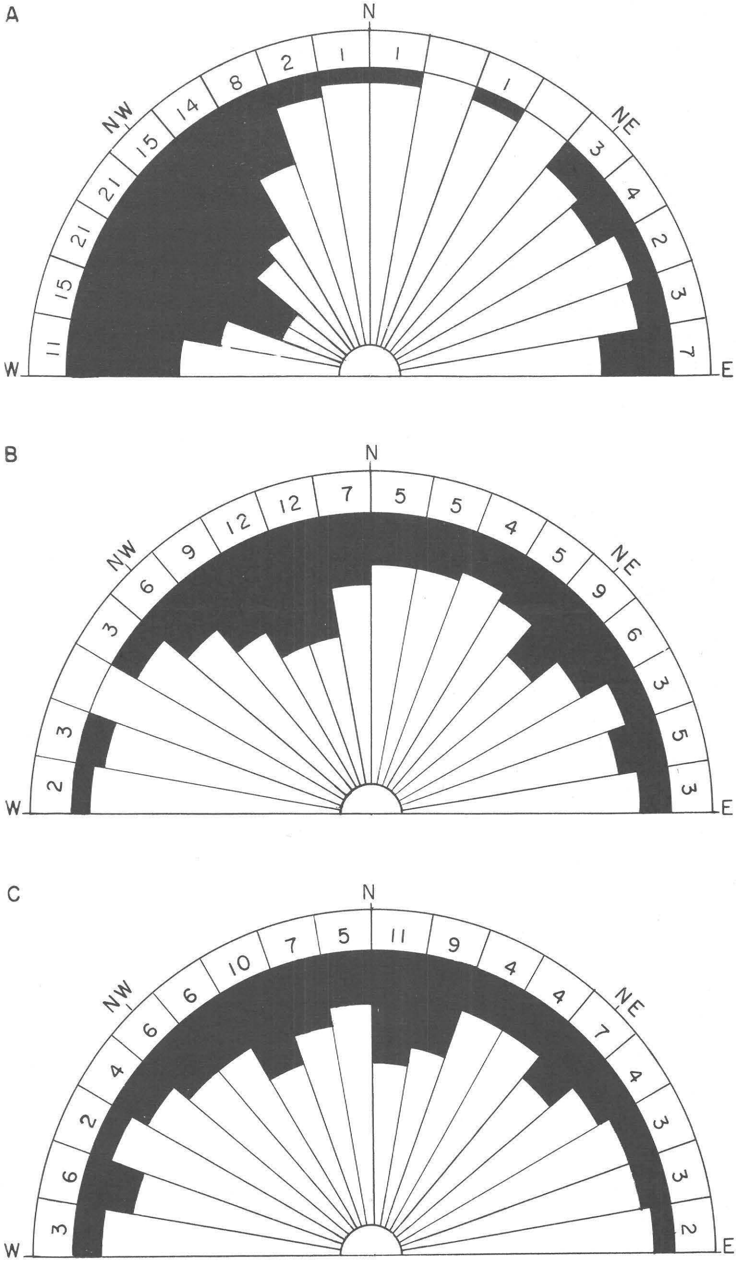

FIGURE 19.—Distribution of (*A*) fractures: (*B*) rods; and (*C*) silicified wood in the Monument No. 2 mine.

width from one channel flank to the other (75 to 95 ft), and ranges in thickness from 1 to 18 feet, although it averages 7 feet.

CORVUSITE-TYPE ORE BODIES

Irregular-shaped sandstone masses, filled with blue-black vanadium minerals, principally "corvusite," are scattered along the length of the Monument No. 2 channel. These have been called corvusite-type ore bodies. Some of these bodies are near the base of the channel, whereas others are near the surface, about 40 feet above the channel floor. In the corvusite-type ore bodies that are along the channel base, the vanadium minerals fill interstices in both the Shinarump member of the Chinle formation and, locally, in the De Chelly sandstone member of the Cutler formation, which in this area underlies the channel. The shapes and margins of these corvusite-type bodies are so irregular that specific dimensions are difficult to determine. In general, the bodies range in length from 100 to 600 feet, are about 100 feet wide, and are as much as 40 feet thick.

In corvusite-type ore bodies the concentration of vanadium minerals differs from place to place. Locally, the vanadium minerals have so thoroughly impregnated the strata that they appear a deep blue black. Near the margins of these vanadium-rich areas, small dark-brown irregular-shaped limonite-rich and vanadium-poor splotches appear. The margins commonly are gradational, and consist of limonite-rich strata weakly impregnated with vanadium minerals.

As far as can be perceived, these corvusite-type ore bodies near the base of the channel have no specific trend, lack recognizable margins, and impregnate rocks of both the Shinarump member and the De Chelly sandstone member.

Within the corvusite-type ore bodies are small concretionlike masses of rock that show a rudimentary zoning. Generally these are crudely ellipsoid and irregular in outline (fig. 20), and commonly they lie in a nearly horizontal position. They are about 10 feet long, about 8 feet wide, and about 4 feet high. The outer shell consists of limonite-impregnated sandstone about 6 inches thick. Within this limonite-rich shell is an irregular zone, ranging in thickness from 1 to 8 feet, that is formed of strata impregnated with blue-black vanadium minerals. The core ranges in thickness from 2 feet to as much as 5 feet and consists of white opal which fills interstices in the sandstone. In a few localities the white material encloses fragments of an extremely friable coaly substance (vitrain?).

The corvusite-type ore bodies are most abundant near the base of the channel although a few crop out near the surface. The near-surface bodies have been oxidized to deep red hewettite.[4] In those

[4] The color is so prevalent that the workings in the mine are referred to as the West Red Oxide, East Red Oxide, and South Red Oxide workings.

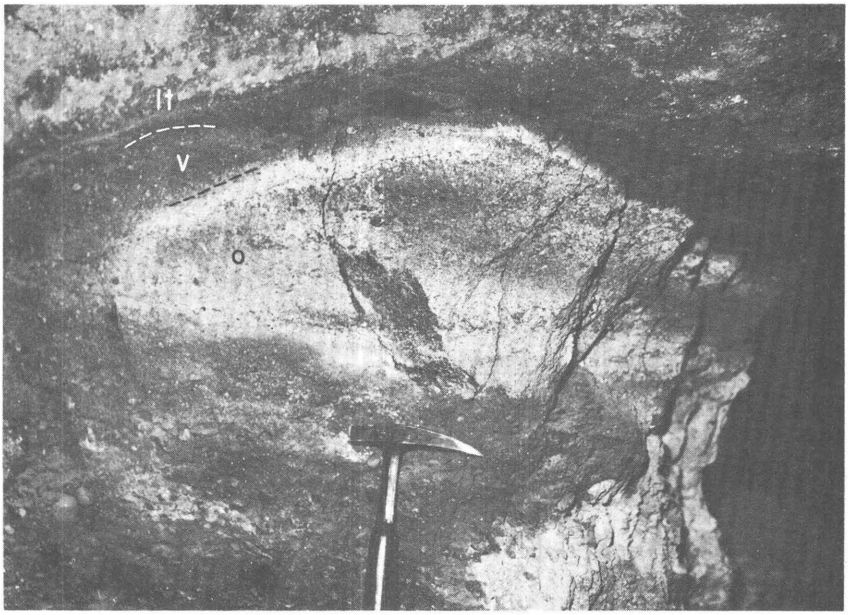

FIGURE 20.—Concretionlike body in part of corvusite-type ore body in the Monument No. 2 mine. Core is sandstone with white opal (o) filling interstices. Surrounding this core is a layer of black vanadium-impregnated sandstone (v). A limonite-rich (lt) rim surrounds the entire body.

bodies that are near the base of the channel, the principal vanadium mineral is corvusite, although hewettite is also present.

ROLLS

The fourth type of ore body, known as a roll, is prevalent in ore deposits in the Morrison formation on the Colorado Plateau. Rolls, however, are very minor features in the ore deposits of the Monument Valley area. They are best displayed in the Monument No. 2 mine where two types are found.

Those in the Shinarump member of the Chinle formation consist of bands of yellow uranium minerals filling interstices in the sandstone. These bands range in size from some that are about 2 inches thick and can be traced for 6 to 8 feet, to others as much as 1 foot wide and 12 to 15 feet long. Each band is separated from its neighbor by weakly mineralized or barren rock 1 to 2 feet thick.

The rolls in the De Chelly sandstone member of the Cutler formation are found only in those parts of the mine that underlie corvusite-type ore bodies. They consist of curved bands of vanadium minerals, principally corvusite, alternating with barren rock. These mineralized bands resemble diffusion bands, and each ranges in thickness from ½ to 3 inches. Each mineralized band is separated from its neighbor by barren rock which is about 4 inches thick. These rolls seem to be related to the intersection of crossbedding planes and fractures, for the size of the rolls is determined by the spacing between the joints. The rolls, which are small features, form ellipsoids about 3 feet wide, and about 2 feet high. Their length is unknown. In places the vanadium-rich bands follow crossbedding planes. Where fractures intersect the crossbedding planes, the vanadium minerals have followed the fracture and impregnate the rocks adjacent to the fracture. Several localities were noted where vanadium minerals were profuse near the upper end of a vertical fracture but lessened as the fracture closed with depth. The minerals seem to have moved in waves of concentration both laterally and vertically from the crossbedding planes and joints into that part of the rock free of vanadium minerals. The resulting effect has been to create a series of curving vanadium-rich bands that parallel the bedding in places, and elsewhere cross it. As the rolls are controlled to some extent by the crossbedding planes, the attitude of the rolls depends upon the strike and dip of the crossbeds.

AGE OF THE ORES

In 1949, L. R. Stieff and T. W. Stern, of the U.S. Geological Survey, began a study of the age of the Colorado Plateau uranium deposits. This work has developed data that are convincing in answering the basic questions as to the time of formation of the deposits.

As an inherent part of this program, 12 samples of ore from the Monument No. 2 mine area were studied (table 2). Of these, nine were discrete specimens of uraninite, becquerelite, uranophane, or carnotite which were collected from the mines in the area. The remaining three were mill-pulp samples.

The work completed by Stieff and Stern (1952a, b), and Stieff, Stern, and Milkey (1953) is interpreted by them to mean that completely reliable age determinations can be made only on ore samples that have not been altered in any way since their deposition. Unfortunately, none of the twelve samples can be described as unaltered. Indeed, the range is extreme, extending from samples of uraninite that are but slightly altered to mill-pulp samples that contain considerable altered material. This degree of alteration is reflected in the uncorrected age determinations. The Pb^{206}/U^{238} age determinations completed on relatively unaltered uraninite specimens give an average (unweighted arithmetic mean) computed age of about 78 million years (table 2). The range in computed age of these specimens is from a minimum of 60 million years to a maximum of 100 million years. Determinations completed on secondary uranium minerals (uranophane, becquerelite, and carnotite) range from a minimum of 5 million years

TABLE 2.—*Calculated Pb^{206}/U^{238} ages, in millions of years, of uranium ore from the Monument No. 2 mine area, Apache County, Ariz.*

[Determinations made by L. R. Stieff and T. W. Stern, U.S. Geological Survey]

Mine	Type of sample	Pb^{206}/U^{238} age to the nearest 5 million years
Vanadium Corporation of America Monument No. 2.	Uraninite	70
Do	do	85
Do	do	100
Climax Uranium Cato Sells Tract No. 1	do	60
Average age of uraninite specimens		78
Vanadium Corporation of America Monument No. 2.	Uranophane	175
Do	do	130
Do	Becquerelite	15
Do	Carnotite	75
Climax-Uranium Cato Sells Tract No. 1	Becquerelite	5
Vanadium Corporation of America Monument No. 2.	Mill pulp	170
Do	do	250
Do	do	330

to a maximum of 175 million years. The mill-pulp samples range from 170 to 330 million years.

The ages calculated for the specimens of relatively unaltered uraninite would appear to be the most reliable (p. 96). However, Stieff, Stern, and Milkey (1953, p. 8) report that if no direct consideration is given to the quality of the samples in determining their arithmetic averages, the computed average ages "are probably higher than the actual age of the ore." It would seem, therefore, that the computed average age of 78 million years determined for uraninite specimens from the Monument No. 2 mine area may be high. How much higher it is than the true age is uncertain. Stieff, Stern, and Milkey (1953, p. 13) note that the most reliable age determinations made (on uraninite specimens from the Happy Jack and Shinarump No. 1 mines in Utah) give apparent ages of 65 and 75 million years. These ages are considered to be within 10 million years of the true age of the samples. It would seem, therefore, that the true age of the ore in the Monument No. 2 mine probably is between 65 and 75 million years.

The age for the Late Triassic (that is, the age of the Shinarump member of the Chinle formation) is given by the Committee on the Measurement of Geologic Time (Marble, 1950) as about 160 million years. In comparison to the 78 million year apparent age determined for the ores in the Monument No. 2 mine, this means that the age of the rocks that contain the ore is twice the age of the contained ore. In contrast, the beginning of the Tertiary is dated as 60 million years (Marble, 1950). It would seem, therefore, that the uraniferous ores in the deposit at the Monument No. 2 mine were emplaced during Late Cretaceous or early Tertiary time.

ORIGIN AND LOCALIZATION

Two basic related questions face most geologists studying the uranium-vanadium ore deposits on the Colorado Plateau. The first involves the source of the ore metals and the method by which they were introduced into the host rock. The second major question is the mode of localization of the uranium-vanadium ore bodies. Both of these questions have been studied in the Monument Valley area, Arizona, by the writers as well as by others. Conclusive answers have not been reached, although progress has been made on these problems and hypotheses have been proposed that may lead eventually to the final answer.

Several sources for the uranium-vanadium deposits have been proposed, as follows:

1. The uranium-vanadium-bearing solutions were derived from a crystallizing buried magma and were carried to the host rock along fractures and faults. During the Late Cretaceous or early Tertiary much of the Colorado Plateau was subjected to vigorous structural deformation and widespread igneous activity. The Henry, La Sal, Abajo, Ute, and Carrizo Mountains may have been emplaced at that time, and they are best interpreted as surface manifestations of the deep-seated buried magma which may have supplied the uranium-vanadium mineralizing fluids.
2. Mineralizing solutions from buried magma mingled with the ground water in the host rocks, and the ensuing mixture then moved laterally through the host rock.
3. The uranium and vanadium were derived from the devitrification of the volcanic ash contained in the Chinle formation. Waters and Granger (1953) suggested this possibility and indicated its probable ineffectiveness.
4. The uranium and vanadium came from both the magmatic waters of the buried magma and the devitrification of the volcanic ash.
5. Minute amounts of uranium and vanadium were leached initially from a weathered granitic or tuffaceous terrane and deposited as insignificant accumulations of low tenor. These deposits were

subsequently buried, and then in time exposed, leached, and reconcentrated, chiefly by circulating ground water. These cycles continued through geologic time, each cycle marked by a richer concentration of uranium-vanadium minerals. The final concentration occurred in favorable host rocks, such as the Shinarump and Morrison, during the Late Cretaceous or Tertiary possibly as a result of the igneous activity that formed the laccolithic centers (Gruner, 1956).

We believe that the uranium-vanadium solutions may have stemmed from two sources: from devitrification of the volcanic ash and from previously formed minor uranium-vanadium concentrations. These mineralizing solutions probably mixed with the ground water of the host rock, and the ensuing mixture then moved laterally through the host rock until it encountered favorable traps in the form of channels. Within these channels uranium minerals are believed to have been deposited in response to two factors, one chemical and the other physical. Localization of the uranium ore seems to be related in some manner to carbonaceous matter, or to the decomposition products therefrom. If the chemical role was dominant, the organic matter may have acted as a precipitant. Conversely, if the physical factors were more important, the change in porosity and permeability at the edge of the rods resulting from the fractured quartz grains may have been instrumental in localizing the uranium minerals.

Probably the rods were originally composed partly of uraninite, pyrite, and associated primary vanadium minerals. In time, most of the uraninite altered to becquerelite and with the addition of some vanadium, to tyuyamunite; the pyrite was oxidized to limonite; and those areas rich in vanadium (montroseite) were altered to corvusite, which is being altered to hewettite.

Following the emplacement of the primary minerals, ground water assumed a role of prime importance as a leaching agent. The ground water leached soluble uranium-vanadium minerals from the rods and then moved them both laterally and vertically, depositing them finally to form large volumes of weakly mineralized channel strata.

We favor the hypothesis that the spacing of the rich ore bodies (that is, rods) is attributable to the original distribution of logs buried in the confining strata of the Shinarump member. Favorable conditions of permeability and porosity in the rods may have been contributing factors in the deposition and localization of the uranium ore. The tabular ore bodies found in some channels (p. 92) are also due to conditions of reduced permeability and porosity. These conditions may stem from poor sorting or the presence of large amounts of calcite, and interstitial clay, rather than from fracturing.

Finnell (1957, p. 25), as a result of his work at the Monument No. 2 mine, has suggested the possibility that structure controlled the ore deposition. Finnell states that

during the Laramide orogeny * * * movement along the bedding planes brecciated the channel-filling sediments. Resistance of the thicker channel sediments to the bedding plane slippage set up stresses that formed a zone of en echelon strike-slip vertical faults along the channel. The ore-bearing solutions may have risen along the vertical faults from a deep source, and spread out to deposit ore in the highly permeable brecciated sandstone and conglomerate.

URANIUM POTENTIALITIES OF THE AREA

As of June 1953, uranium ore was produced in only two places in the Monument Valley area, Arizona; the Monument No. 1 mine area in Navajo County, and the Monument No. 2 mine area in Apache County. In July 1953, 6 mines were operating in the Monument No. 2 mine area, and of these, 5 were closing down. Despite this bleak showing, prospecting continues. This is attributable to the richness of the deposit at the Monument No. 2 mine which will always act as a major stimulant to the search for new deposits of uranium ore in the Monument Valley area. Moreover, drilling programs by the U.S. Atomic Energy Commission as well as by private industry in channels within the Utah part of Monument Valley have indicated that uraniferous deposits are in many channel fills that are barren on the outcrop. This is well shown in the Monument No. 1 channel. Originally a uraniferous deposit was worked at the east edge of the channel. The deposit thinned, and in 1950, the mine was abandoned. Subsequently, drilling in another part of the same channel fill resulted in the discovery of a new uraniferous deposit.

Because the ore deposits in channel strata alternate at irregular intervals with barren strata, and because no method exists at present for differentiating between ore-bearing and barren channel fills, all channels are suspect. This has stimulated an intensive search for the channels.

Finch (1953, p. 32) reports that an arcuate belt of favorable ground extends through the northern part of the Monument Valley area, Arizona. The southern edge of the belt, according to him, is well defined and extends from the Monument No. 2 mine on the east to the Whirlwind mine near the San Juan River, Utah, on the north. The northern edge of the belt parallels the southern edge and is about 4 miles distant from it. Channel fills within this belt presumably are more likely to contain ore than those outside the belt. Finch (written communication) has also suggested that those channel fills nearest a pinchout of the Shinarump member are most favorable.

He postulates such a pinchout just north of the Monument Valley area, Arizona.

We do not agree with Finch on either of these concepts. In the course of our work, we were unable to distinguish any belt of favorable ground throughout the Monument Valley area. Rather than a specific sector of the Monument Valley area being favorable, we believe that all channel fills constitute favorable ground, and that ore deposits are as likely to be found in channel fills away from a pinchout of the Shinarump member, or belt of presumably favorable ground, as well as in those channel fills near the pinchout or in the so-called favorable belt. In general, the drilling programs have been concentrated in those areas near the known ore deposits. Consequently little is known about those channels that are exposed in other areas. This creates a misleading impression that certain parts of the Monument Valley area are more favorable than others, when, in fact, all that is expressed is the degree of knowledge available regarding those parts.

Intensive geologic investigations in the Monument Valley area, Arizona, by both the U.S. Geological Survey and the U.S. Atomic Energy Commission, began in the spring of 1951. Since that time all the known mineralized exposures have been examined, and most have been sampled by geologists of one or the other organization. As of 1954, the U.S. Geological Survey had not drilled in the Monument Valley area of either Arizona or Utah. The U.S. Atomic Energy Commission, however, has completed 4 drilling programs in the Arizona part of Monument Valley and 3 in the Utah part. The four areas in the Arizona part of the Monument Valley area are the Monument No. 2 mine area, Hunts Mesa, Nakai and Hoskinnini Mesas, and the Koley Black area (Cold Mesa).

As it was soon realized that the uranium deposits are localized in channel fills, all the drilling programs attempted to delineate the channels as well as to test them for ore. The results have been inconclusive. Although some mineralized ground was found by the drilling programs, the grades and quantities were low.

As of June 1953, a thorough test of any single channel fill in the Monument Valley area, Arizona, had not been made. The geologic work in this area as well as the drilling completed in the Utah part of Monument Valley suggest that rich deposits of uranium are not continuous along a channel's length (p. 129–130); barren or very weakly mineralized zones alternate at irregular intervals with richly mineralized ground. Because the drilling programs in the Monument Valley area, Arizona, have been confined to that part of the channel fill directly behind the mineralized outcrop and have not tested the entire channel, these tests are inconclusive, and their results do not present a valid picture of the amount of mineralized rock in the entire channel.

In our present state of knowledge we are unable to say conclusively that any one channel either contains economic deposits of uranium minerals or is barren. All should be tested. If the trend, extent, width, and depth of scour into underlying strata of a channel can be determined (and this, in our opinion, can be done most easily and cheaply by geophysical methods), drilling programs entirely within the confines of the channels can test these favorable areas. The drilling would have to extend the entire length of a channel to assure conclusive results.

It is unknown how many channels are in the Monument Valley area. Of the total 700 square miles included, about 300 square miles of the Shinarump member have been removed by erosion. The Shinarump member underlies about 400 square miles. Only 40 square miles of the Shinarump member is exposed, however, and the remaining 360 square miles is buried, most of it deeply, beneath surficial deposits and younger consolidated strata. Sixty-two channels were found in the 40 square miles of the exposed Shinarump member. If the channels are distributed at random, then another 540 channels may be concealed beneath the 360 square miles of the buried Shinarump member. How many channels contain mineralized rock is unknown, but if a fraction of the postulated 540 channels do, then the Monument Valley area must be considered a potential major uranium-producing area.

PROSPECTING GUIDES

The following prospecting guides have been revised and enlarged from the list of guides proposed in 1951 (I. J. Witkind and others, written communication, 1951). These guides, which must still be considered tentative, are of greatest value only in the area covered by this report.

The guides are in two categories, those thought to be reliable in prospecting for uranium-ore deposits throughout the Monument Valley area, Arizona, and those of uncertain reliability. The last named guides exhibit anomalous relationships—in places they are associated with mineralized outcrops, elsewhere they are distant from such exposures.

USEFUL GUIDES FOR PROSPECTING

Guides considered useful in prospecting for uranium-ore deposits in the Monument Valley area, Arizona, are (1) observable uranium minerals, (2) abnormal radioactivity, (3) channel fill, and (4) channel conglomerate containing fossil plant matter.

Guides of uncertain use are (1) limonite that impregnates channel fill; (2) secondary copper minerals; (3) an abnormal thickness of an altered zone in uppermost Moenkopi strata; and (4) clay boulders, cobbles, and pebbles.

OBSERVABLE URANIUM MINERALS

The brilliant yellow minerals tyuyamunite, metatyuyamunite, and carnotite are the most common uranium minerals exposed at mineralized outcrops. Torbernite and autunite, generally apple green, are less common, and these normally are in the shaly siltstone beds forming the bleached zone of the uppermost strata of the Moenkopi formation (p. 20).

ABNORMAL RADIOACTIVITY

In several localities abnormal radioactivity was noted on outcrops without any visible uranium minerals. Generally, analyses of samples from these localities indicated that the source of radioactivity was either small fragments of bony material or podlike lenses of black coaly material (vitrain?). Some bony material and pods of vitrain were found, however, that were not radioactive.

CHANNEL FILL

All known uranium-ore deposits in the Monument Valley area are in and near rocks of the Shinarump member that fill channels (p. 69). Consequently, channel fills are considered to be one of the best guides to deposits of uranium ore. Not all channel fills are mineralized at the outcrop. Of the 62 channel fills noted, only 17 were mineralized at the outcrop, and of these only 7 contained uranium minerals (table 1). The absence of uranium minerals on outcrops of channel strata does not make a channel fill unfavorable. This conclusion is based on the known spotty distribution of mineralized areas in those channel fills that contain ore (p. 129–130).

CHANNEL CONGLOMERATE CONTAINING FOSSIL PLANT MATTER

In the Monument No. 2 mine many of the rods are associated with silicified wood (p. 86); elsewhere in the Monument Valley area, uranium minerals replace carbonaceous matter (p. 107). Generally, these associations are in conglomerate or conglomeratic sandstone lenses in channel fill (p. 107). We suggest, therefore, that the presence of fossil wood, either carbonized or silicified in channel conglomerate or conglomeratic sandstone lenses, is a favorable guide to the discovery of deposits of uranium ore.

GUIDES OF UNCERTAIN USEFULNESS

LIMONITE THAT IMPREGNATES CHANNEL FILL

In the Monument Valley area, limonite both stains the surface of strata in the Shinarump member and in places impregnates the strata thoroughly (p. 108). The light-brown color or limonite stain is on the surface everywhere. However, the widespread limonite effect has been found only in the Monument No. 2 channel (p. 108). Along many channels the surface of the channel fill is stained a light brown; however, fresh exposures of the same channel fill are light gray.

SECONDARY COPPER MINERALS

Secondary copper minerals, principally azurite and malachite, are associated with many of the more promising uranium localities (table 1). These minerals fill fractures and interstices, and coat sand grains. In several localities they replace wood (p. 148). However, only minute amounts of copper are at the Monument No. 2 mine. Secondary copper minerals have also been noted distant from channel fills.

ABNORMALLY THICK ALTERED ZONE IN UPPERMOST MOENKOPI FORMATION

The thickening of an altered zone in the uppermost strata of the Moenkopi formation directly below channel strata was noted at some of the more favorable uranium prospects. The zone also thickens below the Monument No. 1 channel and is present in those wedges of Moenkopi that are preserved below the Monument No. 2 channel. However, the thickening of the altered zone below channels is not consistent, for the zone remains unchanged or thins below several channels.

CLAY BOULDERS, COBBLES, AND PEBBLES

In several mines in the Monument Valley area of Utah and Arizona, clay boulders, cobbles, and pebbles are associated with ore (p. 134). In the Monument No. 2 mine, however, ore is lacking in some places where there are concentrations of clay detritus.

MINES

The uranium-vanadium deposits of the Monument Valley area, Arizona, have been divided arbitrarily into two categories for purposes of description: (1) present operating mines in the Monument No. 2 and Monument No. 1 channels, and (2) promising prospects.

As of 1952–53, only the group of mines in the Monument No. 2 channel were producing uranium-vanadium ore in sizable quantities. There are six mines in this channel: (1) the Vanadium Corporation of America's Monument No. 2 mine; (2) the Climax Uranium Co.'s Cato

Sells Tract No. 1 (also called Cato Sells Monument mine); (3) the Climax Uranium Co.'s Cato Sells Tract No. 2; (4) the Climax Uranium Co.'s Cato Sells Tract No. 1 South; (5) the Black and Blackwater mine (leased in 1953 to W. E. Pollock and B. N. Byler); and (6) the John M. Yazzie mine (operated jointly by John M. Yazzie and Thomas Clani).

In the Monument No. 1 channel, small amounts of ore were produced in 1952 from the Mitten No. 2 mine, but production was so small as to be negligible. In 1954, as a result of a drilling program (p. 130) a new deposit of ore was found in the sedimentary rocks of this channel.

MONUMENT NO. 2 MINE

By far the most prolific producer of uranium ore in the Monument Valley area, Arizona, is the Monument No. 2 mine, located in the Monument No. 2 channel and owned by the Vanadium Corporation of America, which operates it under lease from the Navajo tribal council. The mine, which has been in operation since 1942, exceeds the other mines not only in extent and complexity of workings, but also in amount of uranium and vanadium ore produced.

In an attempt to answer the various problems inherent in the origin and localization of uranium ore, the workings of the Monument No. 2 mine (pl. 6.) were mapped and studied during parts of the summers of 1951 and 1952. In general, the features characteristic of the mine are duplicated in all the other mines in the Monument No. 2 channel. It is worthy of note that the original exposures gave but slight indication of the large amounts of ore contained in the channel fill.

During 1951 and 1952, the U.S. Atomic Energy Commission (John W. Chester and Philip H. Donnerstag, written communication, 1953) completed drilling programs on Yazzie Mesa and on South Ridge (pl. 7).

LOCATION AND ACCESSIBILITY

The mine is in the northern part of Apache County, Ariz. It is at lat 36°55′42″ N. and long 109°55′6″ W., about 4½ miles south of the Utah-Arizona State line and about 1 mile west of Comb Ridge (pl. 1).

In 1953, mining operations involved both stripping (open pit) and underground methods. The underground workings were reached either by inclined shaft, or through adits along the base of the channel. As of June 1953, most of the workings were underground; the only strip mining was in the North workings and near the Red Oxide workings.

All ore produced was trucked to company-owned mills at Durango, and Naturita, Colo.

GEOLOGY

In the area of the Monument No. 2 mine consolidated sedimentary strata range in age from the Halgaito tongue of the Cutler formation of Permian age to the Navajo sandstone of Jurassic age (pl. 2). However, in the immediate vicinity of the mine the strata range only from the De Chelly sandstone member of the Cutler formation of Permian age to the Shinarump member of the Chinle formation of Late Triassic age. The Shinarump member is about 35 feet thick, except where, as a result of channeling, it thickens to 85 feet or slightly more.

These strata form a cuesta that dips to the east about 5° and is part of the east limb of the Monument upwarp. Dissection of this eastward-dipping cuesta has been severe.

Three sets of fractures noted in and near the mine are probably related to the regional structure. They trend about N. 65° W., N. 30° W., and between N. 40° E. and due east. Most of the fractures trend northwestward (fig. 19*A*). Strike-slip movement has been noted on some fractures; commonly the west wall has moved south, although the movement on any single fracture surface does not seem to exceed half an inch. The fractures cut ore.

MONUMENT NO. 2 CHANNEL

The Monument No. 2 mine is in a broad short channel (p. 71) that strikes N. 18° W., ranges in width in its central part from 400 to 700 feet, and has been cut about 50 feet into the underlying strata. Because the beds of the Hoskinnini tongue of the Cutler formation and the Moenkopi formation are thin at this locality, the scour has cut through them with the result that channel strata of the Shinarump member of the Chinle formation rest disconformably on the De Chelly sandstone member of the Cutler formation.

Although regionally both the Hoskinnini and Moenkopi thin eastward, abrupt thinning of these strata near the channel may be significant. Isopach maps of the combined thickness of the Hoskinnini and Moenkopi in the immediate vicinity of the Monument No. 2 channel indicate that an elongate broad swale parallels the channel (pl. 5; p. 81). Inasmuch as the base of the Hoskinnini is even and devoid of relief (fig. 3), this thinning must reflect an undulation in the top of the Moenkopi. This swale is about 3 miles wide and can be traced for a distance of about 3½ to 4 miles before it disappears below the alluvial fill of Cane Valley. We interpret it to be a shallow swale in whose center the Monument No. 2 channel was scoured.

The cross-sectional shape of the Monument No. 2 channel varies from place to place along the length of the channel. In the North workings (pl. 6), the channel appears as a symmetrical scour; this is also true at South Ridge. However, in the South and Bobcat workings, the floor of the channel is divided by a low ridge of sandstone that separates the channel into two unequal parts (pl. 7, cross sections). The ridge of sandstone may be equivalent to the Hoskinnini tongue. It is composed of a light-buff even-bedded medium-grained sandstone that truncates the crossbedded fine-grained De Chelly sandstone member. This even-bedded sandstone layer is in turn truncated on both sides by the strata of the Shinarump that fill the two parts of the divided channel.

The length of the channel has been determined (John W. Chester and Philip H. Donnerstag, written communication, 1953). It extends in a relatively straight line for 1½ to 2 miles, and is divided by 2 deep valleys into 3 segments of unequal length (pl. 7*A*). The north end of the channel (about 1,000 ft long) is on Yazzie Mesa. The middle part of the channel (about 2,800 ft long), and, incidentally, the part that contains the major amount of ore, is on the Monument No. 2 cuesta and has been called Main Ridge. The south part of the channel (2,000 ft long) is on South Ridge.

Data obtained during the drilling and mapping programs were used to contour the base of the channel (pls. 6, 7*B*). Those lines delineating the ends of the channel on Yazzie Mesa and on South Ridge are based on illustrations supplied by the U.S. Atomic Energy Commission prepared from the drill data. These contour lines indicate that both ends of the channel terminate as gently concave upward curves. The contours suggest that locally the floor of the channel is gently undulatory both in cross and longitudinal sections and is marked in places by scoured pits 200 to 250 feet long, about 100 feet wide, and from 5 to 10 feet deep.

Channel strata seem identical to other rocks in the Shinarump member of the Chinle formation and consist principally of medium- to coarse-grained conglomeratic sandstone beds containing as predominant constituents durable materials, such as quartz, quartzite, and chert. Clay and siltstone in the form of boulders, cobbles, and pebbles, are distributed profusely throughout the channel fill. In several places the uppermost channel strata are interrupted by lenticular beds of clay as much as 8 feet thick that can be traced longitudinally and laterally for as much as 300 feet. Fossil plant matter is scattered through the channel fill. Much of it appears as silicified logs and as elongate pod-shaped masses of a coaly substance (vitrain?). In other places the cellular woody structure of former logs has been retained where the logs have been replaced by uraninite and pyrite. Near the portal of incline 3 (pl. 6) a fossil log, partly replaced by vanadium minerals, uraninite, and pyrite, affords excellent specimens of replaced woody texture. Examples of uraninite replacing wood have been found also in the Cato Sells mine (Alice D. Weeks, written communication, 1952). The possibility exists that during deposition of the sediments that filled the channel, many more logs were included in channel fill than can be identified as such under present conditions.

Oxidized minerals are widely disseminated in the mine workings. Limonite impregnates and stains the channel fill, but is not as profuse in rocks of the Shinarump member adjacent to the channel. On the valley sides this is emphasized by the contrast in color between the brown of the channel fill and the light buff of the adjacent sedimentary rock. Throughout the mine workings the limonite is distributed so profusely that those few areas in the mine free of limonite are considered unusual. The limonite-free areas contain only small amounts of uranium-vanadium ore.

URANIUM AND VANADIUM DEPOSITS

All four types of ore bodies (p. 83) are in the Monument No. 2 mine. These are in such abundance that it is difficult to delineate specific ore zones. In general, however, three ill-defined ore zones can be discerned, in which ore bodies seem to alternate at irregular intervals with one another and with barren or very poorly mineralized rocks. Thus, channel strata containing concentrations of rods may be close to, or distant from, corvusite-type areas; no pattern is apparent. The relation of the richly mineralized parts of the channel fill to the weakly mineralized parts seems independent of channel shape, type of channel fill, position of the mineralized parts in the channel fill, or any other discernible feature.

Most of the uranium and vanadium comes from a basal ore zone that ranges in thickness from a pinch out to as much as 40 feet, and seems to be continuous along the entire base of the channel. Locally, it includes about 20 feet of the underlying De Chelly sandstone member of the Cutler formation. The top of the zone is undulatory. Ten to twenty feet above the top of the basal zone is a middle ore zone that contains many rods. This zone ranges in thickness from 5 to 15 feet and is characterized by clusters of rods. It is not continuous for the length of the channel. The third and uppermost zone is near the surface and is about 15 feet above the top of the middle ore zone and is as much as 10 feet thick; here, the principal ore seems to be vanadium. This upper ore zone is discontinuous also.

BASAL ORE ZONE

Ore is mined from the basal ore zone along the entire length of the channel. This zone, which includes the most productive part of the channel fill, contains all type of ore bodies, although, in general, corvusite-type and tabular ore bodies seem to predominate.

At the south end of the channel (South Ridge, pl. 6), the workings are in a corvusite-type ore body. This ore body is about 250 feet long, 100 feet wide, and about 35 feet thick. Only strata of the Shinarump member of the Chinle are mineralized. Rods and tabular ore bodies are rare.

At the south edge of Main Ridge (pl. 6) the channel bifurcates. The east fork of the channel includes the South workings; the west fork includes the Bobcat workings. Both sets of workings are in the basal ore zone. The west edge of the Bobcat workings rises slightly and grades imperceptibly into the middle ore zone which contains the upper Bobcat workings. A clear demarcation between the zones in this part of the channel is impossible. Rods are common in both the Bobcat and upper Bobcat workings.

The west edge of the South workings consist of a large corvusite-type ore body which grades eastward into an area of channel strata marked by many rods and a few tabular ore bodies. Although these irregular-shaped corvusite-type ore bodies are found throughout the mine, there seems to be a greater concentration of vanadium in this part of the South workings. Here, strata of the Shinarump member show the deep blue-black color of vanadium minerals for a length of about 200 feet and a width of about 50 feet. The mineralized ground is about 20 feet thick and includes some of the underlying rocks of the De Chelly sandstone member of the Cutler formation to a depth of 10 to 15 feet. Locally, the blue-black color is broken by irregular streaks of the brilliant scarlet hewettite, or by large irregular masses of a white material (opal) in the interstices of the sandstone. All the basal strata in this part of the channel have been impregnated by the ore which is a deep blue black.

The eastern part of the South workings has many rods in a conglomeratic sandstone that is colored deep brown by limonite. Most of these limonite-colored sedimentary rocks are in a scoured pit along the thalweg of this side of the channel (pl. 6). The scoured pit is elongate, parallel to the trend of the channel, about 250 feet long, 100 feet wide, and about 10 feet deep. The corvusite-type ore body seems to be along a slight rise that marks the west edge of the scoured pit. There is a marked contrast between the two parts of the South workings. On the west the strata are deep blue black and contain only small amounts of yellow uranium minerals. Locally, small patches of the scarlet color of hewettite as well as splotches of white material (opal) interrupt the blue-black color. The east side contains conglomeratic sandstone of similar lithology, but here the rocks are a deep brown, probably due chiefly to limonite impregnation. Scattered irregularly through these relatively barren strata are the richly mineralized yellow rods.

All three ore zones are being mined in the central part of Main Ridge and are more clearly delineated there than elsewhere. The basal zone is mined through inclines 2 and 3 (pl. 6), and the underground workings have extended toward each other along the channel axis since plate 6 was completed. Near incline 2, a corvusite-type ore body is on the west flank of a depression in the channel floor. The depression is elongate, parallel to the trend of the channel, about 200 feet long, 50 feet wide, and about 5 feet deep. Part of the ore body is in the depression, although the margins of the body extend laterally beyond the limits of the scour. In general, the ore body is about 350 feet long, about 50 feet wide, and about 40 feet thick. Of this thickness, 20 feet involves strata of the De Chelly sandstone member; the remaining strata form the basal channel fill.

In several places in this part of the mine, extensive fractures pass through the Shinarump member of the Chinle formation into the underlying De Chelly sandstone member of the Cutler formation (pl. 6). Locally, vanadium minerals have moved through the fractures and permeated the adjacent rocks. The vanadium minerals decrease in quantity with distance away from the contact of the Shinarump member and the De Chelly sandstone member. Distinct rolls, which are so typical of the ore deposits in the Morrison formation of Jurassic age, are in that part of the De Chelly sandstone member which in this area immediately underlies the Shinarump member (p. 95–96). Here the rolls seem to be related to a combination of bedding planes and fractures (p. 96).

Both high-grade uranium and vanadium ore have been mined from this part of the basal ore zone. The vanadium impregnates the rocks thoroughly and all strata, the De Chelly as well as the Shinarump member, are a deep blue black. Uranium commonly is present as disseminated fragments of relatively unoxidized uraninite. Most of the specimens of uraninite used in the age determination studies by Stieff and Stern (1952b) were secured from this part of the basal ore zone. Rods and tabular ore bodies are present locally, but not in such profusion as in other parts of the mine.

The basal ore zone is also being mined through Incline 3. Here the zone consists of limonite-impregnated strata which contain many rods. Several of the rods have cores of uraninite, that are surrounded by a rim of becquerelite, which, in turn, is rimmed by uranophane. Most of the rods, however, are similar to those found elsewhere in the mine.

As of 1953, the main part of the basal ore zone along the north edge of Main Ridge had not been mined (pl. 6). The North workings, which are along the east flank of the channel, probably are in an edge of the basal ore zone. Rods are plentiful and, in addition, tabular ore bodies that range in thickness from 2 to 4 feet and form a crude oblong body about 60 by 80 feet are exposed in the North workings. Yellow uranium minerals associated with much fossil plant matter make up the greatest part of these tabular ore bodies. These bodies are interpreted to be former "trash" pockets—original basins along the flank of the channel in which plant matter accumulated. Secondary vanadium minerals, principally hewettite, impregnate many of the strata in the North workings.

The north end of the channel has been mined on Yazzie Mesa by John M. Yazzie and Thomas Clani. It seems likely that the ore produced came from the basal ore zone. Rods were the principal source of the ore.

MIDDLE ORE ZONE

In 1953, the middle ore zone was being mined at three places—the upper Bobcat workings, the South workings incline, and the Incline 1 workings (pl. 6). Along the south edge of Main Ridge the upper Bobcat workings are in channel strata that contain many rods. In the South workings incline (pl. 6) a similar situation exists. The rods in both these localities seem to be scattered erratically throughout the fill, and in general, are not as plentiful as in other parts of the mine. By far the greatest concentration of rods is exposed in that part of the middle ore zone reached by the Incline 1 workings. Here, a crudely circular mass of rocks of the Shinarump member of the Chinle formation, about 300 feet in diameter and about 15 feet thick, contains rods of all sizes and shapes. As plotted, this circular area is in about the center of the channel with its base about 30 feet above the channel floor. Upper and lower margins are irregular, and its base seems to be about 20 feet above the top of the basal ore zone which directly underlies it. About 20 feet of barren strata of the Shinarump member overlies this part of the middle ore zone.

Rods are best displayed in this area and most seem to be confined to undulatory conglomerate beds that are elongate parallel to the trend of the channel. The rods studied in this area repeated what had been found to be true of other rods in the channel—namely, the larger rods are alined in a northwesterly direction parallel to the channel trend (fig. 21*A*), whereas a similar alinement is not discernible in the smaller rods; these seem to trend in all directions (fig. 21*B*). The greatest concentration of the rods seems to be in the center of this circular mass of strata, although some of the largest rods are along the southwest edge. In this locality, rods as much as 100 feet long and 3 to 6 feet in diameter are common.

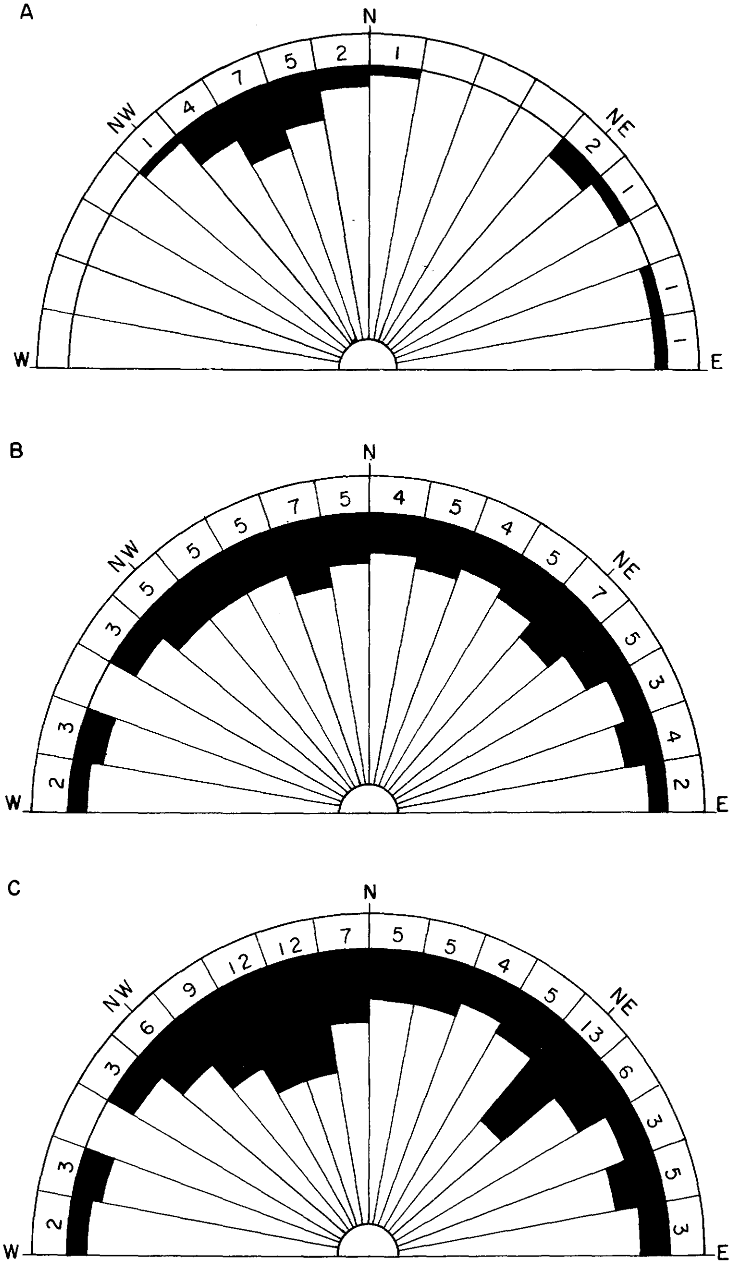

FIGURE 21.—Trends of rods as determined in the Monument No. 2 mine, Apache County, Ariz. *A*, Rods more than 10 feet in length. *B*, Rods less than 10 feet in length. *C*, Rods of all lengths.

Although the rods constitute the richer concentrations of ore, secondary yellow uranium minerals are found elsewhere in the middle ore zone. Between many rods disseminated yellow uranium minerals fill interstices in the sandstone and result in weakly mineralized ground. Commonly this dissemination is very slight, as is illustrated by figure 13. This relationship between the rods and surrounding strata, although best illustrated in the middle ore zone, is found elsewhere in the mine. Thus, channel strata in the basal ore zone also have weakly mineralized ground between the rods. Further, sparse amounts of yellow uranium minerals fill some fractures and coat cross-bedding planes in that part of the De Chelly sandstone member of the Cutler formation which directly underlies the Shinarump member of the Chinle formation.

UPPER ORE ZONE

The upper ore zone is the most restricted of the three zones. It is best exposed near the north edge of the Main Ridge in the East Red Oxide, South Red Oxide, and West Oxide workings and in the Central workings. Although rods are in these workings, the principal ore produced has been vanadium and the Red Oxide workings derive their names from the large amounts of hewettite and metahewettite present. Oxidation has been so complete in this area that most of the rocks contain large amounts of these secondary vanadium minerals; primary vanadium minerals are rare.

MINERALOGY AND PARAGENESIS AT THE MONUMENT NO. 2 AND CATO SELLS MINES

By DONALD H. JOHNSON

As part of a U.S. Geological Survey program in the Monument Valley area, Arizona, the writer spent about 3 weeks in the summer of 1951, 2 months in the summer of 1952, and 6 weeks in the summer of 1953, at the Monument No. 2 mine. In 1951 the writer was associated with Tommy L. Finnell, and in 1952 and 1953 with D. J. Milton.

Fieldwork consisted of reconnaissance mapping in the vicinity of the mines, detailed mapping of parts of the mines, and detailed mineralogical sampling of all the accessible mine workings. Laboratory work during parts of 1953 and 1954 was devoted to mineral identification and study of specimens.

ACKNOWLEDGMENTS

The writer is indebted to Denny W. Viles, vice-president, Robert Anderson, superintendent, and the late Carl Bell, mine foreman of the Vanadium Corporation of America for permission to examine and collect specimens in the Monument No. 2 mine, and to Clarence Cox, mine foreman, of the Climax Uranium Co., for permission to examine and collect specimens in the Cato Sells mines.

Alice D. Weeks, Mary E. Thompson, Leonard B. Riley, and Thomas W. Stern, of the U.S. Geological Survey, visited the mines with me and gave me information and advice.

Personnel of the Survey's Geochemistry and Petrology Branch laboratories performed much of the analytical work. Particular mention should be made of A. T. Myers and J. N. Stitch for spectroscopic analyses; A. J. Gude, 3d, and E. A. Cisney, for X-ray identification; and L. F. Rader and his staff for chemical analyses.

MINERALOGY

Each mineral from the ore deposits at the Monument No. 2 and Cato Sells mines that has been noted and studied is listed below. Descriptions of the minerals follow the list.

Uranium and vanadium minerals

- Autunite
- Becquerelite
- Carnotite
- Corvusite
- Doloresite
- Fernandinite
- Fourmarierite
- Hewettite
- Metazeunerite
- Montroseite
- Navajoite
- Pascoite
- Rauvite
- Steigerite
- Tyuyamunite and Metatyuyamunite
- Uraninite
- Uranophane

Associated minerals

Nonsulfides

- Apatite (carbonate)
- Calcite
- Clay minerals
- Gypsum
- Ilsemannite (?)
- Jarosite
- Limonite
- Opal
- Quartz and chalcedony
- Wad (lithian)

Sulfides

- Bornite
- Galena
- Pyrite
- Sphalerite and sulfur

Unidentified minerals

Uranium and vanadium minerals

Autunite, $Ca(UO_2)_2(PO_4)_2 \cdot 10\text{–}12H_2O$.—Some scattered crystals of autunite were found in the North workings of the Monument No. 2 mine (pl. 6) only a few feet from the cliff face. They appeared as tiny yellow micaceous crystals partly filling the interstices of the conglomerate in which they were found. Locally, they partially coated a few pebbles. The crystals fluoresced a brilliant yellow green under shortwave ultraviolet light.

Becquerelite, $2UO_3 \cdot 3H_2O$.—Becquerelite is found in many places in the deposit, although it forms no great part of the ore. The becquerelite is firm, dense, and ranges in color from dark orange to a bright yellow. It is generally massive, but a few thin sections show wood-cell structure. Most of the becquerelite forms compact halos surrounding ellipsoidal nodules of uraninite. Nodules range from nearly solid uraninite with a paper-thin shell of becquerelite to massive becquerelite with only a tiny relict of unaltered uraninite in the center. A few nodules of becquerelite have been found without the uraninite. Veinlets of becquerelite cut most of the uraninite.

Carnotite, $K_2(UO_2)_2(VO_4)_2 \cdot 1\text{–}3H_2O$.—Apparently carnotite is uncommon in this deposit. In the few specimens that have been identified it appears as a loosely coherent yellow powder mixed with, and concealed by, tyuyamunite. Spectrographic analyses of some samples of yellow ore indicate small amounts of potassium. Carnotite stains and coats pebbles in the conglomerate and forms small patchy impregnations in sandstone. The ratio of carnotite to tyuyamunite appears to be very small.

Corvusite, $V_2O_4 \cdot 6V_2O_5 \cdot nH_2O$ (?).—Corvusite is the most abundant nonuranium-bearing mineral in the mine. It is most plentiful in the workings on South Ridge and in the South workings, and small amounts have been found in all but the northern parts of the workings on Main Ridge (pl. 6).

The corvusite ranges in color from typical blue black through blackish brown to a medium dark brown, and in clayey pellets to orange brown. Locally, it is associated with small quantities of rauvite, hewettite, navajoite, and probably uraninite and other uranium minerals, and limonite. A small number of pellets and small lenses of corvusite mixed with silt were found. The corvusite, which fills interstices in the sandstone and conglomerate, does not seem to have replaced detrital grains in the sandstone as have tyuyamunite and its associated minerals.

Doloresite, $3V_2O_4 \cdot 4H_2O$.—A small vuggy seam of doloresite[5] crystals was collected from the fossil log that is cut by incline 3 (p. 119). The mineral is nearly black and has a submetallic luster and a greenish-black streak (Stern and others, 1957).

Fernandinite, $CaO \cdot V_2O_4 \cdot 5V_2O_5 \cdot 14H_2O$.—Small amounts of fernandinite[5] have been found near the fossil log cut by Incline 3 (p. 119). The fernandinite is greenish black, has a high luster, and is soft with a greasy smear comparable to graphite.

Fourmarierite, $PbU_4O_{13} \cdot 7H_2O$.—A little fourmarierite has been found in specimens of ore from this deposit by Thomas W. Stern and

[5] Data furnished by Alice D. Weeks, U.S. Geological Survey.

others (oral communication). It is in the form of small reddish grains in specimens of uraninite and becquerelite. The fourmarierite appears to be one of the earliest secondary minerals forming from the uraninite.

Hewettite, $CaV_6O_{16}\cdot 9H_2O$.—Hewettite is moderately abundant in this ore deposit. Several varieties have been found. The most abundant is a deep-red earthy variety that coats fractures and fills seams as much as 10 cm thick. These seam fillings are principally in or adjacent to corvusite or tyuyamunite ore, but some small fillings have been found in relatively barren rock several feet from ore. Less abundant are bright-red cross-fibrous seam fillings 1 to 20 mm thick that are in the workings in the north and the south-central part of Main Ridge (pl. 6). Some of these seam fillings resemble the occurrence of navajoite and locally grade into navajoite.

Several radiating clusters of acicular crystals of hewettite were found in the North workings. The crystals were attached to pebbles and projected into small cavities in the conglomerate. Individual crystals were about half a millimeter thick and as much as 15 mm long. A few feet from the above occurrence were found bladed crystals of brownish-red hewettite 1 by 2 by 10 mm. The crystals occurred as divergent to subparallel groups coating pebbles in conglomerate.

As found in the mine, hewettite is a deep red, but when it is removed from the mine it soon becomes a dull chocolate brown. Possibly the change is due to loss of water; but specimens that were sealed in glass jars containing wet paper before removal from the mine also became brown after a period of time, although the air in the jars was still water saturated. Specimens removed from the mine in light-tight containers, not sealed against moisture, changed color to a lesser degree. The writer believes, therefore, that light may cause or hasten the discoloration of hewettite.

Metazeunerite, $Cu(UO_2)_2(AsO_4)_2\cdot 8H_2O$.—In the South workings of the Monument No. 2 mine, a small pocket, about 1 foot in diameter and 2 to 3 feet long is impregnated with metazeunerite. The metazeunerite forms powdery green coatings on pebbles and silicified wood in the conglomerate. Tiny tetragonal crystals of metazeunerite about 0.1 mm on a side are scattered through the interstices of the conglomerate along with white powdery gypsum.

Montroseite, (V,Fe)O(OH) or VO(OH).—No montroseite has been positively identified from the workings on Main Ridge (pl. 6), but on South Ridge, where oxidation has been less extensive, montroseite has been found in the workings.

Montroseite occurs with pyrite as shiny dark crystals, as much as half a millimeter long, and as black masses. The ore is black where montroseite is abundant, but more commonly the ore has the blue-black cast of corvusite ore with only scattered crystals and patches of montroseite. Probably small amounts of montroseite are in the blue-black ore exposed in the Main Ridge workings.

In some specimens the montroseite occurs as tiny black crystals growing upon quartz sand grains that have been markedly corroded and etched. Many of the montroseite crystals, along with their sand-grain bases, are partly or completely enclosed by colorless authigenic quartz.

Much of the montroseitic ore contains little uranium; a Geiger-Müller counter indicates no significant radioactivity in some specimens. Other specimens contain some uraninite, but secondary uranium minerals are nowhere apparent.

Navajoite, $V_2O_5 \cdot 3H_2O$.—Navajoite is a new mineral collected from the South workings of the Monument No. 2 mine and described by Weeks, Thompson, and Sherwood (1954). Although it has not been found elsewhere, it occurs in a number of places in the Monument No. 2 mine, particularly in the southwestern part of the Main Ridge workings. It forms dark-brown fibrous coatings on pebbles in conglomerate and fills fractures in sandstone and siltstone as cross fibers, 1 to 5 mm long. It has been found with hewettite and in blue-black to dark-brown corvusite-type ore with other vanadium minerals, and sometimes pyrite, gypsum, and ilsemannite.

Pascoite, $Ca_3V_{10}O_{28} \cdot 16H_2O$.—Pascoite[6] appears as an orange water-soluble mineral that forms coatings on the mine walls.

Rauvite, $CaO \cdot 2UO_3 \cdot 5V_2O_5 \cdot 16H_2O$(?).—Rauvite is found in many parts of the Monument No. 2 mine, and commonly is confused with other minerals. Much of the rauvite forms resinous, very dark brown, brownish-purple, or reddish-black masses, as much as an inch across, which fill crevices in silicified wood or occupy cavities in the conglomerate. Other forms of rauvite that have been recognized are as blackish, brownish, or orange pellets that resemble claystone in appearance, and as powdery brownish to orange claylike material dispersed throughout conglomerate and conglomeratic sandstone. The rauvite is invariably associated with corvusite, hewettite, and other vanadium minerals, and in many places with tyuyamunite.

Steigerite, $Al_2(VO_4)_2 \cdot 6\frac{1}{2}H_2O$.—Steigerite is always found as powdery yellow coatings on fracture surfaces near high-grade ore. The total amount of steigerite in the mine is very small.

Steigerite was first identified from the Monument No. 2 mine in 1952 by Alice D. Weeks and Mary E. Thompson, of the U.S. Geological Survey, who found it coating a fracture surface in the southern part of the Main Ridge workings. Since then, steigerite has been

[6] Data furnished by Alice D. Weeks, U.S. Geol. Survey (oral communication).

found in several other places in these workings and in the Monument No. 2 mine workings on South Ridge (pl. 6).

Tyuyamunite, $Ca(UO_2)_2(VO_4)_2 \cdot 7\text{–}10\frac{1}{2}H_2O$ and metatyuyamunite, $Ca(UO_2)_2(VO_4)_2 \cdot 5\text{–}7H_2O$.—By far the most abundant uranium-ore mineral in the Monument No. 2 mine is tyuyamunite (metatyuyamunite is considered with tyuyamunite here, as the two cannot be distinguished in the field, and as they may well change from one to the other with changing moisture conditions). The tyuyamunite occurs as tiny (0.1 to 0.5 mm) flaky yellow crystals coating pebbles, silicified wood, and fracture surfaces and as bright-yellow powdery to compact earthy material which fills the interstices of the rock. In places where the sand grains have been completely replaced, the tyuyamunite forms solid masses as much as 6 inches across.

Most of the tyuyamunite is in rods and tabular ore bodies (p 86).

Uraninite, UO_2.—Although it is not abundant enough to make an important contribution to the ore, uraninite has been found in many places in the Monument No. 2 mine, and is important mineralogically.

Three varieties of uraninite have been distinguished in the mine. One variety is hard and massive, with a dull to greasy luster, and a specific gravity of 6 to 7. It appears similar to vein pitchblende. The second variety is moderately hard, with a bright resinous to nearly vitreous luster and a specific gravity of 4 to 5, and probably this variety contains remnants of coalified wood. Most of these specimens show fossil-wood textures. The third variety is softer, with a dull luster and a specific gravity of 5 to 6. Much of it has a sooty appearance, but it will not rub off on the fingers.

Most of the uraninite occurs as ellipsoidal nodules, surrounded by orange to yellow halos of becquerelite and uranophane, all enclosed in coarse-grained to conglomeratic sandstone. The enclosing sandstone is impregnated with yellow tyuyamunite, but most commonly the sandstone is profusely impregnated with a reddish limonite that commonly decreases in amount and becomes browner away from the nodule.

Many uraninite nodules show woody structures or textures, ranging from gross forms of twigs and limbs to actual cell structure. Much of the uraninite that does not replace wood contains relict quartz grains.

On the western edge of the channel, in the South workings (pl. 6), a pillar contained a very compact mass of ore composed of uraninite, becquerelite, tyuyamunite, navajoite, corvusite, pyrite, and other minerals. Most of the uraninite appeared as flat-lying irregular laths, about a quarter of an inch thick, 2 to 5 inches wide, and 1 to 3 feet long. Separating the laths, and filling cracks in them were orange and yellow secondary uranium-vanadium minerals and pyrite. Some of the uraninite laths contained zones of pyrite as thick as the laths, and in these zones replacement of wood cells by uraninite and pyrite was striking. In some, the cells appear to have walls of pyrite and centers of uraninite, whereas in other fragments the reverse was true.

Pyrite is enclosed in many of the uraninite nodules as tiny irregular grains and as ellipsoidal masses as much as a quarter of an inch in long dimension. Most of these pyrite grains are embayed and veined by uraninite.

A cross section of a fossil log is exposed near the portal of Incline 3 (pl. 6). This log, about 10 by 15 inches, is composed of carbonaceous matter that has been largely replaced by uraninite, black and blue-black vanadium minerals, pyrite, and other minerals. The uraninite and vanadium minerals seem to replace the carbonaceous matter, and locally preserve the cell structure. The pyrite occurs mostly as granular nodules and veinlets, but in a few places pyrite has replaced some carbonaceous matter and has preserved the cell structure. Small amounts of secondary yellow uranium-vanadium minerals are scattered throughout the log as films and veinlets. A few tiny yellow crystals of native sulfur were found in a cavity in the log, and several tiny black sphalerite crystals have been identified by Thomas W. Stern. A mineralized halo is in the medium-grained sandstone which surrounds the log. The inner zone of the halo contains blue-black vanadium minerals, a little uraninite, considerable pyrite, and some yellow tyuyamunite. The outer zone contains some tyuyamunite along with orange and brown secondary vanadium minerals and limonite. The halo grades out into barren-looking sandstone.

Two similar, but smaller, logs were found in an opencut north of Incline 3.

Uranophane, $Ca(UO_2)_2Si_2O_7 \cdot 6H_2O$.—Many of the orange to yellow shells surrounding uraninite nodules contain uranophane. Some of the uranophane has a bladed or fibrous texture in hand specimens, but much of it is indistinguishable from becquerelite. In thin section, the uranophane is generally lighter yellow and much more transparent than becquerelite, and is bladed to fibrous. The long axes of the bladed and fibrous crystals are roughly parallel to the radii of the nodules.

Associated minerals (nonsulfides)

Apatite (carbonate), $Ca_{10}(PO_4)_6(CO_3) \cdot H_2O$.—A small pebble of carbonate-apatite was found in the conglomerate of the North workings (pl. 6). The pebble was very light gray and had a claystone texture. The carbonate-apatite probably represents former bone material and is not related to the ore.

Calcite, $CaCO_3$.—Only small amounts of calcite are found in the Monument No. 2 mine, for silica and clay appear to be the dominant cements, particularly in the ore, where calcite is almost totally lacking. A few small patches and small cavity fillings of calcite in the form of dogtooth spar are in the South workings (pl. 6). Some of the patches have a concretionary aspect. One in particular has a nearly spherical core of sandstone, impregnated with tyuyamunite and fine-grained calcite. This core is surrounded by ½- to 1-inch rim of calcite crystals which contains a few scattered sand grains. This body is enclosed in sandstone. The calcite patches or concretions generally are in weakly mineralized conglomerate or conglomeratic sandstone above lenses of high-grade brownish or yellow ore.

Clay minerals.—Mineral grains of clay size (less than $1/256$ mm) are abundant throughout this ore deposit, but actual clay minerals constitute only a small fraction of this material. Although no absolute abundances were estimated from maximum peak heights on X-ray diffractometer graphs for a number of samples, without exception, these samples contained abundant quartz. Whether this quartz is allogenic or authigenic is not known; the frequent occurrence of authigenic quartz rims on quartz grains in the sandstone suggests that much of the quartz in the clay size fractions may also be authigenic. All the samples examined contained hydromica, which, except in a few specimens, was the most abundant constituent. Spectrographic analyses of a number of specimens showed very little vanadium, and it appears that the vanadium hydromica found abundantly in some of the mines elsewhere on the Colorado Plateau is rare or absent in the ore deposit in the Monument No. 2 channel.

Kaolinite was found in more than half the samples, commonly in small amounts, but a few samples contained more kaolinite than hydromica.

Montmorillonite was found in about half the samples. In most of these samples the amount of montmorillonite was about equal to or slightly less than the amount of kaolinite. A few samples contained considerably more montmorillonite than kaolinite, but no sample contained as much montmorillonite as hydromica.

A little apatite, probably carbonate apatite, showed in a few samples.

For comparison, a number of samples of mudstone from the Shinarump member of the Chinle formation away from the ore deposit in the Monument No. 2 channel were examined. These samples showed the same mineralogy and relative mineral abundances as those collected in the ore deposit at the Monument No. 2 channel. It would appear, therefore, that the clay of the Shinarump member in the mine is the same as that away from the mine and shows no changes which can be related to ore-bearing solutions.

Gypsum, $CaSO_4 \cdot 2H_2O$.—Gypsum has been found throughout the mine, although it is nowhere abundant. It occurs mainly as soft powdery fillings of fractures. These fillings commonly are about 1 mm thick, but are known to range from paper thin to as much as 1 cm in thickness. Many of the tiny faults that are found throughout the mine have thin coatings of gypsum or calcite on their surface and, in some places, the faults would be indiscernable except for this coating.

Locally, a few thin plates of selenite, as much as 0.2 mm thick and 1 to 2 mm long, are dispersed among the interstices of conglomerate and conglomeratic sandstone, but in one place a pocket in conglomerate was found where gypsum formed as much as 25 percent of the rock. The pocket was about 18 inches across and 3 feet long, and the gypsum was most abundant in the center, decreasing moderately toward the edges of the pocket. At the borders of the pocket, the abundance of gypsum decreased markedly, so that only scattered selenite flakes were found a few inches away. Associated with the gypsum were abundant silicified wood and a little metazeunerite.

On South Ridge a single crystal of selenite of optical quality, ½ by ½ by 1 inch, was found enclosed in relatively unaltered, conglomeratic, montroseite-uraninite ore. Its occurrence was such as to suggest that it may have been deposited with the primary ore. Only small scattered flakes of gypsum were found in the nearby ore.

Ilsemannite (?), $Mo_3O_8 \cdot nH_2O$.—Powdery blue ilsemannite (?) both coats and impregnates friable conglomerate in a wall along the west edge of the channel in the South workings (pl. 6). It is in a zone 6 inches to 2 feet thick and about 8 feet long.

The ilsemannite (?) is associated with corvusite, navajoite, hewettite, and some uraninite, as well as gypsum, partly altered pyrite, and a little unindentified iron sulfate.

The ilsemannite (?) was so powdery fine grained, and so dispersed that little data could be obtained from it. Identification was on the basis of its blue to grayish-blue color, a chemical test for molybdenum, and solubility in water with the formation of a blue solution. No X-ray comparison data were available.

Although the ilsemannite (?) seems to be secondary, no primary molybdenum mineral from which it could be derived has yet been found.

Jarosite, $KFe_3(SO_4)_2(OH)_6$.—Jarosite has been identified in specimens from the North workings of the Mounment No. 2 mine (pl. 6). It is a light-yellowish-brown earthy material which fills interstices in medium- to coarse-grained strata of the Shinarump member. Identification was by means of its X-ray powder pattern.

The abundance of jarosite in the ore deposit of the Monument No. 2 channel was not estimated. Its brownish color renders it indistinguishable from iron oxides when mixed with these minerals in the form of limonite. The jarosite presumably represents an intermediate stage in the oxidation of pyrite to iron oxides. Inasmuch as it generally cannot be distinguished in the field from the other minerals of the limonite, the limonite mentioned below may or may not contain appreciable quantities of jarosite.

Limonite.—Limonite appears throughout the Shinarump member of the Chinle formation in the Monument Valley area, Arizona, as stains and permeations, but it is nowhere as abundant as in the ore deposit in the Monument No. 2 channel. Strata of the Shinarump member filling the channel are colored dark brown by the limonite, and the channel course can be traced on the basis of color alone.

Within the ore deposit most of the lenses and beds of siltstone, sandstone, and conglomerate are stained and permeated with limonite. The limonite seems to be related to the uranium and vanadium ore; those lenses and beds with very little or no limonite are nearly devoid of uranium or vanadium minerals, whereas the rocks strongly impregnated with limonite commonly contain large amounts of uranium and vanadium minerals. This relationship of limonite with ore is not rigid, for much of the rock that is lightly to moderately stained and impregnated with limonite is of marginal grade and some of it is barren.

The limonite is mostly soft and powdery, and shows no boxwork or other relict structures. No complete mineralogic breakdown of the limonite has been attempted, but most samples appear to contain goethite, hematite, and a little jarosite. The limonite associated with the rods appears to be somewhat redder than the rest, perhaps due to a higher proportion of hematite.

The origin of the excess limonite within the ore deposit is not definitely known, although the oxidation of pyrite might account for it. Concretions of fine-grained interstitial pyrite are found in sandstone throughout most of the unoxidized or slightly oxidized parts of the mines, and a few such concretions, partly oxidized to limonite, have been found in highly oxidized areas. A series of nodular concretions, showing all stages of oxidation from pyrite to limonite, was found in the East Red Oxide workings (pl. 6).

The formation of such large quantities of limonite by the oxidation of pyrite would be accompanied by the formation of great quantities of sulfate. Except for a small amount of gypsum and a little jarosite, no sulfates have been found in the mines. Their absence may be explained by their solubility in ground water; even now the ground water in Cane Valley just below the mines contains relatively large amounts of sulfate in solution.

Opal, $SiO_2 \cdot nH_2O$.—A small amount of opal forms thin coatings on fracture surfaces and on pebbles in conglomerate near the surface or near rim outcrops in the North workings (pl. 6). The coatings range in thickness from minute films to botryoidal incrustations 5 mm thick.

Most of the opal is the variety hyalite, but some translucent white, pale green, and gray opal is found. The opal fluoresces a moderate to brilliant green under shortwave ultraviolet light.

Quartz and chalcedony, SiO_2.—Quartz is by far the most abundant mineral in the ore deposit in the Monument No. 2 channel. The quartz in the Shinarump member of the Chinle formation of the ore deposit at the Monument No. 2 channel occurs as subround to round fine to coarse sand grains and as clastic material as much as 5 inches and averaging about 1 inch in diameter. The sand grains are transparent to translucent colorless to dark-gray smoky quartz.

In many places, the quartz appears to have been corroded and etched rather severely. Etched quartz grains are found within uraninite and other uranium minerals.

Authigenic quartz has been deposited on the older quartz grains in many places, with optical continuity. A large proportion of the strata of the Shinarump member in the mines shows this authigenic quartz, which in places is so well developed as to form moderately well cemented to well-cemented quartz-crystal sandstone. Several specimens of the Shinarump member collected from outside the Monument No. 2 channel lacked authigenic quartz overgrowths. Authigenic quartz has been added to the De Chelly sandstone member of the Cutler formation in most places where ore minerals extend down to or into the top of the De Chelly sandstone member.

Chalcedonic quartz occurs as silicified wood. Silicification of the wood appears to be earlier than the ore, and may have taken place shortly after deposition of the Shinarump member.

Wad (lithian).—Throughout the mine, wad is found as sooty black to brownish-black coatings and fracture fillings. The coatings are soft, often powdery, and without form. The composition of the wad is variable; all specimens contain much manganese, and some specimens contain significant amounts of one or more of the following elements: barium, cobalt, iron, and lithium. The name lithiophorite has been applied by some persons to the lithian wad from the Monument No. 2 mine, but inasmuch as the wad shows none of the scaly or botryoidal structure of typical lithiophorite, it would seem better to term the material from the Monument No. 2 mine lithian "wad."

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Associated minerals (sulfides)

Bornite, Cu_5FeS_4.—Minute amounts of bornite have been recognized in a specimen from the Incline 3 workings (pl. 6). The bornite coats sand grains in films so microscopically thin that attempts to secure a sample for X-ray powder patterns was unsuccessful. Identification was made on the basis of its "peacock ore" appearance under the binocular microscope and microchemical tests for copper and iron.

Except for metazeunerite, this is the only copper mineral found in the Monument No. 2 mine.

Galena, PbS.—Small grains of galena have been found associated with uraninite nodules in the Incline 2 workings (pl. 6). The galena was in the form of small crystals and irregular grains enclosed in the uraninite.

The galena (nonradiogenic lead) was used by Stieff, Stern, and Milkey (1953) for correction of isotopic ratios in their determinations of the age of uraninite from the Monument No. 2 mine (p. 96).

Pyrite, FeS_2.—At least four forms of pyrite have been found in the Monument No. 2 mine. Probably the most important type from the standpoint of paragenetic implications is one that occurs with uraninite. Specimens of fossil wood, replaced by pyrite and uraninite, were found in a pillar in the South workings (pl. 6). The wood was replaced so completely that it was not possible to determine its state at the time of replacement. The striking feature was the inverted replacement relationships shown in two specimens collected only 2 feet apart. In one, the cell walls were pyrite and the cell contents were uraninite; in the other, the cell walls were uraninite and the cell contents, pyrite. Replacement by the two minerals must have been virtually simultaneous, with some subtle influence causing the inverted relationships.

The second form of pyrite was collected from a small greenish-gray claystone lens in the workings on South Ridge (pl. 6). About 20 cubes, 2 to 5 mm on edge, were found singly and in small groups. The crystals were sharp and bright with no sign of alteration, although the uranium and vanadium ore in the vicinity had begun to show appreciable oxidation.

The third type of pyrite occurs as concretionary masses of tiny euhedral crystals interstitial to quartz grains in sandstone and conglomeratic sandstone. The concretions have been found scattered throughout the length and breadth of the mine, but are most abundant in the workings on South Ridge, Incline 1, and the upper levels of the Incline 2 workings. Stratigraphically they range through the Shinarump member of the Chinle formation and into the upper few inches of the De Chelly sandstone member of the Cutler formation. Individual concretions are ellipsoidal to lenticular and range in size from the size of buckshot up to flat lenses a few inches thick and several feet in length and width. The concretions lie roughly parallel to bedding. They may occur singly or in groups; members of groups may be arrayed along bedding, in a narrow stratigraphic zone, or be irregularly scattered. The sand grains in the concretions look the same as in the surrounding sandstone, but the interstices in the concretions are filled with myriad bright euhedral pyrite crystals. Most of the crystals are so small that their form cannot be recognized, but a few of the larger cystals appear as cubes, octahedrons, and pyritohedrons. Many of the concretions appear relatively fresh, with bright pyrite crystals inside and only a thin shell, 1/16 to 1/2 inch thick, of limonitic sandstone. Others are in more advanced stages of oxidation, and some have been completely limonitized. In some groups all stages of oxidation were seen. Most of the concretions had a sharp boundary with the enclosing sandstone, much of which contained little or no limonite. This suggests that the limonite that accompanies much of the ore was not derived from these pyritic concretions. Most of the concretions are in relatively barren sandstone or low-grade ore; none has been found in high-grade yellow ore, although several have been found in lower grade ore adjacent to the high grade.

A fourth type appears as small rosettes of marcasitelike crystals filling a small fault in the Incline 2 workings. The crystals are irregular and poorly formed and are about 1 by 5 mm in size. They were identified as pyrite by X-ray determination.

Sphalerite, ZnS, *and sulfur*, S.—Incline 3 cut through a fossil log and exposed a cross section of it in each wall of the incline (p. 119). The log, composed of carbonaceous matter, had been impregnated and partly replaced by uraninite, pyrite, and other minerals. From the core of the log, two black isometric crystals, 1 mm thick, were collected. These crystals were identified as sphalerite by Thomas W. Stern (written communication).

A tiny cavity in the core of the log yielded several transparent yellow crystals of native sulfur, 1 mm thick.

Unidentified minerals

In addition to the minerals described above, several minerals have been found that are as yet unidentified because of small quantity, low purity, or nonagreement with data on known minerals, and lack of sufficient data to establish them as new species.

Small thin incrustations of a bright-orange mineral were collected on the walls of a damp drift in the Incline 3 workings. The drift was in the otherwise barren De Chelly sandstone member underlying tyuyamunite-bearing sandstone and conglomerate of the Shinarump member. The mineral is a hydrous vanadate, but the X-ray pattern does not match the patterns of pascoite or hummerite, or any other mineral in the film library of the U.S. Geological Survey. The orange mineral had apparently leached from the overlying ore.

In the upper part of the Incline 3 workings, tiny irregular green flakes coat fracture surfaces in siltstone pebbles. These pebbles are in a conglomerate lens, 6 inches thick and about 15 to 20 feet in horizontal extent, that contains small amounts of a viscous oily material. No matching X-ray pattern was found for this green mineral. A microchemical test with potassium mercuric thiocyanate suggests that this mineral might contain nickel.

One or more very impure iron sulfate minerals were found in a drift wall on the west edge of the channel in the Incline 2 workings. The iron sulfate was associated with ilsemannite, partly altered pyrite, and gypsum. Attempts to separate the iron sulfate from the other minerals for identification have been unsuccessful.

Gruner and Gardiner (1952) report having found roscoelite, fernandinite, and alunite in the Monument No. 2 mine. The writer did not find any of these minerals.

PARAGENESIS

The following account of the paragenetic relationships in the ore deposit in the Monument No. 2 channel is based largely on the study of mineral occurrences, study of hand specimens collected in the mines, and microscopic examination of thin and polished sections of the ore and country rock. It is realized that for so large an ore deposit of such varied mineralogy this study is not exhaustive.

No vanadium mineral with the vanadium in a lower oxidation state than V^{+3}, as in montroseite, has been found on the Colorado Plateau. It is, therefore, inferred that the original vanadium mineral in the ore deposit in the Monument No. 2 channel was montroseite.

Uraninite, in which uranium has a valence of four, is the least oxidized uranium mineral known to occur in nature. It is, therefore, concluded from the mineralogy that the ore-forming solutions yielded U^{+4} and V^{+3} ions, along with smaller amounts of Fe^{+2}, Pb^{+2}, Zn^{+2}, Cu^{+2}, Mo^{+4}, Co^{+2}, and S^{-2}. Some silica and carbonate may have been added also, though these materials may have been derived from the host rock.

The fact that montroseite ore is found without uranium and that no vanadium is found in the uraninite implies separate loci of deposition or independent episodes of mineralization. No direct association of uraninite and montroseite has been found; so direct determination of age relationships have not been possible. There is a suggestion that uraninite may be earlier; all the montroseite examined is on strongly etched quartz grains with no evidence of replacement, whereas uraninite seems to have replaced some quartz, perhaps contemporaneously with the etching of quartz elsewhere.

The period of ore formation possibly began with dissolution of quartz. While this was taking place, pyrite began to be deposited and, later, uraninite was deposited simultaneously with pyrite. This stage was followed by deposition of montroseite, and this was followed, in turn, by the deposition of authigenic quartz. Small amounts of galena, sphalerite, bornite, and probably molybdenite and cobalt sulfides were deposited during the epoch of ore mineralization but their age relationships have not been established.

The primary ore in the Monument No. 2 channel, therefore, appears to have been largely uraninite and montroseite, with small quantities of sulfides, and a siliceous gangue in a siliceous country rock. From the age determinations and the regional geology it may be seen that the ore formed at a depth of several thousand feet. The primary ore was thus protected from oxidation for a considerable time, until erosion cut away most of the overlying rocks and circulating ground water began to bring atmospheric agents down to the site of the ore deposit.

The beginning of oxidation is surmised by many geologists to be the period of uplift and erosion that has produced the many great canyons and mesas of the southwest. Since its inception, oxidation has been relatively continuous, probably at an ever-increasing rate until the present.

Although a continuous range of oxidation products may be traced from primary ore to thoroughly oxidized ore, it is convenient to consider the process in stages, based on major mineral assemblages observed in the ore. Although the stages appear to be fairly definite, the boundaries between the stages are indistinct.

The primary ore has been described above. Only small amounts of this type of ore have been found in the ore deposit in the Monument No. 2 channel, and all occurrences were in the workings on South Ridge.

The first distinct oxidation stage is marked by very dark ore, commonly blue black, with locally a dark-greenish or brownish cast. This oxidation stage is commonly referred to as the corvusite stage after the vanadium mineral that predominates in this type of ore and which is largely responsible for the blue-black color. Associated minerals include becquerelite, tyuyamunite, navajoite, uraninite, rauvite, hewettite, and pyrite. The minerals are mostly fine grained and intimately mixed, and in most places individual minerals cannot be recognized except under the microscope or after various separatory techniques; frequently no distinction is possible. Tyuyamunite, particularly, is hidden by the dark colors of the other minerals.

The vanadium has been oxidized from V^{+3} in montroseite to V^{+4} in corvusite with a few minerals oxidized to V^{+5}. Continued oxidation in corvusite would convert all the vanadium to V^{+5} in the minerals navajoite, hewettite, rauvite, and tyuyamunite. Of these, navajoite is probably the first formed, as it represents for the most part a simple vanadium oxide, whereas calcium has been added in hewettite, and both calcium and uranium in rauvite and tyuyamunite. As navajoite (Evans, 1959) is formed, however, only in a highly acid environment (pH about 2) its occurrence may have been governed by this factor.

Concurrently with the oxidation of the vanadium, uranium would be oxidized from U^{+4} to U^{+6}. Some oxidation may have taken place earlier by auto-oxidation. Apparently the uranium oxidized more slowly than the vanadium, as relicts of uraninite are left after the vanadium seems to be entirely oxidized. Pyrite appears to be largely unchanged through the corvusite stage, although in places the presence of iron sulfates indicates oxidation is taking place. The ilsemannite found along with the iron sulfate suggests that perhaps an early molybdenum mineral is oxidized during this stage.

The corvusite stage is represented by the ores in the Incline 2 workings and in the southern two-thirds of the South Ridge workings (pl. 6). Those workings near the surface on Main Ridge contained no corvusite-type ore, although in some places corvusite-type ore underlay these upper workings.

The second oxidation stage (following the corvusite stage) is represented by dark-blackish-brown to medium-brown ore, in which all the vanadium is in the V^{+5} state, and all the uranium, except for scattered relicts of uraninite, is in the U^{+6} state. Minerals present are tyuyamunite, rauvite, hewettite, limonite, and small amounts of uraninite, becquerelite, uranophane, and pyrite. The second oxidation stage represents the completion of the oxidation of the vanadium, and considerable mixing of uranium and vanadium and other ions to form combined minerals. It is represented by border zones a few feet wide around areas of corvusite-type ore.

The third oxidation stage is represented by tyuyamunite-type ore. This ore, which is the most abundant and widespread type in the ore deposit in the Monument No. 2 channel, ranges in color from dark reddish brown through various lighter browns to bright yellow; a small amount of grayish ore with disseminated yellow tyuyamunite is also classed with this type. The chief minerals, beside the quartz of the host rock, are limonite and tyuyamunite, with smaller amounts of hewettite, rauvite, and a little relict pyrite. A few scattered relicts of uraninite rimmed with becquerelite or uranophane have been found in this type of ore, and all the autunite, metazeunerite, and carnotite found in the mine have been in this type of ore. The tyuyamunite-type ore apparently results from continued oxidation of pyrite and continued recombination of the elements of the earlier minerals, such as hewettite, rauvite, and becquerelite, to form the more stable tyuyamunite.

The fourth oxidation stage results from the action of these recombinations, and gives an ore containing little more than limonite, tyuyamunite, and perhaps a little hewettite. This is just the type of ore that is found throughout the uppermost workings and locally near the cliff faces where the deposit has been cut through by the canyons; these are the places where the ore has been longest and most completely exposed to oxidation.

Although oxidation and alteration of the ores in the ore deposit in the Monument No. 2 channel have been extensive, there has been relatively little overall movement of the metals. The primary minerals, particularly uraninite, appear to have oxidized nearly in place, and combination of the oxidation products has taken place with little migration. Vanadium appears to be more mobile than uranium; the secondary vanadium minerals hewettite and steigerite have been found along joints as much as 25 feet from ore, whereas uranium minerals along joints are much closer to the primary ore. Small samples of ore show differing contents of the daughter products of uranium, but the ratios of these elements in bulk samples of ore are near the equilibrium values.

MONUMENT NO. 1-MITTEN NO. 2 MINE AND MONUMENT NO. 1 ANNEX

In 1954 the Monument No. 1 channel was the scene of intensive mining activity, primarily as the result of a discovery of a new ore body in channel fill formerly thought to be barren. Before that, in the period 1942–50, the major producer was the Monument No. 1 mine, operated by the Vanadium Corporation of America. This mine was in basal strata at the east end of a large channel remnant. The ore deposit pinched out and in 1950 mining was discontinued and the adits were caved as a safety measure. From then until 1953 the area lay unclaimed, although some work was done in another small mine about a quarter of a mile distant. This mine, known as the Monument No. 1 Annex, is in a weakly mineralized mass of the Shinarump member of the Chinle formation about 150 feet long and 50 feet wide.

During 1952, several Navajo Indians reprospected the area of the Monument No. 1 mine. Production records do not exist and it is assumed that no ore was produced. In 1953, a new mine, the Mitten No. 2, owned by the Foutz Mining Co. (now the Industrial Uranium Co.) was opened in the flank of the western part of the channel remnant. The mine was in weakly mineralized ground and produced less than

100 tons of ore. In early 1954, however, a new ore body was discovered in this part of the channel fill as a result of a drilling program by the U.S. Atomic Energy Commission, and as of January 1955, it was this ore body that was being mined through the new Monument No. 1-Mitten No. 2 mine workings (Witkind, 1961).

LOCATION AND ACCESSIBILITY

The center of the Monument No. 1 area is at latitude 36°57′24″ N. and longitude 110°14′ W. The area is on a prominent ridge west of the Kayenta-Mexican Hat road (fig. 1; Navajo Indian Reservation Route 1). The mines are reached by an ungraded trail that leads northwest from the Kayenta-Mexican Hat road and ascends to the mine portals by a series of switchbacks.

GEOLOGY

The ridge is capped by remnants of the Shinarump member of the Chinle formation that stand about 30 feet above the general ground surface formed on the Moenkopi formation (fig. 22). Scattered across this Moenkopi surface are deposits of unconsolidated eolian sand as much as 10 feet thick.

Most of the Shinarump member has been eroded from the area near the Monument No. 1 mine and it is only to the west, near Oljeto Creek, that the Shinarump member is preserved. There, however, it is concealed beneath a dune sand and alluvial cover that may be as much as 80 feet thick, although it likely averages 20 feet.

The Shinarump member forms the gently dipping east flank of the asymmetrical Oljeto syncline (p. 63) and the dip averages 3° to the southwest.

MONUMENT NO. 1 CHANNEL

Remnants of the Shinarump member represent part of a former widespread sheet of conglomeratic sandstone. Dissection, however, has been so extensive that the uppermost beds of Shinarump member as well as part of the subjacent strata of Moenkopi age have been largely removed (fig. 22*B*). The result is that strata of the Monument No. 1 channel now appear as two ridges whose alinement is to the northwest (fig. 22*A*). The two ridges, however, do not everywhere reflect the true width of the channel, for locally, part of the channel strata have been eroded. When these remnants are viewed in cross section it is apparent that in places only the east flank of the channel fill is preserved (fig. 22*B*). The channel is estimated, by extrapolation from the preserved channel remnants, to have been about 280 feet wide and to have been cut about 50 feet into the Moenkopi formation. The channel curves to the northwest (fig. 22*A*).

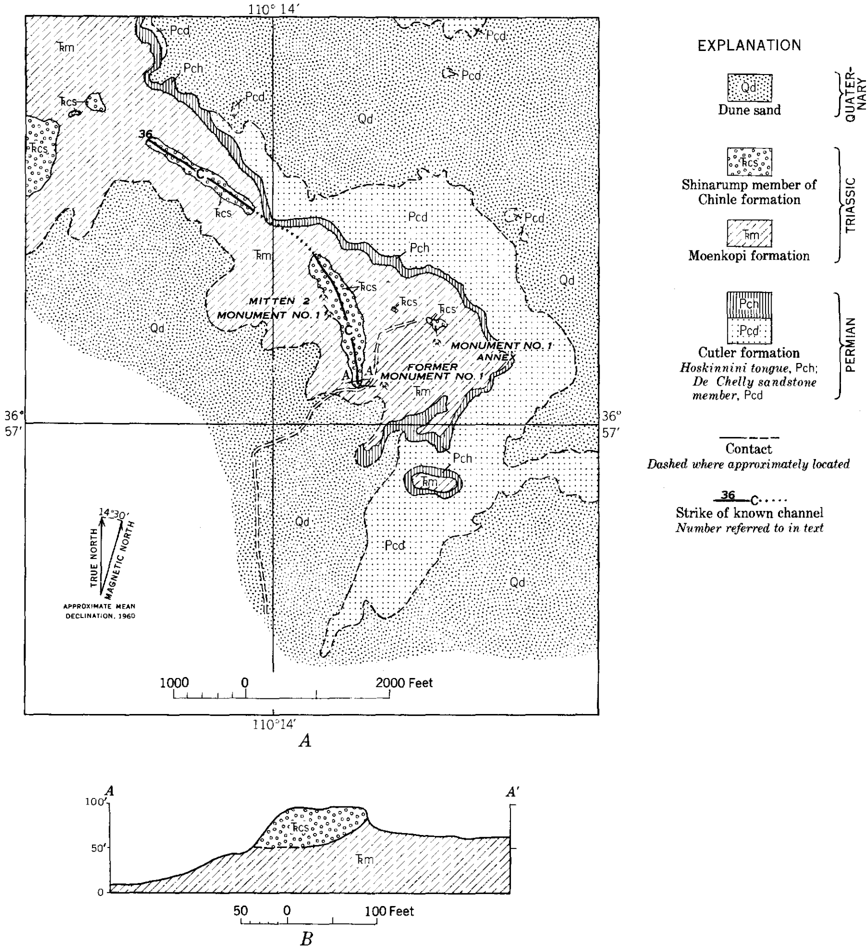


Figure 22.—Geologic map (*A*), and cross section (*B*), of the Monument No. 1 channel. The two channel remnants of the Shinarump member form topographic highs. The channel curves to the northwest. It is uncertain if the Monument No. 1 Annex is in a part of the same channel.

The southern channel remnants, which contain the mine workings, trend about N. 10° W., and the northern remnant trends about N. 55° W.

Sedimentary rocks in the Monument No. 1 channel have the same appearance as strata of the Shinarump member found elsewhere in the Monument Valley area, Arizona. The basal conglomeratic sandstone grades vertically into a massive sandstone in the uppermost beds. Conglomerate lenses are scattered throughout the channel fill. They retain their identity only for short distances, grading laterally into massive sandstone. In a few places, small scours, filled with conglomeratic sandstone, have been cut into the massive sandstone that forms the uppermost channel fill.

Three lithologic units can be differentiated in the basal channel fill: (1) trash-pocket conglomerate, (2) calcite-cemented sandstone, and (3) silica-cemented sandstone (fig. 23). The trash-pocket conglomerate consists of well-rounded pebbles of quartz, chert, and quartzite, as well as angular claystone fragments and fossil plant matter, all in a matrix of coarse-grained sandstone. The calcite-cemented sandstone is a light-tan hard massive crossbedded unit well cemented by calcium carbonate. These calcite-cemented sandstone lenses are composed of well-rounded fine to coarse grains of quartz, chert, and quartzite in an exceedingly tight carbonate cement. The quartz grains lack authigenic overgrowths in marked contrast to those grains in the silica-cemented sandstone. The third lithologic type, the silica-cemented sandstone, is composed of rounded to angular coarse

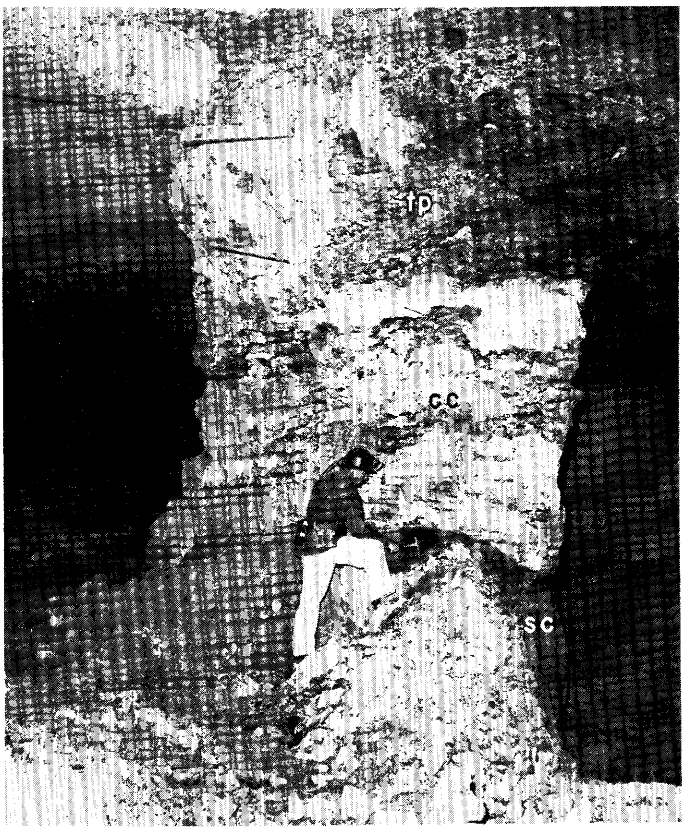


FIGURE 23.—Three lithologic units represented in basal channel fill: tp, trash-pocket conglomerate; cc, calcite-cemented sandstone; and sc, silica-cemented sandstone.

grains of quartz, chert, and quartzite, all enclosed in a loosely knit matrix of chalcedonic cement. A characteristic feature is authigenic overgrowths on the quartz grains.

Inclusions in the basal channel fill consists of silicified wood, ranging from small fragments to logs more than 2 feet in diameter and 10 feet in length, as well as large amounts of carbonaceous matter and clay pebbles. Also included are angular fragments of light-gray siltstone interpreted as having been derived from the Moenkopi formation. Measurements of the trend of 15 silicified logs in the channel fill indicate a range from N. 10° W. to N. 85° W., although most of the logs are alined collinear with the N. 10° W. strike of the channel.

The upper surface of the channel fill is irregular and is marked by depressions as much as 20 feet in diameter and 4 feet in depth, and by rounded hummocks which rise about 20 feet above the general surface.

Near the southernmost exposure of channel strata, a concentration of silicified logs on the surface is surrounded by very dark limonite-colored rocks. This limonitic coloration is not confined to one locality, for elsewhere on the surface, smaller limonite-colored areas are exposed. Unweathered exposures of channel fill lack the limonite coloration.

The channel is underlain by an altered zone in the uppermost strata of the Moenkopi formation that is about 2 feet thick along the channel flanks and increases in thickness to almost 5 feet below the channel. In the uppermost part of the altered zone beneath the channel, minute quantities of secondary copper minerals, such as azurite, malachite, and chrysocolla, are along the bedding planes and fill small fractures.

The possible significance of the altered zone has been investigated (Alice D. Weeks, written communication, 1952). Specimens of both the red unaltered and the gray altered Moenkopi formation were chemically analyzed. Mrs. Weeks reports:

At Monument No. 1 mine, both red and gray clay contain quartz, hydromica, chlorite, and kaolinite. Chemical determinations of total iron, ferric and ferrous iron, titanium dioxide, and vanadium pentoxide, made by R. G. Milkey, showed that in all suites of samples total iron and ferric iron are higher in the red than in the adjacent gray sample. Although the ferrous-ferric ratio is higher in all the gray samples than in the adjacent red clay, the ferrous iron does not vary significantly between the red and gray of each set. To alter the red clay to gray, only 1 percent more or less of ferric iron pigment would have to be leached from the red. Hematite is too small in quantity or too fine grained to show in X-ray patterns of natural red clays.

Mrs. Weeks sought but found no evidence for or against a relationship of the altered zone to ore-mineralizing solutions.

Strata in the Monument No. 1 Annex are similar to those filling the Monument No. 1 channel except that light-gray oval clay pebbles, about half an inch long, are in a matrix of coarse-grained sandstone. The clay pebbles are so alined as to give an impression of rudimentary horizontal bedding. Yellow uranium minerals are disseminated in the interstices of the sandstone near the pebbles, but they are absent elsewhere. A banded appearance results: yellow mineralized bands about 1 inch wide alternate with white barren bands, also about 1 inch wide. Close examination near some of the clay pebbles indicates that in some, yellow uranium minerals impregnate the sandstone to the very edges of the pebbles. In others, a halo about a quarter of an inch thick devoid of uranium minerals surrounds them.

Trash pockets of fossil plant matter are common in the rocks of the Monument No. 1 Annex. These pockets appear in cross section as irregular thin strips of black coaly substance (vitrain?). In plan view, these pockets show as impressions of reedlike plant material in the sandstone.

URANIUM-VANADIUM ORE BODIES

Two ore bodies have been discovered in the basal channel fill of the south channel remnant. They were separated from one another by barren strata. Little is known about the size, shape, and distribution of the ore body mined by the Vanadium Corporation of America at the former Monument No. 1 mine (fig. 22). The second ore body, mined through the Monument No. 1–Mitten No. 2 mine portals (fig. 22), was near the north end of the south channel remnant. It was about 675 feet long and about 75 feet wide, although in places it was as wide as 120 feet. It ranged in thickness from 1 foot to as much as 18 feet, but averaged 7 feet. This ore body trended N. 30° W., and was collinear with the channel trend. In both longitudinal and cross section the ore body appeared planoconvex or biconvex, with its base commonly conforming to the channel floor.

In places, both the trash-pocket conglomerate and the silica-cemented sandstone contained ore and formed ore bodies. Barren calcite-cemented sandstone lenses commonly were intercalated in the ore body (fig. 23). The ore was brillant blue black, principally due to the widespread distribution of the vanadium mineral corvusite. Scattered irregularly through the ore body were specks of yellow, green, and blue, representing secondary uranium (tyuyamunite), copper-vanadium (volborthite), and copper (azurite, malachite) minerals. Copper minerals were common in the southern part of the Monument No. 1 mine workings, but were not found in the Mitten No. 2 mine workings. Semiquantitative spectrographic analyses of the basal channel fill, however, indicated that copper was widespread.

MINERALOGY

The following minerals were collected from channel strata exposed near the former Monument No. 1 mine and have been identified by A. G. King, U.S. Geological Survey, using X-ray powder diffraction patterns:

Mineral	*Formula*	*Abundance*
Apatite(?)	$CaFCa_4(PO_4)_3$	Rare.
Autunite	$Ca(UO_2)_2(PO_4)_2 \cdot 12H_2O$	Do.
Azurite	$Cu_3(OH)_2(CO_3)_2$	Do.
Calcite	$CaCO_3$	Common.
Carnotite	$K_2(UO_2)_2(VO_4)_2 \cdot 1\text{–}3H_2O$	Rare(?).
Chlorite	$Mg_5(Al,Fe)(OH)_8(Al,Si)_4O_{10}$	Rare.
Chrysocolla	$CuSiO_3 \cdot 2H_2O$	Do.
Hydromica	$KAl_2(OH)_2AlSi_3(O,OH)_{10}$	Rare to common.
Kaolinite	$Al_2Si_2O_5(OH)_4$	Rare(?).
Limonite	$2Fe_2O_3 \cdot 3H_2O$	Common.
Malachite	$Cu_2(OH)_2CO_3$	Rare.
Metatorbernite	$Cu(UO_2)_2(PO_4)_2 \cdot 8H_2O$	Do.
Montmorillonite	$(MgCa)O \cdot Al_2O_3 \cdot 5SiO_2 \cdot nH_2O$	Do.
Pyrite	FeS_2	Common.
Torbernite	$Cu(UO_2)_2(PO_4)_2 \cdot 12H_2O$	Rare.
Tyuyamunite	$Ca(UO_2)(VO_4)_2 \cdot 7\text{–}10\frac{1}{2}H_2O$	Common.
Zippeite	$(UO_2)_2SO_4(OH)_2 \cdot 4H_2O$	Rare.

Essentially the same minerals were found at Monument No. 1 Annex.

The following minerals were collected from the Mitten No. 2 mine and were identified by A. G. King, U.S. Geological Survey.

Mineral	*Formula*	*Abundance*
Apatite	$CaFCa_4(PO_4)_3$	Rare.
Azurite	$Cu_3(OH)_2(CO_3)_2$	Rare to common.
Calcite	$CaCO_3$	Common.
Carnotite	$K_2(UO_2)_2(VO_4)_2 \cdot 1\text{–}3H_2O$	Rare.
Chalcanthite	$CuSO_4 \cdot 5H_2O$	Do.
Chalcedony	SiO_2	Rare to common.
Chalcocite	Cu_2S	Rare.
Chrysocolla	$CuSiO_3 \cdot 2H_2O$	Rare to common.
Corvusite	$V_2O_4 \cdot 6V_2O_5 \cdot nH_2O(?)$	Common.
Hewettite	$CaV_6O_{16} \cdot 9H_2O$	Rare.
Malachite	$Cu_2(OH)_2CO_3$	Common.
Metatorbernite	$Cu(UO_2)_2(PO_4)_2 \cdot 8\text{–}12H_2O$	Rare.
Metatyuyamunite	$Ca(UO_2)_2(VO_4)_2 \cdot 7\text{–}10\frac{1}{2}H_2O$	Common.
Pyrite	FeS_2	Do.
Rauvite	$CaO \cdot 2UO_3 \cdot 5V_2O_5 \cdot 16H_2O(?)$	Rare.
Roscoelite	$(Al,V)_2AlSi_3(K,Na)O_{10}(OH,F)_2$	Do.
Tyuyamunite	$Ca(UO_2)_2(VO_4)_2 \cdot 7\text{–}10\frac{1}{2}H_2O$	Common.
Volborthite	$Cu_3(VO_4)_2 \cdot 3H_2O$	Do.

PROSPECTS

The Monument Valley area, Arizona, has been examined thoroughly by white and Navajo prospectors, and few mineralized outcrops remain unclaimed. Those channel exposures that show copper or uranium minerals (table 1) generally have had some development work completed in the form of roads or small adits. The U.S. Atomic Energy Commission has investigated several of these prospects by diamond drilling. As of July 1953, the U.S. Geological Survey had done no physical exploration in the Monument Valley area, beyond several geophysical surveys launched primarily to secure geologic information.

Two areas seem most promising, Hunts Mesa and Mitchell Mesa. The U.S. Atomic Energy Commission completed a drilling program in November 1952 on Hunts Mesa. Thirty-two holes were drilled. Of these, only two holes penetrated mineralized ground and in neither was the material of ore grade.

HUNTS MESA

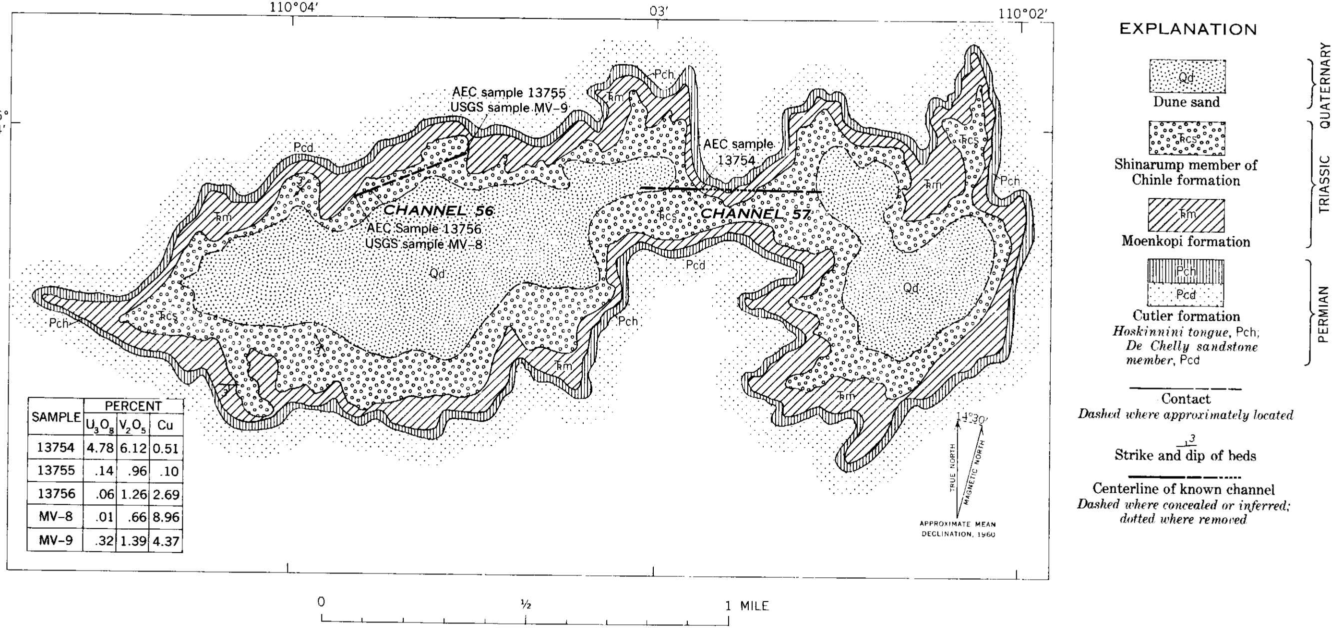
Hunts Mesa is a small mesa in the Monument Valley area, Arizona. At least two channels crop out at the base of the Shinarump member which caps the mesa, and it is within channel fills so exposed that uranium and copper minerals have been found (fig. 24).

Hunts Mesa is in Navajo County at latitude 36°53′ N. and longitude 110°03′ W. The mesa top is reached by two roads, one of which was completed in 1953. The other road is a jeep trail. No ore has been shipped from the mesa.

Sedimentary rocks exposed range from the Organ Rock tongue of the Cutler formation of Permian age at the base of the mesa to the Shinarump member of the Chinle formation of Triassic age at the top. Most of the Shinarump member, however, is concealed beneath sand dunes, and outcrops are best along the mesa rim. The thickness of the Shinarump member varies from place to place. Along the southeast edge of the mesa it is but 2 or 3 feet thick, whereas along the northeast edge it is as much as 75 feet thick.

The mesa is near the crest of the Agathla anticline (pl. 1) and the strata are almost horizontal.

In many places around the mesa, uppermost strata of the Moenkopi formation contain small cracks that are filled with rocks of the Shinarump member. These cracks are almost vertical and follow a zigzag course as they penetrate as much as 20 feet into the underlying Moenkopi formation. They thicken erratically but in general taper from a width of about 6 inches at the base of the Shinarump member to zero at the point where they pinch out. In a few localities, secondary copper minerals, principally malachite and chrysocolla, fill interstices in the upper 3 to 4 feet of the cracks.



SAMPLE	PERCENT		
	U_3O_8	V_2O_5	Cu
13754	4.78	6.12	0.51
13755	.14	.96	.10
13756	.06	1.26	2.69
MV-8	.01	.66	8.96
MV-9	.32	1.39	4.37

Figure 24.—Geologic map of Hunts Mesa showing centerlines of two known channels. Relationship of channel 56 to channel 57 unknown.

At least two channels crop out along the north rim of the mesa, although more may be concealed beneath the thick talus concealing the base of the Shinarump member (fig. 24). The main channel (57) strikes about east, is about 300 feet wide, and has been cut about 50 feet into the underlying Moenkopi formation. The other channel (56) is much smaller, and crops out in two places along the north rim. It strikes about N. 80° E., is about 50 feet wide, and has been cut about 20 feet into the Moenkopi formation. In general, the main channel is broad and relatively shallow. Its flanks dip about 5°. The smaller channel, however, has much steeper flanks, and appears to be cut as a very narrow V into the underlying Moenkopi formation. Whether or not these two channels are related is unknown.

Strata in both channels consist predominantly of a dark-gray conglomeratic sandstone, with conglomeratic material near the base grading upward into a coarse- to medium-grained sandstone near the top. The strata are crossbedded and contain silicified wood, carbonaceous wood fragments (vitrain?), dark-purple to gray clay pebbles (possibly fragments of Moenkopi), and tan fine-grained siltstone pebbles of unknown origin.

Mineralized rock crops out at two of the channel exposures (fig. 24) and consists principally of channel fills impregnated with secondary copper and uranium minerals. This impregnation appears as minute specks of azurite, malachite, and tyuyamunite(?) filling interstices. Clay pebbles in these mineralized exposures have been partly replaced by both copper and uranium minerals. Some of the clay pebbles show concentric zoning involving these minerals. One clay pebble half an inch in diameter is surrounded by a black zone, about one-eighth of an inch thick, of what may be chalcocite, which, in turn, is surrounded by a one-quarter-inch ring of mixed secondary copper and yellow uranium (tyuyamunite?) minerals. Beyond this mixed copper tyuyamunite(?) ring, the sandstone is barren.

Grab and channel samples were collected for analysis by geologists of both the U.S. Atomic Energy Commission (AEC) and the U.S. Geological Survey (USGS). The results of assays completed on the samples are listed below. Locations of samples are shown on figure 24.

Organization	*Sample*	U_3O_8	V_2O_5	*Cu*
AEC	[1] 13754	4.78	6.12	.51
Do	[1] 13755	.14	.96	.10
Do	[1] 13756	.06	1.26	2.69
USGS	[2] MV–8	.01	.66	8.96
Do	[2] MV–9	.32	1.39	4.37

[1] Names of analysts not determinable.
[2] Analysts: R. F. Dufour, C. A. Horr, and W. M. Mountjoy, U.S. Geological Survey.

Samples from basal channel fill at three outcrops along the north rim of Hunts Mesa, collected and identified by the authors, contained the following minerals:

Mineral	*Formula*	*Abundance*
Azurite	$Cu_3(OH)_2(CO_3)_2$	Rare to common.
Calcite	$CaCO_3$	Common.
Carnotite	$K_2(UO_2)_2(VO_4)_2 \cdot 3H_2O$	Rare(?).
Chalcocite?	Cu_2S	Rare.
Chrysocolla?	$CuSiO_3 \cdot 2H_2O$	Rare to common.
Corvusite?	$V_2O_4 \cdot 6V_2O_5 \cdot nH_2O$	Rare.
Jarosite	$K_2Fe_6(OH)_{12}(SO_4)_4$	Common.
Limonite	$2Fe_2O_3 \cdot 3H_2O$	Do.
Malachite	$Cu_2(OH)_2CO_3$	Rare to common.
Torbernite	$Cu(UO_2)_2(PO_4)_2 \cdot 12H_2O$	Rare.
Tyuyamunite	$Ca(UO_2)(VO_4)_2 \cdot nH_2O$	Rare to common.

MITCHELL MESA

Mitchell Mesa is a large irregularly shaped mesa in the north-central part of the Monument Valley area, Arizona (pl. 1). The mesa is capped with the Shinarump member of the Chinle formation, and yellow uranium minerals are in strata filling a channel at the base of the caprock. The mesa is rimmed by sheer cliffs and access to the top can be best gained at one locality, and there, only across talus slopes and smooth steep walls of consolidated sedimentary strata. The cost of constructing a truck trail to the mesa top would be high.

Mitchell Mesa is in Navajo County at lat 36°58′ N. and long 110°07′ W. The mesa is about 2 miles south of the Arizona-Utah State line, and about 7 miles southeast of Gouldings trading post, Utah (fig. 1).

Strata forming Mitchell Mesa range from the Organ Rock tongue at the base to the Shinarump member at the top. Around the mesa crest, the Shinarump member is about 50 feet thick, except where channels have been cut into the Moenkopi formation; in these places the Shinarump member is as thick as 120 feet.

Mitchell Mesa is on the crest of a small unnamed anticline; consequently, the strata are nearly horizontal.

Channel strata crop out around the edges of the mesa (fig. 25). Of these exposures, three are alined so as to leave little doubt that they are exposures of a single channel that strikes about N. 65° W., is about 350 feet wide, and has been cut about 75 feet into the Moenkopi formation. This channel is considered to be the main channel and is called Mitchell Mesa channel No. 1 (table 1, channel 51). It is symmetrical in cross section and is considered typical of channels in the Monument Valley area, Arizona. A fourth channel exposure (fig. 25, channel 50) is farther west and is a longitudinal section along a channel flank. This channel strikes about N. 70° W., is estimated to

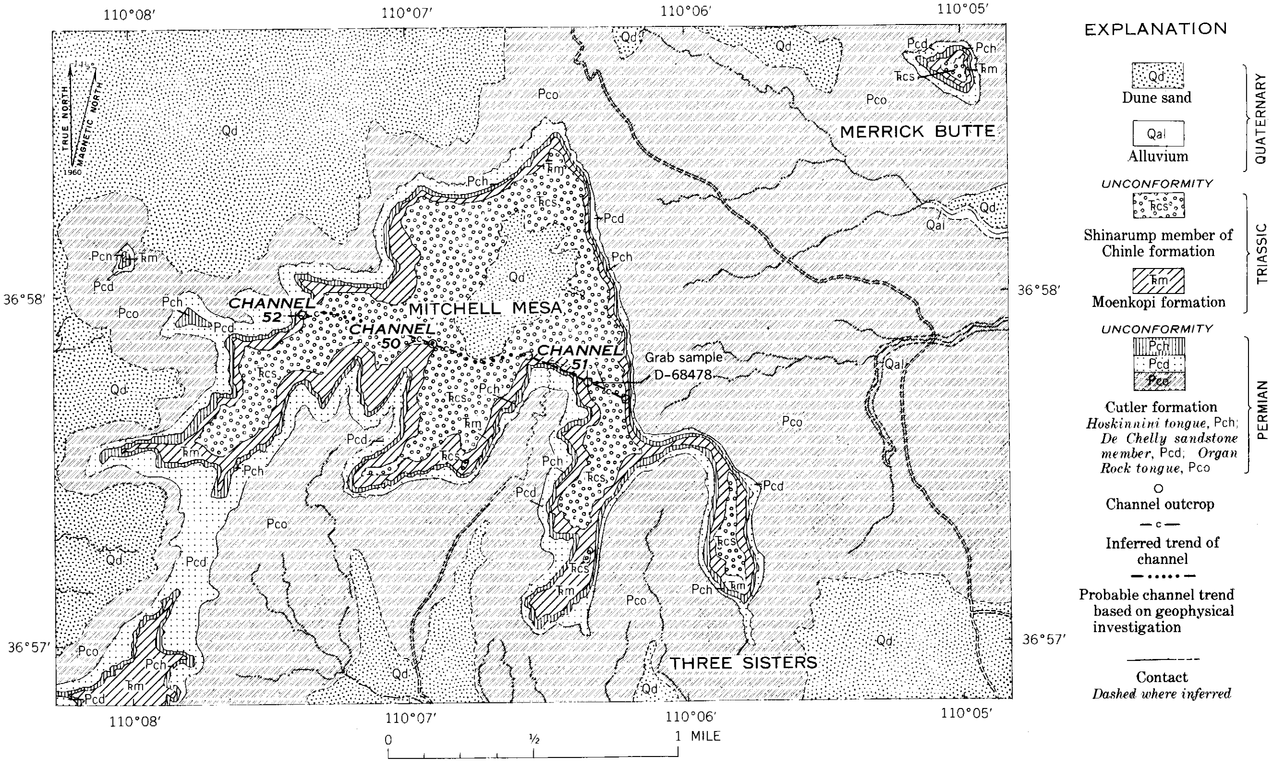


Figure 25.—Geologic map of Mitchell Mesa showing centerlines of known channels. Probable relationship of channels is suggested by geophysical measurements.

be about 350 feet wide, and has been cut about 50 feet into the Moenkopi formation. The channel is named the Mitchell Mesa channel No. 2 (fig. 25; table 1, channel 50). A fifth channel exposure strikes about N. 82° E., is about 300 feet wide, and has been scoured about 70 feet into the underlying Moenkopi formation. It is referred to as the Mitchell Mesa channel No. 3 (fig. 25; table 1, channel 52). Geophysical work completed in 1954 suggests that all these channels join and trend northwestward across the mesa top (fig. 25).

Channel strata consist predominantly of a light-gray to buff massive coarse-grained sandstone that grades locally to conglomeratic sandstone. Near the base of the channel, many rounded clay pebbles about 2 inches in diameter are in a matrix of coarse-grained sandstone. In places these clay pebbles have weathered out, leaving the more resistant cemented sandstone in the form of a fretwork that is local in extent.

Beneath the channel a light-gray altered zone, about 4 feet thick, is in the reddish-brown siltstone beds of the Moenkopi. This zone thins along the channel flanks.

At the base of Mitchell Mesa channel No. 1 (fig. 25, channel 51) yellow uranium-vanadium minerals in a friable coarse-grained conglomeratic sandstone form a seam about 4 feet long and a quarter of an inch thick. Surrounding the seam is a mass of black material, tentatively identified as a mixture of vanadium minerals and carbonaceous matter, that impregnates the conglomeratic sandstone and forms an irregular mass 6 to 8 feet in diameter.

Following heavy rains a small seep appears at the mineralized locality. This seep may represent ground-water movement through basal channel fill—the direction of ground-water flow presumably reflecting the westerly slope of the channel floor. It is suggested that these uranium-vanadium minerals may represent redeposition of material leached from a uraniferous deposit updip.

Geologists of both the U.S. Atomic Energy Commission and the U.S. Geological Survey have examined the mineralized outcrop. One grab sample (USGS D–68478) was collected from the basal strata at the point indicated in figure 25 and submitted for analysis to L. P. Rader, Jr., who reported 0.59 percent eU and 0.71 percent U, and stated that "The sample probably contains small amounts of organic material * * * The yellow uranium mineral is a mixture of tyuyamunite."

This grab sample is not representative of the exposure of mineralized channel fill. It does, however, indicate the presence of uranium minerals in concentrations commensurate with other favorable prospects in the Monument Valley area, Arizona.

The following minerals have been identified tentatively by the authors from samples collected at the base of Mitchell Mesa channel No. 1:

Mineral	*Formula*	*Abundance*
Azurite	$Cu_3(OH)_2(CO_3)_2$	Rare.
Calcite	$CaCO_3$	Common.
Jarosite	$K_2Fe_6(OH)_{12}(SO_4)_4$	Do.
Limonite	$2Fe_2O_3 \cdot 3H_2O$	Do.
Malachite	$Cu_2(OH)_2(CO_3)$	Rare.
Metatyuyamunite	$Ca(UO_2)_2(VO_4)_2 \cdot nH_2O$	Do.
Torbernite	$Cu(UO_2)_2(PO_4)_2 \cdot 12H_2O$	Do.
Tyuyamunite	$Ca(UO_2)(VO_4)_2 \cdot nH_2O$	Do.
Vanadium minerals		Rare to common.

KOLEY BLACK AREA

The Koley Black area is known by various names, as a result of the great interest displayed in it by both geologists and prospectors. In this report it is referred to as the Koley Black area, after the name of the original claimant. During a U.S. Atomic Energy Commission Airborne Radioactivity Survey in the Monument Valley area (Winthrop L. Cummings, written communication, 1952), two anomalies were recorded over the Koley Black area. Each area of anomaly was named; one is known as "Cold," the other as "Sheep." The area known as "Cold" is shown on figure 12 as channel 45. It is uncertain which of the remaining channel outcrops is known as "Sheep"; likely it is channel 44. At the time of its drilling program in the Monument Valley area, the U.S. Atomic Energy Commission named the area "Cold Mesa."

The Koley Black area, at lat 36°48′12″ N., and long 110°09′18″ W., is in Navajo County, Ariz., about 3 miles southeast of Agathla Peak and a similar distance due north of the Porras Dikes (pl. 1). The area is about 8 miles northeast of Kayenta, Ariz. Consolidated sedimentary strata exposed in the Koley Black area range from the De Chelly sandstone member of the Cutler formation, under the valley floors, to the Shinarump member of the Chinle formation, which forms the general upland surface. The Shinarump member in this area is about 25 feet thick, although it thickens to 45 feet or more as a result of channeling. In places on the upland surface the Shinarump member thins laterally as a result of erosion; in these localities the underlying Moenkopi formation forms the surface.

The ground surface is veneered by a thin mantle of sand that thickens locally to 5 feet or slightly more. In places, irregular hummocks of the Shinarump member rise 20 to 30 feet above the general ground surface.

The area is on the south flank of the Agathla anticline, and the strata dip about 5° to the south.

A maze of channels is exposed in this area (fig. 12). They range in width from channels 35 feet wide to others that exceed 250 feet in width. The major geologic problem, as shown in figure 12, has been to relate the 4 channels noted in the southeastern part of the area to the 7 channels in the northwestern part. Data on the channels are given in table 1. All the channels strike northwest, and this suggests that they all may be part of the same channel network. In general, the larger channels are in the southeastern part of the area, and it appears probable that one or more of these larger ones may have branched to form the smaller channels.

Sedimentary rocks filling the channels are coarse conglomerate beds near the base which grade upward into conglomeratic sandstone and coarse-grained sandstone beds near the top. Silicified wood is buried in channel strata as fragments and as logs as much as 2 feet in diameter. Also included are small pod-shaped masses of a black coaly substance (vitrain?) surrounded by conglomeratic sandstone. Limonite stains the surface of the channel fill but does not appear to have penetrated the sandstone.

The Koley Black channels are underlain by a green to light-gray altered zone about 1 foot thick in the uppermost siltstone beds of the Moenkopi. The altered zone thickens slightly below the channels.

Four of the Koley Black group of channels contain small amounts of copper in basal channel fill (table 1). No abnormal radioactivity was noted in a ground check by U.S. Geological Survey personnel, although the airborne radioactivity survey conducted by the U.S. Atomic Energy Commission reported two anomalies (that is, "Sheep" and "Cold") over the Koley Black area (Winthrop L. Cummings, written communication, 1952). These anomalies were then checked by U.S. Atomic Energy Commission ground personnel; their results were negative.

A diamond-drilling program was completed in April 1952, by the U.S. Atomic Energy Commission, across the largest of the channels in the area (fig. 12, channel 45; fig. 26). Seventeen holes were drilled directly behind the outcrop; no mineralized ground was found.

A geophysical program was undertaken by Rudolph A. Black and Wayne H. Jackson, of the U.S. Geological Survey, under the supervision of W. E. Davis. Fieldwork was completed in July 1952. Interpretations of the geophysical investigation substantiate several of the geological interpretations made concerning channels. The concave upward end of channel 45 (fig. 12) indicates that some channels are not continuous (p. 70). On the basis of the resistivity work, channel

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FIGURE 26.—View northward at the Koley Black channel (45). The channel is about 270 feet wide and has been cut about 30 feet into the underlying Moenkopi formation. Ꞧm, Moenkopi formation; Ꞧcs, Shinarump member of the Chinle formation. Men at base give scale.

45 appears to end 350 feet behind the face of the outcrop. The habit of a major channel to divide into subsidiary channels (p. 76) seems well confirmed by the resistivity interpretations of channels 38, 39, and 40 (fig. 12). The existence of deeper scours in the floors of channels (p. 76) is also confirmed as shown by the elongate scour in the main channel southeast of channels 38, 39, and 40.

Two geophysical techniques were used; one involved electrical resistivity measurements, the other, gravity measurements. Details on techniques used and the results obtained have been reported by Rudolph A. Black and Wayne H. Jackson (written communication, 1954).

The authors have identified the following minerals from samples of basal channel fill collected in the Koley Black area:

Mineral	*Formula*	*Abundance*
Azurite	$Cu_3(OH)_2(CO_3)_2$	Rare.
Calcite	$CaCO_3$	Common.
Jarosite	$K_2Fe_6(OH)_{12}(SO_4)_4$	Do.
Limonite	$2Fe_2O_3 \cdot 3H_2O$	Do.
Malachite	$Cu(OH)_2(CO_3)$	Rare.
Manganese dendrites		Rare to common.
Muscovite	$(H,K)AlSiO_4$	Rare.

ALFRED MILES CHANNEL NO. 1

The Alfred Miles channel No. 1 (fig. 27, channel 1; table 1), among the largest noted, can be traced for about 4 miles in Arizona and Utah. The channel is intersected by deep canyons and is broken into segments; channel strata crop out in several localities (fig. 27), and it is on these exposures that claims have been staked by various prospectors. The channel is known by the following names: the Todechenee, Nakai Mesa (C. Clare Gregg, written communication, 1952), Peninsula, and Alfred Miles.

The part of the channel within Arizona is in Navajo County, at lat 36°59′48″ N. and long 110°28′6″ W. Sources of water and supplies are remote. The channel remnants on both the Arizona and Utah parts of Nakai Mesa are accessible by a graded dirt road. Parts of the channel are on a narrow projection of Hoskinnini Mesa (fig. 27), however, and these can be reached by a pack trail that extends along the projection from the southwest edge of Hoskinnini Mesa. Another route to these channel exposures is along the floor of Copper Canyon. An ungraded dirt road extends westward from the Oljeto trading post, Utah (fig. 1), and ends at the base of the steep slopes that underlie the channel remnants on the projection.

Consolidated sedimentary strata exposed in the Alfred Miles channel No. 1 area range from the Organ Rock tongue of the Cutler formation at the base of the Mesa, to the Shinarump member of the Chinle formation, which forms the canyon rims. About 90 feet of the Shinarump member is exposed, and it commonly stands as a vertical cliff. Where there are channels, the Shinarump member thickens to 120 feet or more.

On Nakai Mesa the Shinarump member is covered by dune sand that ranges in thickness from a thin film along mesa edges to 15 feet back from the rim. There is practically no sand cover on the projection of Hoskinnini Mesa. The surface of the Shinarump member is pitted with depressions as much as 20 feet wide and 5 feet deep and marked by irregular hummocks that rise about 20 feet above the general ground surface.

The Alfred Miles channel No. 1 describes a broad curve (fig. 27, channel 1). In Arizona its trend is about N. 50° E., but as it is traced northeastward it curves and where it reenters Utah, its trend is to the northwest. The channel is about 2,150 feet wide (figs. 10, 28) and has been cut about 70 feet into the Moenkopi formation. Channel strata consist predominantly of massive uniform-textured coarse-grained sandstone that forms cliffs. A few small conglomerate lenses are in the basal strata Claystone boulders, cobbles, and pebbles make up the coarse material. These fragments range in size from small rounded

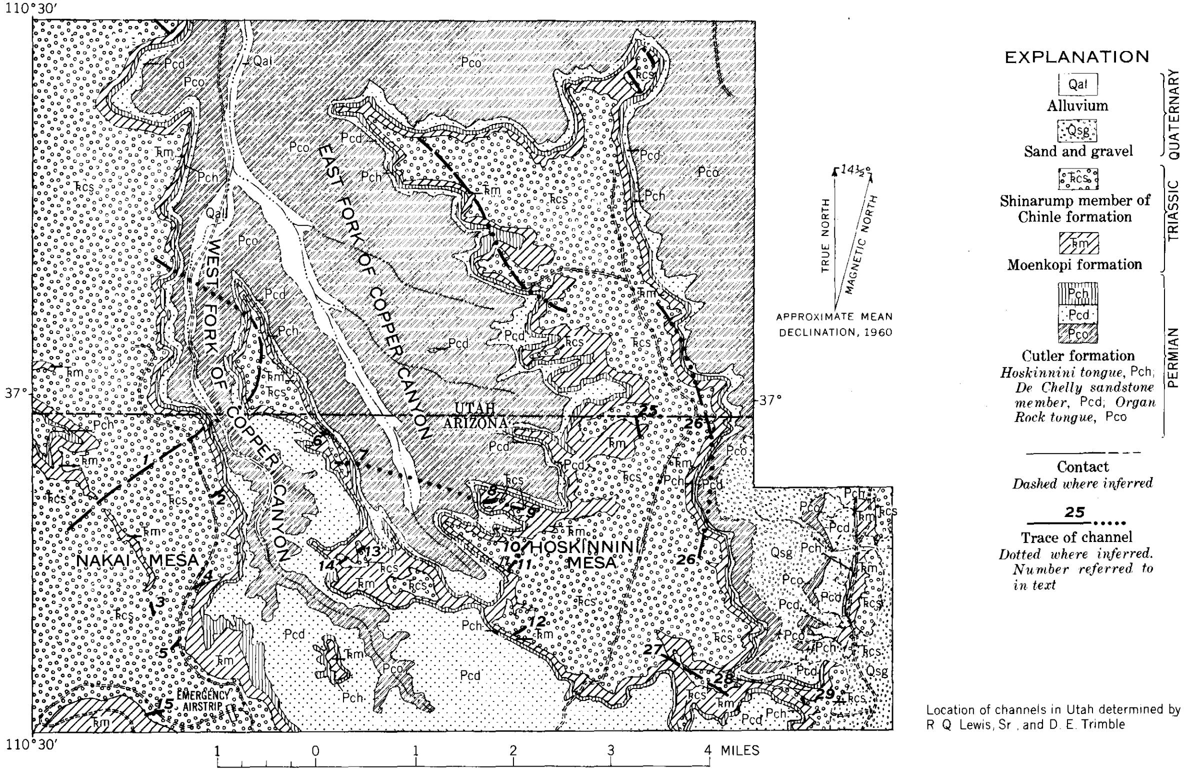

Figure 27.—Geologic map of the south end of the Copper Canyon area showing distribution of channels on parts of Nakai and Hoskinnini Mesas. Data for numbered channels are given in table 1. Channels 27 and 28 are known locally as the "channels at southeast edge of Hoskinnini Mesa."

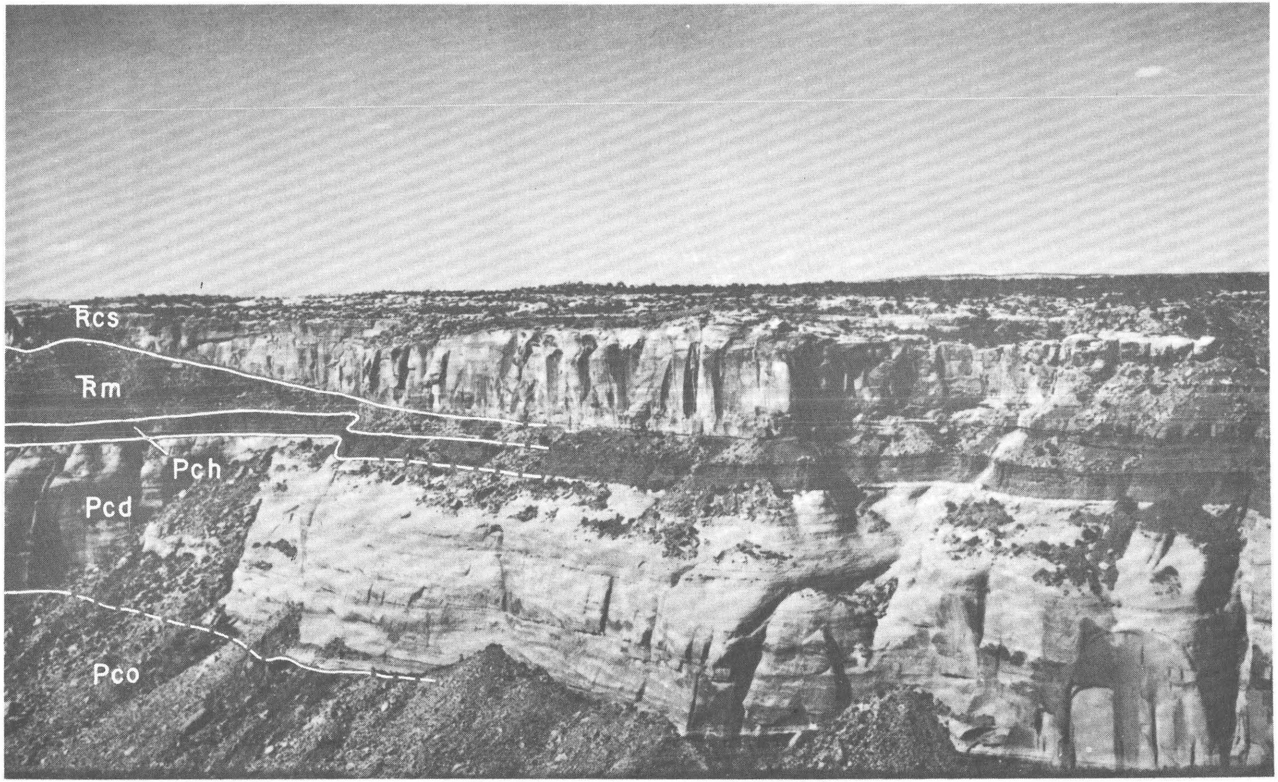

FIGURE 28.—View northeastward across the west fork of Copper Canyon showing broad deep Alfred Miles channel No. 1. Channel is about 2,150 feet wide and about 70 feet deep. Pco, Organ Rock tongue of the Cutler formation; Pcd, De Chelly sandstone member of the Cutler formation; Pch, Hoskinnini tongue of the Cutler formation; R̄m, Moenkopi formation; and R̄cs, Shinarump member of the Chinle formation.

chips about a quarter of an inch in diameter to angular boulders as much as 5 feet in long dimension. In places where the clay fragments have weathered out, the sandstone matrix remains as a fretwork. Much of the clay has been derived from the Moenkopi formation. These fragments can be found in various stages of alteration, from those that are all red and show no alteration, to others that are totally altered and are grayish green. An altered zone, in the uppermost strata of the Moenkopi formation below the channel, ranges in thickness from 2 to 8 inches. This is one of the few channels noted in the Monument Valley area, Arizona, where the altered zone did not thicken under a channel.

A series of anomalies was discovered during an airborne radioactivity survey conducted by the U.S. Atomic Energy Commission (Winthrop L. Cummings, written communication, 1952). Despite the anomalies, only a few uranium minerals were found impregnating the channel fill at one spot along the east face of Nakai Mesa (Fred Todechenee claim). The secondary copper minerals azurite and malachite impregnate sandstone and replace wood along the base of the Alfred Miles channel No. 1 where it crops out on the projection of Hoskinnini Mesa. Similar occurrences have been noted at the channel outcrop on the east face of Nakai Mesa. In a few places copper minerals coat clay galls, and where the galls have been removed the copper minerals remain on the walls of the molds so formed. Malachite was found also in the fractures and bedding planes of siltstone and claystone in the altered zone of the Moenkopi formation directly underlying the mineralized localities.

During the summer and fall of 1952, the U.S. Atomic Energy Commission undertook a diamond-drilling program on Nakai Mesa (figs. 27, 29). Thirty-nine holes were drilled, totaling about 5,600 feet. Only one hole penetrated mineralized ground. A short adit dug subsequently to investigate the type and degree of mineralized rock in this one drill hole found what "appeared to be a halo surrounding a fossil log" (written communication, Grand Junction Exploration Branch of the U.S. Atomic Energy Commission, October 1952). An area extending about 3,100 feet back from the rim was investigated by means of 2 rows of drill holes behind the outcrop. No attempt was made to drill along the length of the channel.

Discussing the geology of the mineralized deposits found along the base of this channel, C. Clare Gregg (written communication, 1952) states:

> Mineralization occurs in the bottom of channels, usually on one side and generally in a roll or gouge where logs and organic trash collect. Generally mineralization is directly above a muddy Moenkopi siltstone, the upper layers of which may be also mineralized. The important associations seem to be carbon

in the form of logs of wood trash; and copper, usually as malachite, although many outcrops revealing the characteristic color of copper mineralization contain no uranium.

During August and September, 1952, the U.S. Bureau of Reclamation undertook, on behalf of the U.S. Atomic Energy Commission, a seismic survey of that part of Nakai Mesa underlain by the Alfred Miles channel No 1. The results obtained by Dart Wantland and R.D. Casey (written communication, 1952) are shown in figure 29. In essence, the survey indicated that the channel bifurcated, a smaller part extending almost due west, and the major part of the channel curving sinuously to the southwest. Additional holes were drilled

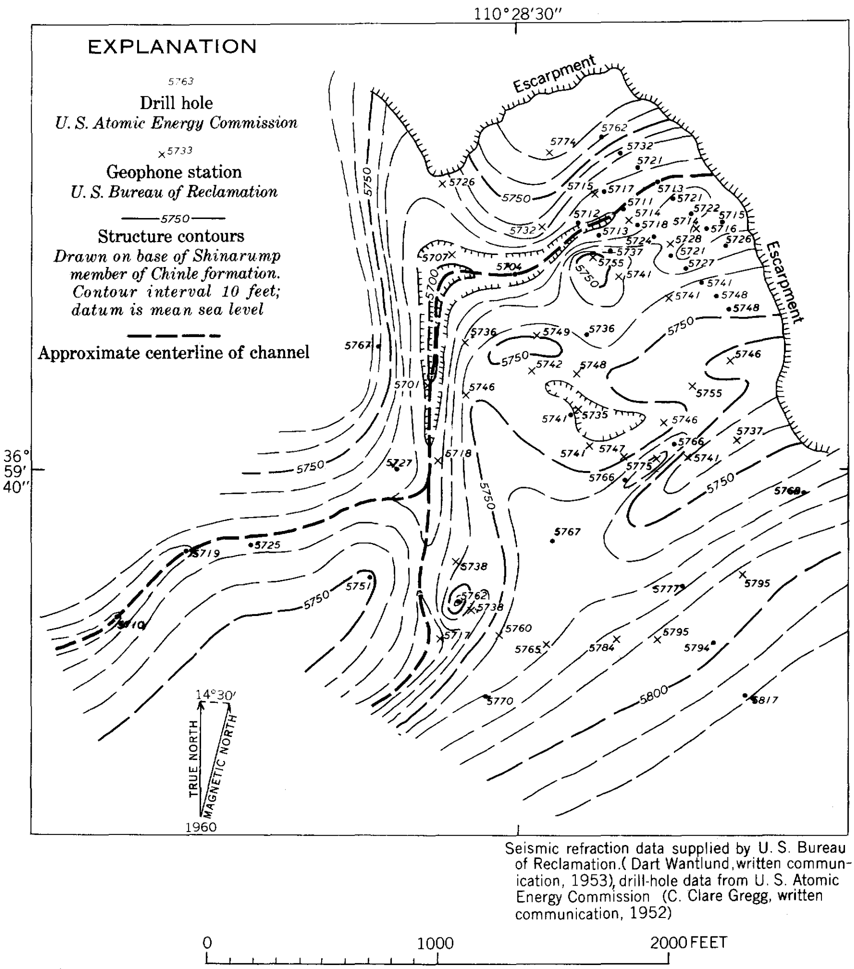

Figure 29.—Possible trend of the Alfred Miles channel No. 1 on Nakai Mesa, based on seismic refraction and drill data.

upon completion of the seismic survey to corroborate the findings. Mineralized ground was not found in these drill holes.

The following suite of minerals identified by the authors from the basal channel fill of the Alfred Miles channel No. 1 is characteristic of mineralized outcrops in the Monument Valley area, Arizona.

Mineral	*Formula*	*Abundance*
Autunite(?)	$Ca(UO_2)_2(PO_4)_2 \cdot 10\text{–}12H_2O$	Rare.
Azurite	$Cu_3(OH)_2(CO_3)_2$	Do.
Calcite	$CaCO_3$	Common.
Carnotite(?)	$K_2(UO_2)_2(VO_4)_2 \cdot 3H_2O$	Rare.
Jarosite	$K_2Fe_6(OH)_{12}(SO_4)_4$	Common.
Limonite	$2Fe_2O_3 \cdot 3H_2O$	Do.
Malachite	$Cu_2(OH)_2CO_3$	Rare.
Torbernite	$Cu(UO_2)_2(PO_4)_2 \cdot 12H_2O$	Do.

CECIL TODECHENEE CHANNEL

At one locality, along the base of the east flank of Skeleton Mesa (pl. 1), a small remnant of the Shinarump member of the Chinle formation is exposed in a deep reentrant. At the base of this remnant is a longitudinal exposure of mineralized rocks that forms the south flank of the Cecil Todechenee channel (table 1, channel 21). A small adit has been opened about 20 feet into the base of the channel. As far as is known, ore has not been shipped from this channel.

The Cecil Todechenee channel is in Navajo County, Ariz., at latitude 36°53′24″ N. and longitude 110°24′48″ W. A graded dirt road passes within 500 yards of the claim. This road extends westward from Navajo Indian Reservation Route 1 (Kayenta-Mexican Hat road) and follows Adahchijiyahi Canyon onto Todicheenie bench where it turns north, passes the Todechenee claim, and ascends Hoskinnini Mesa (pl. 1). A short connecting road could be bulldozed to the claim site with little expense.

Consolidated sedimentary strata exposed near the claim range from the De Chelly sandstone member of the Cutler formation to the Navajo sandstone. These strata form the gently dipping west flank of the asymmetrical Organ Rock anticline (p. 62); strata exposed at the claim dip about 3° to the west.

Although only a part of the south flank of the channel is exposed, it is estimated that the channel trends nearly due east, is about 100 feet wide, and has been cut about 20 feet into the Moenkopi formation. The Shinarump member is about 40 feet thick. Channel strata consist predominantly of a cream-colored coarse-grained sandstone speckled with small limonite stains.

In the mineralized zone the channel strata are conglomeratic and enclose gray claystone fragments and considerable quantities of silicified and carbonized wood. The largest zone of high radioactivity conforms to what apparently is a log 6 to 8 inches in diameter and about 6 feet long. Another spot of high radioactivity does not seem to be related to plant matter.

A sample from a small ore pile assayed 0.23 percent U_3O_8 (C. Clare Gregg, written communication, 1952). A 3-foot channel sample assayed 0.02 percent U_3O_8, and 0.27 percent V_2O_5. Grab samples ran as high as 0.24 percent U_3O_8 and 1.49 percent V_2O_5 (R.C. Cutter and J. H. Leonard, written communication, 1952).

From samples of the channel fill exposed at the Cecil Todechenee claim, the following minerals have been tentatively identified:

Mineral	*Formula*	*Abundance*
Calcite	$CaCO_3$	Common.
Carnotite	$K_2(UO_2)_2(VO_4)_2 \cdot 1\text{–}3H_2O$	Rare.
Corvusite(?)	$V_2O_4 \cdot 6V_2O_5 \cdot nH_2O$	Do.
Jarosite	$K_2Fe_6(OH)_{12}(SO_4)_4$	Common.
Limonite	$2Fe_2O_3 \cdot 3H_2O$	Do.
Malachite	$Cu_2(OH)_2CO_3$	Rare.
Tyuyamunite	$Ca(UO_2)_2(VO_4)_2 \cdot nH_2O$	Do.

CHANNELS AT SOUTHEAST EDGE OF HOSKINNINI MESA

Channels 27 and 28 of figure 27 and table 1 will be considered as a unit, for their general trend suggests that they are part of the same channel. Channel 27, known to geologists of the U.S. Atomic Energy Commission as Hoskinnini No. 1, is at lat 36°57′48″ N. and long 110°22′48″ W. Channel 28, at lat 36°57′30″ N. and long 110°22′12″ W., is known to U.S. Atomic Energy Commission geologists as Crescent (Winthrop L. Cummings, written communication, 1952).

The channels crop out on the southeast edge of Hoskinnini Mesa, and are easily accessible from a graded dirt road on the mesa top. The road extends west from Navajo Indian Reservation Route 1 (Kayenta-Mexican Hat road), follows Adahchijiyahi Canyon to Todicheenie bench, crosses Todicheenie and adjacent uplands and finally ascends Hoskinnini Mesa.

Exposed consolidated sedimentary strata range from the Organ Rock tongue of the Cutler formation, along the base of Hoskinnini Mesa, to the Shinarump member of the Chinle formation, and form the mesa cap. The Shinarump member, which overlies the Moenkopi formation, forms a vertical cliff about 50 feet high, and is veneered by dune sand which ranges in thickness from a thin film to a cover more than 20 feet thick.

These strata form the asymmetrical Organ Rock anticline with its gently dipping west flank and steeply dipping east flank. The two channels crop out near the crest of the structure.

Channel 27 (Hoskinnini No. 1) (fig. 27) strikes about N. 65° W., is about 250 feet wide, and has been cut about 75 feet into the Moenkopi formation. Channel strata seem to be predominantly light-gray massive coarse-grained sandstone with small amounts of included silicified wood. A longitudinal section of the channel is exposed, but along much of its length the altered zone in uppermost strata of the Moenkopi formation is covered by debris or is not exposed. No uranium minerals or abnormal radioactivity were noted.

Channel 28 (Crescent) (fig. 27) strikes about N. 45° W., is about 150 feet wide, and has been cut about 50 feet into the Moenkopi formation. Channel strata consist predominantly of light-gray cross-bedded medium-grained sandstone with local lenses of conglomerate near the base of the channel. Blue and green secondary copper minerals (malachite and azurite) are scattered widely in the basal rocks, and limonite stains the outcrop and the joints. Radioactivity (0.05 milliroentgen per hour) is only slightly above background (0.03 milliroentgen per hour).

Anomalies were reported over these remnants by the U.S. Atomic Energy Commission's airborne radioactivity survey and were subsequently ground checked by U.S. Atomic Energy Commission personnel. Their findings were negative (Winthrop L. Cummings, written communication, 1952).

The following minerals have been tentatively identified from samples collected at these channel outcrops.

Mineral	*Formula*	*Abundance*
Azurite(?)	$Cu_3(OH)_2(CO_3)_2$	Rare.
Calcite	$CaCO_3$	Common.
Hematite	Fe_2O_3	Rare.
Jarosite	$K_2Fe_6(OH)_{12}(SO_4)_4$	Common.
Limonite	$2Fe_2O_3 \cdot 3H_2O$	Do.
Malachite	$Cu_2(OH)_2CO_3$	Rare.

OIL AND GAS POSSIBILITIES

Only two tests for oil and gas have been completed in the Monument Valley area, Apache and Navajo Counties, Ariz. (fig. 30; table 3, Nos. 1 and 2), and in only one (No. 2) was there any show of oil or gas, even though both penetrated strata (pl. 8) that produce in adjacent areas. Of the other tests completed near the Monument Valley area most have been unsuccessful, although a few in the nearby Mexican Hat field (once known as the San Juan oil field) produced small amounts of oil before 1930. After 1930, interest in the commercial oil and gas possibilities of the area waned and drilling ceased. In 1948, interest in northeastern Arizona and southeastern Utah revived and several oil companies began to test promising structures. In 1954,

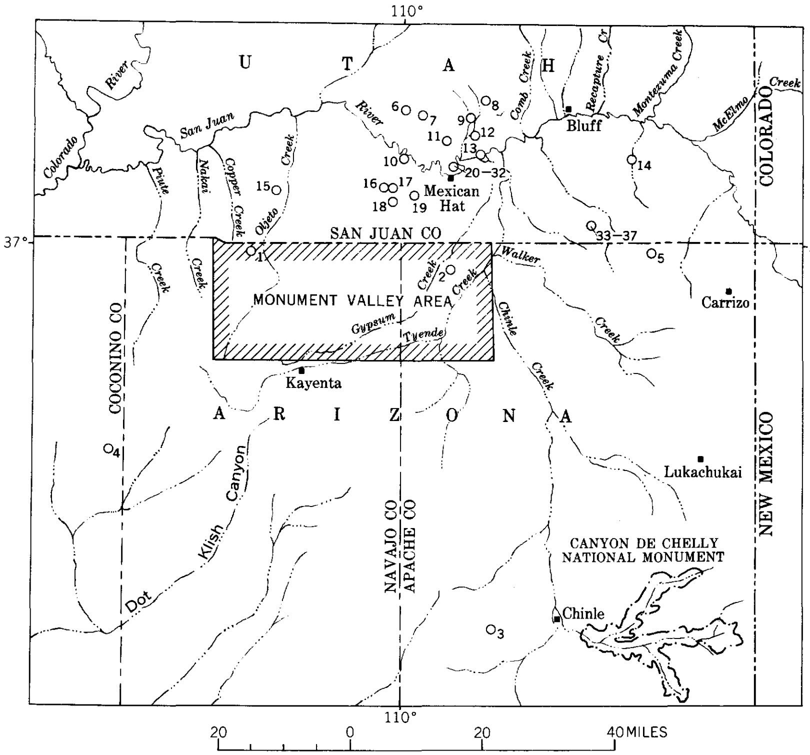

FIGURE 30.—Location of test wells drilled in and adjacent to the Monument Valley area, Apache and Navajo Counties, Ariz.

the Shell Oil Co. completed 2 successful tests about 50 miles to the northeast.

Although oil seeps have been known in this general region since 1882 (Woodruff, 1910, p. 98), oil in commercial quantities was first produced from the Mexican Hat oil field in 1908. Since then, about 115 wells have been drilled in the field; of these, only a few were successful and the more significant ones have been listed in table 3. Production was principally from the Hermosa formation (Pennsylvanian) with minor oil and gas from the Rico formation (Pennsylvanian and Permian?). The field has been described previously by Woodruff (1910), Baker (1936), and Hansen and Bell (1949). The nearest active field is the Boundary Butte field in San Juan County, Utah (T. 43 S., R. 22 E.), about 35 to 40 miles to the northeast. Here, production of both oil and gas is from the Coconino sandstone (the age equivalent of the De Chelly sandstone member of the Cutler formation) in an elongate northwestward-trending anticline on the southwest flank of the Paradox basin.

TABLE 3.—*Significant oil and gas test wells drilled in and adjacent to the Monument Valley area, Apache and Navajo Counties, Ariz.*

[Approximate location of wells is shown on figure 30]

No. on fig. 30	Operator	Well name	Well location			County	State	Type of show	Producing formation
			Sec.	Township	Range				
1	Texas, Sinclair, and Skelly Oil Cos.	Navajo A-1	34	42 N	18 E	Navajo	Arizona	Dry hole	
2	San Juan Oil and Development Co.	Midwest 1 Gypsum	7	41 N	23 E	Apache	do	Oil and gas	
3	Amerada Oil Co	Navajo 1	26	32 N	23 E	do	do	Dry hole	
4	Sinclair Oil Co	do	26	37 N	14 E	Coconino	do	do	
5	Shell Oil Co	Test No. 2 East Boundary Butte.	3	41 N	28 E	Apache	do	Gas	Hermosa.
6	Norwood Oil Co	No. 1	25	40 S	17 E	San Juan	Utah	Oil and gas show	Rico.
7	Utah Southern Oil Co	Utah 1 Noble	28	40 S	18 E	do	do	Gas show	Hermosa.
8	San Francisco-San Juan Co	No. 8	13	40 S	19 E	do	do	Oil and gas show	Rico.
9	Navajo Oil Co	No. 1	33	40 S	19 E	do	do	do	Do.
10	Utah Petroleum Corp	No. 1	36	41 S	17 E	do	do		
11	London-San Juan Oil Co	No. 4	13	41 S	18 E	do	do		
12	Oil Co. of San Juan	No. 1	15	41 S	19 E	do	do	Oil show	Rico.
13	Utah Southern Oil Co	No. 1	27	41 S	19 E	do	do	Gas (CO_2), oil	Hermosa.
14	Shell Oil Co	No. 2 Desert Creek	35	41 S	23 E	do	do	Oil	Do.
15	Wilson-Cranmer and Co	No. 1	35	42 S	14 E	do	do	Oil and gas show	Rico.
16	Monumental Oil Co	No. 1	23	42 S	17 E	do	do		
17	do	No. 1-A	23	42 S	17 E	do	do		
18	do	No. 1	35	42 S	17 E	do	do		
19	do	No. 1	19	42 S	18 E	do	do	Oil and gas show	Hermosa.
20	Southside Oil Co	No. 1	5	42 S	19 E	do	do	Oil	Do.
21	Mexican Hat Oil Co	No. 2	5	42 S	19 E	do	do		
22	Western Investment Co	No. 1	5	42 S	19 E	do	do	Oil	Hermosa.
23	Monumental Oil Co	No. 1	5	42 S	19 E	do	do	do	Do.
24	Anderson Oil and Development Co.	No. 1	5	42 S	19 E	do	do	do	Do.
25	R. L. Raplee	No. 1	5	42 S	19 E	do	do	do	Do.
26	Arcola Oil Co	No. 4	6	42 S	19 E	do	do		
27	Western Investment Co	No. 2	6	42 S	19 E	do	do	Oil	Hermosa.
28	Arcola Oil Co	No. 2	6	42 S	19 E	do	do	do	Do.
29	W. E. Nevills	No. 5	6	42 S	19 E	do	do	do	Do.
30	Unknown	Producers No. 2	6	42 S	19 E	do	do	Oil and gas show	Do.
31	W. E. Nevills	No. 6	7	42 S	19 E	do	do	Oil	Rico.
32	Barney Cockburn	No. 1	8	42 S	19 E	do	do	do	Do.
33	Southwest Oil Co	No. 1	22	43 S	22 E	do	do		
34	Continental Oil Co	No. 1	22	43 S	22 E	do	do	Oil and gas	Shinarump member of Chinle formation.
35	Western Natural Gas Co	No. 1	22	43 S	22 E	do	do	Gas	Hermosa.
36	do	No. 2	22	43 S	22 E	do	do	Oil	Do.
37	do	No. 2	25	43 S	22 E	do	do	Gas	Do.

No. on fig. 30	Discovery depth (feet)	Surface		Total depth of hole (feet)	Deepest formation penetrated	Completion date	References
		Formation	Altitude				
1		Shinarump member of Chinle formation.	6,720(?)	4,523	Elbert	May 23, 1953	Texas, Sinclair, and Skelly Oil Cos.
2	495–500	Cutler	4,920	2,083	do	1924	Baker, 1936; Wengerd and Strickland (1954).
3				5,765	Granite	Oct. 23, 1950	Umbach and Barnes (1952).
4				7,211	do	Oct. 14, 1952	Umbach and Barnes (1953).
5	4,650–4,690					1954	Hager (1954).
6	85, 600, 1,170	Rico		1,938	Hermosa(+)	May 26, 1911	Hansen and Bell (1949).
7		Cutler	5,500	3,633	Mica schist	Sept. 3, 1927	Hansen and Bell (1949); Wengerd and Strickland (1954); Baker (1936).
8		Rico	4,820	595	Rico	July 1908	Hansen and Bell (1949).
9		do	4,720	1,200	do		Do.
10		Hermosa	5,473	1,707	Hermosa	July 21, 1927	Hansen and Bell (1949); Baker (1936).
11		Rico		213	Rico	1923	Do.
12	105	do		500(?)	Hermosa	1909	Hansen and Bell (1949).
13	172 (oil)	Hermosa	4,090	1,870	Mica schist	Mar. 19, 1928	Hansen and Bell (1949); Baker (1936).
14	5,244–5,320					1954	Hager (1954).
15	950	Cutler	4,300	2,323	Pinkerton Trail of Wengerd and Strickland.	1923	Wengerd and Strickland (1954).
16		Rico		756	Hermosa	1924	Hansen and Bell (1949); Baker (1936).
17		do		1,622	do	Dec. 31, 1924	Do.
18		Cutler	4,970	1,300+	do	1920	Do.
19	800–812 890–900	Rico	5,145	1,140	do	1926	Do.
20	600	do	4,175	600+	do	1910	Hansen and Bell (1949).
21		do	4,170(?)	300	Rico	1944	Do.
22	165	do	4,160	500	Hermosa	1909	Do.
23	292, 525–550	do	4,145	635	do	1909(?)	Do.
24	273–301 1,172–1,222	do	4,160	1,222	do	1909(?)	Do.
25	900	do	4,120	900(?)	do	1912	Do.
26		do	4,175		Rico	1909(?)	Do.
27	220	do		517	Hermosa	1909	Do.
28	230–335	do	4,170	713	do	1930	Hansen and Bell (1949); Baker (1936).
29	263	do	4,205	512	do	1931	Hansen and Bell (1949).
30	800	do	4,220	800+	do	1910	Do.
31		do	4,150	194	Rico	Feb. 17, 1933	Do.
32		do		296	do	Dec. 27, 1945	Do.
33		Navajo		1,565	Navajo	October 1923	Hansen and Bell (1949); Baker (1936).
34	1,560–1,569	do		5,612	Leadville(?)	Feb. 4, 1930(?)	Hansen and Bell (1949).(?)
35	4,610–4,660	do		6,090	Lynch dolomite	Jan. 27, 1948	Hansen and Bell (1949); Dorn (1949).
36		do		1,510		Nov. 30, 1948	Hansen and Bell (1949).
37		do	5,121	5,308	Hermosa		Do.

In the Mexican Hat oil field, most of the first wells drilled were extremely shallow and were intended to test the Rico and Hermosa formations. Subsequently, deeper tests were completed and it was soon determined that in places the sedimentary rocks were as thin as 2,000 feet. In the course of drilling, oil and gas shows were found at several horizons, although major production was either from the Rico or Hermosa formations. The oil was in a structural syncline, and production was hampered by low porosity in the lenticular sandstone beds and by low hydrostatic pressure (Hansen and Bell, 1949, p. 198).

Of the wildcat tests completed near the Monument Valley area only the two Shell tests were successful. The first of these, Shell's test No. 2 East Boundary Butte, is in sec. 3, T. 41 N., R. 28 E., Apache County, Ariz., and was completed as a gas producer (table 3). The second well, Shell's No. 2 Desert Creek, in sec. 35, T. 41 S., R. 23 E., San Juan County, Utah, was completed as an oil well. Both wells produced from the Hermosa formation.

The most recent test in the Monument Valley area was in sec. 34, T. 42 N., R. 18 E., Navajo County, Ariz. (unsurveyed), on the crest of the Organ Rock anticline (pl. 1). The test, known as Navajo A-1, was a joint venture by the Texas, Sinclair, and Skelly Oil Cos. and penetrated 4,523 feet to the Elbert formation (Late Devonian) before it was abandoned as a dry hole (table 3). There were no shows of oil or gas. The log of the hole is quoted here in full by courtesy of these oil companies (terms denoting age are those used by oil companies, and not all agree with U.S. Geological Survey usage).

Sample descriptions of the Texas, Sinclair, and Skelly Oil Companies' well, Navajo A-1, sec. 34, T. 42 N., R. 18 E., Navajo County, Ariz.

MESOZOIC ERA

TRIASSIC PERIOD

Shinarump formation		0–93	(93 ft)
0–50	(50)	Sandstone, white, medium-coarse grained.	
50–93	(43)	Sandstone, white, medium-coarse grained, with some light gray shale stringers, conglomeratic at base. Some milky and amber chert.	
Moenkopi formation		93–263 ft	(170 ft)
93–190	(97)	Shale, brown-maroon.	
190–212	(22)	Siltstone, buff, slightly limy.	
212–263	(51)	Shale, brown, slightly sandy.	

PALEOZOIC ERA
PERMIAN PERIOD

Cutler formation		263–2,207 ft	(1,944 ft)
Hoskinnini member		263–336 ft	(73 ft)
263–290	(27)	Sandstone, red-white, very fine grained, slightly limy.	
290–300	(10)	Shale, brown, sandy.	
300–326	(26)	Siltstone, red-brown, slightly limy and conglomeratic.	
326–336	(10)	Shale, brown, sandy.	
De Chelly member		336–697 ft	(361 ft)
336–360	(24)	Sandstone, red-tan, fine-grained, limy trace of milky chert.	
360–410	(50)	Sandstone, red-tan, fine-medium grained, slightly conglomeratic.	
410–490	(80)	Sandstone, pink, medium-grained, slightly conglomeratic and limy.	
490–500	(10)	Shale, brown.	
500–697	(197)	Sandstone, pink-tan, medium- to coarse-grained slightly conglomeratic and limy.	
Organ Rock member		697–1325 ft	(628 ft)
697–910	(213)	Shale, red, hard, sandy, micaceous.	
910–930	(20)	Sandstone, white, medium-grained.	
930–1, 325	(395)	Shale, red, very sandy, slightly limy.	
Cedar Mesa member		1,325–1,835 ft	(510 ft)
1, 325–1, 400	(75)	Sandstone, pink-white, very fine grained, limy.	
1, 400–1, 480	(80)	Sandstone, light-gray to white, very fine grained, limy.	
1, 480–1, 650	(170)	Sandstone, orange-pink, very fine to fine-grained, some free quartz grains, hard to friable, limy, with some red shale stringers.	
1, 650–1, 660	(10)	Shale, red, sandy, limy.	
1, 660–1, 750	(90)	Sandstone, orange-gray, fine-grained, limy. with some red and green shale stringers.	
1, 750–1, 780	(30)	Shale, red, micaceous, limy.	
1, 780–1, 835	(55)	Sandstone, orange, very fine grained, limy. with red shale stringers.	
Halgaito member		1,835–2,207 ft	(372 ft)
1, 835–2, 130	(295)	Shale, red, limy, interbedded with some gray limestone and pink-gray sandstone. Traces of green shale.	
2, 130–2, 207	(77)	Shale, red-brown, limy, sandy, with some stringers of red and gray limestone.	

Sample descriptions of the Texas, Sinclair, and Skelly Oil Companies' well, Navajo A–1, sec. 34, T. 42 N., R. 18 E., Navajo County, Ariz.—Continued

PALEOZOIC ERA—Continued

PERMIAN PERIOD—Continued

Rico formation		2,207–2,785 ft (578 ft)
2, 207–2, 310	(103)	Sandstone, white-pink, fine-grained, limy, interbedded with some red and brown shale and gray limestone.
2, 310–2, 360	(50)	Shale, red, sandy, limy, with some limestone and sandstone stringers.
2, 360–2, 380	(20)	Sandstone, white-pink, fine-grained, limy.
2, 380–2, 490	(110)	Shale, red, limy, sandy, with some stringers of limestone.
2, 490–2, 555	(65)	Limestone, gray-green, fine-crystallline, sandy, with some red shale stringers.
2, 555–2, 590	(35)	Sandstone, white to gray, medium-grained, limy, hard to friable.
2, 590–2, 600	(10)	Shale, red, sandy.
2, 600–2, 610	(10)	Shale, purple, sandy, micaceous.
2, 610–2, 640	(30)	Limestone, white to light-gray, fine- to medium-crystalline, slightly oölitic.
2, 640–2, 660	(20)	Sandstone, white, fine-grained, friable.
2, 660–2, 670	(10)	Shale, red, limy, sandy.
2, 670–2, 700	(30)	Limestone, tan, to light-gray, fine crystalline dense, slightly sandy.
2, 700–2, 710	(10)	Shale, red, limy.
2, 710–2, 760	(50)	Sandstone, white, fine- to medium-grained.
2, 760–2, 770	(10)	Shale, red, interbedded with red-gray limestone and white sandstone.
2, 770–2, 785	(15)	Sandstone, purple-gray, limy.

PENNSYLVANIAN PERIOD

Hermosa formation		2,785–3,488 ft (703 ft)
2, 785–2, 795	(10)	Limestone, light-gray to gray, dense, sandy.
2, 795–2, 820	(25)	Sandstone, white to light-gray, fine-medium grained, limy, interbedded with red shale and some gray chert.
2, 820–2, 980	(160)	Limestone, light- to dark-gray, dense, siliceous, interbedded with amber, gray, and milky chert, and gray sandstone.
2, 980–3, 225	(245)	Limestone, white to light-gray, fine crystalline to dense, sandy, interbedded with amber and milky chert, and red and brown shale.
3, 225–3, 280	(55)	Limestone, gray-brown, medium crystalline, slightly oölitic, some honeycombed, interbedded with amber chert and gray sandstone.
3, 280–3, 450	(170)	Limestone, white to light-gray, medium to fine crystalline, some honeycombed and chalky, interbedded with amber chert, gray sandstone, and some calcite.
3, 450–3, 488	(38)	Limestone, white to light-gray, dense, with some amber chert.

PALEOZOIC ERA—Continued

PENNSYLVANIAN PERIOD—Continued

Molas formation		3,488–3,585 ft (97 ft)
3, 488–3, 515	(27)	Limestone, light-gray, dense, interbedded with amber chert and green shale.
3, 515–50	(35)	Shale, green and purple, interbedded with some light-gray limestone, and amber chert.
3, 550–80	(30)	Shale, red-maroon.
3, 580–85	(5)	Shale, purple.

MISSISSIPPIAN PERIOD

3, 585–3, 670	(85)	Limestone, white, chalky, with some amber chert, and red-purple shale.
3, 670–3, 740	(70)	Limestone, light-gray to white, fine crystalline to chalky, oölitic, with some gray dolomite and milky chert.
3, 740–3, 820	(80)	Dolomite, tan to dark-gray, fine crystalline to sucrose, with some limestone and calcite.
3, 820–3, 855	(35)	Limestone, dolomitic, white, coarse to crystalline.
3, 855–3, 900	(45)	Dolomitic, white to light-gray, fine crystalline to sucrose with some white and amber chert; interbedded with light-gray limestone.
3, 900–4, 077	(177)	Dolomite, white to gray, fine crystalline to sucrose, interbedded with chalky limestone.

DEVONIAN PERIOD (Drilled 446 ft)

Upper Devonian

4, 077–4, 192	(115)	Limestone, white to light-gray, fine crystalline to dense, some chalky, interbedded with red, purple, and green shale.
Lower Devonian, Elbert		4,192–? (Drilled 331 ft)
4, 192–4, 260	(68)	Dolomite, tan to gray, coarse crystalline to dense, with some milky chert, interbedded with red and green shale.
4, 260–4, 275	(15)	Shale, purple, limy, with some gray dolomite.
4, 275–4, 370	(95)	Dolomite, gray to dark-gray, coarse crystalline to dense, with some milky and amber chert, and traces of green shale.
4, 370–4, 425	(55)	Dolomite, dark-gray to black, coarse crystalline, interbedded with gray sandstone.
4, 425–4, 440	(15)	Sandstone, white to light-gray, fine grained, glauconitic.
4, 440–4, 475	(35)	Dolomite, tan to gray to black, fine to medium crystalline, slightly sandy, with some thin gray sandstone and red shale stringers.
4, 475–4, 495	(20)	Sandstone, red, fine-grained, arkose, slightly limy.
4, 495–4, 523	(28)	Dolomite, tan to gray to black, fine to medium crystalline, dense, slightly siliceous, with some interbedded amber and milky chert, and light-gray limestone.

Total Depth 4,523 ft in Elbert formation

The other test in this area is on the crest of the Gypsum Creek dome (pl. 1), in sec. 7, T. 41 N., R. 23 E., Apache County, Ariz. (unsurveyed), and was completed in 1924. The well, known as the Midwest 1 Gypsum, was drilled by the San Juan Oil and Development Co. to a depth of 2,083 feet. It started in the Halgaito tongue of the Cutler formation and was bottomed in the Elbert formation. It was abandoned as a dry hole.

The depth to basement rocks over most of the Monument Valley area (pl. 8) probably does not exceed 6,000 feet, and many parts of the area can be tested by relatively shallow drilling. The area seems to be in a favorable structural location, for its major part is astride the south end of the Monument upwarp; its east edge is on the southwest flank of the Paradox basin; and its south edge abuts the north rim of the Black Mesa basin. Although the sedimentary cover is thin, the rocks thicken rapidly to the northeast, south, and west. Favorable host rocks for oil and gas accumulations include strata of Hermosa (Pennsylvanian) and Rico (Permian), as well as Devonian and Cambrian age.

Although possible oil-bearing strata underlie the area, uncertainty exists as to which type structures are favorable for accumulation of oil and gas. Many of the tests in this part of Utah and Arizona have been on the crests of local structures, and as most were dry holes, it has been suggested (Baker, 1936, p. 98) that the troughs of the synclines, rather than the anticlinal crests, are favorable sites for oil accumulation. Baker notes that current theories of oil migration suggest that oil will migrate to the crests of anticlines if water is abundant in the reservoir rocks. Conversely, a lack of water will result in the oil moving to the synclinal troughs. This is well-demonstrated in the Mexican Hat oil field. Despite this viewpoint, most of the recent tests, including the successful Shell tests, were on anticlinal crests.

As yet, there has not been sufficient exploratory work in this general area to warrant a specific statement on this problem. Many of the wells drilled on the crests of anticlines were either dry holes or they struck water or gas. However, as the area was deformed in Tertiary time, it seems likely that the original oil accumulations have been either displaced or dispersed. As yet, no thorough test has been completed on structural terraces, stratigraphic traps (such as the reef limestone at the base of the Hermosa (Wengerd, 1951)), or near faults, to appraise these features as possible oil reservoirs. Until more drilling has been done, a conclusive answer cannot be given as to the potentialities of the area for oil and gas.

The favorable location of the area in terms of regional structure, the presence of oil-bearing strata, and the many possible oil traps suggest that the Monument Valley area is a likely site for oil and gas accumulations in the concealed Paleozoic rocks. If nothing else, the success of the two Shell wells reemphasizes the promising oil and gas possibilities of this sector of the Four Corners area.

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