GEOLOGY AND ORE DEPOSITS OF THE MONUMENT VALLEY AREA, APACHE AND NAVAJO COUNTIES, ARIZONA

by

Irving Jerome Witkind, 1917-

OPEN FILE REPORT

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1956

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TABLE OF CONTENTS

PAGE

PAGE

LIST OF ILLUSTRATIONS

<u>Frontspiece.</u> -- <u>A.</u> - View to the northeast 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.

<u>B.</u> - View of Mitchell Mesa Channel No. 1 showing the symmetrical nature of the scour. The channel is about 350 feet wide and 75 feet deep.

Ꞧs - Shinarump conglomerate member of the Chinle formation.
Ꞧm - Moenkopi formation.
Ph - Hoskinnini tongue of the Cutler formation.
Pd - DeChelly sandstone member of the Cutler formation.
Po - Organ Rock tongue of the Cutler formation.

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Apache and Navajo Counties, Arizona

by Irving ~~Jerome~~ Witkind
Denver, Colorado

ABSTRACT

In 1951 the U. S. Geological Survey undertook a program of uranium investigations in Apache and Navajo Counties, northeastern Arizona. The work had three major objectives. The first was to accumulate data basic to an understanding of the regional geology. The second was to appraise the Triassic strata as host rocks for uranium deposits, and to select areas favorable for exploration for concealed deposits. The third objective was to study the controls that influence uranium deposition and from this study, to establish guides useful in prospecting for uranium deposits.

Exposed consolidated sedimentary strata range in age from Permian to Jurassic. Minettes and vogesites form volcanic plugs and dikes. Several rubble pipes filled with rounded cobbles and boulders that range in age from pre-Cambrian (?) to Cretaceous are in a matrix of antigorite on Garnet Ridge.

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

Five small asymmetrical folds are in the mapped area; (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 conglomerate member of the Chinle formation (Late Triassic), a light-gray crossbedded conglomeratic sandstone that contains a few intercalated light-gray mudstone lenses. The Shinarump caps most of the isolated mesas and buttes and normally appears as a cliff about 50 feet high. It rests unconformably on the Moenkopi formation of Early and Middle Triassic age. The unconformity is marked by elongate shallow erosional depressions termed swales, and by symmetric and asymmetric channels scoured as much as 75 feet into the underlying Moenkopi formation. These channels range from narrow ones 15 feet wide to broad ones as much as 2,300 feet wide.

Sixty-two channels and channel segments were noted; of these 18 have mineralized exposures. The Monument No. 2 channel, containing one of the richest deposits in the Monument Valley area, strikes N. 18° W. and is about 1-3/4 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 channel floor is irregular and near its southern end is divided by a low narrow sandstone ridge that parallels the channel trend. Four types of ore bodies were noted: (1) rods, (2) tabular ore bodies, (3) corvusite-type ore bodies, and (4) rolls. The rods are cylindroidal bodies about 3-5 feet wide, 2-3 feet high, and 15-20 feet long. The tabular ore bodies are blanket-like masses of channel sediments 40-50 feet long, 20-30 feet wide, and 3-5 feet thick. The corvusite-type ore bodies are irregular-shaped masses of sediment thoroughly penetrated by vanadium and uranium minerals. Rolls similar to those mined in the Morrison formation (Jurassic) are the fourth type of ore body.

Swales and channels are important prospecting guides. Other useful guides are (1) observable uranium minerals and abnormal radioactivity, (2) channel fill, (3) channel conglomerates containing carbonaceous matter. Guides of uncertain usefulness are (1) limonitic impregnation of sandstone, (2) secondary copper minerals in channel fill, (3) an abnormal thickness of an altered zone in 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 1924, the Midwest No. 1 Gypsum penetrated 2,083 feet to the Elbert formation (Late Devonian) as a test of the Gypsum Creek dome. Although small shows of oil and gas were reported the hole was abandoned. The Navajo A-1, was completed in 1953 on Hoskinnini Mesa, and tested the southern part of the Organ Rock anticline. The hole was abandoned as a dry hole after being drilled 4,523 feet. No oil or gas shows were reported. It also bottomed in the Elbert formation. As favorable strata and structures underlie the Monument Valley area, the area is deemed worthy of further investigation.

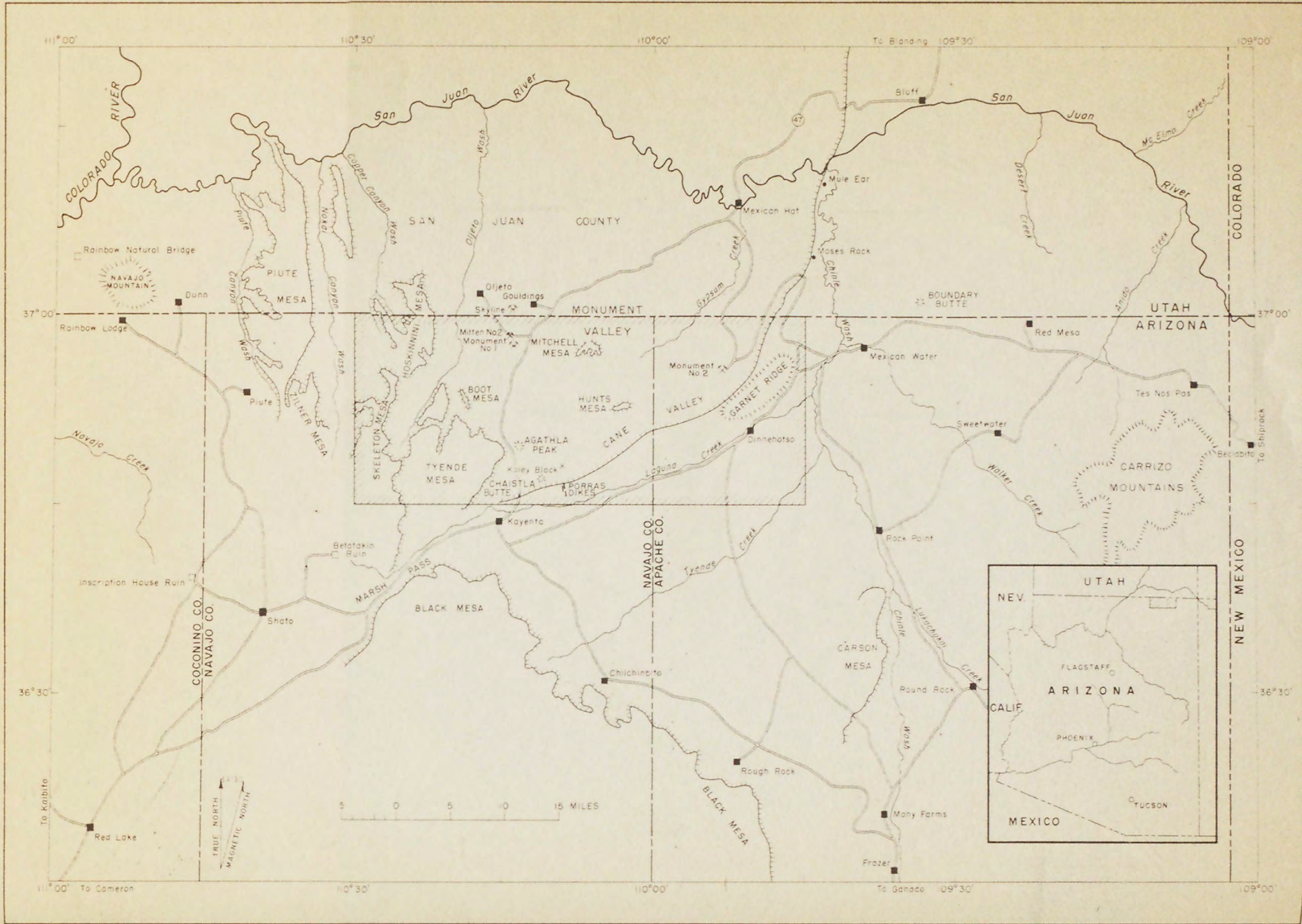

Figure 1. -- Index map of part of the Navajo Indian Reservation showing the area mapped (slanted lines).

INTRODUCTION

Purpose of work

In 1951 and 1952 the U. S. Geological Survey undertook, on behalf 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. The first was to accumulate data basic to an understanding of the regional geology. The second was to appraise the Triassic strata as host rocks for uranium deposits, and to select areas favorable for exploration for concealed deposits. The third objective was to study the controls that influence uranium deposition and from this study to establish guides useful in prospecting for uranium deposits.

Many of the results obtained and concepts evolved have been presented previously in unpublished reports of the U. S. Geological Survey Trace Elements series.

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 was carried on concurrently with the mapping program. Those areas marked by abnormal radioactivity were sampled. Results are given in figure 3.

Acknowledgments

I wish to express appreciation to the geology faculty of the University of Colorado for help and criticism. Especially am I indebted to Dr. Warren O. Thompson who has given considerable time and thought to the problems involved.

Special thanks for geologic assistance during the course of this project are due to C. B. Hunt, J. D. Sears, J. F. Smith, Jr., R. E. Thaden and R. P. Fischer, all of the Geological Survey.

The local inhabitants advised and assisted in securing water and supplies; to all I am most grateful.

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

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

Among the many geologists who participated in the geologic mapping of the area are R. E. Thaden, 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.

GEOGRAPHY

Location of area

Monument Valley lacks clearly delineated geographic boundaries. In general it occupies parts of both Utah and Arizona and is near the eastern border of both states. The northern part of the valley was studied by Baker (1936); the southern part is the area described in this report. The Monument Valley area of this report extends from the 109° 45' W. to the 110° 30' meridian west, a distance of about 41 miles. Its northern boundary is near the 37° 00' parallel north and it extends southwards to the 36° 45' parallel north, a distance of about 17 miles. In all, the mapped area consists of three 15-minute quadrangles and covers about 700 square miles. The three quadrangles occupy parts of Apache and Navajo Counties in northeastern Arizona, 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 hence has much of the scenery, climate, and topography typical of that section of the country. The scenic features of the area 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 (A, pl. 1). The altitude of the area rises gradually and imperceptibly from about 4,500 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, Ariz.; Dinnehotso, Ariz.; Gouldings, Utah; and Oljeto, Utah (fig 1).

Roads

Roads are poor and vehicular movement is almost impossible during or following severe sandstorms or rainstorms. Most vehicular traffic is restricted to four principal roads of which the most important is the Mexican Hat-Kayenta road, known as Navajo Indian Reservation Route No. 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. Work during the summer of 1952 by both State and Federal highway

Plate 1. -- A. - View looking northwest into Tee Biyi from crest of Hunts Mesa. Many of the buttes, monuments, and crags are named. An unimproved road suitable only for vehicles equipped with 4-wheel drive winds around the base of the monuments.

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

agencies has so improved this road that the major part of it is suitable for all-weather traffic. The fourth road extends northeastward from Kayenta to Dinnehotso Junction, and then turns southward to Chinle, Ariz. and Canyon DeChelly.

GEOLOGY

Stratigraphy

General statement

Sedimentary strata exposed range in age from Permian to Recent. In general the older consolidated rocks crop out in the northcentral part of the area with younger rocks rimming the east, west, and south edges of the area. Scattered irregularly across the outcrops of all the consolidated sedimentary strata are intermittent 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 (Table I). 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 look alike; commonly they range from light buff to reddish brown massive or bedded sandstones. A prominent exception is the Chinle formation. The DeChelly sandstone member of the Cutler formation resembles the Wingate sandstone as well as the Navajo sandstone. The Organ Rock and the Hoskinnini tongues of the Cutler formation are so alike that north of this area in the vicinity of Monitor Butte, where the intervening DeChelly sandstone pinches out, the Organ Rock and the Hoskinnini are distinguished only with difficulty. (Mullens and Hubbard, 1952, unpublished report) Most of the units, however, are easily recognizable and the contacts are well-exposed.

Wherever the massive sandstone beds are protected by a resistant cap rock they form vertical cliffs. In those localities where they are unprotected, however, they form rounded, steep-sided knolls alternating with deep narrow ravines.

The areal distribution of the formations is shown in fig. 2. Thicknesses and details of the lithologies are shown schematically in Table I.

Permian system

Cutler formation

The Cutler formation is exposed over a large area in the northern part of the Monument Valley area, Ariz. 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 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.

In the Monument Valley area, Ariz. 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 DeChelly sandstone member, and the Hoskinnini tongue. The DeChelly and Cedar Mesa sandstones are buff to gray massive crossbedded sandstones. The Halgaito, Organ Rock, and Hoskinnini tongues are red fine-grained sandstones, siltstones, mudstones, and claystones. The Halgaito, Cedar Mesa, and Organ Rock maintain a uniform thickness over most of their area of exposure. The DeChelly sandstone thins northwards and pinches out at Monitor Butte, but thickens both to the east and south. The Hoskinnini tongue thickens northwards and thins eastwards.

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

During most of Cutler time westward flowing streams spread red sediments across the area. This depositional sequence was interrupted twice; once by the Cedar Mesa sandstone which had a source area to the northwest, and the second time by the DeChelly sandstone which came either from the southeast or northwest (Baker and Reeside, 1929, p. 1447). Thus, the Cutler can be conceived as a thick series of red thin-bedded claystones, siltstones, and fine-grained sandstones into which two massive sandstone units interfinger. The lower sandstone, between the Halgaito and the Organ Rock, is the Cedar Mesa, and the upper sandstone, separating the Organ Rock and the Hoskinnini, is the DeChelly.

Halgaito tongue.-- The Halgaito tongue of the Cutler formation, the basal member of the Cutler, is the oldest sedimentary rock exposed in the Monument Valley area, Ariz. It crops out in the core of Gypsum Creek dome (fig. 2), a small breached dome that straddles the Arizona-Utah state line just south of Mexican Hat, Utah.

The Halgaito forms a broad quaquaversally sloping plain in the central part of its outcrop of about 8 square miles. Here and there the even slope is interrupted by hummocks and knobs of more resistant material. In a few places, intermittent streams have cut gullies as much as 50 feet deep. The plain is bounded on all sides by beds of increasingly steep dip that 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 a veneer of chips and flakes up to 3 inches in length.

In the Monument Valley area, Ariz. the Halgaito consists of red siltstones and fine-grained silty sandstones with a few small thin lenses of interbedded blue and gray limestones. Remarkably uniform in color, the rock is a moderate reddish brown with a gray cast (approximately 10R 4.5/3) (N.R.C. color chart, 1948). The major constituent of the Halgaito is poorly-sorted sub-angular clear colorless polished quartz. Minor constituents are muscovite and rare grains of opaque minerals. The predominant grain size is about 0.02 mm although some grains are as small as 0.003 mm and as large as 0.06 mm.

In any bed 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. Most of the beds are from 1/16 to 1 inch thick, locally, however, a few lenses of silt-pebble conglomerate are as thick as 8 feet. The pebbles of the conglomerate beds are as much as 2 inches in long dimension and are well-rounded. The conglomerates may extend several hundreds of feet, but invariably they grade laterally into typical thin-bedded Halgaito.

A heavy 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 point that the local name for the Halgaito is the "red lime" (Gregory, 1938, p. 42).

Several lenticular limestones, 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 in an otherwise hummocky terrain. At these places the limestone beds consist primarily of 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 Halgaito is not exposed in its entirety in the Monument Valley area, Ariz. However, more than 300 feet of the upper part of the unit crop out and the base of the unit 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 in the vicinity of Mexican Hat, Utah, appears sharp and conformable with the underlying Permian Rico formation. Here the basal beds of the Halgaito are reddish-brown thin-bedded silty claystones or are gray to dark-brown lenticular rubbly limestone beds up to 3 feet thick interbedded with the silty clays. At none of the localities visited in the Monument Valley area was the 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, even in the concretionary limestone pellets of the limestone lenses. Baker (1936, p. 30), however, reports vertebrate remains tentatively identified as either Ephiacodon or Sphenacodon found in Halgaito exposures in the Utah part of Monument Valley. 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 the westward flowing streams. East of the Monument Valley area the sediments are in large part coarse arkoses. As these sediments are traced westward they become finer-grained and eventually pass into non-red beds (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 and by relatively slow moving streams. The thin interbedded blue and gray limestones and the silt pebble conglomerates suggest the presence of intermittent playa lakes. The conglomerate pebbles probably represent places where earlier beds were laid bare and allowed to dry. Dried chips and flakes were produced on this flat. When the waters reoccupied the basins the chips were broken, rounded, and then incorporated into the next overlying beds.

Cedar Mesa sandstone member.-- The outcrop of the Cedar Mesa sandstone member of the Cutler formation extends into the Monument Valley area, Ariz. from the north only as far as the base of Meridian Butte (fig. 2). On the east the Cedar Mesa flanks the Gypsum Creek dome as a series of low parallel hogbacks as high as 30 feet, and on the west and southwest as nearly horizontal beds.

In the Monument Valley area, Ariz. 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 Cedar Mesa strata from coarser to finer material with an accompanying change in color is well-displayed.

Much of the Cedar Mesa is a moderate orangish-brown (3YR 5/5) well-sorted silty very fine-grained quartz sandstone. The quartz grains are subround, are covered by a faint iron oxide stain, and average about 0.06 mm in diameter. The grains range from

0.03 mm to 0.09 mm. The only significant minor constituents are calcite and green grains of a chlorite-like mineral. Calcite cement is abundant.

Another prominent 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 site suitable for measuring a section of the Cedar Mesa is available in the Monument Valley area, Ariz. However, several crude field measurements and about four measurements made by photogrammetric methods suggest an average thickness of about 315 feet. This figure contrasts with 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 member 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. The clearest contact is at the base of Meridian Butte (fig. 2). At that locality there is an abrupt transition in color. The uppermost bed of Cedar Mesa is a light blue, calcareous, sandy siltstone, and the lowest bed of the Organ Rock is a dark reddish-brown micaceous siltstone with almost no 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 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 the change from sandstone in the north to thin-bedded interfingering sandstone and red shaly siltstone beds marks the first break in the depositional sequence of Cutler red beds. The Cedar Mesa came from the northwest (Baker and Reeside, 1929, p. 1447). Near its limits of deposition to the south, it loses its entity as a sandstone and becomes more and more a transitional unit; -- interfingering sandstone (Cedar Mesa) and siltstone beds (Cutler red beds).

Organ Rock tongue. -- The Organ Rock tongue of the Cutler formation is exposed throughout the north half of the Monument Valley area, Ariz. It forms the floor of Copper Canyon (fig. 2) 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 DeChelly, the Organ Rock stands as a gently concave clope that steepens near the top of the unit and is nearly vertical at the contact.

The Organ Rock is predominantly a reddish-brown (10R 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 comparable to the DeChelly.

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 and sorting is poor. Enough very small grains are also included, however, to refer to the member as a clayey siltstone.

The cement appears to be a mixture of calcite and iron oxides. Splotches of clear calcite up to several millimeters in diameter are scattered through the member. This calcite has etched the quartz where it is in contact. Calcite also forms small bundles of crystals, each crystal rhombic in thin section. The crystals are about the same size as the quartz grains and under the hand lens could be mistaken for them. 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 siltstones in beds 2 inches thick, or sandstone in beds 20 feet thick. Some of the siltstone and many of the sandstone beds show cross-bedding gently inclined to the horizontal.

The Organ Rock is about 670 feet thick near the Monument No. 2 area (fig. 1), one of the few places where the member is exposed in its entirety. Baker (1936, p. 34) cites a thickness of 696 feet for the Organ Rock on the east side of Monument Pass, Utah. This agrees well with our measured thickness but contrasts with the 347 feet noted by Gregory (1938, p. 46) in White Canyon, Utah. Gregory's measurements at other places in San Juan County, Utah, and measurements by Miser (1924, p. 120 et seq) along the San Juan River tend to 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 DeChelly 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 the upper 25 to 50 feet of the Organ Rock grade in color and in grain size to material that is megascopically identical to the DeChelly. The slope gradually steepens and approaches the vertical in the vicinity of, 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 DeChelly strata several tens of feet. For mapping purposes 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 DeChelly, and the color changes from dark reddish-brown of the Organ Rock to the light tan of the DeChelly.

No fossils were foundin Organ Rock strata. 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.

The Cedar Mesa sediments came from the northwest (Baker and Reeside, 1929, p. 1447) and temporarily halted the westerly flowing streams that were depositing the sequence of red beds so typical of the Cutler. As these streams regained the initiative, red sediments were once again deposited under arid conditions across the Monument Valley area. These sediments constitute the Organ Rock member. The type of bedding plus the fine-grained sediments deposited suggests that the streams were relatively quiescent. Near the close of Organ Rock deposition, light-colored sands either from the southeast or northwest, the forerunner of DeChelly sediments, (Baker and Reeside, 1929, p. 1447) gradually mingled with the red fluviatile sediments and eventually displaced them.

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

Wherever the DeChelly sandstone is protected by younger more resistant formations it forms unscalable vertical walls. The unit, however, is not extremely resistant and where unprotected weathers to round hummocky knolls. In places joints and bedding planes, weathered by wind and water have contributed to the formation of a great variety of alcoves, recesses, and tunnels at the base of the DeChelly. These range in size from very small ones to great arched alcoves that are of a size sufficient to accomodate whole villages of cliff dwellings (B, pl. 2).

The DeChelly is a poorly sorted fine-grained sandstone with the grains ranging in size from 0.06 mm to 0.50 mm, although a bimodal grain size distribution exists. One grain size ranges from 0.25 mm to 0.50 mm (the average is about 0.30 mm) in diameter, the other ranges from about 0.06 mm 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 angular, primarily as a result of the overgrowth of authigenic quartz. Most

Plate 2. -- A. - Keet Seel, the largest and best preserved cliff-dwelling in the Monument Valley area. The dwelling is in a large alcove in the Navajo sandstone.

B. - Small cliff-dwelling in a shallow alcove in the DeChelly sandstone member of the Cutler formation. Most cliff-dwellings in the Monument Valley area are this shape and size. Marks on the wall above and behind the dwelling are pictographs.

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 unit is friable.

The DeChelly sandstone ranges in thickness from 300 feet to 550 feet, thinning and disappearing 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 DeChelly is about 300 feet thick and decreases rapidly in thickness northward to its pinch-out. The DeChelly thickens in an easterly and southerly direction, for in the center of the Monument Valley area, near Tse Biyi, it is about 450 feet thick. Farther east, near the Monument No. 2 area (fig. 1), it is as much as 550 feet thick, and to the south near Canyon DeChelly, beyond the limits of the mapped area, the DeChelly sandstone is well over 800 feet thick (McKee, 1934, p. 224).

A prominent and distinct unconformity is apparent at the top of the DeChelly sandstone (pl. 3). This unconformity is marked by the abrupt truncation of the light-tan massive crossbedded DeChelly sandstone by dark-red even-bedded sandstone beds of the basal part of the Hoskinnini tongue of the Cutler formation. These basal dark-red massive even-bedded sandstone beds are considered to be a "re-worked zone" composed in part of DeChelly sediments.

The top of the DeChelly sandstone member of the Cutler as here selected differs from that chosen by Baker (Baker, 1936). Baker recognized the unconformity but chose to include it and the "re-worked zone" within the DeChelly sandstone. Hence he indicates the boundary between the DeChelly 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 the massive crossbedded sandstone of the DeChelly to the even-bedded red beds.

The unconformity, however, is so widespread and so persistent that I consider it significant. I suggest tentatively, therefore, that not only does the unconformity mark the boundary between two stratigraphic units, but that it also probably marks the rock system break between the Permian and the Triassic. Unfortunately the complete absence of fossils in this re-worked zone prevents any conclusive determination as to the relative ages of the units involved. Lacking paleontologic evidence, the point of view expressed above is not followed on the map (fig. 2).

Fossils were not found in the DeChelly sandstone although vertebrate and invertebrate footprints were noted in several localities. The best track locality that has been discovered is along the east edge of Todicheenie Bench near the upper end of Adachijiyahi Canyon (fig. 2). Baker (1936, p. 37) also reports a lack of fossils in the DeChelly sandstone although he found specimens of _Walchia piniformus_ and _Yakia hetophylla_ of known Permian age in the transitional beds that mark the change from the Organ Rock tongue to the DeChelly sandstone member.

The DeChelly is the uppermost of two sandstone beds that interfinger with typical Cutler red beds. The broad sweeping cross-laminae so typical of the DeChelly imply eolian modification of DeChelly sediments prior to their consolidation. Baker (1936, p. 36) also postulates an eolian origin for the DeChelly. The source area for the sands that formed the DeChelly is unknown; however, the DeChelly interfingers with the Cutler red beds from the southeast and thickens in the direction. If the source area is considered to be near the greater thickness, it would appear that the DeChelly 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. However, despite this evidence, they conclude, "It seems to the writers highly probable that all of the light-colored sandstones came from the north or northwest."

Plate 3. -- A. - Permian and Triassic formations cropping out in the Monument Valley area. The contact between the Hoskinnini (Ph) and DeChelly (Pd) is a surface remarkably free of irregularities.

B. - Permian and Triassic formations showing relationship of channel to other strata. Note the symmetrical scour formed by the channel (Mitchell Mesa Channel No. 1) in the Moenkopi.

Rs - Shinarump conglomerate member of the Chinle formation.
Rm - Moenkopi formation.
Ph - Hoskinnini member of the Cutler formation.
Pd - DeChelly sandstone member of the Cutler formation.

Hoskinnini tongue.-- The Hoskinnini tongue of the Cutler formation 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 back 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 closely parallels that of the DeChelly. 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 (i.e., Oljeto Wash). 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 DeChelly sandstone 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 T. E. Mullens and H. A. Hubbard of the Geological Survey in the Red House Cliffs district of Utah has suggested that the Hoskinnini can be differentiated from the Organ Rock tongue. Mullens and Hubbard (1952, unpublished report) have found that the Hoskinnini has the distinctive lithology of 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 Red House Cliffs district, Mullens and Hubbard contend is adequate to separate the Hoskinnini from the underlying Organ Rock. Williams and his associates (Williams and others, 1953, unpublished report, p. 10), using the criteria established by Mullens, have traced the Hoskinnini northward from the Red House Cliffs district, where it is as much as 100 feet thick, to a pinch-out in the middle of the White Canyon area, Utah.

As used in this report the Hoskinnini tongue can be divided into two distinguishable facies. Because of their thinness, however, these divisions have been combined and mapped as one unit (Ph). The lower unit consists of a dark-red massive sandstone, which lies disconformably on the DeChelly. The upper unit is the dark-red even-bedded sandstone of the type Hoskinnini. Locally small discrete blocks of DeChelly sandstone are embedded in the lower Hoskinnini sandstone. Elsewhere small tan-colored whorls can be traced from the DeChelly into the basal few feet of this same sandstone. As a consequence, this lower sandstone can be considered to be a re-worked zone consisting in part of DeChelly, and in part of Hoskinnini sediments. In many places the re-worked zone is missing and in these localities the red beds of the upper unit of the Hoskinnini tongue lie directly on the truncated surface of the DeChelly sandstone.

In the lower sandstone, grains of two sizes are apparent; some are distinctly coarse and average about 0.40 mm in diameter although a few oval-shaped grains are as much as 1.30 mm along their long axis. The other grains are dominant and average about 0.06 mm in diameter. Much of the coarser material is within the small tan-colored whorls that can be traced into the underlying DeChelly sandstone. The uppermost unit of the Hoskinnini consists of even-bedded fine-grained sandstone. Locally, 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 overgrowth of secondary quartz.

The major granular constituent of the Hoskinnini, as with most of the other sedimentary units in the area, is quartz. Small amounts of microcline, plagioclase feldspar and chalcedony appear as accessory minerals. Coating all grains is a thin film of iron oxide which imparts a red color to the beds. Calcium carbonate is the principal cementing agent, although iron oxide and secondary silica are also present in small amounts.

The Hoskinnini thins eastward although it is remarkably persistent over most of the area, being about 35 feet thick. All measurements included both the lower and upper units. Mullens and Hubbard (1952, unpublished report, p. 4) report the Hoskinnini as 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 (Williams and others, 1953, unpublished report, p. 10). Baker (1936, p. 39) cites a thickness of 55 feet in the Canyon of the San Juan River at the mouth of Nokai Creek, and about 50 feet near the northeast corner of Hoskinnini Mesa. In the Monument Valley area, Ariz., the Hoskinnini is about 45 feet thick along the flanks of Hoskinnini Mesa but near the Monument No. 2 area (fig. 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 was the Hoskinnini absent.

The following section of the Hoskinnini tongue of the Cutler formation measured at the southwest end of Hoskinnini Mesa about 12 miles north west of Agathla Peak (fig. 2) is characteristic.

	Feet	Inches
Moenkopi formation		
Hoskinnini tongue of Cutler formation		
Limestone, crinkly, contains mixture of calcite and pink quartz		1/4
Sandstone, even-bedded, dark red	3	
Limestone, crinkly, contains mixture of calcite and pink quartz		3/4
Siltstone, shaly, dark red, thin-bedded nodular weathering	10	

	Feet	Inches
Sandstone, massive, dark red, fine-grained, thin-bedded; weathers as rounded ledges	6	
Sandstone, dark red, massive, fine-grained	19	
	38 ft.	1 in.

Unconformity

DeChelly sandstone member of Cutler formation

Although the Moenkopi is reported as unconformably overlying the Cutler formation (Longwell, C. R., and others, 1923, p. 9) Baker (1936, p. 40-43) could find no evidence of this unconformity in the Utah part of Monument Valley. However, he cites several localities in Arizona where this unconformity could be observed. These could not be found nor were any localities noted during the mapping where the Moenkopi unconformably overlay the Hoskinnini.

The upper contact of the Hoskinnini is gradational and extremely vague. Baker (1936, p. 40) selects the upper contact at a horizon 8 to 11 feet above two crinkly limestones. Both limestones are unusually persistent in the western part of the Monument Valley area despite their extreme thinness. 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 limestones change from the arenaceous even-bedded red beds to chocolate-colored beds composed of shaly siltstone. This lithologic change is expressed topographically by the transition from a nearly vertical wall formed by the Hoskinnini red beds to moderate slopes composed of shaly siltstone of 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 comprising 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 dark reddish-brown (10R 3/4) easily eroded shaly siltstone and sandstone beds of the Moenkopi formation of Early and Middle Triassic age. Wherever it is protected by a cap of Shinarump conglomerate, the Moenkopi forms gentle to moderately steep talus-covered slopes between the cliffs formed by the underlying DeChelly sandstone and the ledge formed by the overlying Shinarump. Where unprotected, the Moenkopi is intricately dissected into a maze of canyons, ridges, low cliffs, benches, and isolated tables.

On weathered surfaces the Moenkopi is dark brown with local areas colored a chocolate brown. Its coloration is diagnostic in the Monument Valley area and contrasts markedly with the light gray of the overlying Shinarump and the light tan of the underlying DeChelly. Fresh surfaces of the Moenkopi formation are light brown to pinkish brown. In places certain restricted zones within the Moenkopi are a light yellowish gray (5Y 7/2) to a light olive gray (5Y 5/2). These zones have no great extent and laterally grade imperceptibly into the dark siltstone and sandstone beds of typical Moenkopi.

The formation is even-bedded and extremely fissile; this fissility is best shown by the shaly siltstone beds although the massive sandstone beds locally show some parting parallel to the bedding planes.

Among the most distinctive features of the Moenkopi are the numerous minor structures such as ripple marks, rain pits, and shrinkage cracks. Three main types of ripple marks were observed. The dominant type, confined principally to shaly siltstones, consists of even, 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 cusp-like and commonly appear as small hemispheres about 3 inches in diameter. McKee (1954, p. 60) considers these characteristic of stream deposits. In the Monument Valley area they are common in the sandstones. Interference ripples (or "tadpole nests") constitute 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 of the Moenkopi. In many places these shrinkage cracks ("mud-cracks") are filled with a fine-grained sand.

Scattered through 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 size from about 0.10 mm to a maximum of about 0.30 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 of the grains are coated with a thin film of iron oxide that imparts the distinctive reddish brown color to the formation. Calcium carbonate is the main binding agent, with both chalcedony and iron oxide also cementing the grains, but to a lesser extent.

Along the east and west flanks of Skeleton Mesa (fig. 2) thin lenticular beds of white gypsum 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 (Smith and others, 1952, unpublished report, p. 11), and near the western edge of the Monument Valley area it is only about 250 feet thick. As one traces the formation eastward in the Monument Valley area it continues to thin gradually 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, Ariz.:

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

	Feet
Shinarump conglomerate member of Chinle formation.	
Unconformity	
Moenkopi formation	
Siltstone, shaly, dark reddish brown with light gray green zone 2 feet thick near top; thin-bedded, interleaved lenticular sandstone beds each about 2 feet thick through 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 erosional depressions, termed swales, are cut in the top of the Moenkopi. 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. Commonly this contact is marked by a topographic break between the cliff-like 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 unconformable, for an undulatory erosional surface of wide extent bevels the top of the Moenkopi formation. No evidence of angular discordance was noted. This plane of erosion shows but slight relief when viewed in gross aspect although the swales referred to above cause it to be wavy and deep channel scours interrupt the smooth undulations of the disconformity. In general, however, relief along the disconformity, if one excepts the deep channel scours and the broad swales, commonly does not exceed 3 to 5 feet.

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

In the Monument Valley area a discoloration or bleaching of Moenkopi sediments is nearly everywhere below the disconformity.

Generally this discoloration occurs as a 6 inch uninterrupted gray green zone which contrasts markedly with the underlying reddish brown of normal Moenkopi sediments. Locally, however, especially below channels, this light gray green zone may increase in thickness to as much as 4 feet. The gray green discoloration is strongest in those sediments directly below the disconformity. A few inches below the Shinarump. however, the intensity of the gray green color diminishes through a transitional zone about 6 inches thick that consists of alternating bands of gray 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 possible Middle Triassic vertebrate fauna has been found in the general area of Meteor Crater, Ariz. (Welles, 1947).

The Moenkopi in the Monument Valley area appears to have been deposited in a marginal marine area which was exposed to sub-aerial 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 suggests 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 sediments 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 delta-like deposits were built onto this sloping plain by westward flowing rivers (McKee, 1954, p. 79).

As the seas that deposited the silts and sands of the Moenkopi withdrew a surface of low relief was exposed to subaerial erosion. McKee (1951 a, p. 88) considers that this surface was subjected to dissection 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, I believe that the period of exposure was relatively short and that Shinarump deposition began shortly after the Moenkopi surface was exposed. Thus, I suggest that most of the channels, swales, ridges, and other features that mark the Moenkopi-Shinarump contact were formed by the streams that deposited Shinarump sands and gravels. These clastics were deposited by northward flowing streams from a newly raised highland mass in central and southern Arizona (McKee, 1951 b, p. 493).

Chinle formation

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

Badland topography is characteristic, due primarily to the easily eroded claystones and mudstones. A cliff about 50 feet high, formed by the Shinarump conglomerate member, commonly marks the basal part of the unit. Locally, large masses of talus composed of red sandstone and siltstone derived from the overlying strata form a protective cap over small hummocks of Chinle claystone and mudstone. As the Chinle weathers back these small mounds are preserved as demoiselles. Wherever exposed, the Chinle formation is marked by large landslide blocks. Blocks as much as one-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 division was given a letter of the alphabet with Division A representing the youngest and Division D the oldest. In order to conform to common stratigraphic practice I have designated each of the members of the Chinle by a geographic name and propose, therefore, that the following nomenclature be used in the Monument Valley area, Ariz. for those four members of the Chinle formation, delineated by Gregory. In 1956, the Geologic Names Committee of the Geological survey approved the inclusion of the Shinarump conglomerate as the basal member of the Chinle formation. As used, therefore, the Chinle in the Monument Valley area consists of five members.

Gregory	Proposed usage
Division A of Chinle formation	Church Rock member of Chinle formation (new)
Division B of Chinle formation	Owl Rock member of Chinle formation (new)
Division C of Chinle formation	Petrified Forest member of Chinle formation (Gregory, 1950, p. 67)
Division D of Chinle formation	Monitor Butte member of Chinle formation (new)
Shinarump conglomerate	Shinarump conglomerate member of Chinle formation (new)

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

The Shinarump conglomerate is exposed over large parts of the Monument Valley area, Ariz., in the form of a broad "W" whose open end faces northeast. Its principal outcrops are along the northwest edge of the area; as isolated remnants capping mesas and buttes in the north-central part of the area; and as a narrow northeast trending band across the central part of the area (fig. 2). Normally it crops out 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 above which rise the dissected hills and cliffs formed by the other members of the Chinle and the Glen Canyon group.

Where the Shinarump is the cap-rock it forms a vertical cliff commonly about 50 feet high. Its surface is marked by round irregular hummocks about 30 feet high and broad shallow swales 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 cross-bedding is perhaps one of the most characteristic features of the formation 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. These proportions change from locality to locality; sedimentary studies at both Hoskinnini and Nakai Mesas (McKee and others, 1953) give the following average values:

Sandstone	75 percent
Conglomerate	20 percent
Mudstone	5 percent

In places almost three-fourths of an exposed face may be conglomerate, and this can give way to a wall of medium-grained sandstone in a lateral distance of 200-300 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 interfinger with lenses of conglomerate which may wedge out or grade laterally into sandstone, siltstone, and claystone.

On weathered surfaces the Shinarump ranges in color from white to brown although commonly it is a 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 silicified wood in all sizes and shapes. The smaller wood fragments are slightly rounded. This profusion of silicified wood is characteristic of the Shinarump conglomerate but probably more wood fragments are in sediments that fill channels than in the Shinarump elsewhere.

The pebbles range in degree of roundness from subround to round but the majority are round. Measurements made by McKee and his associates (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. Williams and others (1953, unpublished report, p. 21) studying a much larger area in southern Utah and northern Arizona states that "the pebbles of the Shinarump are mainly well-rounded fragments of vitreous quartz, quartzite, and chert. . . ."

Some pebbles are as much as 5 inches in diameter although most are considerably smaller, their average sizes being about three-fourths to 1 inch. The pebbles are predominantly quartz with smaller amounts 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 range in shape from subangular to subround with considerable authigenic 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; calcite and iron oxide are subordinate cements. In a few small areas argillaceous material acts as a cement.

The Shinarump maintains a relatively uniform thickness. Although it does thicken and thin erratically, this appears to be more of a local phenomenon than a regional trend. In the Zion Park area the Shinarump ranges in thickness from 75 feet to a maximum of about 200 feet (Gregory, 1950, p. 65). It ranges from 150 to 350 feet thick in the Kanab area (Williams and others, 1953, unpublished report, p. 13), and from 0-75 feet in the Capitol Reef area (Smith and others, 1952, unpublished report, p. 13). 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, pp. 45-46). In the Monument Valley area, Ariz. the Shinarump conglomerate 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 one-fourth of a mile may decrease from 50 feet to a pinch out. The maximum thickness measured in the Monument Valley area, Ariz. 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, about 2 1/2 miles due east of Agathla Peak, is characteristic:

Section of Shinarump conglomerate member of Chinle formation about 2 1/2 miles east of Agathla Peak.

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

In most places the contact of the Shinarump with the overlying Monitor Butte member of the Chinle is extremely vague. Gregory (1913, p. 433) and Woodruff (1910, p. 87) both suggest that an unconformity may be at the top of the Shinarump conglomerate in this region but no evidence to substantiate this has been found in the Monument Valley area. On the contrary, several localities were noted where intertonguing exists between the Shinarump and the Monitor Butte member. Lewis and Trimble (in preparation) studying the Utah part of Monument Valley, report an absence of unconformity and state unequivocally that intertonguing exists between the Shinarump and the overlying Chinle. Baker (1936, p. 46) reports the same and concludes that the Shinarump can be regarded as the basal conglomerate of the Chinle formation.

In all localities that I examined in the Monument Valley area, Ariz., the contact between the Shinarump conglomerate and the overlying sediments is gradational. The sandstone of the Shinarump passes gradually into a series of alternating sandstones and claystones of the Monitor Butte member. Elsewhere the upper contact of the Shinarump conglomerate is selected arbitrarily as the bed that is marked by a concentration of black concretions, each about 1/32 inch in diameter. Almost directly above this zone are the crossbedded sandstones and somber clays of the Monitor Butte member of the Chinle formation.

Vertebrate and invertebrate fossils are practically nonexistent in the Shinarump conglomerate, probably because they were destroyed by the processes of sedimentation that formed 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. These pebbles suggest to McKee a source for the Shinarump to the south and east of Monument Valley.

Large quantities of wood were buried during Shinarump time. Existing opinion is that these trees grew on the uplands and along the banks of the streams that deposited the Shinarump sediments. Thus, their age is the age of the enclosing sediments. All of the logs that have been examined in the Shinarump had undergone some transportation. Daugherty (1941, p. 29) reports that although the majority 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 long and 3 to 5 feet in diameter to 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 as Late Triassic. He believes that all of the fossil plants in the Shinarump are identical with species found in the Chinle and that the area probably consisted of broad open-forest grass-covered uplands dissected by tree-lined streams. He suggests that present-day savannah-like areas are the closest approach to conditions that existed during Early Chinle (Shinarump) time. Daugherty contends that the climatic range was from tropical to sub-tropical. Rainfall was ample and these periods of adequate moisture were interrupted by short periods of aridity.

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

The Monitor Butte member is well-exposed along the northeast flank of Monitor Butte, its type locality. The butte is about 15 miles northeast of Oljeto, Utah.

In the Monument Valley area, Ariz. the Monitor Butte member is best exposed near the volcanic neck, Agathla Peak, and along the flanks and around the nose of the Agathla anticline (fig. 2). In these areas it consists predominantly of crossbedded conglomeratic sandstone beds interleaved with dark gray claystones. Topographically 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 are extremely irregular and do not conform to the regional strike and dip. Folding, faulting, intra-formational unconformities, and other evidence of pene-contemporaneous deformation are at most exposures. These phenomena, however, are not repeated in either the overlying or underlying strata.

Many features common in the Shinarump conglomerate are duplicated in the Monitor Butte. Crossbedding is extensive in both units, as is interfingering of the several beds. However, the Monitor Butte member is marked by several distinctive features. Among these are perfectly formed and extensive foreset beds. Locally these simulate bedding planes and the normal bedding is difficult to discern. Peculiar imbricating cusp-like 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 pebbles of calcareous siltstone. These pebbles are as large as 76.0 mm. Included with these are quartz, quartzite, and chert pebbles similar in shape, size, and color to those of the Shinarump.

Much of the Monitor Butte member is dark-gray to grayish-orange crossbedded fine- to medium-grained sandstone lenses. In these lenses the individual grains are angular to subrounded 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 argillaceous matter, silica and iron oxide important locally.

Because the upper and lower contacts of the Monitor Butte member are gradational, and because of the large amount of intraformational disturbance, no firm figure is possible as to the thickness of the unit. 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. Williams and others (1953, unpublished report, p. 15) state that the "D" member of the Chinle (Monitor Butte member) is about 200 feet thick in most of the Colorado Plateau region.

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, (e.g., near Agathla Peak), the upper contact is selected as the last sandstone above which is an uninterrupted sequence of variegated siltstone and claystone beds; the overlying sequence is devoid of sandstone facies. 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 a light gray green.

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 SE$\frac{1}{4}$, sec. 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	
Siltstone and claystone, grayish orange to moderate yellowish brown, containing 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, cusp-like 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, cusp-like ripple marks, forms cliff	25
Claystone, siltstone, and sandstone sequence 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 conglomerate member of Chinle formation	

No recognizable vertebrate or invertebrate fossils were found although rare bone fragments are in the conglomerate beds. The fossilized wood resembles that in the Shinarump 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 excellent intertonguing between the two units. Subsequently, the flow dwindled and the size of the material deposited in the Monument Valley area decreased.

Petrified Forest member.--Overlying the dark sandstone and mudstone beds of the Monitor Butte member are a series of 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 sediments 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, and deep steep-walled ravines separated by narrow ridges. Dendritic stream patterns have dissected the slopes intricately and sculptured the entire area into a hummocky plain.

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.

A large part of the Petrified Forest member is a massive uniform-textured well-indurated siltstone and mudstone. Locally small discontinuous lenses of mud pebbles form a conglomerate which interrupts this sequence. In the massive facies the dominant grains are angular quartz about 0.006 mm long. Dispersed through 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 are light-gray claystones which swell notably when wet. In these, 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 Chinle sediments. Allen (1930, p. 286), commenting on the mottled effect of the Chinle, suggests that this peculiar type of coloration developed in bentonitic sediments 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. Williams and others, (1953, unpublished report, p. 15) report the unit as about 450 feet thick in the Monument Valley area; this variance, however, reflects differing concepts of the upper and lower contacts.

The section measured on the east flank of Tyende Mesa below Owl Rock (fig. 2) is characteristic:

Section of Petrified Forest member of Chinle formation measured at Owl Rock, about 7 1/2 miles north of Kayenta, Ariz.

	Feet
Owl Rock member of Chinle formation	
Petrified Forest member of Chinle formation	
Claystone, mudstone, and siltstone grayish brown to red, mottled; interbedded platy lenses of brown medium-grained sandstone; locally 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 popcorn-like, surface weathers to form angular to rounded fragments; locally mudstone gives way laterally to siltstone with intercalated medium-grained sandstone lenses about 2 feet 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 distributed sparsely 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 Ariz., but elsewhere in northern Arizona, (Camp and others, 1947, p. 8) invertebrates such as molluscs are present, as well as vertebrates such as fishes, (Pyctodonts, Semionotids) amphibians, (Metoposaurus) and reptiles (Coelophysis).

With the continued slackening of stream flow first apparent during the later stages of Monitor Butte deposition siltstones and claystones 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 even and monotonous. Some volcanic activity is suggested by the presence of volcanic shards.

<u>Owl Rock member</u>.--The Owl Rock member of the Chinle formation is a series 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, Ariz., 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 included subangular to angular nodules of black chert scattered irregularly throughout the beds. A light blue gray (5B 7/1) color predominates although locally greater concentrations of chert tend to darken the limestone beds to gray-blue. The ledges formed by these limestones normally range from about 2 to 20 feet thick 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 feet to about 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 in thickness. A comparable thickness for this unit is reported by Gregory (1917, pp. 44-45) who cites a thickness of 152 feet for this member of the Chinle at the mouth of Tseyi-hat sosi Canyon near Boot Mesa (fig. 2). Williams and others, (1953, unpublished report, p. 16) report, however, a thickness of 300 feet for the "B" member (Owl Rock) of the Chinle in the Monument Valley area. The discrepancy between my measurements and those of Williams and his associates results from the selection of different contacts by the two parties.

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 7 1/2 miles north of Kayenta, Ariz.

	Feet
Church Rock member of Chinle formation	
Owl Rock member of Chinle formation	
Limestone, pale gray green, cherty, persistent cliff-former; weathers to form blocky masses	7
Mudstone, pale red brown, some intercalated siltstone lenses; forms gentle slopes	11
Limestone, pale gray green; includes black angular chert nodules; persistent cliff-former	2
Mudstone, pale red brown, forms gentle slopes ..	2
Limestone, gray green; includes black angular chert nodules; cliff-former	2

	Feet
Siltstone, brown, massive, very slightly fissile; locally stands as vertical face	11
Mudstone, pale red 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 red 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, red 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 contrast markedly with the underlying gray-green mudstone, siltstone, and cherty limestone beds.

Although the upper contact commonly is easily discerned, in places the sediments of the Owl Rock member intertongue with the overlying Church Rock member. Along Comb Ridge in the Monument No. 2 area the mottled gray-green siltstone beds of the Owl Rock member are replaced laterally by the red-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 sediments. 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 J. B. Reeside, Jr. 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 Shinarump deposition had slackened sufficiently by the close of Petrified Forest time to permit the formation of ephemeral fresh-water playa lakes. In these, dense, massive, dark-gray limestones of limited extent were deposited. These limestone beds in turn were soon buried by siltstones and claystones brought in by sporadic revivals of stream flow.

Church Rock member.--Overlying the gray-green cherty limestone and claystone beds of the Owl Rock member are the reddish-brown (10R 4/3) parallel and crossbedded 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 (Williams and others, 1953, unpublished report, p. 20). The sorting is consistent and uniform. Most of the material is silt size although local lenses of sandstone are present. Grains are sub-angular with only a very few showing any degree of rounding. The major mineral is colorless quartz with all of the grains coated by a thin film of iron oxide.

The Church Rock is remarkably uniform along most of its outcrop. The following section measured along Comb Ridge near Kayenta, Ariz. is considered typical:

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

	Feet
Wingate sandstone	
Church Rock member of Chinle formation	
Siltstone, reddish brown, fissile, even-bedded; weathers to form nodular ledges	12

	Feet
Siltstone, reddish brown, crossbedded; locally interbedded lenses of fissile shaly siltstone	11
Sandstone, graybrown, 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 feet on a side	3
Siltstone, reddish orange to reddish brown, even-bedded, slightly fissile; mottled surface covered with light gray spots about two inches in diameter	75
Siltstone, reddish brown, even-bedded; locally discontinuous; mottled 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, massive, fissile; locally discontinuous	6
Siltstone, reddish brown, even-bedded although locally cross-bedded; 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.

Wherever seen 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 showing 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 sediments of the Wingate sandstone.

I interpret the intertonguing between the Owl Rock and Church Rock members as confirming the concept that the Church Rock is an integral part of the Chinle formation. This viewpoint is not held by J. W. Harshbarger and C. A. Repenning of Ground Water Branch, Water Resources Division, Geological Survey, who have studied the Chinle-Wingate relations south of the Monument Valley area. In several localities on the Navajo Indian Reservation they have noted an irregular erosional surface overlain by a thin granule pebble conglomerate between Divisions A and B (Church Rock and Owl Rock members) of the Chinle (Harshbarger and others, 1951, p. 96). Further, they cite intertonguing relationships that exist 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 plus the erosional surface and the overlying granule pebble conglomerate Harshbarger and Repenning contend that the Chinle-Wingate contact is below the Church Rock (Division A). This interpretation would remove the Church Rock (Division A) from the Chinle and assign it as the basal member of the Wingate sandstone.

I am 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., I was unable to find such a horizon. In the Monument Valley area I have not found a pebble granule conglomerate at the base of the Church Rock member nor have I found an erosional surface. Moreover, I have not perceived any intertonguing relations between the Church Rock and the Wingate in the area studied. Similar lack of intertonguing between Division A of Chinle (Church Rock) and the Wingate sandstone was reported by A. F. Trites for the White Canyon district, Utah; J. D. Sears for the San Juan River area; and R. Q. Lewis for the Monument Valley, Utah area, and the Elk Ridge area, Utah (all personal communications).

Unfortunately what fossil evidence is available affords little assistance in the solution of this controversy. Faced with this problem and pending further stratigraphic work the Geologic Names Committee of the Geological Survey has ruled that north of Laguna

Creek (fig. 2) Division A (of the Chinle) is to be known as the Church Rock member of the Chinle formation. South of Laguna Creek, however, the same sequence of strata is to be known as the Rock Point member of the Wingate sandstone.

I am indebted to C. A. Repenning of Ground Water Branch, U. S. Geological Survey, for the following information concerning the fossil content of strata (i.e., Rock Point) stratigraphically equivalent with 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 Letten Kohle and Lower Keuper of the German Triassic. Hence, on what fossil evidence exists the age of the Rock Point (i.e., Church Rock) is Triassic.

Glen Canyon Group

Wingate sandstone

Overlying the Church Rock member of the Chinle formation is the reddish-brown (10R 5/4) crossbedded massive fine-grained Wingate sandstone, the basal member of the Glen Canyon group. The unit is a cliff-former and commonly crops out in its full thickness. A close-spaced near-vertical fracture system has been superimposed 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 built trails.

On weathered surfaces the Wingate is a deep reddish brown although locally darker surface stains give the formation a much more somber hue. On fresh surfaces the rock is much 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 selected grains an angular appearance. 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 predominantly by calcium carbonate and to a lesser extent by secondary silica and iron oxide. Coating all of the grains is a thin film of iron oxide.

The Wingate sandstone thins to the east and to the southeast from the Monument Valley area (Harshbarger and others, 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. At the northeast tip of Skeleton Mesa, however, it is about 360 feet thick. At Boot Mesa the Wingate is about 350 feet thick, and Harshbarger and his colleagues (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 his colleagues (1951, p. 96) report such intertonguing relationships and Baker (1936, p. 49) similarly reports that in the Utah sector 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 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, Ariz. Previous reports have tentatively classified the Wingate as Jurassic (?). However, in the

Lukachukai area fossils of Triassic age have been found in sediments (i.e., Rock Point) that intertongue with the Wingate. On this basis, J. W. Harshbarger and C. A. Repenning have proposed, and the Geologic Names Committee of the U. S. Geological Survey accepted, a Triassic age for the Wingate sandstone.

The tangential crossbedding that marks the Wingate sandstone of the Monument Valley area indicates that the unit was formed by winds under terrestrial conditions of extreme aridity. Most of the sediments came from the northwest (Williams and others, 1953, unpublished report, p. 20). The Monument Valley area seems to be near the center of the Wingate's gross distribution pattern, which is in the form of a huge 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 formed by a commingling of water-worked and wind-worked material. They consider the center of the basin, however, to be composed of eolian material.

Jurassic (?) system

Kayenta formation

The middle member of the Glen Canyon group is the Kayenta formation, probably of Jurassic age. The Kayenta is a pale reddish-brown (10R 5/5) to grayish-red (5R 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 small step-like 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 lithology 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, massive, and show good large scale crossbedding. Lenticularity is typical of all the beds comprising the Kayenta whether they are of shale, sandstone, limestone, or conglomerate. Intertonguing between these units is common and results in rapid changes in lithology along the strike.

In gross aspect the Kayenta is reddish brown, and locally grayish red. The strata range in color from dark orange 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 mm - 0.15 mm) to fine-grained (0.20 mm). Most of the grains range in shape from subangular to round but some grains 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 lithology 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. All 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. This erratic thickening and thinning is well-displayed in a series of measured sections which extend from Skeleton Mesa on the west to Garnet Ridge on the east (fig. 2). At Skeleton Mesa the Kayenta maintains an average thickness of 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 Adachijiyahi Canyon about 9 1/4 miles west of Agathla Peak

	Feet
Navajo sandstone	
Kayenta formation	
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

	Feet
Sandstone, light gray to buff, platy, crossbedded, fine-grained, ledge-former	5
Sandstone, 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 feet thick by local lenses of pebbles	29
	102

Wingate sandstone

The upper and lower contacts are arbitrary. I have included within the Kayenta all those units that show distinct irregular bedding planes. In many localities throughout the area I 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 unio pelecypods, 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. Dept. 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) reads as 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 conglomerates, irregular bedding, channeling, and general coarseness of the sediments 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 (Williams and others, 1953, unpublished report, p. 20). 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 (10YR 8/2) massive cross-bedded sandstone. Where it is protected by a resistant cap rock it forms high cliffs. Unprotected, the formation weathers into rounded steep-sided mammillary forms; but 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 (A, pl. 2), and Inscription House are in the larger of these alcoves.

Although most of the Navajo consists of massive and cross-bedded 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 vitreous quartz scattered through a limestone matrix. In the eastern part of the area these beds cap mesas.

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 the majority of the grains ranging from 0.10 mm to 0.26 mm in diameter. 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 (fig. 2), 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 (fig. 2). 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 on a tilted plane parallel to the planes of crossbedding of the Navajo sandstone. 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 a huge accumulation of wind-worked sand that probably came from the west or northwest (Williams and others, 1953, unpublished report, p. 20). The local dark-gray dense unfossiliferous limestones 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 northeast trending wedge-shaped mass of eolian sand

(Baker, Dane, and Reeside, 1936, p. 44) that constitutes the Navajo sandstone.

San Rafael group

Carmel formation.--The Carmel formation, basal member of the San Rafael group, is exposed only in the southeastern and eastern parts of the Monument Valley area, Ariz. 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 (10R 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 chlorite-like mineral are accessory minerals. The average grain size is about 0.06 mm but many of the grains are as small os 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 mm 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.

Ripplemarks 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 up to 8 inches high and 6 inches thick. The walls may represent mud cracks that were filled with sand and that were subsequently cemented. The walls now are more resistant to erosion than the surrounding rock.

The Carmel is about 118 feet thick at Garnet Ridge (fig. 2). 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 member 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, Ariz. The formation, however, 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 innundation 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 (i.e., 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, Ariz., 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 re-advance of the Carmel Sea resulted in deposition of silts and sands 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 orangish 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 covered by boulders below a vertical wall formed by the upper part of the formation. On Garnet Ridge (fig. 2), 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 to the "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 orangish-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 as 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 0.10 mm. in diameter. The orangish 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 lithology of the whole formation changes rapidly 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, giving the rock a dull dark reddish brown color. Iron oxide is the principal cementing agent although calcite and authigenic silica are important locally. The siltstone beds range in thickness from 1/10 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 (A, pl. 4). The sandstone is even-bedded and 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 prior to 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 prior to deposition of the overlying Summerville formation, as the undeformed basal sandstone of the Summerville rests on the truncated edges of the folded upper Entrada beds (B, pl. 4).

The thickness of the Entrada, as measured on Garnet Ridge, is about 100 feet. The thickness varies 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 Entrada sandstone beds have been planed smooth and are overlain directly by about 5 feet of massive Summerville sandstone.

On the withdrawal of the Carmel sea a surface of low relief was exposed. On this surface wind-worked material was deposited most of it derived 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, C. T., 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 (fig. 2). 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.

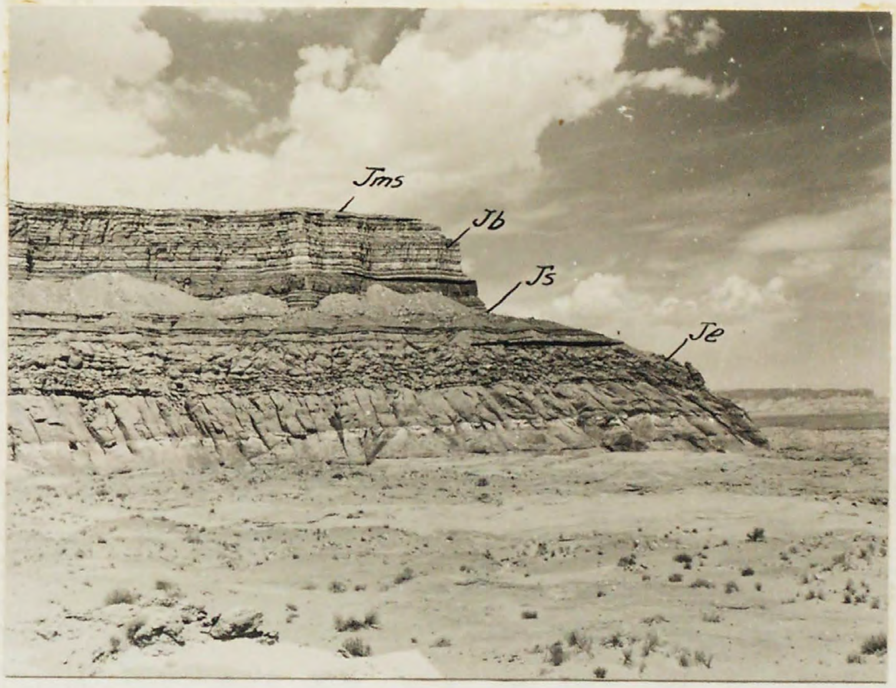

Plate 4. -- A. - Sedimentary strata forming Baby Rocks Point. The Point is capped by the Salt Wash member of the Morrison formation and has part of the Entrada sandstone exposed at its base.

B. -- Unconformity between the crumpled and distorted uppermost beds of the Entrada and the even-bedded overlying Summerville at Baby Rocks Point.

Jms - Salt Wash member of the Morrison formation.
Jb - Bluff sandstone.
Js - Summerville formation.
Je - Entrada sandstone.

Lithologies 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 which contains in its upper part, some sandstone beds that are white and silty. At Baby Rocks Point the Summerville is about 35 feet thick (A, pl. 4). A section measured on the west flank of Baby Rocks Point is considered characteristic of the Summerville at that locality.

Section of Summerville formation measured at Baby Rocks Point about 10 miles southwest of Dinnehotso, Ariz.

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

Measurements of the thickness of the Summerville formation at Garnet Ridge range from 39 to 47 feet. A section measured on the northwest side of Garnet Ridge 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 orangish brown, very well-sorted, fine-grained, cross-bedded; lower 18 inches bleached white or very pale green; the bleaching locally extends downward about an inch into the Entrada sandstone	5
Total thickness of Summerville	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 in diameter 0.13 mm. 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 encountered 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 near shore 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, Ariz. 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 (B, pl. 4). 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 at Baby Rocks point.

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

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

	Feet
Shale, chocolate brown; bounded by one-quarter of an inch thick white sandstone seams	1
Sandstone, reddish brown, even-bedded fine-grained	4
Shale, reddish brown, even-bedded, fissile; intercalated white sandstone lenses	6
Total thickness of Bluff	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; with 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

	Feet
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
Total thickness of Bluff	99

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 degrees 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 sandstones are locally crossbedded. The grains are frosted, cemented by calcite, and range in size from 0.06 to 0.28 mm. Polygonal networks similar to those on sandstone beds in the Carmel formation, 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 essentially one massive bed of white crossbedded medium to coarse-grained sandstone 200 to 350 feet thick. In the Monument Valley area, Ariz., 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 mud-cracks, suggests that the Bluff was deposited in a near-shore environment similar to that of the Carmel. Farther northeast, the massive cross-bedded character of the Bluff suggests a more landward environment.

Morrison formation

Salt Wash sandstone member.--Only the basal part of the Salt Wash sandstone of the Morrison formation is preserved in the Monument Valley area, Ariz. On Baby Rocks Point and Red Point (fig. 2) the basal 30 to 50 feet of the Salt Wash form a more or less flat-topped cap rock (A, pl. 4). On Garnet Ridge only 32 feet of the Salt Wash are preserved.

The Salt Wash remnant on Garnet Ridge is predominantly a yellowish-orange (10R 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 beds but some layers contain grains of coarse sand, and even pebbles up to an 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 sub-round to round and consist primarily of quartz, with minor amounts of chert.

The Salt Wash is very weakly cemented by the 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 principle 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). 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, Ariz., include dune sand, alluvium, colluvium, talus breccia, 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. C. B. Hunt (1955) has made some attempts at dating the archeological sites in Cane Wash (fig. 2) through a study of the surficial deposits.

Two ages of dune sand are in Cane Valley. These have been identified tentatively as "old dunes" (pre-occupation) and "new dunes" (post-occupation). No attempt was made to separate these in the field, however, and they are shown on figure 2 as dune sand (Qd). The new dunes are post-occupation, unconsolidated, and subject to transport by the wind; they have not been stabilized. The older dunes are pre-occupation, stabilized, dark brown in color, and contain fossil plant matter, principally as tree stumps of cottonwood, juniper, and pine (Hunt, 1955, p. 584).

Throughout the area alluvium, more or less 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 in Oljeto Wash have suggested a combined dune sand and alluvial

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Throughout the area alluvium, more or less 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 in Oljeto Wash 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 pre-pottery inhabitants (Hunt, 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 post-occupation alluviation.

A study by Hunt (1955) of the interrelationships between the alluvial fills, the two ages of dune sand, and the archeological sites in Cane Wash (i.e., 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) A period of great aridity (the Thermal maximum) when the "old dunes" formed.

(3) A moist period when alluvial fill (i.e., the Tsegi formation) and lake beds developed. The area was inhabited by a pre-pottery people at this time.

(4) A gradual diminuation of water supply coupled with several severe drouths resulted in a gradual exodus of the inhabitants (the Anasazi people) from the Navajo country. The exodus occurred in the period 1275-1300 A.D.

(5) A third alluvial fill (the Naha formation) was formed in the period 1300-700 A.D.

(6) Dune sand, post-occupation, began covering the alluvial fills.

(7) The present arroyo cutting began in the last two decades of the 19th century.

Eruptive Rocks

General statement

The sedimentary rocks of the Monument Valley area, Ariz. 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 color of the sedimentary rocks through which they protrude.

Three types of eruptive structures can be distinguished; these are:

(1) Volcanic plugs composed principally of lamprophyric tuff-breccia;

(2) Igneous dikes also composed of lamprophyric rocks;

and

(3) Rubble pipes, composed of ultra-basic material, and a heterogenous mixture of sedimentary and igneous inclusions.

The plugs and dikes are more or less widely scattered throughout the eastern half of Monument Valley. Structures of similar form and composition are common elsewhere on the Navajo Indian Reservation (Williams, 1936). The rubble pipes, on the other hand, are rare. There are about half a dozen of them in this part of Arizona, and these are confined to 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 volcanic and called diatremes (Williams, 1936) bear a superficial resemblance to the rubble pipes. The diatremes differ, however, in structure and chemical composition from the rubble pipes and are not to be compared with them. The rubble pipes appear to be chemically and structurally similar to the diamond pipes of South Africa. Balk (1954, p. 381) describes kimberlite tuff plugs exposed in Buell Park, Ariz. which seem to be similar to the rubble pipes at Garnet Ridge.

Igneous plugs and dikes

The denuded volcanic plugs are the most spectacular of the eruptive bodies. They are concentrated near the middle of Monument Valley in a rude line that trends somewhat west of north. In general, the line of plugs is near the crest of the major structural feature of the region, the Monument upwarp. The most conspicuous plugs are Church Rock (just south of the area), Chaistla Butte, and Agathla Peak, (fig. 2 and B, pl. 1) the latter a tremendous monolith that rises over 1,400 feet above the surrounding plain and is visible for many miles.

All the volcanic plugs bear a certain resemblance. They are all a dark gray green, all stand as cones surrounded by a flaring apron of sedimentary rocks, and all are oval in plan. Lithologically they are coarse tuff-breccias and are composed of a chaotic mass of angular to rounded fragments of volcanic debris, as well as sedimentary and crystalline rocks. Large angular blocks of lamprophyre are incorporated in a younger lamprophyric matrix which in some places 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, and without structure. The included blocks range in size from pebbles and cobbles to huge boulders 20-30 feet on a side. Pulverized sediments fill the interstices between the larger fragments. The entire mass has been thoroughly cemented by calcite, and it is this cement, in large part that imparts the strength to the tuff-breccia. The included fragments are only slightly altered. A few of the sedimentary inclusions have weakly bleached surfaces but appear to be otherwise unaltered, and so are presumed to be unchanged from their original condition.

Most of the crystalline inclusions are acidic rocks of the granite family and the majority seem to be unaltered. A few, however, principally those that contain much feldspar have light pink porous "rinds" up to one-quarter of an inch thick formed mainly on their exposed surfaces. Secondary minerals are scarce.

Most of the material in the volcanic plugs is a heterogeneous mixture of unsorted debris. A prominent exception to this lack of sorting is in the upper part of Agathla Peak;--here the debris shows some sorting and rudimentary bedding.

All of the volcanic plugs are cut by black dense dikes, that trace irregular courses through the tuff-breccia. Although most of the dikes are less than 12 feet thick, several are more than 50 feet thick. Others swell and pinch as they branch and anastamose or thin abruptly as they pass around large sedimentary inclusions in the tuff-breccia. On Agathla Peak a few of the dikes appear to have followed bedding planes in the tuff-breccia.

These dense black dikes are found principally in Agathla Peak and Chaistla Butte. Elsewhere the dikes that cut the sedimentary strata are composed primarily of tuff-breccia. These are in elongate swarms and most are confined to the eastern part of the Monument Valley area. One extensive series of dikes occupies fractures along the crest of the Gypsum Creek dome (fig. 2) and trends parallel to the long axis of the dome. Most of the tuff-breccia type of dikes, however, are on the flank of Comb Ridge where they occupy fractures that are radial to the Monument upwarp.

Many of the tuff-breccia dikes are less than 10 feet in width, and less than one-half mile long, although one dike is 1-1/4 miles in length. Some dikes merge to form wide spots that can properly be called necks. Such is the case at the Porras Dikes (fig. 2) where the necks stand as towers that rise about 400 feet above the surrounding ground, but the dikes form low irregular ridges 2 to 30 feet high that protrude above the enclosing sedimentary rocks.

All of the dikes including those that cut the tuff-breccias in the volcanic plugs as well as those that occur as dike swarms are relatively homogeneous in structure and texture. Further, all of the dikes contain inclusions almost all of which are crystalline. Only a few sedimentary inclusions have been found in the dikes, and these are but a few inches in long dimension. The inclusions are slightly altered, principally along the rims and fractures.

Most of the dikes are much more foliate near the contacts than away from them 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 although weak chilled zones are found locally. The intruding masses have torn off and included small pieces of the country rock but many lack chilled zones. Further, the mineralogic composition of igneous material several feet from a contact is identical to that at the contact. The country rock, however, is altered at the Porras Dikes and at the dike swarm that is exposed on Gypsum Creek dome. At the Porras Dikes the wall rock is silicified locally and the silicification extends laterally several inches from the dike contacts.

Along Gypsum Creek dome a limestone lens in the Halgaito that is pierced by one of the dikes is considerably darker than normal and apparently is silicified.

All of the dikes are nearly alike mineralogically, and are also similar to the matrix of the tuff-breccias. Minor variations in composition are normal and expected but the paucity of mineralogic differences points up the close relationship between the various plugs and dikes of the Monument Valley area. In general the igneous intrusives are basic alkaline rocks characterized by a high potash content (Williams, 1936, p. 148). Both the plugs and dikes are best classified as minettes.

Megascopically, the intrusives are sugary-textured, medium purplish or greenish gray to black, and are spotted with phenocrysts of biotite and diopside which locally form aggregates. The biotite phenocrysts occur as thin books and are distinctly of two generations. The larger ones are as much as 4 millimeters in size and the smaller ones range up to about 2 millimeters. The largest diopside crystals are about 3 millimeters long and 1 millimeter wide, but, except for small second generation crystals disseminated throughout the groundmass, they are bunched into aggregates as much as 8 millimeters across.

Microscopically, the groundmass is mostly hypautomorphic orthoclase feldspar laths with interspersed small automorphic crystals of second generation biotite and diopside. No plagioclase was identified but it is possible that small quantities do exist. Minerals forming both the tuff-breccias and the black dense dike rocks 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 rock are fresh.

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

	Rock No. 1	Rock No. 2	Rock No. 3	Rock No. 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	2.4		
Quartz	2.0			

The age of the volcanic disturbances in the Monument Valley area 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. I found Late Cretaceous (Mancos) fossils in several of the sedimentary xenoliths embedded in the tuff-breccia. Hence my evidence suggests that the intrusions were post-Mancos.

Rubble pipes at Garnet Ridge

Along Comb Ridge, and straddling the Utah-Arizona state line, are several pipe-like bodies made up of a macro-breccia of sedimentary rocks surrounded by eruptive material containing included sedimentary and crystalline rocks. Four of these rubble pipes are in the Garnet Ridge area, Ariz. (fig. 2) where one, about 1,200 feet in diameter, is near the crest of the Ridge and the other three form a group about 2,500 by 4,000 feet in size near the northeast end of the ridge.

The ridge takes its name from the widespread distribution of small garnets on the present ground surface. The garnets seem to be derived principally from the weathering of igneous xenoliths that make up part of the debris in the rubble pipes. Garnets in xenoliths from this area have been reported previously by Sterrett (1909, p. 825), and Williams (1936, p. 135).

Consolidated sedimentary strata that form the ridge consist of the Jurassic San Rafael group, the Bluff sandstone, and the Salt Wash sandstone member of the Morrison formation (table 1). The strata are deformed into an elongate flexure whose axial plane strikes about N. 45°E. and dips 5°-7° to the northwest. Along the northwest flank of the flexure, dips are as much as 10° to the southeast, whereas along the southeast edge, the dips lessen and do not exceed 1° to the southeast.

The surface of the rubble pipes at Garnet Ridge is marked by small hummocks and shallow irregular depressions. Commonly, the breccia blocks of sedimentary material stand as, or hold up, irregularly surfaced knobs which may be as high as 40 feet. In places the rubble weathers to depressions; elsewhere it caps knobs.

The breccia blocks are from tens of feet to many hundreds of feet in length. The largest block seen was nearly 800 feet long, although the average length is about 150 feet. The breccia is made up exclusively of sedimentary rocks of Carmel and younger age. The majority of the blocks are Morrison (Jurassic) in age but several blocks of black shale contain foraminifera which date them as Mancos (late Cretaceous). The blocks are grossly angular, with the largest faces commonly parallel to the bedding, but the edges and corners are abraded and rounded. The dip of the bedding in the blocks longer than 20 feet, is generally toward the center of the pipe but it is not possible in all cases to say whether a block is upright or overturned.

Between the breccia blocks has been injected a light green, slippery-feeling material that is composed predominantly of serpentine altered from olivine. Within this serpentiniferous matrix are inclusions of rounded to angular fragments of clastic sediments, limestones, and crystalline rocks. The sediments are derived largely from Paleozoic strata and the crystalline rocks are presumed to have been brought from the basement. Gregory (1915, p. 109) reports the following crystalline rock types from the Garnet Ridge area; biotite granite, garnetiferous diorite, diabase (?), minette, granite gneiss, prophyritic granite gneiss, garnetiferous diorite gneiss, muscovite schist, and chlorite schist. These crystalline xenoliths range from dust size to rounded boulders more than 20 feet in longest dimension, and they make up the bulk of the eruptive material.

Malde and Thaden (in preparation), state that the serpentiniferous matrix contains the following minerals, listed in order of decreasing abundance: serpentine (antigorite altered from olivine), calcite, white mica altered from olivine, melilite, clay, fresh biotite (perhaps exotic), chrome-diopside, opaque metallic minerals (probably ilmenite and chromite), and zeolites. Minor minerals, some of which may be exotic, include actinolite, hornblende, microcline and other feldspars, pyrope garnet, quartz, gypsum and chrysotile. The matrix is cemented locally by calcite and limonite. Petrographically the matrix resembles serpentinized kimberlite.

The structure of the rubble changes from place to place. The percentage of xenolithic inclusions ranges from less than 20 percent to more than 80 percent without apparent reason. The size of the inclusions may be governed partly by the size of the openings through which the rubble was injected; small openings have only small inclusions in the matrix. The rubble is foliate at many places within a foot or two of its contact with the breccia blocks and with the wall rock. The long dimensions of the inclusions are oriented sub-parallel to the edges of the nearby breccia blocks and wall rock and give the impression that the rubble flowed around them. The rubble matrix seems structureless, possibly due to the microscopic size of the serpentine crystals.

Contact of the green serpentiniferous matrix with the wall rock and with the breccia blocks is everywhere sharp. Many of the sedimentary rocks have been rounded, smoothed, and slickensided; chemical alteration, however, is rare, for even the fossiliferous limestones show little evidence of metamorphism. Where the sedimentary rocks in the breccia or the country rock have been altered, the alteration can be attributed to ground water action. Bleached fractures were seen in one breccia block and in the adjacent rock of the pipe wall, but similar features were not seen elsewhere on Garnet Ridge. Some of the crystalline inclusions have bleached porous rinds. In particular, the acidic rocks seem to have been subjected to this corrosion of their surfaces. It is suggested that at depth the parent material of the green matrix was sufficiently hot or charged with fluids to be highly reactive, especially to the acidic rocks of the basement complex. By the time the parent material in its upward penetration reached the Paleozoic sediments it may have become inert, either through a temperature or pressure drop or through a change in chemical composition.

At two places the rubble has extended into the country rock from the pipes as sills and dikes. The material in these is the same as in the pipes except for short discontinuous veinlets of ankerite parallel to the dike walls. The maximum thickness of the dikes and sills is about 4 feet and, except for the bleached fractures, are the only sites of wall rock alteration. In one place, at the crest of the ridge, the walls adjacent to a rubble dike are cemented by silica so that they stand as ribs several inches thick on either side of the dike.

As the pipes on the northeast end of Garnet Ridge are now exposed at a level near the top of the Jurassic Navajo sandstone, we have but to reconstruct the Mancos surface to demonstrate a subsidence as great as 1,500 feet. The bulk of the breccia, however, is Morrison in age, indicating that most of the subsidence was on the order of 500 to 600 feet and that some of the differential movement of the blocks was greater than 1,000 feet.

A dike at the northeast end of the ridge has been stained with iron to a brownish green color, in addition to having 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 but widen along fractures in the country rock that intersect the dike. The zone closest to the dike is 1-3 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 1-2 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 more abundant in the copper-bearing zone. Tyuyamunite is the only uranium-bearing mineral that has been identified. The uranium and copper seem to be present in specimen quantities only and are probably not derived from the dike material, for the dike contains only trace amounts of uranium and copper.

During the winter of 1951-1952, 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 encountered but the grade was considered inadequate to justify additional work.

Large areas of rubble, in places several thousand feet from the pipes, are interpreted by Malde and Thaden (in preparation), as surficial flows that were derived from the intrusive rubble and that were extruded on a surface only 60 feet or so above the present level of erosion. The required evolution of the pipes, then, that satisfies the structural interpretations of these authors, is an initial period of gaseous explosion, collapse, and rubble injection during Tertiary time under a sedimentary cover that included the Mancos shale, and reactivation of pressure from below in late Quaternary time, 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) classifies all of the eruptive features in Monument Valley as volcanoes and notes their resemblance to the diatremes of the Shwabian Alb. Shoemaker (1953, p. 1514) similarly considers them diatremes and attributes their dissimilar topographic shapes and mineralogic compositions to differing stages of development and levels of exposure. I cannot agree and in general believe that two distinct and different types of eruptive bodies are in the Monument Valley area. Most common are diatreme-like features such as the volcanic plugs. These are represented by Agathla Peak, Chaistla Butte, Church Rock, Alhambra Rock, and many others. Less common are rubble pipes such as are exposed on Garnet Ridge. Two prime factors influence me. First is the totally different mineralogic composition that exists between the rubble pipes and the volcanic plugs. The rubble pipes consist principally of serpentine (antigorite altered from olivine), whereas the plugs are composed primarily of alkalic feldspar (orthoclase), biotite, and diopside, and olivine is present only as a very minor constituent. Second is the totally different shape. All of the plugs are distinct topographic highs, commonly standing well above the surrounding surface. The rubble pipes, on the other hand, have little relief, and normally blend with the adjacent ground surface.

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 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.

Structure

Folds

In this sector 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. 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, Ariz., delineate five subordinate structural elements (fig. 2) near the crest of the Monument upwarp. 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 known structural elements, three others have been noted and are here named. The first, and most prominent, is the Agathla anticline, a broad, symmetrical fold plunging to the southwest. The second is the Tse Biyi syncline, a shallow elongate north-trending irregular-shaped basin. The third is the Gypsum Creek dome, an asymetrical structure with steeper dips on the east flank than on the west.

Organ Rock anticline

The Organ Rock anticline, as exposed in the Utah part of Monument Valley, has been described by Baker (1936, p. 67). Baker has traced it southward from the San Juan River to the 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. It ends 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 west and trends north. 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. The west flank is less steep and dips do not exceed 5° to the west. This flank is marked by minor undulations that are barely perceptible. The west flank extends for about 10 miles to the trough of the Nokai 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 south to the state line. In both Utah and Arizona the axis of the syncline approximately follows the course of Oljeto Wash (fig. 2). South beyond the southern reaches of Oljeto Wash the synclinal axis is within the swale which marks the west edge of Tyende Mesa (fig. 2). The syncline is an asymmetric fold and the steeply-dipping east flank of the Organ Rock anticline forms the west flank of the Oljeto syncline. Because of the asymmetrical nature of the syncline, dips along its east flank 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 sedimentary strata forming the northwest flank of the anticlinal nose (fig. 2). The anticline is a broad symmetrical southwest plunging feature whose southeast flank is Comb Ridge and whose northwest flank merges with the east flank of the Oljeto syncline.

The general trend of the anticlinal axis is to the northeast, although northward it gradually curves to the north and alines with the north trending synclinal axis that marks the Tse Biyi syncline (fig. 2). 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 rocks are flexed downward into a north-trending elongate irregular-shaped basin (fig. 2) here named the Tse Biyi syncline. Near the south end of the basin the synclinal axis, which is continuous with that of the Agathla anticline, 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 lessen along the west flank, where they average 4° although locally dips of 6° have been recorded. Dips along the northeast flank of the basin are low and do not exceed 1°.

<u>Gypsum Creek dome</u>

The third structural element not previously described is here named the Gypsum Creek dome (fig. 2). The axis of the dome forms a broad arc with its concave side facing west. Essentially, the axis trends northeast along the south edge of the dome; near the crest the trend is almost north; and at the north edge the axis strikes northwest. In all, the axis is about 8 miles long. The dome is asymetrical with dips averaging 7° along the east flank, and 3° along the west flank. To both the north and south, the plunge is about 1°. Closure on the dome is about 400 feet.

Southwest of the dome and separated from it by a small downward flexure of the strata is a small anticline whose center is about 1 mile south of Meridian Butte (fig. 2). The axis of the anticline trends northeast and may be continuous with the axis of the Gypsum Creek dome.

Dikes occupy a series of fractures that are along the crest of the dome and are parallel to the axial trend. Most likely, north trending tension joints were developed along the crest of the anticline at the time of the flexing. Subsequent igneous material was intruded into these fractures and consolidated to form the dikes.

Fractures

Both faults and joints are exposed in the Monument Valley area, Ariz. In general, faults are rare and commonly appear as small scale normal and reverse faults involving displacements of only a few inches or feet. Many of the faults are intraformational and are restricted to the Monitor Butte member of the Chinle formation. Joints are common and prominent. They include minor breaks that can be traced for distances of a few hundred feet, as well as large cracks that extend for miles. They penetrate all formations and commonly will pass from one formation to another without any lateral displacement. On the surface as a result of differential erosion, most of the joints appear as gaping cracks 6-10 inches wide; some, however, are filled with sand and support a growth of grass and shrubbery that contrasts markedly with the adjacent barren rock. Along many mesa tops a reticulate pattern is formed by the grass growing in the sand-filled joints. Many of these joints appear as individual widely spaced features. At depth in those mines where the workings permit examination of the joints they commonly are clustered in fracture zones 2 to 6 feet wide. Most are near vertical and sealed with fibrous quartz, calcium carbonate, and gypsum.

In the sandstone beds that act as 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 with the normal reddish brown color of the strata altered 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 joints extend parallel with the cliff face, 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 the third set strikes about due east. All sets are vertical or near vertical.

GEOLOGIC HISTORY

For purposes of brevity the pertinent details of the geologic history of the Monument Valley area, Ariz., are summarized in Table VII (in pocket).

ECONOMIC GEOLOGY

Ore deposits

General statement

Deposits of economic interest in the Monument Valley area, Ariz. include uranium, vanadium, and oil. Elsewhere in the same general region small exposures of gold, silver, and copper have excited interest but no sizeable deposits have been found. The great interest displayed by the public since 1948 in uranium-vanadium deposits has furnished, in part, some basis for this report. In general, this part of the report discusses the history of the Monument Valley area, Ariz. in terms of uranium-vanadium production, and attempts to furnish some concepts and prospecting guides that might assist the general public in their search for new and valuable deposits of uranium and vanadium.

Uranium-vanadium minerals have been reported from the Monument Valley area at various times. Gregory (1917, p. 148) mentions carnotite among pebbles of the Shinarump conglomerate, and Baker (1936) in his unpublished notes compiled during his work in the Utah sector of Monument Valley also notes the presence of "carnotite" associated with fossilized wood in the Shinarump conglomerate member of the Chinle formation.

The history of uranium and vanadium ore production from the Monument Valley area, Ariz., is essentially the history of two deposits: the Monument No. 1 and the Monument No. 2 areas (fig. 1). Both of these areas contain scour channels filled with Shinarump sediments in which sizeable deposits of uranium and vanadium ore have been found. In both places, the Vanadium Corporation of America has been the major concern mining uranium and vanadium ore.

Relatively little is known concerning their early history. Both appear to have been active in the period 1942 to 1944 as producers of vanadium ore, and the Monument No. 2 area assumed considerable importance as a producer of uranium and vanadium ore on the Colorado Plateau after 1948.

The Monument No. 1 area began producing ore in 1942 and continued intermittently until 1950 at which time the Vanadium Corporation of America abandoned their mine and destroyed the adits as a safety measure. 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 Company of Farmington, N. Mex., dug a small adit into the flank of the Monument No. 1 channel and began producing 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 area in 1953. In 1954 the Footz Mining Company drilled an unexplored part of the Monument No. 1 channel and discovered and began to mine a sizeable ore body.

In 1942 a Navajo Indian named Luke Yazzie staked a claim on the Monument No. 2 area and then told one of the traders in the vicinity, Mr. Harry Goulding, of this mineralized exposure. Goulding contacted Mr. Denny W. Viles, one of the officials 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 from the Navajo Tribal Council.

Mining was carried on during the period 1942-1945 but production was slight. In 1948 production began on a large scale when a bulldozer operation uncovered rich vanadium ore at the surface. At first, the ore was mined by stripping methods. By 1949 production had tripled and the Vanadium Corporation of America began underground mining operations. In 1950 the first underground mining was started at the North Red Oxide Workings (fig. 4) and subsequently in the same year other underground workings were begun at the South Workings (fig. 4). Since then the underground workings have extended along the length and width of the channel. In 1952 the company began to alter the operation gradually from underground to stripping methods. 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. Thus, the Climax-Uranium Company has mined along both flanks of the channel and at the very southern tip. The northern tip of the channel has been mined by a Navajo Indian named John M. Yazzie and his associate Thomas Clani. Two Navajo Indians, Black and Blackwater, have also mined ore from the flank of the channel. Their workings were leased in 1953 to two white men, W. E. Pollock and B. N. Byler.

Because the ore deposits in the Monument Valley area differ markedly one from another, no single description suffices. In general the ore deposits are in Shinarump sediments that fill scour channels in underlying strata. These deposits are composed of more or less discrete ore bodies scattered irregularly through the channel sediments. The ore bodies differ in shape and size; many are cylindrical and log-like, others are tabular and irregular in shape, but all seem to be related in some inexplicable fashion to these scour channels.

Any statement made concerning the uranium-vanadium ore deposits of the Monument Valley area, Ariz., would necessarily have to be based on only two deposits; the Monument No. 1 and No. 2 areas. Consequently, such a statement could rightly be regarded as hardly more than a qualified guess. However, when the much larger area included in the Arizona and Utah parts of

Monument Valley is considered, the number of ore deposits increases. Further, new exploration programs carried on near Oljeto, Utah primarily by the U. S. Atomic Energy Commission but also by private operators has increased our knowledge of favorable ground. In general, the known ore deposits, plus the data secured by the exploration programs suggest that the ore deposits in the Monument Valley area have some features in common; these are:

1. They are all in the Shinarump conglomerate.
2. They are all in Shinarump sediments that fill channel scours.
3. The predominant amount of ore is in the basal part of the channel fill, although mineralized ground is found elsewhere in channel sediments.
4. In channel sediments many of the ore deposits are associated with some form of plant remains, either silicified wood, carbonized wood, or carnotitized wood.

If one puts aside for the moment that the Shinarump conglomerate is important primarily because it is the host rock, and concentrates on which of the other features noted above are most significant, the occurrence of ore deposits in channel sediments seems highly meaningful. The importance of channels and channel sediments is emphasized by the known occurrence and distribution of the mineralized outcrops;--almost all are in channel sediments. The channels and their fill, therefore, have assumed considerable importance in the discovery of new deposits of uranium ore. A major part of our work concerned questions regarding channel types, extent, widths, depths of scour, origins, time of formation, and a general inquiry into all of the questions that might assist in explaining why uranium ore is localized in channel sediments.

Ore bearing beds

Channels

Appearance.--The work in the Monument Valley area, Arizona and Utah, has repeatedly confirmed the fact that all of the uranium ore bodies are in symmetric and asymmetric troughs cut into the Moenkopi and filled with Shinarump sediments. These troughs are known as channels and they accentuate the unconformity between the Shinarump and the Moenkopi. Cross-sections of some typical channels of the Monument Valley area, Ariz., are shown in figure 5 and frontispiece.

The channels crop out in two different ways in the Monument Valley area. Principally, they are exposed along mesa edges and in valley walls as U-shaped depressions cut into the Moenkopi formation and filled with conglomeratic sandstone. In this mode of outcrop the channels are buried beneath overlying beds of Shinarump conglomerate and are exposed only along canyon walls or mesa rims (A, fig. 6). Where erosion has been more extensive and the overlying beds of Shinarump have been removed, the channel sediments appear as narrow elongate exposures of gray conglomeratic sandstone bounded by the red shaly siltstone of the Moenkopi formation. Where erosion has proceeded still farther, the softer sandstone and shale beds of the Moenkopi have been removed, leaving the more resistant channel fills as ridges (B, fig. 6).

Classification.--Commonly, the channels are difficult to trace, many because they are not well-exposed, others because they vary 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, 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. The shorter ones are designated "short channels", and the longer ones "long channels". A distance of 2 miles has been established arbitrarily as the dividing line between the basin-like short channels, and the more continuous long ones.

As a result of a drilling program completed by the U.S. Atomic Energy Commission (Chester and Donnerstag, 1953, unpublished report) in the Monument No. 2 channel, it is now known that these shorter channels terminate in curves, gently concave upward (B, fig. 7). Because there has been no extensive drilling in continuous long channels, how they end is unknown.

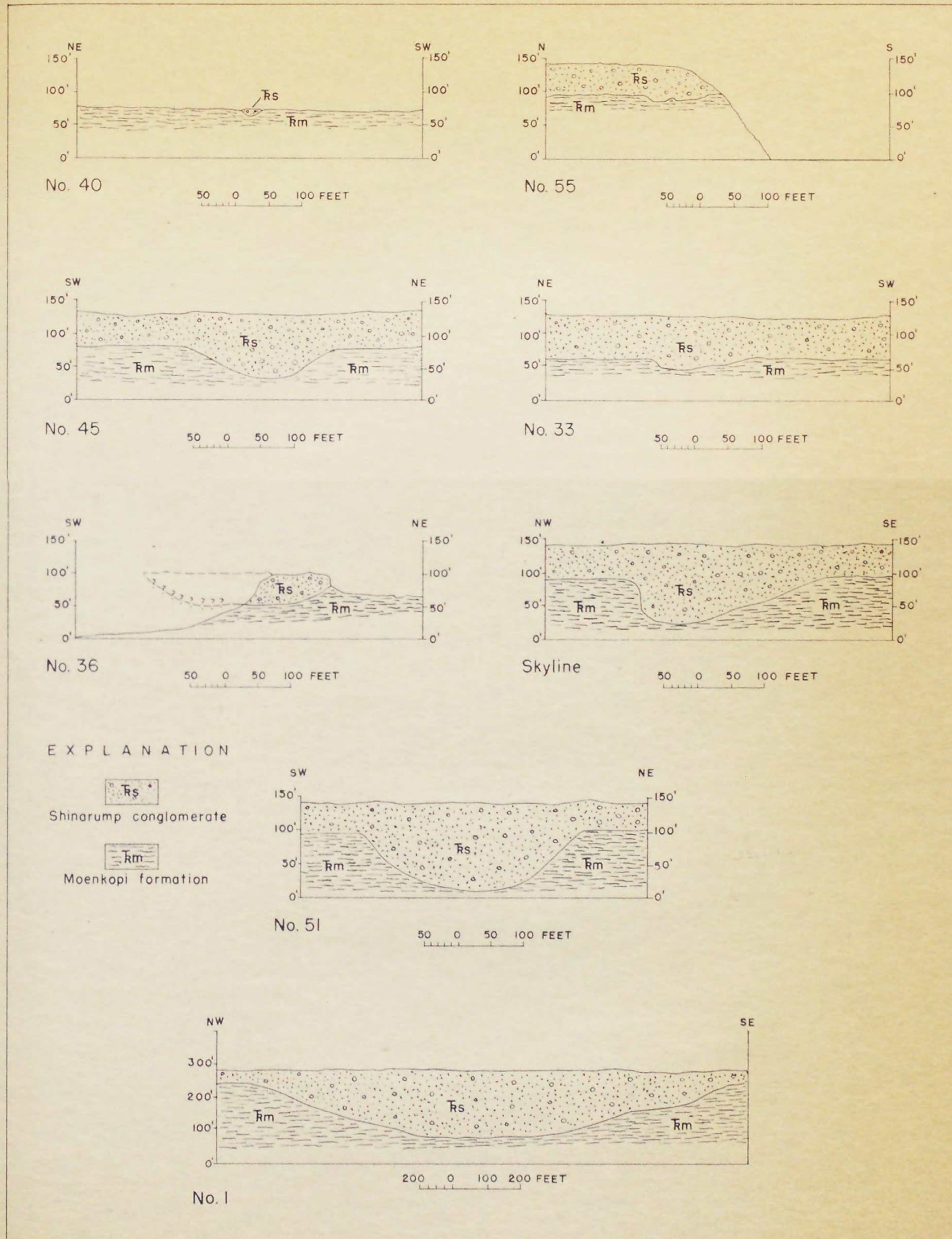


Figure 5. -- Cross-sections of typical channels in the Monument Valley area, Ariz. Locations of channels are shown in figure 3. Uppermost pair are classified as narrow channels. All the remainder, excepting the bottom one, are classified as intermediate channels. The bottom channel is classified as a broad channel.

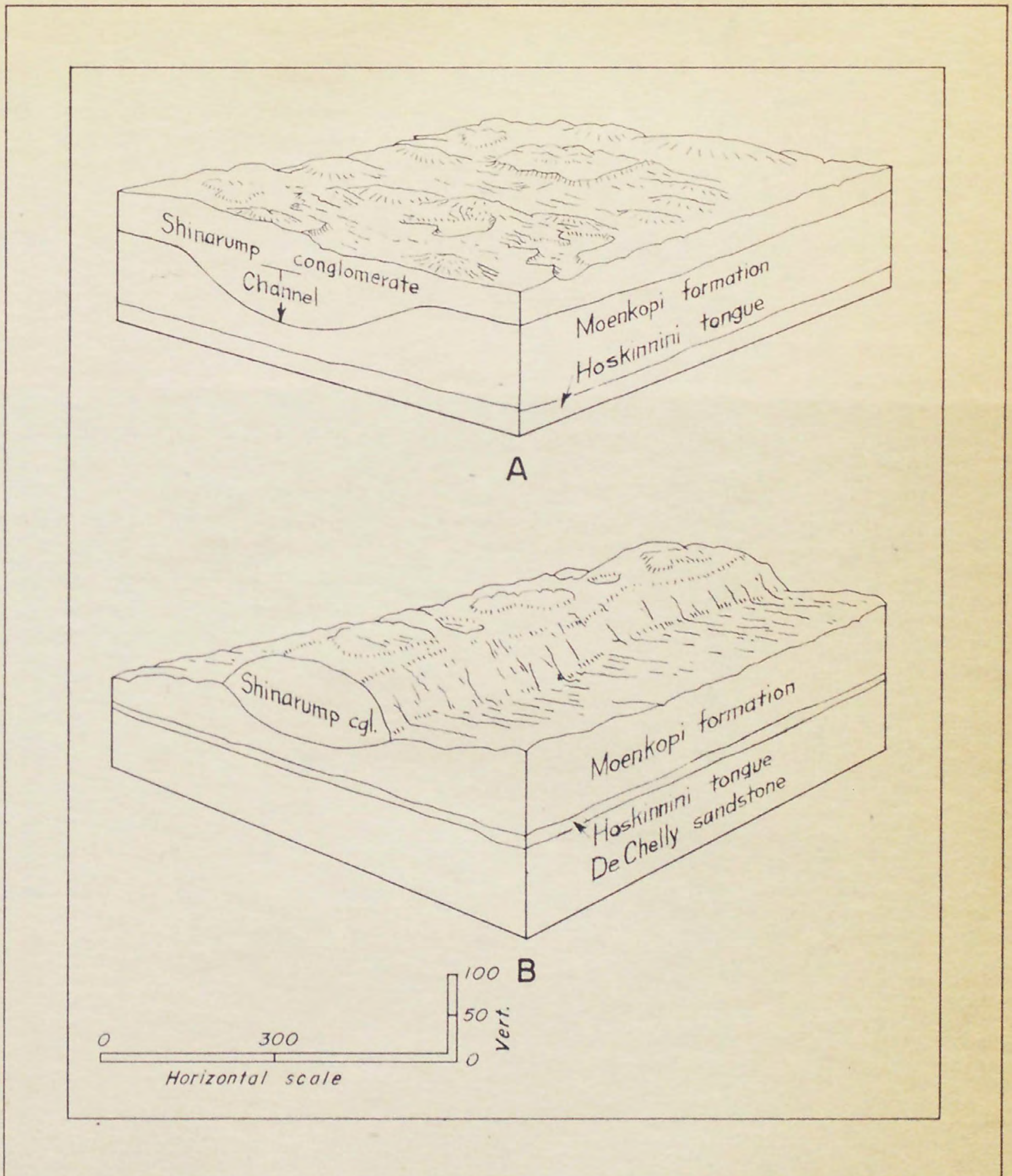


Figure 6. -- Block diagrams illustrating modes of outcrop of channels in the Monument Valley area, Ariz.

A. - Channel buried beneath overlying beds of Shinarump conglomerate.
B. - Erosion has removed overlying beds and adjacent shaly siltstones leaving the resistant channel sediments standing as a ridge.

Trends

Many channels trend northwest, although this is not universal as figure 3 exhibits. It does seem, however, that a northwest trend is the dominant orientation. In an area as small as Monument Valley, Ariz., this northwest orientation is merely suggested by a diagram of the channel trends (A, fig. 8). However, when a diagram (C, fig. 8) is prepared of all the channels noted in a much larger area (the Utah and Arizona parts of Monument Valley), it indicates clearly the dominant northwest orientation.

Geologic field data indicate that most channels are relatively straight. One channel, traced about 1 mile, apparently deviated only 200 feet from a straight course. A few channels, however, such as the Monument No. 1 channel (fig. 15), apparently describe wide curves.

Confirmation of both the relative linearity and the short character of some channels stems from a geophysical investigation in the Koley Black area (fig. 9) by R. A. Black and Wayne Jackson (unpublished report, 1954) of the Geophysics Branch, Geological Survey. An interpretation of their results is shown in figure 9. Another interpretation of this same area based on geologic data is shown in figure 9. The fact that Channel No. 45 (fig. 9) ends within 350 feet of the outcrop could not be foreseen from surface exposures.

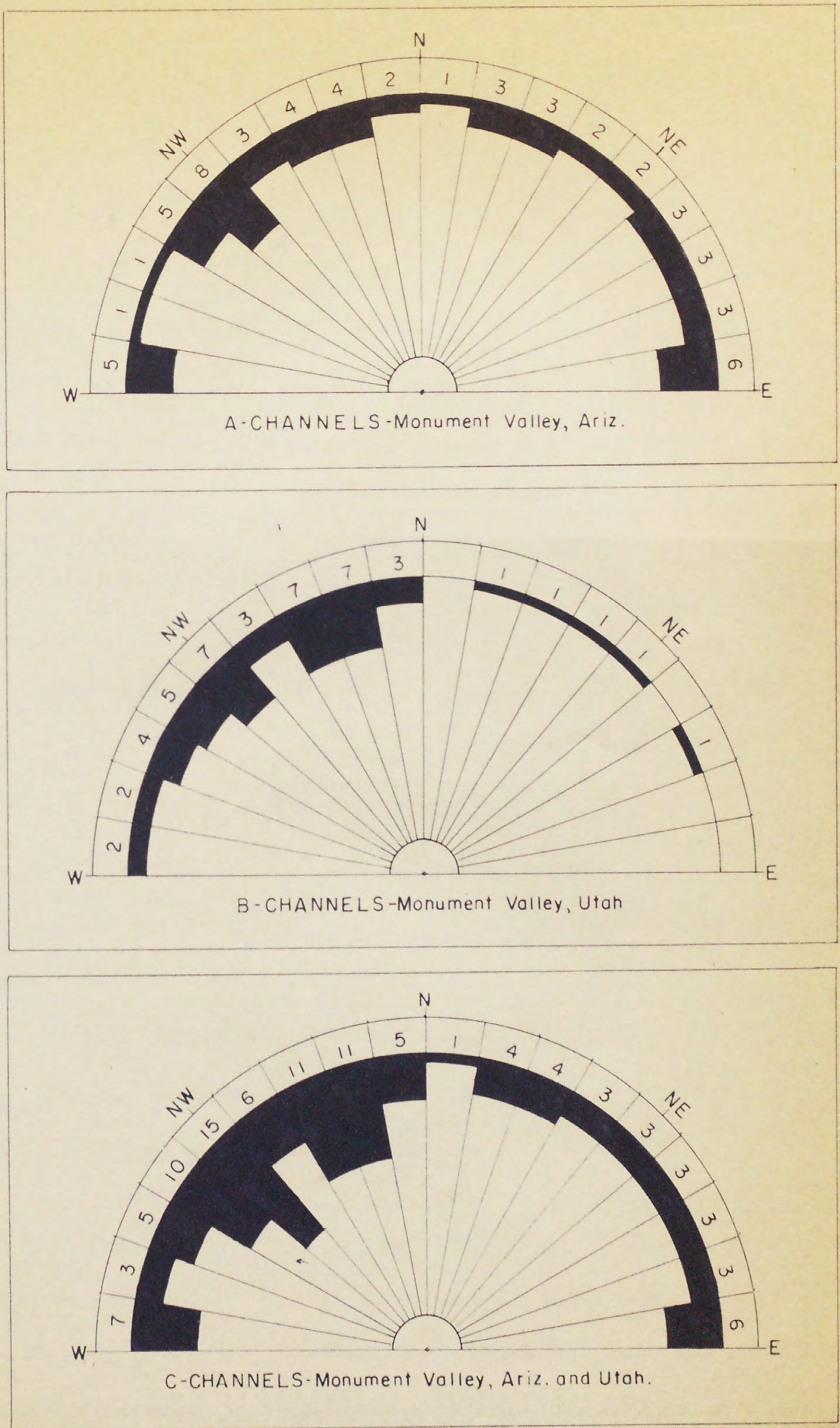


Figure 8.--Channel trends, Monument Valley area, Arizona and Utah. A. - Channel trends in the Monument Valley area, Ariz.; a faint northwesterly orientation. B. - Channel trends in the Monument Valley area, Utah; a strong northwesterly orientation. C. - Channel trends Monument Valley area, Arizona and Utah; a dominant northwesterly orientation is clearly shown.

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. 9). The Monument No. 2 channel also bifurcates, the two parts joining after several hundred feet to form again one large channel (B, fig. 7).

Widths.--The channels may be divided into three classes based upon width. The first is narrow and includes channels up to 50 feet in width. The second class comprises channels ranging from 50 feet to 350 feet in width. The third class is still broader and includes channels ranging in width from 350 feet to 2,300 feet (fig. 3). Channel sediments, sorting, and bedding seem identical in all three classes.

During the course of the field work, 62 channels were noted. Of this number 17 are included in the first class (i.e., relatively narrow). Thirty-two are broader and deeper and are in the second class (i.e., intermediate size channels). The third class (i.e., broad) is represented by 13 channels.

Floors.--Little is known about the configuration of channel floors. From mine workings in the Monument No. 2 and Skyline channels (fig. 1), the floors are known to be undulatory and locally extremely irregular, both in longitudinal extent and normal to the channel length (C, fig. 7). Geophysical work in the Koley Black area (fig. 9) and along the Alfred Miles Channel No. 1 has also indicated that broad shallow scours are in channel floors. Similar scours are also in the floor of the Monument No. 2 channel (fig. 4). It has been suggested by some geologists of the U. S. Atomic Energy Commission (Chester and Donnerstag, 1953, unpublished report, p. 14) that these basal scours are important in localizing uranium 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."

The mapping of the Vanadium Corporation of America's Monument No. 2 mine suggests that although these scours may be favorable localities for ore, by no means are they the only ones. In general, the major deposits of uranium ore are in the basal sediments, however, ore is found along the flanks, in the center, and in the uppermost channel sediments.

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

My impression is that the channels contain relatively 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 altered to carbon. Flattened logs of black carbonaceous material (vitrain ?) have been found associated with several ore deposits. Some of the rich ore bodies at the Monument No. 2 mine may represent deposition of uranium minerals around logs. Pieces of wood partly replaced by secondary copper minerals (azurite, malachite) have been found in basal sediments of the Alfred Miles Channels No. 1 and 2 and in Double Channel (fig. 3).

At least two distinct types of clay fragments are included in Shinarump sediments. By far the most abundant are altered and unaltered clay fragments derived from the Moenkopi. Lesser amounts of a different type of clay are represented by altered volcanic ash fragments included during original deposition of the Shinarump.

In the Skyline channel (fig. 1) angular boulders of clay of unknown origin, as much as 4 feet on a side, and clay fragments of all sizes, are distributed profusely throughout the channel sediments. Similar clay fragments are found in other channels. Preliminary X-ray work by D. H. Johnson, of the Geological Survey, has indicated that most of these clay pebbles are composed of quartz, hydromica, and possibly a little montmorillonite (table 2).

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

Associated swales.--Several channels are along the axes of broad shallow swales cut in the top of the Moenkopi. Whether all channels are so associated with swales is unknown; it seems likely that they are for this channel-swale relationship has been noted repeatedly at several widely separated localities in the Monument Valley area (Witkind, 1955). The swales parallel the channel, 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 3 1/2 to 4 miles. Because the swales are so wide in comparison to their depth they are difficult to perceive visually. Commonly they are ~~easily~~ apparent on maps that reflect the base of the Shinarump. Experience has indicated that such maps are compiled most easily and accurately in the Monument Valley area by isopaching the Moenkopi and Hoskinnini strata (table 1). This interval is used because of the ease of recognizing the unconformity at the base of the Hoskinnini either on the ground or on aerial photographs. The unconformity is

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

Determined by D. H. Johnson

Table 2. -- Composition of some clay pebbles from the Monument Valley area, Arizona and Utah, as determined by means of the X-ray spectrometer.

an excellent datum for isopachous work as it is remarkably free of relief. Consequently whatever vagaries appear as a result of isopaching the Moenkopi-Hoskinnini strata reflect variations in the top of the Moenkopi. The end result is a contour map of the base of the Shinarump.

This channel-swale relationship is best illustrated in the Monument No. 2 area (fig. 10). Isopachous maps of the combined Hoskinnini-Moenkopi strata in the Monument Valley area indicate a gradual thinning in an easterly direction. In the Monument No. 2 area the regional thickness of the Moenkopi and Hoskinnini has decreased to 80 feet. As the channel is approached, the combined thicknesses diminish rapidly to about 30 feet along the flank of the channel. Beyond the channel this sequence is reversed and the strata increase in thickness until the regional figure of 80 feet is once again attained. Inasmuch as the datum used (Hoskinnini-DeChelly unconformity) is even and devoid of relief, 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 Moenkopi and Hoskinnini are removed as well as an additional 20 feet of the DeChelly sandstone. In this one locality the Shinarump sediments filling the Monument No. 2 channel rest disconformably on the DeChelly.

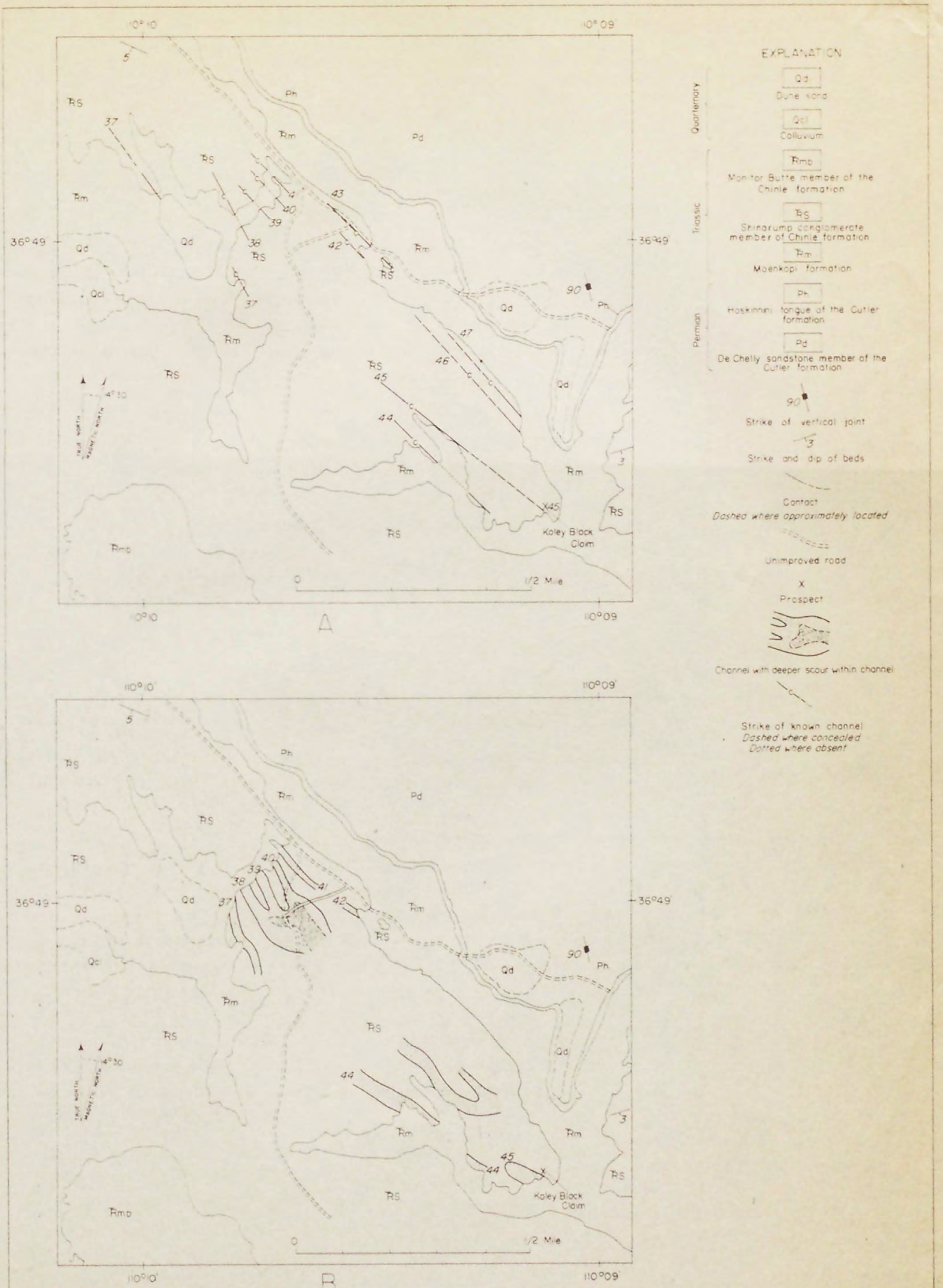


Figure 9. -- A. - The Koley Black area showing the many channels exposed. Channel trends based on geologic work and interpretations.

B. - Same area but extent, trends, widths, and characteristics of buried channels determined as a result of geophysical program.

Swales similar to this one have been noted 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. Isopachous maps of the combined Hoskinnini-Moenkopi thickness could be prepared on the basis of surface exposures. Such maps, properly prepared, 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 the channels do occupy a position near the axis of the swale, subsequent "fences" of holes drilled normal to the trend of the swale might be able to locate the channel more exactly.

I interpret these swales to represent former broad valleys in which ancient streams carved their channels.

Origin.--At least two hypotheses have been proposed concerning the origin of channels. The first suggests that the channels were formed during an episode of erosion subsequent to the formation of the Moenkopi but prior to the deposition of the Shinarump. 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 conglomerate 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, and therefore, are contemporaneous in age with basal Shinarump sediments.

There appears to be general agreement that the Shinarump 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 in turn represents a pediment deposit. McKee (1951a, p. 91), however, considers it to have been an already formed floodplain upon which the Shinarump was deposited

Apparently, streams transported sands and gravels from a raised area to the south and gradually spread them northward as a thin blanket. When one considers the coarse-grained and resistant materials that compose the Shinarump conglomerate, it seems unlikely that the formation could have been deposited without some scouring in the softer siltstones and shales of the underlying Moenkopi formation. It is suggested, therefore, that most of the channel scouring occurred during deposition of the Shinarump conglomerate and not in any period of erosion prior to this deposition.

Why one channel is continuous and another not is unknown. The short channels may represent sporadic scour depressions within broad shallow stream valleys (i.e., swales). If these basin-like 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 Shinarump. As yet, such alinement of channel remnants has not been found.

Bryan (1920, p. 191), in discussing present day streams, suggests that scour 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, it may be that a former meandering stream carrying Shinarump sediments cut these deeper scours wherever it swung about. Monument No. 1 (fig. 15), 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 scour 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.

Ore Bodies

General statement

Four distinct types of ore bodies can be differentiated in channel sediments of the Shinarump conglomerate in the Monument Valley area, Arizona and Utah. Of these the most striking are cylindrical, log-like masses of very rich ore that have been called "rods" (Witkind, 1954, unpublished report). The second type of ore body consists of blanket-like deposits of uranium ore that are generally in the basal part of a channel and are elongate 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 sediments 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 sediments of both the Shinarump and the underlying DeChelly sandstone. Rolls are the fourth type of ore body, and they can be divided into two categories based on exposures in the Monument No. 2 mine. The first category includes rolls formed only in Shinarump sediments. These consist of channel sediments impregnated with yellow uranium minerals that form curved bands which cut across bedding planes. The second type of roll is found only in DeChelly sediments and consists of curving laminae of ore that cross the bedding. These rolls seem to be related to the intersection of fractures and bedding planes.

The rods are exposed in the Monument No. 2 mine where they appear in profusion and form richly mineralized bodies apparently scattered at random through the channel sediments. The channel sediments surrounding these rods commonly contain but trace amounts of uranium and vanadium. The uranium percentage about 1 foot away from the edge of a rod will be as low as 0.002 percent; whereas, a sample collected from the edge of the rod will be as much as 14 percent uranium (fig. 11). This unusual discrepancy in grade between rods and confining sediments is repeated throughout the mine.

The tabular ore body is best exemplified in the Monument No. 1 - Mitten No. 2 mine, Navajo Co., Ariz. (fig. 2). Here the ore forms an ore body that is about 675 feet long, 50 to 120 feet wide, and ranges in thickness from 1 to 18 feet, although it averages 7 feet thick. The outline of the ore body parallels the channel.

The corvusite-type ore bodies are a deep blue-black, due principally to the vanadium mineral "corvusite". These ore bodies lack well-defined outlines and shapes and generally are elongate

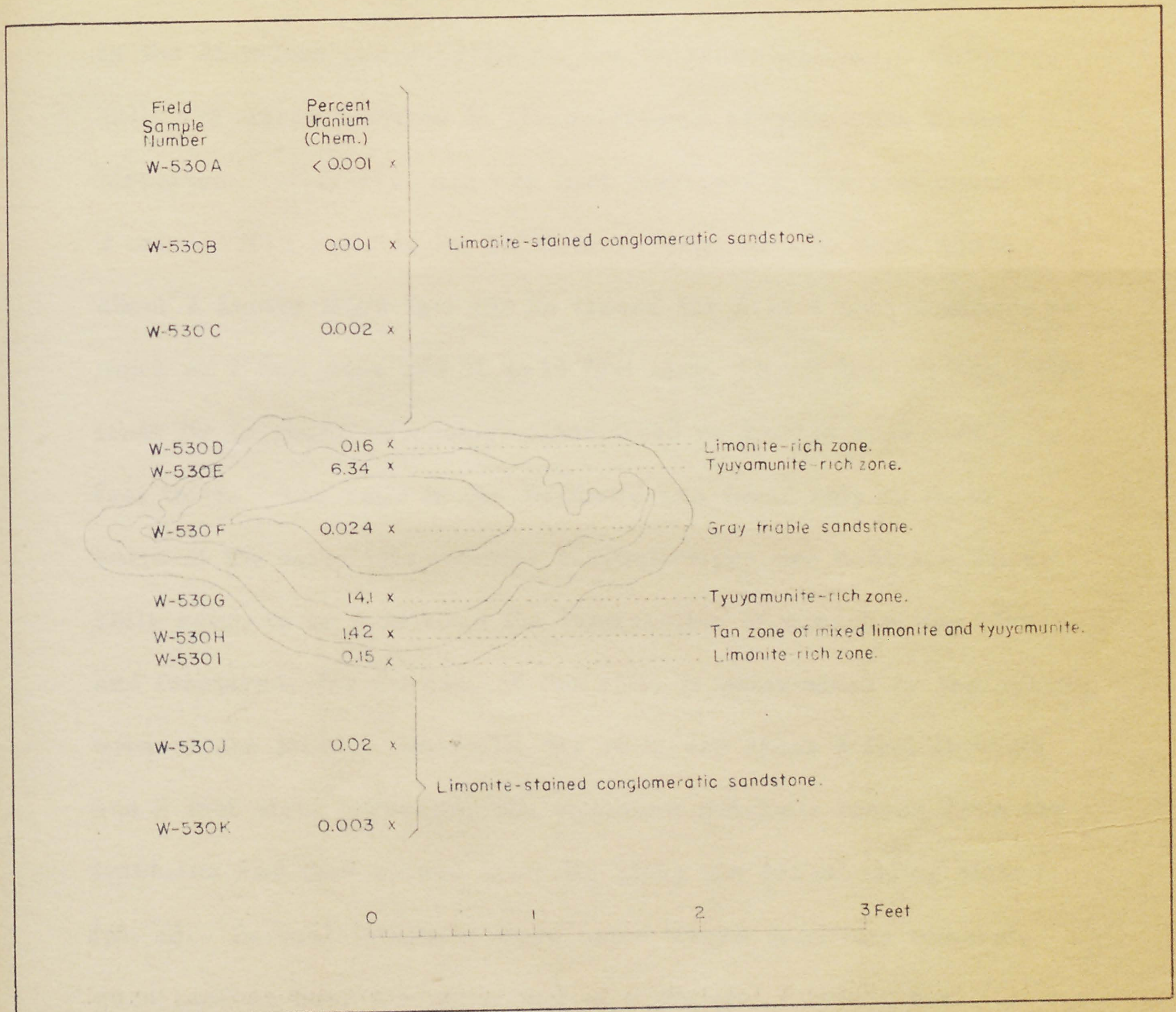


Figure 11. -- Samples across a typical rod, Monument No. 2 mine. The rod is seen in cross-section. Although present practice is to mine and ship the entire face, it is apparent that the bulk of the rock, even that 1 foot or less from the rod, is essentially barren. The friable sandstone centers of the rods also are weakly mineralized.

parallel to the channel trend. They are about 200 feet long, 100 feet wide, and range in thickness from a pinch-out to as much as 40 feet.

The fourth type of ore body, known as a roll, is prevalent in the Morrison ore deposits on the Colorado Plateau. However, rolls are minor features in the Shinarump conglomerate of the Monument Valley area and are best displayed in the Monument No. 2 mine. The rolls in the Shinarump range in size from bands about 2 inches thick that 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 DeChelly are found only in those parts of the mine that underlie corvusite-type ore bodies. 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. Normally the rolls are about 3 feet in width and 2 feet high. Possibly the vanadium minerals moved down the fractures and then spread laterally along the crossbedding planes (pl. 5). 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.

Plate 5. -- A. - View of basal sediments in Monument No. 2 channel. The Shinarump conglomerate (TRs) is exposed in the upper left-hand corner. Remainder of the sediments are the DeChelly sandstone (Pd). Contact marks the channel floor. Vanadium minerals seem to have migrated along fractures and into body of rock. Hammer lies in the center of small "roll" in the DeChelly sandstone.

B. - Close-up view of the contact between basal channel sediments and the DeChelly sandstone. Hammer head marks the contact between the Shinarump (TRs) and the DeChelly (Pd). Vanadium minerals are distributed vertically and laterally in the DeChelly along bedding planes and fractures.

Rods

Throughout the Monument No. 2 mine, the richest deposits of uranium ore are in flattened cylindrical log-like bodies scattered in an apparent erratic fashion through the channel sediments. These bodies are known as "rods" (Witkind, 1954, unpublished report). Bodies similar to these have been noted in the Morrison formation and have been referred to as "cylindrical masses" (Coffin 1921, p. 163). All the rods are in channel sediments of the Shinarump; none are in any of the underlying strata.

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

The rods in the Shinarump can be classified roughly into two categories: simple and complex. The simple type of rod is illustrated in figure 12. Essentially, it consists of an outer rim of sandstone impregnated with limonite within which is a rim of tyuyamunite-impregnated sandstone. The tyuyamunite in turn surrounds a core of extremely friable light gray sandstone.

The complex type of rod is bounded similarly by an outer rim of limonite-impregnated sandstone within which is a rim of tyuyamunite-impregnated sandstone. These rims, however, are much more irregular than in the simple type of rod. A further subdivision of the complex rod is possible. One type contains irregular masses of mixed limonite and tyuyamunite randomly distributed throughout the gray sandstone center (A, fig. 12, A, pl. 6 and A, pl. 7). 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 (B, fig. 12; B, pl. 7; and pl. 8).

Near many of the rods the bedding of the confining strata is interrupted at the rims; elsewhere, the bedding can be traced arching over the rods (pl. 9). Grain size changes abruptly at the edges of some rods. Most rods are remarkably straight, and where mining operations have followed them many have been found to 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 the rods (block diagram, fig. 12; and A and B, pl. 8). In several rods exposures are large enough to afford longitudinal examination of the gray sandstone core filling the center of the rods. In these the direction of crossbedding is totally different from the direction of crossbedding of those sediments outside the rods.

Small fractures cut the sand grains that form the rims of the rods (pl. 10). In consequence a crudely circular pattern of fractures delineates each rod (fig. 12). 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

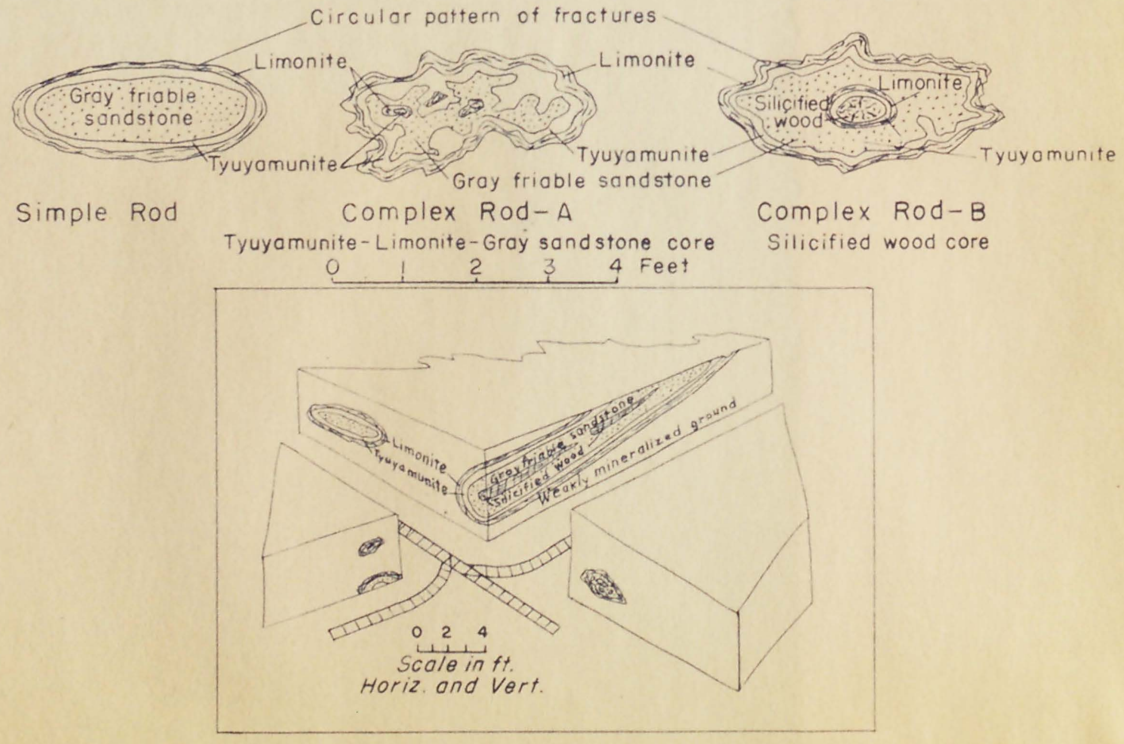


Figure 12. -- Cross-sections of simple and complex rods. Idealized block diagram of mine workings shows relationship of rods to one another and to mine drifts.

length of the rod. These fractures are not apparent in those grains that fill the cores of the rods, nor in the grains beyond the boundaries of the rods. The fracturing is restricted to (1) the limonite-impregnated sandstone zone and (2) the tyuyamunite-impregnated sandstone zone, both of which form the rims of the rods. Moreover, the fracturing halts along very definite boundaries (A, pl. 10). For example, in one thin section of an edge of a rod, the grains on part of the slide are intensely fractured, whereas the grains on the remainder of the slide are whole. The separation between fractured and unfractured grains is 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 (B, pl. 10) with a subsidiary set trending more or less at right angles; the other is a plexus of fractures that lacks orientation (C, pl. 10). Each fracture of the parallel set is about 0.20 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, devoid of

Plate 6. -- A. - Photograph of cross-section of a richly mineralized rod. Light area is tyuyamunite-rich (ty) that may contain over 20 percent U_3O_8. Darker areas are weakly mineralized sediments that contain only trace amounts of U_3O_8.

B. - Cross-section of carbonized log in open-pit near North Workings in the Monument No. 2 mine. Log has a core of black carbonized wood (cw) and silicified wood (sw), and an outer rim of uraninite (u). A halo about 8 inches wide of limonite-impregnated sandstone (lt) surrounds log. Sediments within 1 foot of the log are barren. At the time of this photograph, this log had been mined for 40 feet.

Plate 7. - - A. - View of large complex rod. Rod is about 5 feet across and about 2 feet from top to bottom. Mining has removed the lower part of the rod and the poorly consolidated interior has fallen out, leaving the center of the rod hollow.

B. - Oblique view of a large complex rod showing core of silicified wood (sw) surrounded by gray friable sandstone with mixed limonite and tyuyamunite (ss) which in turn is surrounded by rings of tyuyamunite (ty) and limonite (lt). Black lines emphasize boundaries between the various units.

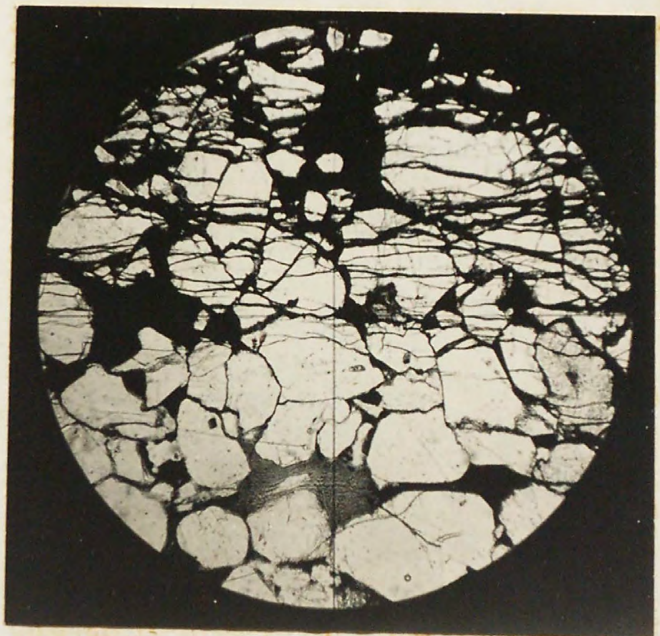
ty - tyuyamunite
lt - limonite
ss - friable gray sandstone with mixed limonite and tyuyamunite
sw - silicified wood

Plate 8. -- A. - Longitudinal view of rod showing a core of silicified wood (sw) collinear with the rod. Darker outer margins are limonite (lt), within which is rim of tyuyamunite (ty). Inner layer around core of silicified wood is a mixture of gray friable sandstone with mixed limonite and tyuyamunite (ss).

B. - Longitudinal section through rod showing collinear relationship between core of silicified and carbonized wood and rod. The core of the rod is silicified wood (sw) rimmed by carbonized wood (cw). Surrounding the core are irregular bands of tyuyamunite and limonite-impregnated sandstone (lt). Mining has broken through the rod in the area marked by the hammer and removed part of the core.

Plate 9. -- A. - Photograph showing modifications in attitude of bedding near rod. Rod is about 3 feet in long dimension.

B. - View showing abrupt change in size of material between that surrounding rod and that forming rod. Hammer head is along lower right hand corner of cross-section of rod.



A

B

C

Plate 10. -- Photomicrographs of thin sections prepared from specimens collected in Monument Valley, Ariz. Photomicrographs A-C show uranium and vanadium minerals in fractures and interstices; all enlarged 22 diameters.

A. - Photomicrograph showing sharp boundary between fractured and unfractured grains. Specimen from upper edge of rod.

B. - Photomicrograph showing parallel fractures. Specimen from lower edge of rod.

C. - Photomicrograph showing irregular fractures. Specimen collected about 1 foot away from edge of rod.

orientation or system.

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 circular pattern formed by the fractures as they outline the rods is distinctive and has been found only in the Monument No. 2 mine. 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.

Many of the rods were interpreted by me to represent supplantation of coalified logs by sand, silt, and clay as well as by those primary minerals which upon oxidation would alter to limonite and tyuyamunite. To test this concept six samples were sent to James M. Schopf in the Coal Geology Laboratory of the Geological Survey. 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 six samples submitted Schopf itentified only one as fossil wood, and that was the one collected from the 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 (figs. 4 and 13), however, and the collinearity apparent between many rods and silicified remnants of logs suggests 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, such as sand, silt, and clay, deposited in the voids so formed. The removal of the organic matter and its subsequent supplantation was probably a gradual process and affected only part of any log at any one time. It may have been during this episode that porosity and permeability conditions were changed sufficiently to localize the ore-bearing solutions. Thus, those rods over which the bedding arches, as well as those that show abrupt changes in grain size between the confining strata and the rod boundaries, may represent merely the former presence of buried logs which have since been supplanted by sand, silt, and clay.

Other rods may have been formed by mineralizing solutions in response to halos of decomposition products such as humic colloids, organic resins, and various 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 may have occurred along the zones represented by the former edges of the log. In the voids formed by this 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 sediments, and organic matter in the Morrison formation of Jurassic age. Still referring to the Morrison formation, Fischer and Hilpert (1952, p. 12), in a later report, 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. From my observations in the Monument Valley area on the habits of uranium ores in the

Shinarump conglomerate, I concur with the concept expressed by Fischer and Hilpert and believe that a close spatial relationship exists between pockets of uranium ore, channel sediments, 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 channel sediments. Other plant material may have been rafted into the channels and also buried. Subsequently, when mineralizing solutions moved through the Shinarump, favorable conditions of permeability and porosity, resulting primarily from the former presence of buried logs, may have been responsible for the formation of rods.

Fractures as related to rods.-- Basic factors involved in the localization of the uranium ore have been described. The effect of fractures that cut the channel sediments in localizing the uranium deposits is unknown. In an attempt to resolve this question three diagrams were prepared. The first is of the fractures noted and mapped in the Monument No. 2 mine (A, fig. 13). Most of the fractures trend northwest. The second diagram (B, fig. 13) includes all the rods on which strikes were taken. A random trend is apparent. The third diagram indicates the trend of silicified logs noted in the mine workings (C, fig.13).

Again a random orientation is apparent. If fractures were a controlling influence, one would expect a northwest orientation of the major ore bodies (i.e., rods) comparable to that shown by the fractures. As the diagram of the rods lacks this orientation, there seems to be some negative evidence against fracture control. Contrary evidence is suggested by the resemblance between the diagrams of the silicified logs and of the rods. The similarity between the random orientation apparent in the diagrams of the rods and the silicified wood suggest that some relationship, as yet unestablished, exists between the rods and silicified wood. Parallelism between rolls of ore and fossil logs 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 mines (fig. 2). 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 bi-convex in both longitudinal and transverse section and range in width from 20 to 40 feet, are as much as 6 feet thick, and are about 60 feet long. They thicken downward into small depressions in the channel floor; the richest ore seems to be concentrated in these depressions. A tabular ore body is also in the Monument No. 1-Mitten No. 2 mine (fig. 2). This one, however, is much larger and is probably representative of 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. Drilling by the U. S. Atomic Energy Commission on Holiday Mesa, Utah has disclosed a similar type of ore body there. Two sedimentary 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, lime-cemented sandstone. The ore body is biconvex or planoconvex, about 675 feet long, extends in width from one channel flank to the other (50 to 120 feet), and ranges in thickness from 1 to 18 feet, although it averages 7 feet thick.

Corvusite-type ore bodies

Irregular-shaped masses of sandstone thoroughly impregnated with blue-black vanadium minerals, principally corvusite, are scattered along the length of the Monument No. 2 channel. Some of these bodies are near the base of the channel, whereas others are near the surface and are about 40 feet above the channel floor. In

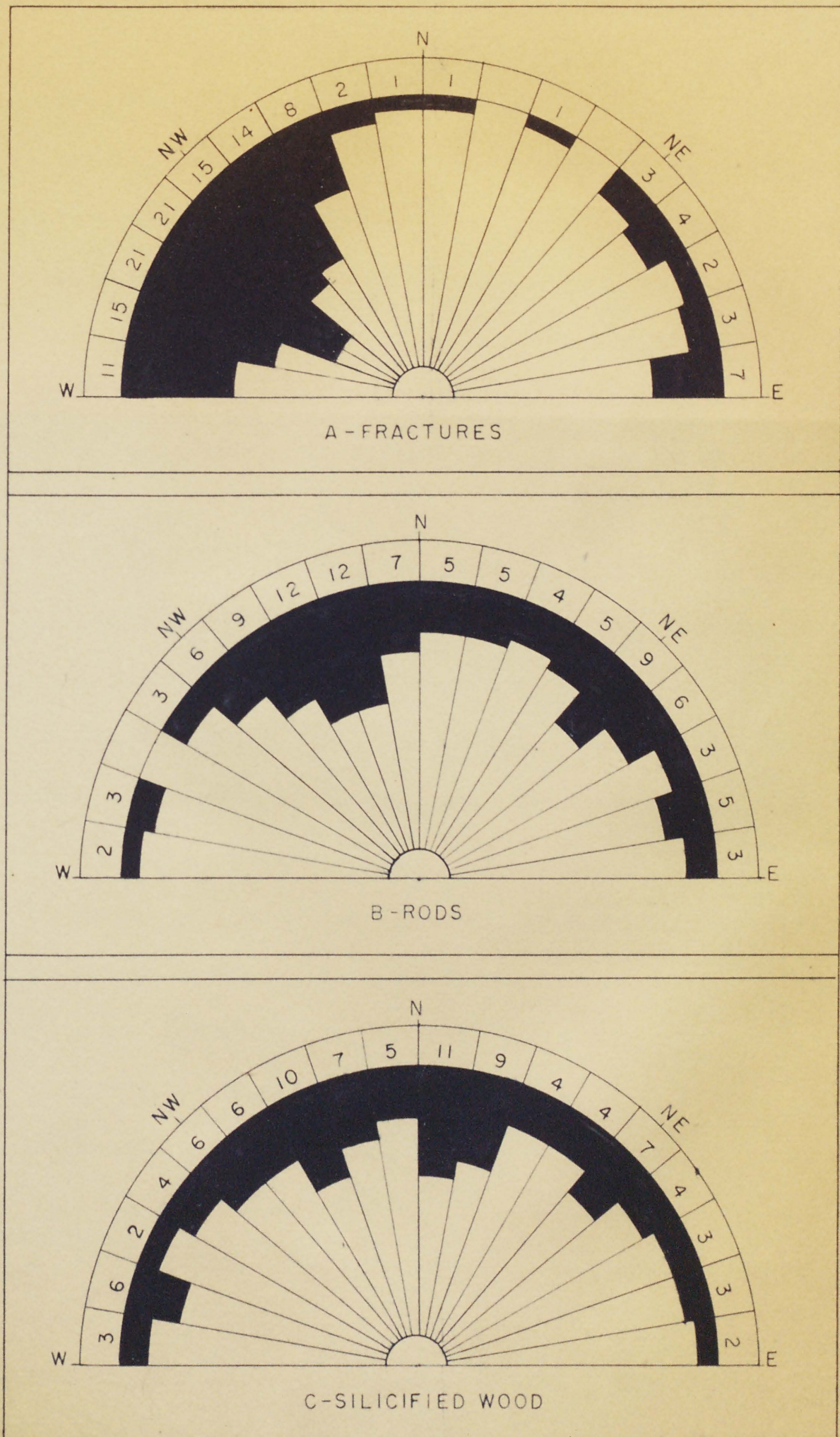


Figure 13. -- Distribution of fractures, rods, and silicified wood in the Vanadium Corporation of America's Monument No. 2 mine. Most fractures are oriented to the west-northwest. A like orientation is not strongly apparent in the diagram of the rods or of the silicified wood.

those corvusite-type ore bodies that are along the channel base the vanadium minerals fill interstices in both the Shinarump conglomerate and locally in the DeChelly sandstone, 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 seem to 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 seems to differ 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 of these corvusite-type ore bodies are vague and commonly are gradational. They seem to consist of small patches of sediments weakly impregnated with vanadium and enclosed in limonite-rich sediments.

As far as can be perceived, these corvusite-type bodies near the base of the channel have no specific trend, lack recognizable margins, and impregnate both Shinarump and DeChelly sediments.

Within the corvusite-type ore bodies are small concretionary-like masses of sediment that show some rudimentary zoning. Generally these are crudely oval, irregular in outline (pl. 11), and commonly 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 from 1 to 8 feet thick formed of sediments impregnated with blue-black vanadium minerals. The core ranges in thickness from 2 to as much as 5 feet and consists of white opal that fills interstices in the sandstone. In a few localities the white material surrounds 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 above the base and east flank of the channel. These near-surface bodies have been oxidized, for they contain large quantities of deep-red hewettite._/ In those

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_/ 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.

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bodies that are near the base of the channel, the principal vanadium mineral is corvusite, although hewettite is also present. Other vanadium minerals collected are navajoite and steigerite (Weeks and Thompson, 1954) as well as specimens of uraninite, becquerelite, and uranophane. Tyuyamunite and carnotite are abundant near the margins of these ore bodies, commonly as rods, although in places they appear as yellow disseminated specks contrasting markedly with the blue-balck color of the vanadium-rich areas.

Plate 11. -- A. - Photograph taken in Vanadium Corporation of America's Monument No. 2 mine showing concretionary-like body in part of corvusite-type ore body. 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.

B. -- Photograph showing another concretionary-like mass in corvusite-type ore body in basal channel sediments.

Rolls

The fourth type of ore body, known as a "roll" is prevalent in the Morrison ore deposits 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 consist of yellow uranium minerals impregnating selected parts of the Shinarump conglomerate. Commonly these mineralized bands are curved concave upward and consist of yellow uranium-vanadium 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 DeChelly 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 a half inch to 3 inches. Each mineralized band is separated from its neighbor by barren sediments that are about 4 inches thick. The rolls are small features and form flattened oblongs with rounded corners, each about 3 feet wide, and about 2 feet high (A, pl. 5). Their length is unknown. In places the vanadium-rich bands follow the crossbedding planes (B, pl. 5). Where fractures intersect the crossbedding planes the vanadium minerals have followed the fracture and impregnate the sediments adjacent to the fracture. 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 cross-bedding planes, the attitude of the rolls depends upon the strike and dip of the cross-beds. Commonly the rolls are inclined at some angle to the floor of the channel.

Age determinations

Since 1951 L. R. Stieff and T. W. Stern of the U. S. Geological Survey have been studying 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 twelve samples of ore from the Monument No. 2 area were studied (Table III). Of these, nine were discrete specimens of uraninite, becquerelite, or carnotite which were collected in the mines in the area. The remaining three were mill pulp samples.

The work completed by Stieff and Stern (1951, 1953, unpublished reports) and Stieff, Stern, and Milkey, has indicated that "completely reliable age determinations can be made only on ore samples which have not been altered in any way since their deposition" (Stieff and Stern, 1953, unpublished report, p. 5). Unfortunately, none of the twelve samples can be described as unaltered. Indeed, the range of alteration is extreme, extending from samples of uraninite that are but slightly altered to mill pulp samples that are practically completely altered. This degree of alteration is reflected in the uncorrected computed age determinations. Thus, the Pb^{206}/U^{238} age determinations completed on relatively unaltered uraninite specimens give an average computed age of about 78 million years. 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) give an average computed age of about 78 million years; here, however, the range is from a minimum of 5 million years to a maximum of 175 million years. The mill pulp samples computed give ages that average 250 million years and range from 170 million years to 330 million years.

The ages calculated for the specimens of relatively unaltered uraninite would appear to be the most reliable. 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". This type of error is

CALCULATED Pb^{206}/U^{238} AGES OF URANIUM ORES
FROM MONUMENT NO. 2 AREA

Mine	Sample Description	Pb^{206}/U^{238} age to the nearest 5 million years
V.C.A. Monument No. 2	Uraninite	70
V.C.A. Monument No. 2	Uraninite	85
V.C.A. Monument No. 2	Uraninite	100
Climax-Uranium Cato Sells Tract No.1	Uraninite	60
Average age-Uraninite specimens		78
V.C.A. Monument No. 2	Uranophane	175
V.C.A. Monument No. 2	Uranophane	130
V.C.A. Monument No. 2	Becquerelite	15
V.C.A. Monument No. 2	Carnotite	75
Climax-Uranium Cato Sells Tract No.1	Becquerelite	5
Average age - altered specimens		80
V.C.A. Monument No. 2	Mill pulp	170
V.C.A. Monument No. 2	Mill pulp	250
V.C.A. Monument No. 2	Mill pulp	330
Average age - mill pulp sample		250

Table 3. -- Age determinations of uranium ores from the Monument No. 2 area. The most reliable determinations are those made from relatively unaltered uraninite specimens; these suggest a Late Cretaceous - Early Tertiary age for the emplacement of the ores (78 million years).

present in the averages shown on Table III. It would seem, therefore, that the computed average age of 78 million years determined for uraninite specimens from the Monument No. 2 area is 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 ages of 65 and 75 million years. These ages are considered to be within 10 million years of the true age of the samples (Stieff, Stern, and Milkey, 1953, p. 13). 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 old.

The age for the Late Triassic (i.e., the age of the Shinarump conglomerate) is given by the Committee on the Measurement of Geologic Time, National Research Council (1949-1950) as about 160 million years. In comparison to the 78 million year apparent age determined for the Monument No. 2 ores, this means that the age of the sediments 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 (Committee on Measurement of Geologic Time, 1949-1950). It would seem, therefore, that the uraniferous ores in the Monument No. 2 ore deposit were emplaced during Late Cretaceous or Early Tertiary time.

Origin and localization

Two basic related questions face most geologists studying the uranium and vanadium ore deposits on the Colorado Plateau. The first of these involves the source of the ore metals and the method by which these 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, Ariz. 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.

During the 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 were emplaced at that time and may represent surface manifestations of a deep-seated buried magma. Most of the uranium-vanadium ore deposits are grouped around these igneous complexes. This spatial distribution suggests that some relationship exists between the ore deposits and the igneous bodies. Possibly mineralizing fluids, derived from this crystallizing buried magma, were carried to the surface along fractures and faults resulting from the structural deformation. I suggest that these solutions mingled with ground water in the Shinarump, and that the ensuing mixture then moved through the host rock.

Possibly the mineralizing solutions moved laterally through the host rock until they encountered favorable traps in the form of channels. Within these channels uranium minerals may have been deposited in response to two factors; one of these being chemical, 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 precipitation of uranium minerals in and around organic material may have been induced by a change in the pH of the solutions involved. The organic matter may have acted, then, 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.

The rods were probably bodies composed partly of uraninite, pyrite, and associated 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 were altered or are being altered to hewettite.

Following the emplacement of the primary minerals, ground water assumed a role of prime importance. Large sectors of weakly mineralized channel sediments may result from ground water leaching of soluble uranium-vanadium minerals from the rods and their dispersal and subsequent deposition both laterally and vertically.

I tend to favor the hypothesis that the spacing of the rich ore bodies (i.e., rods) is attributable to the original distribution of logs buried synchronously with the confining Shinarump sediments. Further, I suggest that favorable conditions of permeability and porosity in the rods may have been contributing factors in the deposition and localization of the uranium ore. I also attribute the tabular ore bodies found in some channels to conditions of reduced permeability and porosity. These conditions may stem from poor sorting or the presence of large amounts of interstitial clay, rather than fracturing.

T. L. Finnell (in preparation), of the Geological Survey, as a result of his work at the Monument No. 2 mine, has suggested the possibility that structure controlled ore deposition. Finnell states, "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 length. 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."

Prospecting guides

The following prospecting guides have been revised and enlarged from the list of guides proposed in 1951 (Witkind and others, unpublished report, 1951). These guides must still be considered tentative and subject to change. Further, they are of greatest value only in the area covered by this report.

The guides are in two categories, those thought to be useful in prospecting for uranium ore deposits throughout the Monument Valley area, Ariz., and those of uncertain use. These last 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, Ariz. are:

1. Observable uranium minerals and abnormal radio-activity.

2. Channel fill.

3. Channel conglomerates 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

4. Clay boulders, cobbles, and pebbles.

Observable uranium minerals and abnormal radioactivity.--The brilliant yellow minerals, tyuyamunite, metatyuyamunite, and carnotite, are the most common uranium minerals exposed at the face of mineralized outcrops. Torbernite and autunite, generally apple-green in color, are less common, and these normally are in the shaly siltstone beds forming the bleached zone of the uppermost Moenkopi strata. 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 pod-like lenses of black carbonaceous material (vitrain ?). 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 sediments of the Shinarump conglomerate that fill channels. Consequently, channel fills are considered to be one of the best guides to deposits of uranium ore. Not all channels are mineralized at the outcrop. Of the 62 channels noted, only 18 were mineralized at the outcrop. Of these, only seven contained uranium minerals (fig. 3). The absence of uranium minerals on outcrops of channel sediments does not, in my opinion, make an area unfavorable. This conclusion is based on the known spotty distribution of mineralized areas in those channels that contain ore.

Channel conglomerates containing fossil plant matter.--In the Monument No. 2 mine many of the rods are associated with silicified wood, elsewhere in the Monument Valley area uranium and vanadium minerals replace carbonaceous matter. Generally, these associations are in conglomerate or conglomeratic sandstone lenses in channel fill. 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 new deposits of uranium ore.

Guides of uncertain usefulness

Limonite that impregnates channel fill.--In the Monument Valley area limonite both stains Shinarump sediments and in places impregnates them thoroughly. The light brown color of limonite stain is found everywhere. However, the more penetrating limonite effect has been found only in the Monument No. 2 area. Along many channels the surface of the channel fill is stained a light brown, however, fresh surfaces 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 (fig. 3). These minerals fill fractures and interstices, and coat sand grains. In several localities they replace wood. However, only minute amounts of copper are at the Monument No. 2 mine. Secondary copper minerals have also been noted distant from channel sediments.

An abnormal thickness of an altered zone in uppermost Moenkopi strata. -- The thickening of an altered zone in uppermost Moenkopi strata directly below channel sediments was noted at some of the more favorable uranium prospects (fig. 3). 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. In the Monument No. 2 mine, however, concentrations of clay detritus are in some places where ore is lacking.

Mines in the Monument Valley area, Arizona

Two ore deposits that are considered typical are described, the Monument No. 2 area, one of the richest ore deposits on the Colorado Plateau, and the Monument No. 1 ore deposit.

As of 1952-1953, only the group of mines in the Monument No. 2 area were producing uranium and vanadium ore in sizeable quantities. Small amounts of ore were produced in 1952 from the Mitten No. 2 mine (Monument No. 1 area) but production was so small as to be negligible. In 1954, as a result of a drilling program a new deposit of ore was found in the channel sediments of the Monument No. 1 channel.

Monument No. 2 area

(Channel No. 58 of fig. 3)

Six mines are in the Monument No. 2 channel; these are:

1. The Vanadium Corporation of America's Monument No. 2 mine.
2. The Climax-Uranium Company's Cato Sells Tract No. 1 (also called Cato Sells Monument Mine).
3. The Climax-Uranium Company's Cato Sells Tract No. 2.
4. The Climax-Uranium Company's Cato Sells Tract No. 1--South.
5. The Black and Blackwater mine (leased in 1953 to Pollack and Byler).

6. The John M. Yazzie mine (operated jointly by John M. Yazzie and Thomas Clani).

Of these, the largest is the Vanadium Corporation of America's Monument No. 2; it exceeds the others not only in extent and complexity of workings, but also in amount of dry tons of ore produced. In an attempt to study the various problems inherent in the origin and localization of uranium ore, the workings of the Monument No. 2 mine were mapped and studied during the summers of 1951 and 1952 (fig. 4). In general the features characteristic of the mine are duplicated in all of the other mines in this channel.

Monument No. 2 mine

Introduction.--By far the most prolific producer of uranium ore in the Monument Valley area, Ariz., is the Monument No. 2 mine owned by the Vanadium Corporation of America and operated under a lease from the Navajo Tribal Council. The mine has been in operation since 1942.

No other mine in the area has even closely approached it in the production of uranium and vanadium ores. Yet, in general, nothing about the geologic or geographic setting seems distinctive. Channel sediments are similar to those cropping out elsewhere in the valley. The size and shape of the channel do not seem unusual; it is not as large as some, nor as narrow as others. It is worthy of note that the original exposures gave but slight indication of the large amounts of ore contained in the channel sediments.

During 1951 and 1952 the U. S. Atomic Energy Commission completed wagon and diamond drilling programson Yazzie Mesa and on South Ridge (fig. 7). (Chester and Donnerstag, 1953, unpublished report.)

Location and accessibility.-- The mine is in a remote sector of Apache County in Monument Valley, Ariz. It is at latitude 36° 55.7' N. and longitude 109° 55.1' W., about 4-1/2 miles south of the Utah-Arizona state line and about 1 mile west of Comb Ridge (fig. 1). The nearest trading posts are at Mexican Hat, Utah, about 28 miles away and at Dinnehotso, Ariz. about 50 miles distant.

In 1953 mining operations involved both stripping (open-pit) and underground methods. The underground workings are 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 had been in the North Workings and near the Red Oxide Workings (fig. 4).

All ore produced is trucked the 185 miles to a company-owned mill at Durango, Colorado.

Geology.--In the Monument No. 2 area consolidated sedimentary strata range in age from the Halgaito beds of Permian age to the Navajo sandstone of Jurassic age (Table I). However, in the immediate vicinity of the mine the strata range only from the De Chelly sandstone of Permian age to the Shinarump. The Shinarump 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 at about 5° and is part of the east limb of the Monument upwarp. Dissection of this eastward-dipping cuesta has been severe, forming a series of comb-like ridges and isolated mesas.

Three sets of fractures were noted in the mine workings and on the surface in the immediate vicinity of the mine. These sets probably are related to the regional structure. They trend about: (1) N. 65° W., (2) N. 30° W., and (3) N. 40° E. to east-west. As the diagram of the fractures noted in the mine indicates (A, fig. 13), most of the fractures trend northwest. Strike-slip movement has been noted on the fractures; commonly the west wall has moved south. Slickensides are formed although the movement on any single fracture surface does not appear to exceed a half inch. The fractures cut ore.

Channel.--The Monument No. 2 mine is in a broad short channel 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 Moenkopi and Hoskinnini beds are thin at this locality, the scour has cut through these formations with the result that channel sediments of Shinarump age rest unconformably on the DeChelly sandstone.

Although the regional thinning of both the Hoskinnini and Moenkopi is eastward this abrupt thinning of these strata near the channel may be most significant. Isopach maps prepared of the combined thickness of the Moenkopi and Hoskinnini in the immediate vicinity of the Monument No. 2 channel indicate that an elongate broad swale parallels the channel (fig. 10). Inasmuch as the base of the Hoskinnini is even and devoid of relief (A, pl. 3), this thinning must reflect the undulation of the top of the Moenkopi. This swale in the top of the Moenkopi is about 3 miles wide and can be traced for a distance of about 3-1/2 to 4 miles before it disappears below the alluvial fill of Cane Valley. I interpret this swale to represent a former broad valley in whose center a deeper and narrower channel (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 (fig. 4), the channel appears as a symmetrical scour; this is also true at South Ridge (fig. 4). However, in the South and Bobcat Workings (fig. 4), the floor of the channel is divided by a low ridge of sandstone that separates the channel into two unequal parts (C, fig. 7). The ridge of sandstone is of unusual lithology and is distinctive in appearance. It may be equivalent to the Hoskinnini. It is composed of a light-buff even-bedded medium-grained sandstone that truncates the crossbedded fine-grained DeChelly sandstone. This even-bedded sandstone layer is in turn truncated on both sides by the Shinarump sediments that fill the two parts of the divided channel.

The length of the channel has been determined (Chester and Donnerstag, 1953, unpublished report). It extends in a relatively straight line for 1-1/2 to 2 miles, and is divided into three unequal parts by two deep re-entrants (A, fig. 7). The north end of the channel (about 1,000 feet long) is on Yazzie Mesa. The middle part of the channel (about 2,800 feet long) and, incidentally, the part that contains the major amounts of ore, is on the Monument No. 2 cuesta and has been called "Main Ridge." The south part of the channel (2,000 feet long) is on South Ridge.

Data obtained during the drilling and mapping programs were used to contour the base of the channel (B, fig. 7 and fig. 4). Those lines delineating the ends of the channel on Yazzi 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 the floor of the channel is gently undulatory both in cross and longitudinal sections and is marked in places by scour pits 200 to 250 feet long, about 100 feet wide, and from 5 to 10 feet deep (fig. 4).

Channel sediments seem identical to other sediments in the Shinarump 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 as boulders, cobbles, and pebbles, are distributed profusely throughout the channel sediments. In several places the uppermost channel sediments 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 sediments. Much of it appears as silicified logs and as elongate pod-shaped masses of a carbonaceous material (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 No. 3 (fig. 4) a fossil log, partly replaced by vanadium minerals, uraninite, and pyrite, affords excellent specimens of woody texture preserved by metallic minerals. Examples of uraninite replacing wood have been found also in the Cato Sells mine (Weeks, 1952a, unpublished report, p. 10). The possibility exists that during deposition of the sediments that filled the channel, many more logs were included than can be identified as such under present conditions. Many of the rods which form the rich uranium-vanadium ore bodies may once have been logs.

Oxidized minerals are everywhere apparent in the mine workings. Limonite impregnates and stains the channel sediments but is not as profuse in Shinarump sediments adjacent to the channel. On the surface this is emphasized by the contrast in color between the brown of the channel sediments and the light buff of the adjacent sediments. 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 are weakly mineralized.

Uranium and vanadium deposits.--All four types of ore bodies described are found in the Monument No. 2 mine. These seem to be scattered at random through the channel sediments and are in such profusion that it is difficult to delineate specific ore zones. In general, however, three ill-defined zones can be discerned. Ore bodies in each of these zones seem to alternate at irregular intervals with one another and with barren or very poorly mineralized sediments. Thus, channel sediments containing concentrations of rods may be close to, or distant from corvusite-type areas, --no pattern is apparent. The distribution of the richly mineralized parts of the channel to the weakly-mineralized parts seem independent of channel shape, channel sediments, position in channel sediments, or any other discernable feature.

The principal production of both uranium and vanadium is 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 DeChelly sandstone. The top of the zone is irregular and undulatory. Ten to 20 feet above the top of this basal zone is a middle ore zone that contains many rods. This zone ranges in thickness from 5 to 20 feet and consists of irregular-shaped masses of channel sediment marked 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 as much as 15 feet thick; here, the principal ore is 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 includes the most productive part of the channel sediments. All types of ore bodies are in this zone, although corvusite-type ore bodies seem to predominate.

At the south end of the channel, (South Ridge) (fig. 4) the workings are in the basal ore zone and are in a corvusite-type ore body. Only Shinarump sediments are mineralized. Rods and tabular ore bodies are rare.

At the south edge of Main Ridge (Monument No. 2 cuesta) (fig. 4) 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 rise slightly and grade 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 Bobcat and Upper Bobcat workings.

The west edge of the South Workings consists of a large corvusite-type ore body which grades eastward into an area of channel sediments 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, Shinarump sediments show the deep blue-black of vanadium minerals. The mineralized ground locally includes some of the underlying DeChelly sediments to a depth of 10 to 15 feet. Corvusite is so profuse in these workings that the brown limonite coloration typical of Monument No. 2 channel sediments is almost obliterated. Locally the blue-black color is broken by irregular s reaks of the brilliant deep red mineral hewettite, or by large irregular masses of white opal that impregnates the sandstone and fills the interstices. All of the basal sediments in this part of the channel have been impregnated and the ore produced from this part of the South Workings is always a deep blue-black.

The east part of the South Workings has many rods in a conglomeratic sandstone that is stained a deep brown by the limonite. Most of these limonite-stained sediments are in a scour pit along the thalweg of this side of the channel (fig. 4). The scour pit is elongate, parallel to the channel trend, 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 scour pit. The contrast between the two parts of the South Workings is marked. On the west the sediments are dyed a deep blue black and contain only small amounts of yellow uranium minerals. Locally small patches of the deep red color of hewettite as well as splotches of white opal interrupt the blue black color. The east side contains conglomeratic sandstone of similar lithology but here the sediments are a deep brown as a result of the limonite stain. Scattered irregularly through these relatively barren sediments are the very richly mineralized yellow-colored 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 Nos. 2 and 3 (fig. 4), and the underground workings have extended towards each other along the channel axis since figure 4 was completed. Near Incline No. 2, a corvusite-type ore body is on the west flank of a depression in the channel floor. The scour 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 scour although its margins extend laterally beyond the limits of the scour.

In several localities in this part of the mine extensive fractures pass through the Shinarump into the underlying DeChelly (pl. 5 and fig. 4). Locally vanadium minerals have moved through the fractures and permeated the adjacent sediments. The vanadium minerals decrease in quantity with distance away from the Shinarump-Dechelly contact. Distinct rolls, which are so typical of the ore deposits in the Morrison formation, are in that part of the DeChelly sandstone which in this area immediately underlies the Shinarump. Here the rolls seem to be related to a combination of bedding planes and fractures.

Both high-grade uranium and vanadium ore have been mined from this part of the basal ore zone. The vanadium impregnates the sediments thoroughly and all strata, DeChelly as well as Shinarump, are dyed a deep blue black. Commonly uranium is present as disseminated fragments of relatively unoxidized uraninite. Most of the specimens of uraninite used in the age determination studies by Stieff, Stern, and Milkey (1953) were secured from this part of the basal ore zone. Rods and tabular ore bodies are present locally but not in such profusion as seen in other parts of the mine.

The basal ore zone is also being mined through Incline No. 3. Here, however, the zone consists of limonite-impregnated sediments that contain many rods. Several of the rods have cores of uranite 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 (fig. 4). 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, as are tabular ore bodies. 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 sediments 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.

<u>Middle Ore Zone</u>.--In 1953 the middle ore zone was being mined in three places; the Upper Bobcat Workings; the South Workings Incline; and the Incline No. 1 Workings (fig. 4). Along the south edge of Main Ridge the Upper Bobcat Workings are in channel sediments that contain many rods. In the South Workings

Incline (fig. 4) a similar situation exists. The rods in both these localities seem to be scattered erratically through the sediments, 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 No. 1 workings. Here, a crudely circular mass of Shinarump sediments 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 10 feet above the top of the basal ore zone which directly underlies it. About 20 feet of barren Shinarump sediments overlie 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 channels' trend. The rods studied in this area repeated what had been found to be true of all the rods in the channel; the larger rods are alined in a northwesterly direction parallel to the channel trend (A, fig. 14) whereas a similar alinement is not discernable in the smaller rods; these seem to trend in all directions (B, fig. 14). The greatest concentration of the rods seems to be in the center of this circular mass of sediments, although some of the largest rods are along the southwest edge.

Although the rods comprise the richer concentrations of ore, secondary yellow uranium minerals are found elsewhere and in different forms in the middle ore zone. Between many rods disseminated yellow uranium minerals fill interstices in the sandstone and result in weakly mineralized ground between the rods. Commonly this dissemination is very slight, as is illustrated by figure 11. This relationship between the rods and surrounding sediments, although best illustrated in the middle ore zone, is found elsewhere in the mine. Thus, channel sediments 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 false bedding planes in that part of the DeChelly sandstone which directly underlies the Shinarump.

Upper ore zone.-- The upper ore zone is the most restricted of the three zones. It is best exposed near the north edge of Main Ridge in the East, South, and West Red Oxide Workings. The Central Workings also probably are in the upper ore zone. 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 sediments contain large amounts of these secondary vanadium minerals. Primary vanadium minerals are rare. It may be that each of these

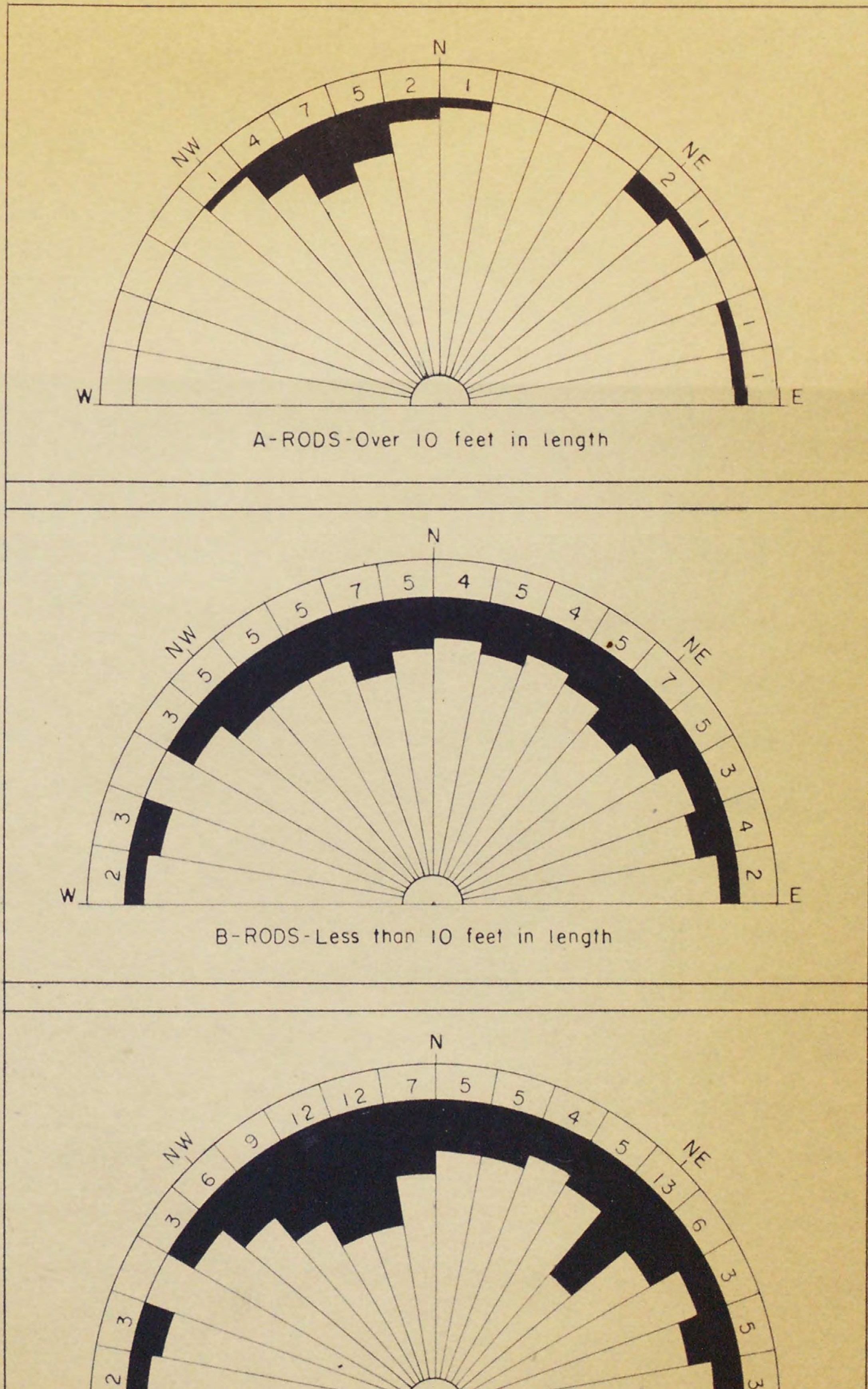


Figure 14. -- Trends of rods, Monument No. 2 mine. A. - Rods 10 feet or more in length. B. - Rods less than 10 feet in length. C. - All the rods. The larger rods may represent trees that were rafted into position; because of their length some orientation and alinement would be expected, and this alinement would approximate the channel trend of N. 18° W.

workings represent corvusite-type ore bodies that have been oxidized.

These workings all are along the east side of the channel, and only the West Red Oxide Workings are near the channel axis.

In those parts of the mine that contain few rods only small quantities of uranium ore have been produced. In the North Drifts, (fig. 4) for example, which are along the east flank of the channel, one can walk for hundreds of feet through weakly mineralized conglomeratic sandstone and only encounter yellow uranium minerals where the drifts have intersected rods. The sparsity of the rods in the North Drifts contrasts markedly with their profusion in the Incline No. 1 workings (fig. 4). However, concentrations of rods are not confined to any one sector of the channel. Repeatedly the work at the Monument No. 2 mine has indicated that channel sediments are not richly mineralized through their entire extent. Barren and weakly mineralized ground alternate both laterally and vertically at irregular intervals with richly mineralized ground. Further, the richer parts of the mine are marked by a concentration of rods and a direct ratio exists between the richness of an area and the number of rods present. In a sense an isolated rod on the flank of a channel will contain as high an average grade of uranium and vanadium oxide as will a similar appearing rod in the midst of a group of rods.

Vanadium-uranium ratios.--On the basis of ore production for the period 1948 to 1953 the vanadium-uranium (V:U) ratio for the mine is 4:1. However, during the course of the mine mapping channel chip samples were collected from all ore zones and along the entire length and width of the channel. The vanadium-uranium ratios determined from chemical analyses of these samples show great variation (Table IV).

A comparison of the V:U ratios determined from samples collected in any one of the mine workings vary considerably. Thus, in the Incline No. 1 Workings (fig. 4) the range is from a low of 0.2:1 to a high of 59:1 (Table IV). In the North Drifts the range is from 1:1 to 28:1 (Table IV). A similar disparity is noted when a comparison is made of the means of the V:U ratios determined from each set of workings (Table IV). Despite the fact that both the Incline No. 2 and No. 3 Workings are in the same part of the channel and in the same ore zone, the means of the V:U ratios differ widely. Even when the mean of the V:U ratios for the entire mine is considered, the standard deviation is high (Table IV).

These aberrant variations can be summarized as follows:

(1) Great variations of samples exist within each mine workings;

(2) Great variations of the average of samples exist between mine workings; and

(3) Even when the average of all the samples of the deposit are considered, considerable variation persists.

MINE WORKINGS (Workings in north end of channel at top of column)	Number of SAMPLES	Means of V:U RATIOS	STANDARD DEVIATION	RATIO RANGES
YAZZIE MESA	2	24	8	18 and 30
NORTH WORKINGS	5	5	5	0.6 to 12
NORTH DRIFTS	5	10	11	1 to 28
WEST RED OXIDE	3	2	2	0.01 to 4
SOUTH RED OXIDE	2	12	13	2 and 21
INCLINE NO. 3	8	7	10	0.3 to 22
CENTRAL WORKINGS	2	6	6	1 and 10
INCLINE NO. 1	11	13	18	0.2 to 59
INCLINE NO. 2	8	14	14	1 to 46
SOUTH WORKINGS INCLINE	5	19	15	1 to 37
BOBCAT AND UPPER BOBCAT	5	5	5	1 to 12
SOUTH WORKINGS	8	8	17	1 to 50
SOUTH RIDGE	5	24	22	6 to 50
TOTALS FOR ENTIRE DEPOSIT	69	11	14	0.01 to 59

Table 4. -- Vanadium uranium (V:U) ratios in the Monument No. 2 mine, Apache Co., Ariz.

This suggests that both vanadium and uranium are distributed at random through the channel sediments. It seems likely that a V:U ratio of 50:1 indicates a sample composed dominantly of vanadium minerals such as corvusite or hewettite. Conversely, a V:U ratio of 0.01 to 1 indicates a sample made up almost entirely of uranium minerals such as uraninite or becquerelite, and practically devoid of vanadium minerals.

Mineralogy.-- An intensive study of the mineralogy of the Monument No. 2 mine is under way at the present time (1952-1955) by D. H. Johnson of the Geological Survey. The list of minerals given below are those that have been identified to date and must be considered a preliminary statement on a subject that will be treated more fully by Johnson.

(1) Apatite ($(CaF)Ca_4 (PO_4)_3$). Rare

(2) Autunite ($Ca(UO_2)_2 (PO_4)_2 \cdot 10\text{-}12\ H_2O$). Rare

(3) Becquerelite ($2UO_3 \cdot 3\ H_2O$). Rare to common

(4) Calcite ($CaCO_3$). Common

(5) Carnotite ($K_2(UO_2)_2 (VO_4)_2 \cdot 3\ H_2O$). Common

(6) Corvusite ($V_2O_4 \cdot 6\ V_2O_9 \cdot n\ H_2O$). Abundant

(7) Fourmarierite ($PbU_4O_{13} \cdot 7\ H_2O$). Rare

(8) Galena (PbS) Rare

(9) Hyalite uraniferous ($SiO_2 \cdot n\ H_2O$). Rare

(10) Hydromica (?). Rare

(11) Hewettite ($CaV_6O_{16} \cdot 9 H_2O$). Common

(12) Jarosite ($K_2Fe_6(OH)_{12}(SO_4)_4$). Common

(13) Kaolinite (?) ($(OH)_8Al_4Si_4O_{10}$). Common

(14) Limonite (Goethite?). Common

(15) Metahewettite ($CaV_6O_{16} \cdot 9 H_2O$). Common

(16) Metazeunerite ($Cu(UO_2)_2 (AsO_4)_2 \cdot 8 H_2O$). Rare

(17) Montroseite (Vo(OH) Rare

(18) Muscovite ($(H,K) AlSiO_4$). Common

(19) Navajoite ($V_2O_5 \cdot 3 H_2O$). Rare

(20) Pitchblende (UO_2). Rare

(21) Pyrite (FeS_2). Rare

(22) Rauvite ($CaO \cdot 2 UO_3 \cdot 5 V_2O_5 \cdot 16 H_2O$). Rare

(23) Steigerite ($Al_2(VO_4)_2 \cdot 6\text{-}1/2 H_2O$). Rare

(24) Sphalerite (ZnS). Rare

(25) Sulphur (S). Rare

(26) Tyuyamunite ($Ca(VO_2)_2 (VO_4)_2 \cdot n H_2O$). Abundant

(27) Unknown minerals possibly Hewettite (?) or Metahewettite (?)

(28) Uranophane ($Ca(UO_2)_2 Si_2O_7 \cdot 6 H_2O$). Rare

(29) Uraninite (UO_2). Rare

(30) Wad.

(31) Zeunerite (?) ($Cu(UO_2)_2 (AsO_4)_2 \cdot 10\text{-}16 H_2O$). Rare

Besides the above minerals Gruner and Gardner (1952) report the following minerals in the Monument No. 2 mine:

1. Roscoelite (vanadium mica)
2. Fernandinite ($CaO \cdot V_2O_4 \cdot 5\ V_2O_5 - 14\ H_2O$)
3. Veins of green and white alunite ($KAl_3(SO_4)_2(OH)_6$).

Monument No. 1 area

(Channel No. 36 of fig. 3)

Monument No. 1-Mitten No. 2 mine and Monument No. 1 annex

Introduction

In 1954 the Monument No. 1 area was the scene of intensive mining activity, primarily as the result of a discovery of a new ore body in channel sediments formerly thought to be barren. Before that, in the period 1942 to 1950, the major producer was the Monument No. 1 mine, operated by the Vanadium Corporation of America. This mine was in the basal sediments at the east end of a large channel remnant. In 1950 the ore deposit pinched out; 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, in in a weakly mineralized mass of Shinarump conglomerate about 150 feet long and 50 feet wide.

During 1952 several Navajo Indians re-prospected the Monument No. 1 area. 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 Company (now the Industrial Uranium Co.) was opened in the flank of the west 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 sediments as a result of a drilling program by the Foutz Mining Company, and as of January 1955, it was this ore body which was being mined through the new Monument No. 1-Mitten No. 2 workings.

Location and accessibility

The center of the Monument No. 1 area is at latitutde 36° 57.4' N. and longitude 110° 14.0' W. The area is on a prominent ridge west of the Kayenta-Mexican Hat road (Navajo Indian Reservation Route No. 1) (fig. 2). The mines are reached by an ungraded trail that leads northwest from the Kayenta-Mexican Hat road and which ascends to the mine portals by a series of switchbacks.

Geology

The ridge is capped by remnants of Shinarump conglomerate which stand about 30 feet above the general ground surface formed by the Moenkopi formation (fig. 15). Scattered across this Moenkopi surface are deposits of unconsolidated eolian sand as much as 10 feet thick.

Most of the Shinarump has been eroded from the Monument No. 1 area and it is only to the west, near Oljeto Wash, that Shinarump 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 strata form the gently-dipping east flank of the asymmetrical Oljeto syncline and dips average 3° to the southwest.

Channel

The Shinarump conglomerate remnants represent part of a former widespread sheet of conglomeratic sandstone. Dissection, however, has been so extensive the uppermost beds of Shinarump as well as part of the adjacent strata of Moenkopi age have been largely removed (B, fig. 15). The result is that channel sediments now appear as two ridges whose alinement is to the northwest (A, fig. 15). The two ridges, however, do not everywhere reflect the true width of the channel for locally part of the channel sediments have been eroded. When these remnants are viewed in cross-section it is apparent that in places only the east flank of the channel is preserved (B, fig. 15 and A, pl. 12). Extrapolating from the channel remnants preserved, the channel is estimated to have been about 250 feet wide, and to have been cut about 50 feet into the

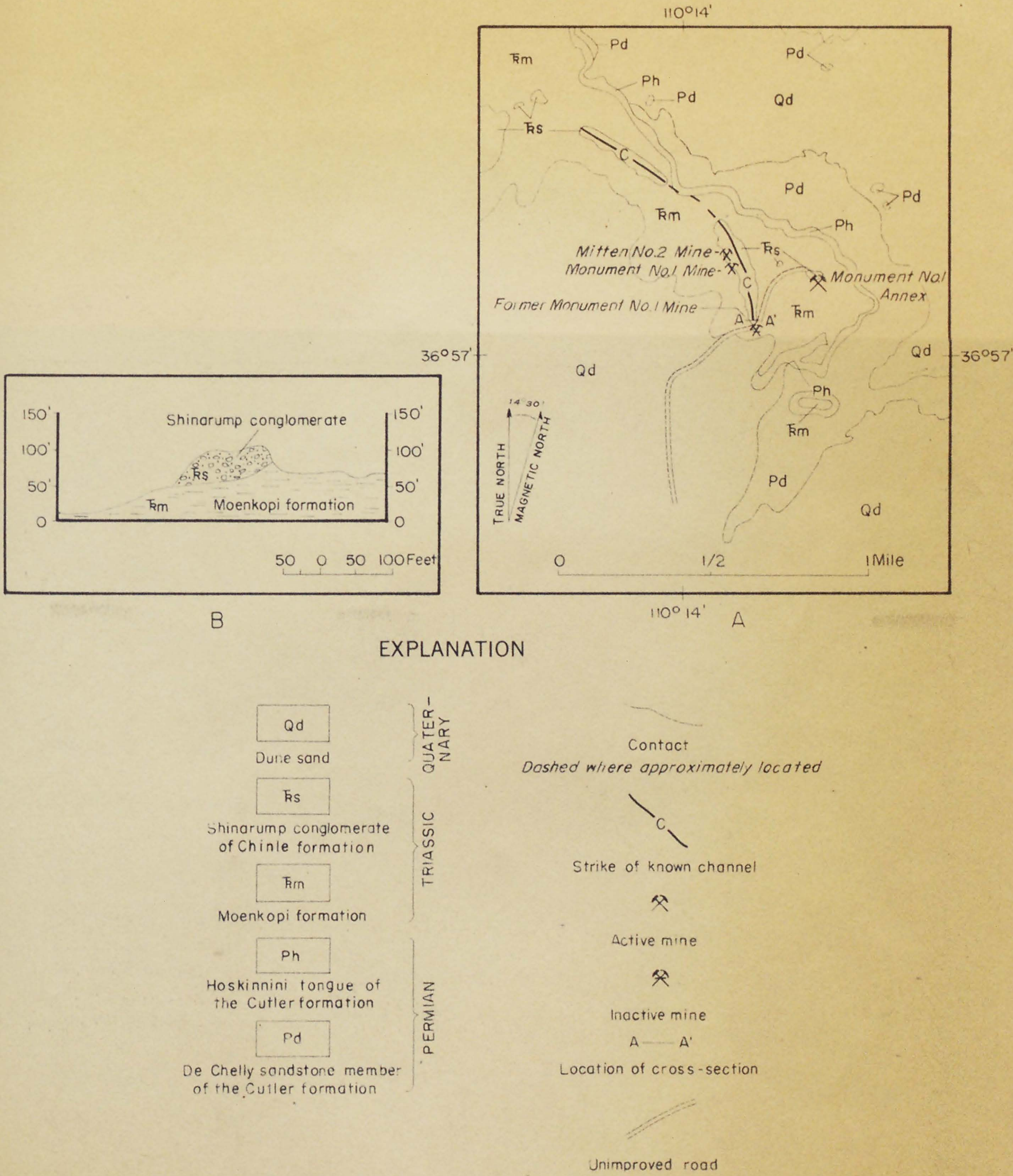


Figure 15. -- Geologic map and cross-section of the Monument No. 1 channel. The two channel remnants of Shinarump form topographic highs. The channel curves to the northwest. It is uncertain if the Monument No. 1 Annex is a part of the same channel.

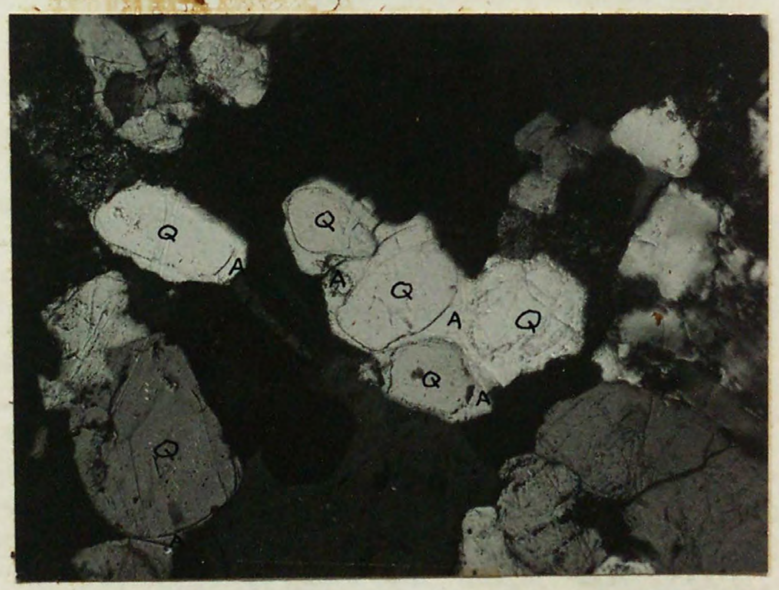
Moenkopi. The channel curves to the northwest (A, fig. 15). The southern channel remnant, which contains the mine workings, trends about N. 10°W., and the northern remnant trends about N. 55°W.

Monument No. 1 channel sediments look the same as Shinarump sediments found elsewhere in the Monument Valley area, Ariz. The basal conglomeratic sandstone grades vertically into a massive sandstone in the uppermost beds. Conglomerate lenses are scattered through the channel sediments. They retain their identity only for short distances, grading laterally into massive sandstones. In a few places, small scours, filled with conglomeratic sandstone, have been cut into the massive sandstone that forms the uppermost channel sediments.

Three lithologic types can be differentiated in the basal channel sediments; these are (1) a trash-pocket conglomerate, (2) a silica-cemented sandstone, and (3) a calcite-cemented sandstone (A, pl. 13). 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 silica-cemented sandstones are composed of rounded to angular coarse-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 (B, pl. 13). The third lithologic type, the calcite-cemented sandstone, is a light-tan, hard, massive crossbedded unit

Plate 12. -- A. - The isolated mass of Shinarump conglomerate (TRs) that forms the Monument No. 1 channel remnant. Tailings mark approximate location of Vanadium Corporation of America's former Monument No. 1 mine.

B. - Sandstone block at the Monument No. 1 Annex showing impression of reed-like plant matter.



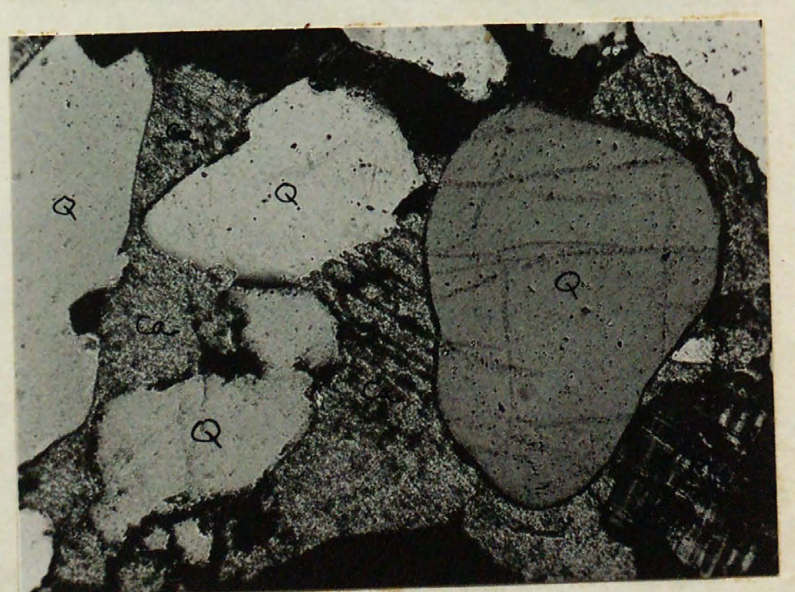


Plate 13. -- A. - Exposures of three lithologic units in basal channel sediments, Monument No. 1 mine workings. Note gradational character of contact between trash-pocket conglomerate (Tp) and calcite-cemented sandstone (Lr), and sharp contact between calcite-cemented sandstone (Lr) and silica-cemented sandstone (ore-bearing in this locality)(Cs).

B. -- Photomicrograph of silica-cemented sandstone showing authigenic quartz overgrowths (A) on rounded quartz (Q) grains. (C-chert)

C. - Photomicrograph of calcite-cemented sandstone showing tight bind between calcite (ca) and included grains. (M-microcline).

channel sediments lack the limonite coloration.

The channel is underlain by an altered zone in the uppermost Moenkopi strata 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 is being investigated (Weeks, 1952b, unpublished report). Specimens of both the red unaltered Moenkopi and the gray altered Moenkopi were chemically analyzed. Weeks reports (1952b, op. cit., p. 12):

> 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.

Weeks (1952b, op. cit., p. 13) sought but found no evidence for or against a relationship of the altered zone to ore mineralizing solutions.

Sediments 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 are absent elsewhere. A banded appearance results, with yellow mineralized bands about 1 inch wide alternating with white "barren" bands, also about one inch wide. Close examination near some of the clay pebbles indicates that in some yellow uranium minerals impregnate the sandstone to their very edges. 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 sediments 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 reed-like plant material in the sandstone (B, pl. 12).

Uranium-vanadium ore bodies.--Two ore bodies have been discovered in the basal channel sediments of the south channel remnant. They are separated from one another by barren sediments. Little is known about the size, shape, and distribution of that ore body mined by the Vanadium Corporation of America at the former Monument No. 1 mine (fig. 15). The second ore body, currently being mined through the Monument No. 1-Mitten No. 2 mine portals (fig. 15) is near the north end of the south channel remnant. It is about 675 feet long, about 75 feet wide, (although it is as wide as 120 feet), and it ranges in thickness from 1 foot to as much as 18 feet, (although it averages 7 feet in thickness). This ore body trends N. 30°W., and is collinear with the channel trend. In both longitudinal- and cross-section the ore body appears plano-convex or biconvex, with its base commonly conforming to the channel floor.

In places, both the trash-pocket conglomerate and the silica-cemented sandstone contain ore and form the ore body. Barren calcite-cemented sandstone lenses commonly are intercalated in the ore body (A, pl. 13). The ore is brilliant blue-black, principally due to the widespread distribution of the vanadium mineral, corvusite. Scattered irregularly through the ore body are specks of yellow, green, and blue, representing secondary uranium (tyuyamunite), copper-vanadium (volborthite), and copper (azurite, malachite) minerals. Copper minerals are common in the south part of the Monument No. 1 mine workings, but are not found in the Mitten No. 2 workings. Semiquantitative spectrographic analyses of the basal channel sediments, however, indicates that copper is widespread.

Mineralogy.--The following minerals were collected from channel sediments exposed near the former Monument No. 1 mine.

1.	Apatite (?)	$CaFCa_4(PO_4)_3$	Rare
2.	Autunite	$Ca(UO_2)_2(PO_4)_2 \cdot 12H_2O$	Rare
3.	Azurite	$Cu_3(OH)_2(CO_3)_2$	Rare
4.	Carnotite	$K_2(UO_2)_2(VO_4)_2 \cdot 3H_2O$	Rare (?)
5.	Calcite	$CaCO_3$	Common
6.	Chlorite	$Mg_5(Al,Fe)(OH)_8(Al,Si)_4O_{10}$	Rare
7.	Chrysocolla	$CuSiO_3 \cdot 2H_2O$	Rare
8.	Hydromica	$KAl_2(OH)_2AlSi_3(O,OH)_{10}$	Rare to common
9.	Kaolinite	$(OH)_4Al_2Si_2O_5$	Rare (?)
10.	Limonite	$2Fe_2O_3 \cdot 3H_2O$	Common
11.	Malachite	$Cu_2(OH)_2CO_3$	Rare
12.	Meta-torbernite	$Cu(UO_2)_2(PO_4)_2 \cdot 8H_2O$	Rare
13.	Montmorillonite	$(MgCa)O \cdot Al_2O_3 \cdot 5SiO_2 \cdot nH_2O$	Rare
14.	Pyrite	FeS_2	Common
15.	Torbernite	$Cu(UO_2)_2(PO_4)_2 \cdot 12H_2O$	Rare
16.	Tyuyamunite	$Ca(UO_2)(VO_4)_2 \cdot nH_2O$	Common
17.	Zippeite	$(UO_2)_2SO_4(OH)_2 \cdot 4H_2O$	Rare

Essentially the same minerals are found at Monument No. 1 annex.

The following minerals were collected from the Mitten No. 2 Mine:

1	Apatite	$CaF(Ca_4)(PO_4)_3$	Rare
2	Azurite	$Cu_3(OH)_2(CO_3)_2$	Rare to common
3	Calcite	$CaCO_3$	Common
4	Carnotite	$K_2(UO_2)_2(VO_4)_2 \cdot 1\text{-}3H_2O$	Rare
5	Chalcanthite	$CuSO_4 \cdot 5H_2O$	Rare
6	Chalcedony	SiO_2	Rare to common
7	Chalcocite	Cu_2S	Rare
8	Chrysocolla	$CuSiO_3 \cdot 2H_2O$	Rare to common
9	Corvusite	$V_2O_4 \cdot 6V_2O_5 \cdot nH_2O$ (?)	Common
10	Hewettite	$CaV_6O_{16} \cdot 9H_2O$	Rare
11	Malachite	$Cu_2(OH)_2CO_3$	Common
12	Meta-torbernite	$Cu(UO_2)_2(PO_4)_2 \cdot 8\text{-}12H_2O$	Rare
13	Meta-tyuyamunite	$Ca(UO_2)_2(VO_4)_2 \cdot 7\text{-}10\frac{1}{2}H_2O$	Common
14	Pyrite	FeS_2	Common
15	Rauvite	$CaO \cdot 2UO_3 \cdot 5V_2O_5 \cdot 16H_2O$(?)	Rare
16	Roscoelite	$(Al, V)_2AlSi_3(K, Na)O_{10}(OH, F)_2$	Rare
17	Tyuyamunite	$Ca(UO_2)_2(VO_4)_2 \cdot 7\text{-}10\frac{1}{2}H_2O$	Common
18	Volborthite	$Cu_3(VO_4)_2 \cdot 3H_2O$ (?)	Common

Oil and gas possibilities

Only two test wells have been completed in the Monument Valley area, Apache and Navajo Counties, Ariz. (Table V), and in only one was there any show of oil or gas even though both penetrated strata that produce in adjacent areas. The most recent test in the Monument Valley area was in sec. 34, T. 42 N., R. 18 E., Navajo Co., Ariz. (unsurveyed) on the crest of the Organ Rock anticline. The test, known as Navajo A-1, (number 1, Table V) was a joint venture by the Texas, Sinclair, and Skelly Oil Companies and penetrated 4, 523 feet to the Elbert formation (Late Devonian) before it was abandoned as a dry hole (Table VI). There were no shows of oil or gas. The log of the hole is published in full as Appendix A by agreement with these oil companies. The other test in this area is in sec. 7, T. 41 N., R. 23 E., Apache Co., Ariz. (unsurveyed) and was completed in 1924 on the crest of the Gypsum Creek dome. The well, known as the Midwest 1 Gypsum, was drilled by the San Juan Oil and Development Company to a depth of 2, 083 feet. It started in the Halgaito tongue of the Cutler formation and bottomed in the Elbert formation.

The depth to basement rock over most of the Monument Valley area (Table VI) 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 southern 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 sequence is thin, the rocks thicken rapidly to the northeast, south, and west. Favorable host rocks for oil and gas accumulations include the Hermosa and Rico, as well as Devonian and possibly Cambrian strata.

Of other test wells 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 Mexican Hat 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, the Shell Oil Company completed two successful wells (numbers 5 and 14, Table V) about 25 miles east and northeast of the northeast corner of the report area.

Although oil seeps have been known from this general region since 1882 (Woodruff, 1910, p. 98), oil in commercial quantities was first produced from the Mexican Hat (San Juan) oil field in 1908. Since then about 115 wells have been drilled in and north of the Mexican Hat (San Juan) field; of these only a few were successful. The more significant tests and wells in the field have been listed on Table V. Production was principally from the Hermosa formation (Pennsylvanian) with lesser oil and gas from the Rico formation (Permian). The Mexican Hat (San Juan) field has been described by Woodruff (1910), Baker (1936) and Hansen and Bell (1949).

In the Mexican Hat (San Juan) oil field, most of the wells drilled at first 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 sequence was as thin as 2, 000 feet. In the course of the drilling oil and gas shows were found at several horizons, although major production was either from the Rico or Hermosa. The oil was in a syncline and production was hampered by low porosity in the lenticular sandstone beds and by low hydrostatic pressure (Hansen and Bell, 1949, p. 198).. The nearest active field is the Boundary Butte field in San Juan County, Utah, about 15 miles northeast of the east boundary of the Monument Valley area. Here, production is from the Coconino sandstone, the age equivalent of the DeChelly sandstone of the Cutler formation. The Boundary Butte field in T. 43 S., R. 22 E., produces both oil and gas from an elongate northwest trending anticline on the southwest flank of the Paradox Basin.

Of the wildcat tests completed near the Monument Valley area only the two tests drilled by the Shell Oil Co. were successful. The first of these, test No. 2 East Boundary Butte is in sec. 3, T. 41 N., R. 28 E., Apache County, Ariz., (number 5, Table V) and was completed as a gas producer. The second well, test No. 2 Desert Creek is in sec. 35, T. 41 S., R. 23 E., San Juan Co., Utah, (number 14, Table V) and was completed as an oil well. Both wells produce from the Hermosa formation.

Although possible oil-bearing strata underlie the area, uncertainty exists as to which type structures are favorable. Many of the tests in this part of Utah and Arizona have been on the crests of local structures. 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 (San Juan) 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 tight holes or encountered water or gas. However, inasmuch as the area was deformed in Tertiary time, it seems likely that the original oil accumulations have been either displaced or dispersed. It seems possible that unsuccessful tests on the crests of anticlines do not lessen the favorability of the Monument Valley area as a potential source of oil and gas.

The favorable location of the Monument Valley area in terms of regional structure, the presence of oil-bearing strata in nearby areas, and the many possible oil structures, all 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 re-emphasizes the promising oil and gas possibilities of this sector of the Four Corners area.

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Appendix A.

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

MESOZOIC ERA

TRIASSIC PERIOD

Shinarump fm. 0-93' (93')

0-50'	(50')	Sandstone, white, medium-coarse grained.
50-93'	(43')	Sandstone, white, medium-coarse grained, with some light gray shale stringers, conglomeritic at base. Some milky and amber chert.

Moenkopi fm. 93-263' (170')

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 fm. 263-2207' (1944')

Hoskinnini member 263-336' (73')

263-290'	(33')	Sandstone, red-white, very fine grained, slightly limy.
290-300'	(10')	Shale, brown, sandy.
300-326'	(26')	Siltstone, red-brown, slightly limy and conglomeritic.
326-336'	(10')	Shale, brown, sandy.

De Chelly member 336-697' (361')

336-360'	(24')	Sandstone, red-tan, fine-grained, limy, trace of milky chert.
360-410'	(50')	Sandstone, red-tan, fine-medium grained, slightly conglomeritic.
410-490'	(80')	Sandstone, pink, medium-grained, slightly conglomeritic and limy.
490-500'	(10')	Shale, brown.
500-697'	(197')	Sandstone, pink-tan, medium-coarse grained, slightly conglomeratic and limy.

Organ Rock member		697-1325' (628')
697-910'	(213')	Shale, red, hard, sandy, micaceous.
910-930'	(20')	Sandstone, white, medium grained.
930-1325'	(395')	Shale, red, very sandy, slightly limy.
Cedar Mesa member		1325-1835' (510')
1325-1400'	(75')	Sandstone, pink-white, very fine grained, limy.
1400-1480'	(80')	Sandstone, light gray-white, very fine grained, limy.
1480-1650'	(170')	Sandstone, orange-pink, very fine-fine grained, some free quartz grains, hard-friable, limy, with some red shale stringers.
1650-60'	(10')	Shale, red, sandy, limy.
1660-1750'	(90')	Sandstone, orange-gray, fine grained, limy, with some red and green shale stringers.
1750-80'	(30')	Shale, red, micaceous, limy.
1780-1835'	(55')	Sandstone, orange, very fine grained, limy, with red shale stringers.
Halgaito member		1835-2207' (372')
1835-2130'	(295')	Shale, red, limy, interbedded with some gray limestone and pink-gray sandstone. Traces of green shale.
2130-2207'	(77')	Shale, red-brown, limy, sandy, with some stringers of red and gray limestone.
Rico formation		2207-2785' (578')
2207-2310'	(103')	Sandstone, white-pink, fine grained, limy interbedded with some red and brown shale and gray limestone.
2310-60	(50')	Shale, red, sandy, limy, with some limestone and sandstone stringers.
2360-80	(20')	Sandstone, white-pink, fine grained, limy.
2380-2490'	(110')	Shale, red, limy, sandy, with some stringers of limestone.
2490-2555'	(65')	Limestone, gray-green, fine-crystalline, sandy, with some red shale stringers.
2555-2590'	(35')	Sandstone, white-gray, medium grained, limy, hard to friable.
2590-2600'	(10')	Shale, red, sandy.
2600-10'	(10')	Shale, purple, sandy, micaceous.
2610-40'	(30')	Limestone, white-light gray, fine-medium crystalline, slightly oolitic.
2640-60'	(20')	Sandstone, white, fine grained, friable.
2660-70'	(10')	Shale, red, limy, sandy.

2670-2700'	(30')	Limestone, tan-light gray, fine crystalline-dense, slightly sandy.
2700-10'	(10')	Shale, red, limy.
2710-60'	(50')	Sandstone, white, fine-medium grained.
2760-70'	(10')	Shale, red, interbedded with red-gray limestone and white sandstone.
2770-85'	(15')	Sandstone, purple-gray, limy.

PENNSYLVANIAN

Hermosa formation — 2785-3488' (703')

2785-95'	(10')	Limestone, light gray-gray, dense, sandy.
2795-2820'	(25')	Sandstone, white-light gray, fine-medium grained, limy, interbedded with red shale and some gray chert.
2820-2980'	(160')	Limestone, light-dark gray, dense, siliceous, interbedded with amber, gray, and milky chert, and gray sandstone.
2980-3225'	(245')	Limestone, white-light gray, fine crystalline-dense, sandy, interbedded with amber and milky chert, and red and brown shale.
3225-3280'	(55')	Limestone, gray-brown, medium crystalline, slightly oolitic, some honeycombed, interbedded with amber chert and gray sandstone.
3280-3450'	(170')	Limestone, white-light gray, medium-fine crystalline, some honeycombed and chalky, interbedded with amber chert, gray sandstone, and some calcite.
3450-3488'	(38')	Limestone, white-light gray, dense, with some amber chert.

Molas formation — 3488-3585' (97')

3488-3515'	(27')	Limestone, light gray, dense, interbedded with amber chert and green shale.
3515-50'	(35')	Shale, green and purple, interbedded with some light-gray limestone, and amber chert.
3550-80'	(30')	Shale, red-maroon.
3580-85'	(5')	Shale, purple.

MISSISSIPPIAN — 3585-4077' (492')

3585-3670'	(85')	Limestone, white, chalky, with some amber chert, and red-purple shale.
3670-3740'	(70')	Limestone, light gray-white, fine crystalline-chalky, oolitic, with some gray dolomite and milky chert.
3740-3820'	(80')	Dolomite, tan-dark gray, fine crystalline-sucrose, with some limestone and calcite.
3820-3855'	(36')	Limestone, dolomitic, white, coarse-crystalline.

3855-3900'	(45')	Dolomitic, white-light gray, white-light gray, fine crystalline sucrose with some white and amber chert, interbedded with light gray limestone.
3900-4077'	(177')	Dolomite, white-gray, fine crystal-line-sucrose, interbedded with chalky limestone.

DEVONIAN 4077 - ? (Drilled 446')

Upper Devonian 4077-4192' (115') Limestone, white-light gray, fine crystalline-dense, some chalky, inter-bedded with red, purple, and green shale.

(Lower Devonian) Elbert 4192 - ? (Drilled 331')

4192-4260'	(68')	Dolomite, tan-gray, coarse crystalline-dense, with some milky chert, interbedded with red and green shale.
4260-75'	(15')	Shale, purple, limy, with some gray dolomite.
4275-4370'	(95')	Dolomite, gray-dark gray, coarse crystalline-dense, with some milky and amber chert, and traces of green shale.
4370-4425'	(55')	Dolomite, dark gray-black, coarse crystalline, interbedded with gray sandstone.
4425-40'	(15')	Sandstone, white-light gray, fine grained, glauconitic.
4440-75'	(35')	Dolomite, tan-gray-black, fine-medium crystalline, slightly sandy, with some thin gray sand-stone and red shale stringers.
4475-95'	(20')	Sandstone, red, fine grained, arkose, slightly limy.
4495-4523'	(28')	Dolomite, tan-gray-black, fine-medium crystalline, dense, slightly siliceous, with some interbedded amber and milky chert, and tight gray limestone.

TD 4523' in Elbert Formation

Pink and buff-colored massive cross-bedded sandstone with interbedded thin lenses of siliceous limestone.

TRo	Owl Rock member
TRp	Petrified Forest member
TRmb	Monitor Butte member
TRs	Shinarump conglomerate
TRm	Moenkopi formation
Ph	Hoskinnini tongue
Pd	DeChelly sandstone member
Po	Organ Rock tongue
Pc	Cedar Mesa sandstone member
Pha	Halgaito tongue

Paleozoic

ERUPTIVE ROCKS

TQr	Tertiary or Quaternary rubble
Ti	Tertiary intrusives

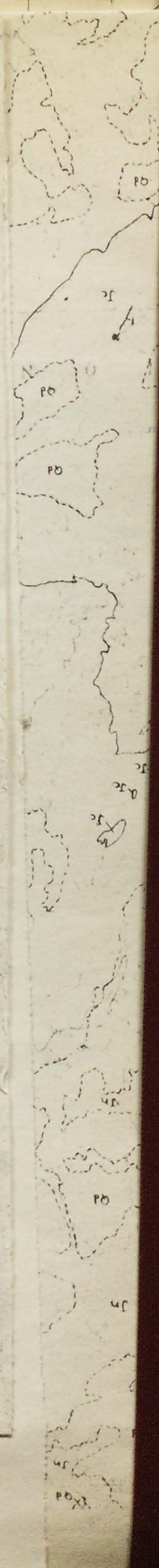

Fig. 3