

The Uranium-Vanadium Ore Deposit at the Monument No. 1-Mitten No. 2 Mine, Monument Valley Navajo County, Arizona

GEOLOGICAL SURVEY BULLETIN 1107-C

*Prepared on behalf of the U.S. Atomic
Energy Commission and published with
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By IRVING J. WITKIND

CONTRIBUTIONS TO THE GEOLOGY OF URANIUM

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UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

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THE URANIUM-VANADIUM ORE DEPOSIT AT THE MONUMENT NO. 1-MITTEN NO. 2 MINE, MONUMENT VALLEY, NAVAJO COUNTY, ARIZONA

By IRVING J. WITKIND

ABSTRACT

The Monument No. 1-Mitten No. 2 uranium-vanadium mine is in a remote sector of the Navajo Indian Reservation, Navajo County, Ariz. Near the mine, the strata range in age from Permian (De Chelly sandstone member of the Cutler formation) to Late Triassic (Shinarump member of the Chinle formation). Erosion has removed most of the Shinarump from the Monument No. 1 area, and only several small remnants remain. Two of these, each about 2,000 feet long, are part of a once continuous channel fill; they aline to form a broad curve trending northwestward. The channel ranges in width from 50 to 280 feet, and has been scoured about 50 feet into the underlying strata.

Three major lithologic units make up the basal channel fill: trash-pocket conglomerate, silica-cemented sandstone, and calcite-cemented sandstone.

Ore minerals impregnated parts of both the trash-pocket conglomerate and the silica-cemented sandstone and formed an ore body that was collinear with the channel and that extended for about 650 feet. The ore body, which has been mined out, ranged in width from 10 to 95 feet and in thickness from 1 to 18 feet. It was both biconvex and planoconvex in longitudinal section and in cross section and, in general, conformed to the channel floor. Lenses of the calcite-cemented sandstone were enclosed in the ore body. The core of the ore body consisted of low-valent relatively unoxidized minerals. Adjacent to and overlying the core were two incomplete concentric sheaths of oxidized minerals, the more intensely oxidized minerals being farthest from the core. The ore body was probably oxidized in place.

The uraniferous material was in approximate equilibrium. The ratio of vanadium to uranium for the mine was about 2.5:1.

The ore is adjacent to calcite-cemented sandstone lenses; possibly the carbonate was instrumental in precipitating the ore minerals from the ore-bearing solutions.

INTRODUCTION

Interest in the Monument Valley area of northeastern Arizona and southeastern Utah as a potential source of uranium-vanadium ore began largely in 1948 and had reached a peak by about 1956. Much

of this interest stems from uraniferous ore deposits in the general area that were known before 1948. Because of the remoteness of the area and the difficulty of mining in that barren part of Arizona and Utah, extensive prospecting did not begin until 1952. In the period 1952-55, however, roads were constructed into once inaccessible localities, and most of the region was examined. Mineralized prospects have been developed into established mines, and, as of 1956, intensive drilling by private agencies had revealed new large uranium-vanadium ore deposits.

The Monument Valley area ranges in altitude from about 4,800 feet along the east edge to about 7,800 feet at the west edge where it joins the Segi Mesas. The Monument No. 1-Mitten No. 2 mine is near the middle of the area and is at an altitude of about 5,600 feet (fig. 21).

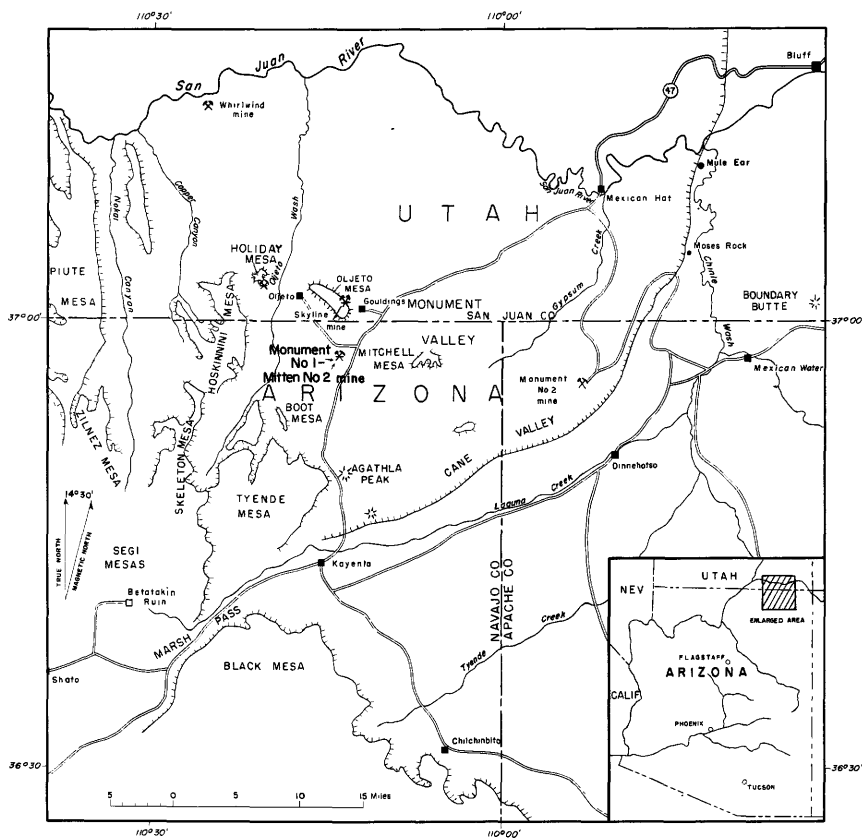


FIGURE 21.—Index map of parts of Navajo and Apache Counties, northeastern Arizona, and San Juan County, southeastern Utah, showing location of the Monument No. 1-Mitten No. 2 mine.

The area is a desert. Vegetation consists principally of sage brush, juniper, and piñon pine. Dust storms are frequent in the spring, and severe thunderstorms are common in the summer.

An all-weather road extends from Mexican Hat, Utah, to Kayenta, Ariz. All the other main roads are graded and, locally, graveled. Vehicular travel on any of the roads is difficult during dust storms or following torrential rainstorms.

PURPOSE OF WORK

This paper has two objectives: to describe and explain the principal and distinctive features of the mine and to call attention to another instance of the relation between carbonate-cemented sandstone and uraniferous deposits, first noted in the southern Black Hills (Gott, 1956).

LOCATION OF THE MINE

The Monument No. 1-Mitten No. 2 mine owned in 1959 by the Copper Canyon Industries, Inc. (formerly the Foutz Mining Co.), of Farmington, N. Mex., is in the northeast corner of Navajo County, Ariz. (fig. 21), near the north end of the Navajo Indian Reservation. The mine is about 15 miles north of Kayenta, Ariz., and about 8 miles southeast of Oljeto, Utah. It is in an erosional remnant of the Shinarump member of the Chinle formation (Upper Triassic) that forms a ridge about 1 mile west of the main route northward from Kayenta to Mexican Hat. This ridge is known locally as the Monument No. 1-Mitten No. 2 Mesa.

Three mines are in this area (fig. 22). The southernmost one is known as the Monument No. 1 mine of the Vanadium Corp. of America. Its workings were abandoned in 1950 and its portals closed at that time. The remaining two mines are known as the Monument No. 1 and Mitten No. 2. Of these, the southern one is known as the Monument No. 1 mine, deriving its name from the abandoned mine of the Vanadium Corp. of America. The northern mine is known as the Mitten No. 2. As the workings of both mines were continuous and were separated only by an arbitrary line, they are considered here as a geologic entity.

HISTORY OF MINING

The complete history of the development of the Monument No. 1 area is not known. Apparently the property was claimed about 1942 by the Vanadium Corp. of America, and a uranium-vanadium ore body at the very southern tip of a remnant of the Shinarump was mined for vanadium. This mine was named the Vanadium Corp. of America Monument No. 1 (fig. 22). In 1950 the Vanadium Corp.

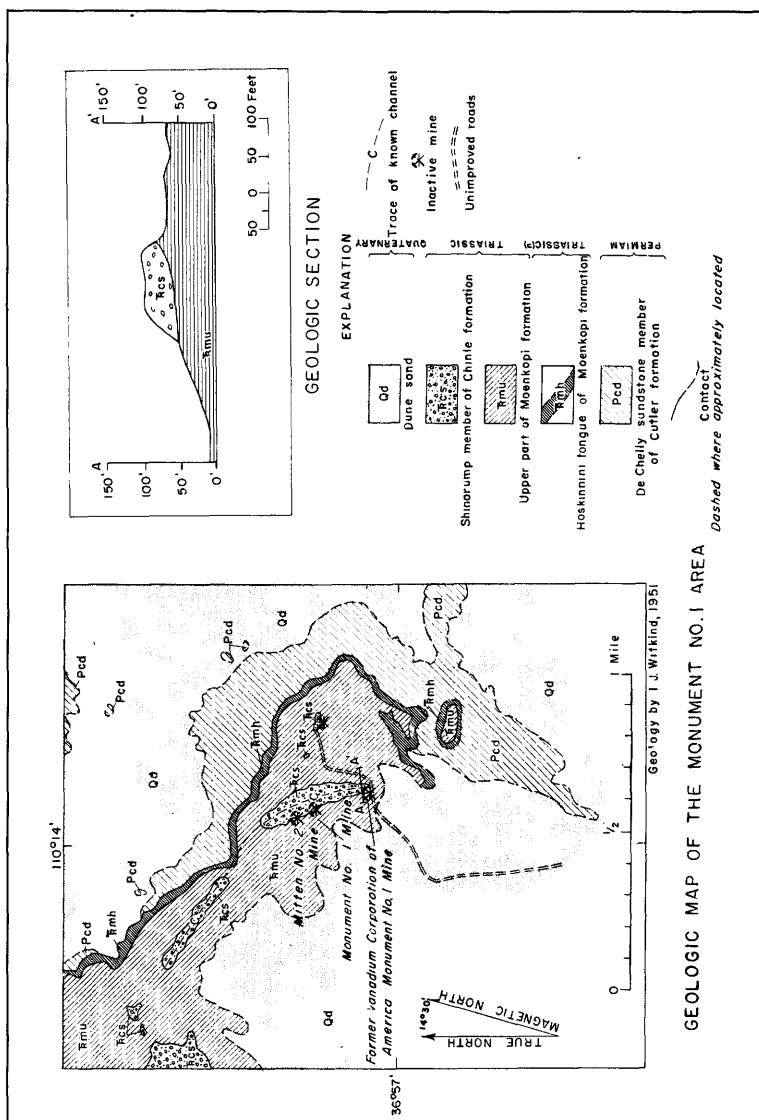


FIGURE 22.—Geologic map and section of the Monument No. 1 area. Only the eastern part of the Monument No. 1 channel is preserved at the southern tip of the south-channel remnant.

of America discontinued and abandoned its mining operations. Some slight prospecting was done in 1952, principally by Navajo Indians.

During the late summer of 1952, the Foutz Mining Co. became interested in the property and began an exploratory drift into the west flank near the north end of the Shinarump remnant. Weakly mineralized ground was found, and a small amount of uranium-vanadium ore was shipped. This mine was named the Mitten No. 2 (fig. 22). Early in 1954, the U.S. Atomic Energy Commission began a program of wagon drilling on the Monument No. 1-Mitten No. 2 Mesa under the direction of C. G. Evenson and M. V. Anthony. Mineralized ground was found near the former Monument No. 1 workings of the Vanadium Corp. of America, and the Foutz Mining Co. began a drift toward the mineralized ground. Upon completion of the Commission's drilling program, the Foutz Mining Co., spurred by the original find, engaged the Texas Mining Co. to continue the test of the north end of the Shinarump remnant. During the course of this second drilling program, the major part of a new ore body was found. This ore body was mined out between 1954 and 1956, and at that time the remaining ore pillars were removed and the mine was abandoned. The present report deals chiefly with this ore body.

PREVIOUS WORK

The U.S. Geological Survey, on behalf of the Division of Raw Materials of the U.S. Atomic Energy Commission, completed a study of the Monument Valley area in 1952 before the Monument No. 1-Mitten No. 2 mine was opened (Witkind and Thaden, in press). Bain (1952) studied the uranium deposits of the southwestern Colorado Plateau and visited the Monument No. 1 area in 1952, also before the mines were opened. The first detailed study of these mines was undertaken in 1954 by C. G. Evensen, I. B. Gray, and several of their associates in the U.S. Atomic Energy Commission. The mine map shown in plate 1 was compiled by them, and was modified slightly by the author in May 1955.

ACKNOWLEDGMENTS

C. G. Evenson, I. B. Gray, and their associates in the U.S. Atomic Energy Commission were most helpful in supplying data and available maps.

Thanks are due also to Messrs. Foutz and Ashcroft for permitting the examination of their mine. Mr. Tom Fraka, mine Superintendent, and Mr. Jerry Peabody, mine foreman, assisted materially during the course of the work.

I am indebted to R. H. Morris for his assistance during my study of the mine.

GEOLOGY

GENERAL

Sedimentary rocks in the Monument Valley area range in age from Permian (Cutler formation) to Jurassic (Morrison formation) and have an aggregate thickness of about 5,000 feet. Near the mine, the stratigraphic range is less and extends only from the De Chelly sandstone member of the Cutler formation to the Shinarump member of the Chinle formation of Late Triassic age (see following table).

Sedimentary rocks exposed in the Monument No. 1 area

Age		Stratigraphic unit		Thick- ness (feet)	Lithologic and topographic characteristics
		Formation	Member		
Triassic	Early and Middle(?)	Chinle formation	Shinarump member	0-150	Conglomeratic sandstone, light-gray to light-brown, massive, crossbedded; much silicified wood and clay fragments included with detrital quartz, chert, and quartzite; erosion channels at base; uranium-bearing in part.
			Unconformity		
		Moenkopi formation	Upper part of Moenkopi formation	65-250	Siltstone, reddish-brown, fissile, well-sorted, ripple-marked, thin- and even-bedded; forms low-angle rubble-covered slopes; in places intercalated massive sandstone beds form benches.
			Hoskinnini member	15-50	Siltstone with interbedded sandstone lenses, reddish-brown, even-bedded; forms benches.
Permian		Cutler formation	Unconformity		
			De Chelly sandstone member	350-550	Sandstone, light-gray to light-brown, massive, crossbedded; forms cliffs where protected; forms rounded slopes where unprotected.

In the Monument No. 1 area, the Shinarump consists of only a few scattered remnants, all that remain of a sheet that once blanketed the area. Dune sand mantles most of the bedrock, and exposures near the mine are poor (fig. 22).

Igneous rocks, chiefly minettes and biotite vogesites, cut the sedimentary strata of the Monument Valley area to form volcanic necks and dikes. The nearest igneous intrusive mass is a minette dike along the south edge of Oljeto Mesa, about 4 miles northwest of the mine.

The sedimentary rocks in the Monument Valley area have been deformed into asymmetrical anticlines and synclines whose axes trend northward. The synclines are marked by short, steep west flanks and long, gently dipping east flanks. The Monument No. 1-Mitten No. 2 mine is on the east flank of the Oljeto syncline, and strata near the mine strike about N. 20° W. and dip about 3° SW.

Two fracture sets cut the strata in and near the mine. The major fracture set trends N. 40° to 50° W.; a second set trends about N. 20° E. On the surface both sets can be traced for as much as a quarter of

a mile. In the mine workings, the fractures are thin cracks that extend vertically for 2 to 3 feet (fig. 29) and can be traced laterally for as much as 70 feet (pl. 1). The fractures, which cut all lithologic units in the mine, probably were formed during the deformation of the area in Late Cretaceous time.

MOENKOPI FORMATION

Near the mine, the Moenkopi formation of Early and Middle(?) Triassic and Triassic(?) age consists of reddish-brown to dark-brown shaly siltstone, shale, and platy thin-bedded fine-grained sandstone. In sharp contrast, the Moenkopi throughout a thickness ranging from 2 to 7 feet directly below the remnants of the Shinarump member of the Chinle formation is altered to a uniform light-grayish green that locally becomes a light green. Below the altered rock is a transitional zone about 6 inches thick, which consists of alternating light-grayish-green and reddish-brown beds. Below the transitional zone are unaltered reddish- to dark-brown shaly siltstone beds, characteristic of the Moenkopi formation.

This zone of altered Moenkopi strata directly below the Shinarump member is common in the Monument Valley area; generally it thickens below channels. The geologic work in the Monument Valley area suggests that such a thickened zone of altered Moenkopi strata directly below channels may be a favorable guide to uranium-vanadium deposits. In fact, geologic prospecting for uraniferous deposits in the Morrison formation of southwestern Colorado has been guided by this thickening of altered mudstone beneath channel-fill sandstone (McKay, 1955, p. 271). In that area, the normally red mudstone is altered to gray, near and directly below ore-bearing sandstone (Weir, 1952, p. 20).

The mineralogic differences between the altered zone and unaltered Moenkopi rocks in the Monument No. 1 area are small. Both the red and gray clay contain chiefly quartz and hydromica with possibly a little chlorite and kaolinite; but, in general, the red beds contain more total iron and ferric iron than adjacent gray beds (A. D. Weeks, 1952, written communication).

CHINLE FORMATION

In the Monument Valley area the Chinle formation of Late Triassic age consists of five members. In ascending order these are the Shinarump member, the Monitor Butte member, the Petrified Forest member, the Owl Rock member, and the Church Rock member. Of these, only the Shinarump member is preserved in the Monument No. 1 area, and the mine was in a remnant of that unit. Consequently,

only the overall characteristics of the Shinarump, as it is exposed in the Monument No. 1 area, are discussed here. Detailed lithologic descriptions of the unit are given under "Channel fill" (p. 227).

SHINARUMP MEMBER OF THE CHINLE FORMATION

The Shinarump member of the Chinle formation is the chief host rock for the uranium-vanadium ore deposit in the Monument Valley area. In general, it is a crossbedded fine- to coarse-grained conglomeratic sandstone that is light gray to light brown and massive, and that ranges in thickness from 0 to as much as 375 feet. It rests unconformably on the Moenkopi formation, and in the Monument No. 1 area the contact is sharp and distinct.

The mine was in an erosional remnant of the Shinarump member that caps a ridge trending about N. 45° W. The remnant is about 50 feet thick and consists chiefly of crossbedded poorly sorted fine- to coarse-grained sandstone that is light brown and massive. The sandstone consists of trough sets, 5 to 15 feet thick, composed of small- to medium-scale crossbedded strata. Intraformational channels of sandstone in sandstone are common and lateral variations in both lithologic character and texture are extreme.

Conglomerate, near the base of the remnant, consists of well-rounded varicolored pebbles of quartzite, chert, and quartz in a matrix of coarse-grained sandstone. Most of the pebbles average 1 inch in diameter, although some are as large as 2 inches. Locally, a bed of conglomerate grades laterally into a conglomeratic sandstone, which in turn becomes a fine- to coarse-grained sandstone, and this may grade into claystone. Siltstone boulders, cobbles, and pebbles derived mostly from the underlying Moenkopi formation are common in the basal strata.

Fossil plant remains are plentiful and widely distributed throughout the Shinarump remnant. Many of the logs and wood fragments have been silicified, some have been coalified, and some have been replaced by ore minerals (p. 230).

CHANNELS

In the Monument Valley area, the contact between the Shinarump and the Moenkopi is marked locally by symmetrical and asymmetrical depressions filled with Shinarump strata. These depressions, known as channels, contain in their fill all the known uranium-vanadium ore deposits (Witkind, 1956).

The Monument No. 1-Mitten No. 2 ore deposit was in the channel fill of the Monument No. 1 channel.

MONUMENT NO. 1 CHANNEL

Two of the isolated Shinarump remnants on the northwestward-trending ridge represent all that remains of the Monument No. 1 channel fill. These two remnants align to form a broad curve trending northwestward (fig. 22). The south remnant, which contains the mine workings, trends about N. 10° W., and the north remnant trends about N. 55° W. Dissection has been so extensive that in places, especially near the northern and southern tips of the remnants, part of the channel fill has been removed. Thus, at the very southern tip of the south remnant, only the east part of the channel fill remains, and it is about 50 feet wide (fig. 22). In contrast, the entire channel width of about 280 feet is preserved near the center of this same remnant.

The exact depth of the channel is uncertain because adjacent Moenkopi as well as Shinarump strata were removed by erosion. By extrapolating from the channel remnants, it is estimated that the channel was cut about 50 feet into the Moenkopi. This depth, however, is not constant along the entire channel, for the channel floor is undulatory and locally contains small shallow depressions. Near the south end of the Monument No. 1 workings (pl. 1) two small elongate shallow depressions are cut in the channel floor parallel to the channel trend. One depression is about 80 feet long, 15 feet wide, and 6 to 10 feet deep. The other depression, 70 feet to the north, is about 50 feet long, 20 feet wide, and also 6 to 10 feet deep. Depressions similar to these have been noted elsewhere in channel floors.

CHANNEL FILL

Three lithologic units form the basal channel fill: A trash-pocket conglomerate, a silica-cemented sandstone, and a calcite-cemented sandstone (fig. 23). The sandstones differ in their cements and in their content of uranium-vanadium minerals. Wherever examined the calcite-cemented sandstone contained few or no uranium-vanadium minerals, whereas the silica-cemented sandstone was marked locally by large concentrations of these minerals.

The uranium-vanadium minerals impregnated parts of both the trash-pocket conglomerate and the silica-cemented sandstone to form an ore body that locally included lenses of barren calcite-cemented sandstone. The trash-pocket conglomerate and the silica-cemented sandstone extend for an unknown distance beyond the margins of the ore body.

TRASH-POCKET CONGLOMERATE

The trash-pocket conglomerate consists chiefly of well-rounded pebbles of quartz, chert, quartzite, angular siltstone fragments, and fossil plant matter in a matrix of silica-cemented sandstone. The



FIGURE 23.—Exposure of three lithologic units in basal channel fill, Monument No. 1 mine workings. Note irregular character of contact between trash-pocket conglomerate (*tp*) and lenses of calcite-cemented sandstone (*cc*), and sharp contact between calcite-cemented sandstone (*cc*) and silica-cemented sandstone (*sc*) that contains ore in this locality.

conglomerate lenses are as much as 12 feet thick, and range in width from 50 to 75 feet. In many lenses angular, tabular fragments of mudstone, about 6 inches long and 1 inch thick, aline to form crude bedding planes (fig. 25). The matrix of the conglomerate and some included sandstone beds are composed of angular to round, fine (0.04 mm) to very coarse (2.6 mm) grains, consisting chiefly of quartz (about 85 percent), chert (about 10 percent), and feldspar (about 5 percent). These grains are weakly bound by chalcedonic

cement. Most of the quartz grains have overgrowths, which have been more or less etched. The contact of the trash-pocket conglomerate with both overlying and underlying sedimentary rocks ranges from gradational to sharp.

The name "trash-pocket conglomerate" is indicative of the original mode of deposition. The shape, size, and general configuration of these conglomeratic lenses suggest that they formed in shallow depressions in a stream floor. These depressions presumably acted as catchment basins for most of the coarser debris moving downstream.

SILICA-CEMENTED SANDSTONE

The silica-cemented sandstone is composed chiefly of subangular to rounded quartz grains, many rimmed with quartz overgrowths. These grains range in size from about 0.04 mm (very fine grained) to as much as 1.0 mm (very coarse grained), although most are about 0.5 mm (medium-sized grains). About 85 percent of the sandstone is composed of quartz; the remainder is of feldspar (about 10 percent) and chert (about 4 percent), plus small amounts of kaolin clay, mica, zircon, and apatite. All grains are weakly cemented by silica.

This sandstone forms lenses that are as much as 12 feet thick and range in width from 50 to 75 feet. Where the ore minerals are concentrated, the sandstone is extremely friable. Conversely, slightly mineralized strata are better cemented. The contact of the silica-cemented sandstone with the trash-pocket conglomerate commonly is irregular; that with the calcite-cemented sandstone is sharp and distinct (fig. 23 and 25).

CALCITE-CEMENTED SANDSTONE

The calcite-cemented sandstone is light brown to gray, massive and crossbedded, and is composed of subangular to well-rounded fine (0.04 mm) to very coarse (1.4 mm) grains of quartz (about 78 percent); chert and quartzite (about 18 percent), and feldspar (about 4 percent), firmly cemented by calcite (fig. 24). The quartz grains lack quartz overgrowths, in marked contrast to similar grains that form the matrix of the trash-pocket conglomerate and the silica-cemented sandstone. In thin section, many of the quartz grains are seen as separated by coarsely crystalline calcite, which is optically continuous around several included grains. Some of the quartz grains in contact with the calcite cement are embayed and have ragged boundaries (fig. 24).

The lenses of calcite-cemented sandstone differ in size and shape and locally merge laterally with one another (pl. 1). During the course of the mapping, two large calcite-cemented sandstone lenses

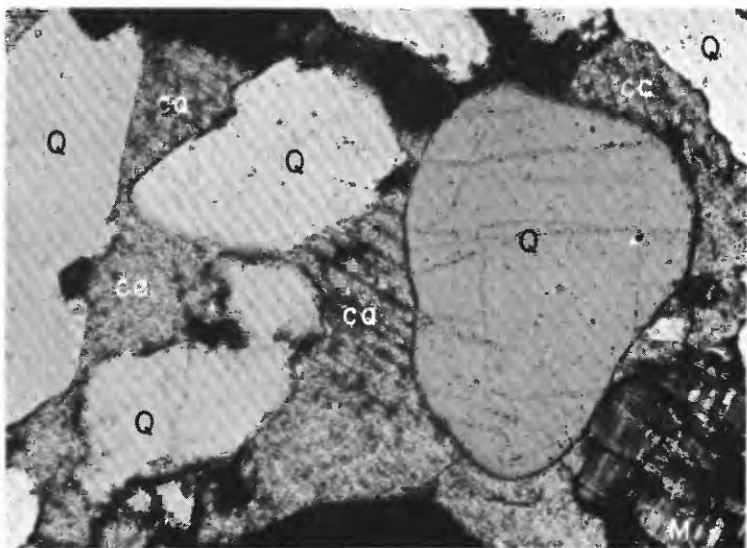


FIGURE 24.—Photomicrograph of thin section of calcite-cemented sandstone collected in the Monument No. 1-Mitten No. 2 mine, Navajo County, Ariz., showing the tight bind between calcite (*ca*) and other included grains. Some quartz grains (*Q*) are embayed by calcite. Microcline (*m*) is also shown. Polarized light, $\times 45$.

were noted in the mine, each enclosed in the ore body. One, near the center of the ore body, was about 110 feet long, 15 to 40 feet wide, and 2 to 5 feet thick. The other was larger and occupied most of the southern part of the ore body. This lens was about 175 feet long, 30 to 60 feet wide, and had a maximum thickness of about 6 feet.

Locally, these calcite-cemented lenses appeared as single lithologic units of fine-grained to very coarse grained sandstone well cemented by calcite. Elsewhere, they could be subdivided into several thin lenses separated vertically by beds of trash-pocket conglomerate (fig. 23). Each of these thinner calcite-cemented lenses extended laterally for only 15–20 feet, although other overlying or underlying calcite-cemented sandstone lenses persisted for greater distances and retained the characteristic appearance of the larger unit.

Several of these small, thin calcite-cemented sandstone lenses, ranging from 6 inches to 1 foot in thickness and estimated to be 10 to 15 feet in diameter, were noted as discrete units in the northern part of the mine. These lenses also appeared to have been wholly enclosed in the ore body.

FOSSIL WOOD

Three types of fossil wood are found in the Monument No. 1 channel fill. Slightly flattened silicified logs as much as 10 feet long and 2 to 4 feet in diameter are most plentiful. Most of them appear

randomly oriented, although those longer than 8 feet lie parallel to the trend of the channel. The small fragments of silicified wood have rounded edges. Partly coalified wood fragments are less plentiful. Most of them are dark brown, about half an inch long, and are enclosed in black oval-shaped pods as much as 24 inches long and 2 to 3 inches thick (fig. 25). The black color of these pods is due to



FIGURE 25.—Irregular contact between the trash-pocket conglomerate (*tp*) and the silica-cemented sandstone (*sc*). Each small podlike mass of vanadium minerals (*v*, chiefly roscoelite) contains a small fragment of partly coalified wood near its center. (Fragments labeled *mf* are angular mudstone in trash-pocket conglomerate.)

impregnation by vanadium minerals, chiefly roscoelite. Elsewhere in the channel fill, fossil logs as much as 3 feet long, which are composed of black coalified material similar to the smaller fragments, are enclosed in barren strata. Least plentiful are fossil wood particles replaced by chalcocite, azurite, and malachite, which locally retain the original cell structure. The chalcocite occupies the cellular cavities, and unknown gangue minerals form the cell walls.

ORE DEPOSIT

Two distinct ore bodies occupied the south remnant of the Monument No. 1 channel fill. One, chiefly in the southern tip of the south

channel remnant (p. 221), was mined through the workings of the former Vanadium Corp. of America Monument No. 1 mine (fig. 22). The other ore body occupied most of the remainder of the south channel remnant and was separated from the Monument No. 1 ore body of the former Vanadium Corp. of America by about 20 feet of barren to weakly mineralized strata. It was mined through two portals—the Mitten No. 2 and the Foutz Mining Co. new Monument No. 1.

The Monument No. 1-Mitten No. 2 ore body was in the basal channel strata and trended about N. 30° W., collinear with the channel trend. It is estimated to have been about 650 feet in length, to have averaged 75 feet and reached a maximum of 95 feet in width, and to have averaged 7 feet and ranged from 1 foot to as much as 18 feet in thickness (pl. 1). It was thickest and widest midway in its length. The boundaries of the ore body were irregular; but, in general, it was planoconvex or biconvex in both longitudinal and transverse cross section. Overall it appeared as an elongate flattened ellipsoid. All the ore was contained in the trash-pocket conglomerate and the silica-cemented sandstone, and these units enclosed lenses of barren calcite-cemented sandstone that were collinear with the ore body. Some secondary uranium-vanadium minerals lined fractures and coated exposed surfaces of the calcite-cemented sandstone but were not in the body of that unit.

Commonly the base of the ore body conformed to the channel floor; in at least one place, however, at the northernmost of the two depressions in the channel floor (p. 227 and pl. 1), the base of the ore body was about 4 feet above the channel floor and the rocks below the ore body were weakly mineralized or barren. The top of the ore body was an irregular plane coinciding more or less with the top of the lenses of trash-pocket conglomerate. The edges of the ore body were near the channel flanks.

The uraniferous ores in the Monument No. 1-Mitten No. 2 mine were in relatively good radioactive equilibrium. The general ratio of vanadium to uranium for the mine, as determined from channel samples, was about 2.5:1, although the range was much more extreme, extending from a low of 0.33:1 to a high of 14.20:1 (fig. 26).

MINERALOGY

The major detrital minerals in the host rock are identical in all three lithologic units. Quartz grains are most plentiful and average about 85 percent; chert grains commonly compose about 10 percent; feldspar, both as alkalic feldspar and plagioclase, composes the remaining 5 percent. Minor accessory minerals include a few discrete grains of apatite, zircon, and some mica. The chief interstitial clay mineral

appears to be kaolinite, and it occurred chiefly as a decomposition product along the fractures in the feldspar grains.

The ore minerals were concentrated in both the silica-cemented sandstone and the trash-pocket conglomerate, and in these units they filled voids, interstitial pore space, and embayed areas in the grains; they also lined fractures and coated grains and pebbles.

In the calcite-cemented sandstone, the ore minerals were all secondary and found chiefly in the fractures. No ore minerals were found in the body of that unit.

Most of the following minerals have been identified by A. G. King, U.S. Geological Survey. Subsequent work by T. G. Botinelly, also with the U.S. Geological Survey, confirmed some of King's original determinations and resulted in the identification of other minerals given. Many of the determinations were confirmed by X-ray powder diffraction patterns.

Host rock minerals, mostly detrital

Apatite, $\text{Ca}_5(\text{PO}_4)_3(\text{F}, \text{Cl}, \text{OH})$ -----	Rare.
Calcite, CaCO_3 -----	Common.
Chalcedony, SiO_2 -----	Locally common.
Chert, SiO_2 -----	Common.
Chlorite, $\text{Mg}_5(\text{Al}, \text{Fe})(\text{OH})_3(\text{Al}, \text{Si})_4\text{O}_{10}$ -----	Rare.
Gypsum, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ -----	Common.
"Hydromica," (?) $\text{K}_2(\text{Al}, \text{Fe}, \text{Mg})_{2-3}(\text{Si}, \text{Al})_4\text{O}_{10}(\text{OH})_2$ -----	Rare.
Microcline, $\text{KA1Si}_3\text{O}_8$ -----	Rare.
Quartz, SiO_2 -----	Common.
Zircon, ZrSiO_4 -----	Rare.

Ore minerals

Unoxidized uranium and vanadium minerals

Coffinite, $\text{U}(\text{SiO}_4)_{1-x}(\text{OH})_{4x}$. Uraninite has been found Rare.
in an adjacent mine (I. B. Gray, 1956, written communication), and montroseite was found in the Monument No. 2 mine in the Monument Valley area.

Doloresite, $3\text{V}_2\text{O}_5 \cdot 4\text{H}_2\text{O}$ ----- Rare.

Roscoelite, $\text{K}(\text{Al}, \text{V})_2(\text{Al}, \text{Si}_3)\text{O}_{10}(\text{OH}, \text{F})_2$ ----- Rare.

Vanadium-bearing hydrous mica----- Common.

Oxidized uranium minerals

Autunite, $\text{Ca}(\text{UO}_2)_2(\text{PO}_4)_2 \cdot 10-12\text{H}_2\text{O}$ ----- Rare.

Carnotite, $\text{K}_2(\text{UO}_2)_2\text{V}_2\text{O}_8 \cdot 1-3\text{H}_2\text{O}$ ----- Rare.

Metatorbernite, $\text{Cu}(\text{UO}_2)_2(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$ ----- Rare.

Metatyuyamunite, $\text{Ca}(\text{UO}_2)_2\text{V}_2\text{O}_8 \cdot 3-5\text{H}_2\text{O}$ ----- Common.

Rauvite, $\text{CaO} \cdot 2\text{UO}_3 \cdot 5\text{V}_2\text{O}_5 \cdot 16\text{H}_2\text{O}$ ----- Common.

Torbernite, $\text{Cu}(\text{UO}_2)_2(\text{PO}_4)_2 \cdot 12\text{H}_2\text{O}$ ----- Rare.

Tyuyamunite, $\text{Ca}(\text{UO}_2)_2\text{V}_2\text{O}_8 \cdot 5-8\frac{1}{2}\text{H}_2\text{O}$ ----- Common.

Zippeite, $\text{K}_4(\text{UO}_2)_6(\text{SO}_4)_3(\text{OH})_{10} \cdot \text{H}_2\text{O}$ ----- Rare.

Oxidized vanadium minerals

Corvusite, $V_2O_4 \cdot 6V_2O_5 \cdot nH_2O$ -----	Common.
Hewettite, $CaV_6O_{16} \cdot 9H_2O$ -----	Locally common.
Volborthite, $Cu_3(VO_4)_2 \cdot 3H_2O$ -----	Common.

Associated metallic minerals

Unoxidized minerals

Chalcocite, Cu_2S -----	Rare.
Galena, PbS -----	Rare.
Pyrite, FeS_2 -----	Locally common.

Oxidized minerals

Azurite, $Cu_3(OH)_2(CO_3)_2$ -----	Locally common.
Chalcanthite, $CuSO_4 \cdot 5H_2O$ -----	Rare.
Chrysocolla, $CuSiO_3 \cdot 2H_2O$ -----	Locally common.
Malachite, $Cu_2(OH)_2(CO_3)$ -----	Locally common.
Limonite, hydrous iron oxides-----	Common

DISTRIBUTION OF MINERALS

Overall the ore body appeared as incomplete concentric layers of mineralized rock. Its core was elongate and contained low-valent, relatively unoxidized minerals. This core was encircled on the sides and top by two zones of oxidized minerals, the most intensely oxidized minerals being farthest from the core.

Some of the richest uranium ore came from the core, which was a deep blue black. The primary uranium mineral, coffinite, was found in this part of the ore body. Vanadium minerals from this same locality include doloresite (V^{+4}), corvusite (V^{+4}), and roscoelite (V^{+3}). The presence of the low-valent doloresite suggests that mon-troseite may have been the primary vanadium mineral deposited. Some of the roscoelite associated with fossil wood appeared as brownish to brownish-orange fibers in woody texture and some as brownish-black massive material surrounding the woody material (p. 231 and fig. 25). Sulfides present were chalcocite (as small nodules and as wood replacements), galena, and pyrite (filling interstices in the sandstone).

The core was sheathed by an inner zone of dark-gray to bluish-black mineralized rock containing sporadically distributed patches of brown limonite. In this zone, autunite (U^{+6}) and tyuyamunite (V^{+5}) were the common uranium minerals, occurring as small widely disseminated specks; corvusite (V^{+4}) was the dominant vanadium mineral. Rauvite (V^{+5}) and hewettite (V^{+5}) were also in the inner zone of oxidized minerals. Minute amounts of chalcanthite filled voids in the sandstone.

The outermost zone of oxidized minerals was light brown to light gray, chiefly the result of limonite stain. The mineral assemblage included carnotite, hewettite, metatyuyamunite, rauvite, tyuyamunite,

and volborthite—all high-valent minerals. These minerals filled voids and commonly formed patinas on pebbles and grains. In many places, the minerals lined cavities or filled fractures; and, in general, they seemed to have moved from their original point of deposition. Secondary copper minerals such as azurite, chalcantite, chrysocolla, and malachite filled interstices in the sandstone, coated pebbles, and lined cavities and fractures.

These three mineral assemblages suggest that a continuous oxidation sequence existed from low-valent weakly oxidized minerals in the core of the ore body to high-valent oxidized minerals in the outer sheath. Thus coffinite, doloresite, some corvusite, and roscoelite were in the core of the ore body. These altered to form the inner zone of oxidized minerals, marked by predominant corvusite, rauvite, hewettite, autunite, and tyuyamunite. These minerals, in turn, were then further modified to form the outer zone of oxidized minerals, an assemblage of carnotite, hewettite, metatyuyamunite, rauvite, tyuyamunite, and volborthite.

The pyrite, originally deposited, presumably had been oxidized to limonite, and the copper minerals had been altered to azurite, malachite, chalcantite, and chrysocolla.

LOCALIZATION OF THE ORE

RELATION OF ORE TO HOST ROCKS

The mineral assemblage in both the silica-cemented sandstone and the trash-pocket conglomerate differs from that in the calcite-cemented sandstone. Thin sections of both the silica-cemented sandstone and the trash-pocket conglomerate indicate that most of the grains have quartz overgrowths. Etching has been extensive and has formed embayments in both the quartz overgrowths and the original grains. Ore minerals fill most of the voids, interstices, and embayed areas (figs. 27 and 28). Those voids not filled by ore minerals are filled by chalcedonic quartz. The suggested sequence of formation is quartz overgrowths on the quartz grains, embayment to form voids, deposition of ore minerals, and deposition of chalcedonic cement in the voids not filled with ore minerals.

In the calcite-cemented sandstone, the quartz grains are free of quartz overgrowths, and most are surrounded and separated from one another by calcite (fig. 24). The quartz grains are etched; the etching, however, has not progressed far enough on most grains to destroy the original grain boundaries. Very small amounts of secondary uranium minerals fill fractures in the calcite and other small voids. Although the suggested sequence of formation here is (a) etching of the quartz grains, possibly by carbonate-bearing solutions,

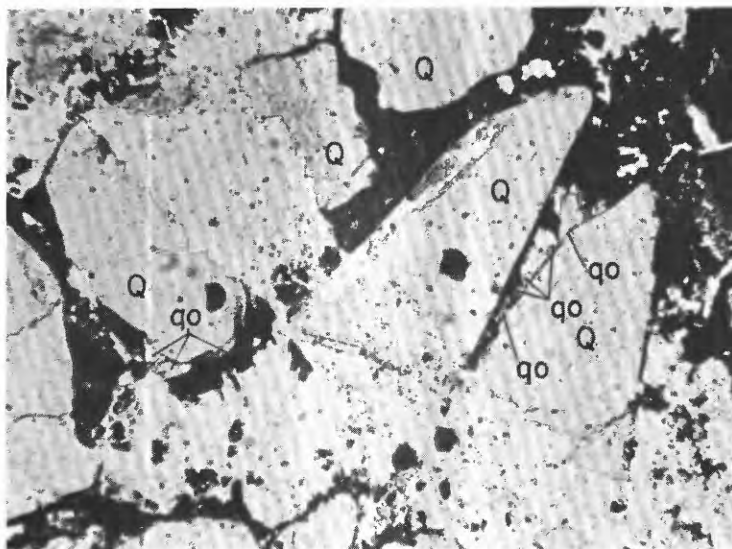


FIGURE 27.—Photomicrograph of thin section of silica-cemented sandstone showing ore minerals (black) in interstices and embayed areas. A few fragments of quartz overgrowth (*qo*) still remain on the etched quartz grains (*Q*). Plain light, $\times 45$.

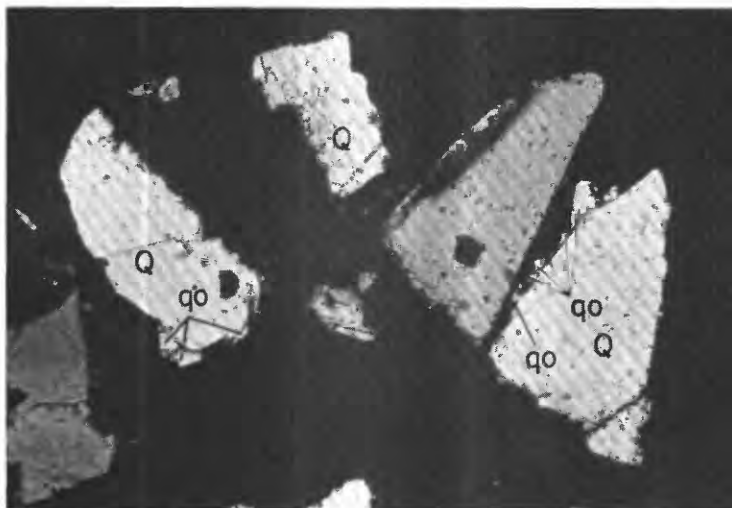


FIGURE 28.—Same thin section as shown in figure 27 under polarized light. Quartz overgrowths (*qo*) are in optical continuity with larger quartz grains (*Q*). $\times 45$.

with synchronous deposition of calcite to cement the sandstone; (b) fracturing; and (c) deposition of primary (subsequently oxidized), or secondary uranium-vanadium minerals in the fractures, another

sequence is possible. Recent work by Walker (1957, p. 267-268) has indicated that quartz can be selectively replaced by carbonate. Apparently the carbonate replaces the secondary quartz overgrowths, and this replacement tends to halt along the original quartz-grain boundaries. Thus, where carbonate replacement has been extensive, the quartz overgrowths are removed, and locally the original quartz grains show etched boundaries. Walker (1957, p. 267) states:

The silica of the overgrowths * * * is more susceptible to replacement than is the silica of the original quartz grains, and replacement tends to halt at the grain boundaries. Selective replacement has removed the overgrowth quartz on most grains and has produced frosted relics which have the well-rounded shapes of the original grains.

During the replacement of the quartz overgrowths by carbonate, the excess silica may have moved both laterally and vertically and been redeposited in adjacent sediments. Walker (1960, p. 146) notes that "replaced silicate grains commonly occur in or near strata containing authigenic silica, and the association strongly suggests that the silica is derived at least in part from that released by replacement." From this point of view, the suggested sequence of formation for the calcite-cemented sandstone could well be (a) quartz overgrowths on the original quartz grains, (b) solution of silica by carbonate-bearing water to remove the overgrowths and etch the quartz grains; calcite is deposited in one place while the excess silica is being deposited elsewhere, (c) fracturing, and (d) deposition of primary or secondary uranium-vanadium minerals in the fractures.

Thus, two hypotheses are available to explain the formation of the calcite-cemented sandstone lenses. The first involves the filling of available pore space by calcite, presumably before the advent of the ore-bearing solutions. The second hypothesis involves the progressive replacement of the quartz overgrowths by carbonate. Here also the carbonate antedates the ore-bearing solutions.

In both hypotheses, the calcite-cemented sandstone would have acted as a relatively impermeable unit to the ore-bearing solutions; the only passageways through the calcite-cemented sandstone would have been along fractures (fig. 29), which probably were formed during the deformation of the area, before the advent of the ore-bearing solutions. The abrupt termination of an ore body where it is in contact with a lens of a calcite-cemented sandstone is also most remarkable.

RELATION OF ORE TO FRACTURES

In one locality, a thin vertical fracture cuts both the calcite-cemented sandstone and the underlying ore-impregnated silica-cemented sandstone. The silica-cemented sandstone extends upward into the calcite-cemented sandstone to form a bulge about 8 inches

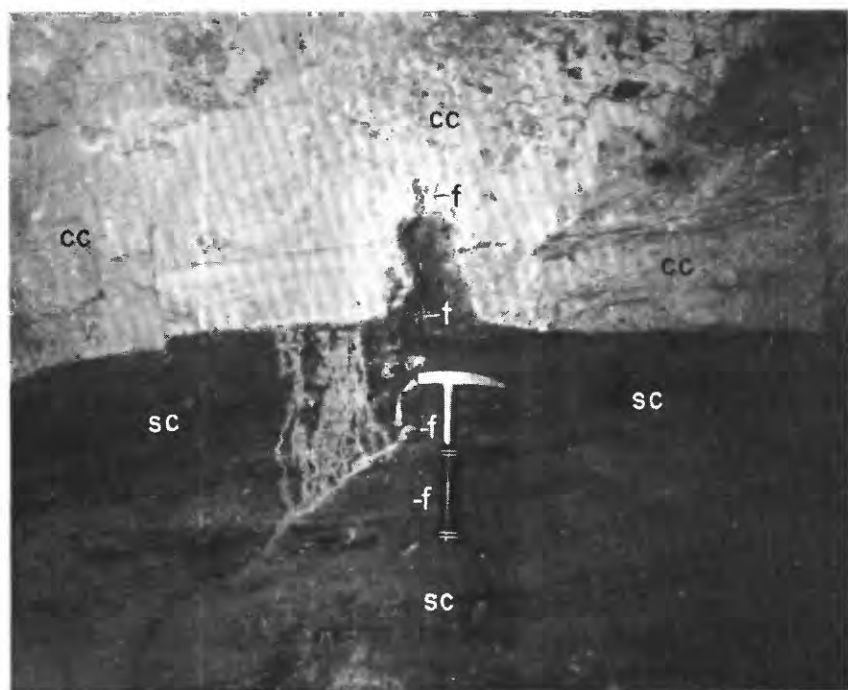


FIGURE 29.—Embayment of ore-bearing silica-cemented sandstone (*sc*) in calcite-cemented sandstone (*cc*) along a fracture (*f*). Note abrupt termination of the ore body where it is in contact with the calcite-cemented sandstone.

high and 3 inches wide parallel to the fracture (pl. 1). This feature can be interpreted in several ways. One possibility involves leaching of the carbonate along the fracture before the advent of, or by, the ore-bearing solutions. Ore minerals were then deposited in the rocks that fill this bulge. From this point of view, the ore-bearing solutions may have been nearly neutral or slightly acid. Another interpretation is that the carbonate along the fracture was leached after deposition and during oxidation of the ore minerals. At this time some pyrite may have been oxidized, turning the ground water slightly acid. Hydrostatic pressure of the ground water or capillary action may then have moved the ore minerals upward into the bulge. In this concept, the state of the ore-bearing solutions, whether neutral, acid, or alkaline is not germane to this specific problem.

THE ORE-BEARING SOLUTIONS

The source of the ore-bearing solutions is unknown, although hypotheses have been proposed suggesting syngenetic, penesynthetic, and epigenetic origins. By whatever means the ore-bearing solutions were added to the Shinarump member, it seems likely (judging by the

widespread uraniferous deposits in Monument Valley) that they mingled with the ground water and that the resulting mixture then moved far and wide. The composition of these ancient solutions is uncertain; but considerable evidence has accumulated as a result of recent geochemical studies that they were neutral to strongly alkaline (Gruner, 1956) or moderately to strongly alkaline (Garrels and others, 1957) and that the uranium was carried as hexavalent uranium di- and tri-carbonate and the vanadium as tetravalent vanadite under mild reducing conditions. It has long been known that uranyl ions form soluble carbonate complexes. Garrels and Christ (1959) have discussed the behavior of this complex with respect to pH changes of the carbonate solutions.

In a more strongly reducing environment, the solubility of the uranium compounds is decreased drastically, and the uranium minerals are precipitated as coffinite and uraninite; the primary vanadium mineral precipitated is montroseite. Even as these minerals are deposited, primary sulfides such as pyrite, galena, and chalcocite may have formed. Much of the uranium would be redissolved and moved again under subsequent oxidizing conditions if it were not fixed in stable form by vanadium and phosphorus.

In the Monument Valley area, the neutral to strongly alkaline ore-bearing solutions made their way into, and were entrapped in, the basinlike Monument No. 1 channel where they percolated through the permeable silica-cemented sandstone and trash-pocket conglomerate, and around the calcite-cemented sandstone. In the permeable units, the solutions were in a reducing and more acid environment, generated by the decomposition products and organic acids derived from the buried wood. In consequence, the solubility of the compounds in the ore-bearing solutions decreased sharply, resulting in precipitation of some of the primary minerals, and a sharp change in the nature of the solutions from alkaline to neutral or slightly acid. It may have been at this time that the carbonate along fractures was leached. As these solutions reacted with the calcite, additional uranium minerals may have been precipitated, for as Gruner (1954, p. 72) suggests: "an environment moderately high in CaCO_3 could always precipitate uranium minerals as it would be able to adjust the pH of the solutions to the required figure."

During oxidation after deposition, the uranium combined with vanadium and phosphate to form stable, relatively insoluble compounds.

In the period since deposition of the primary ore minerals, erosion has stripped the overlying strata with a resultant drop of the water table. This permitted air to circulate about the moist ore body, and

the ensuing oxidation has altered most of the original minerals. This probably occurred in place with montroseite(?) (V^{+3}) altering to doloresite (V^{+4}), which in turn altered to corvusite (V^{+4}) and it, in turn, altered to hewettite (V^{+5}). The primary uranium minerals, coffinite and uraninite(?), also oxidized to a higher valent state, and inevitably, as soon as the vanadium became available, both carnotite (V^{+5}) and tyuyamunite (V^{+5}) were formed. Since then, ground water has dissolved and reprecipitated some of the more soluble secondary uranium-vanadium minerals, but this redistribution has been on a relatively minor scale. Additional chalcedonic quartz and calcite have been added.

GEOLOGIC HISTORY OF THE ORE DEPOSIT

The following geologic history is suggested for the Monument No. 1-Mitten No. 2 ore deposit.

Shortly after the Moenkopi formation was exposed to subaerial erosion, distinct channels were carved in its surface by the northward flowing streams that deposited the Shinarump member of the Chinle formation. These streams were lined with trees that sooner or later toppled into the water and were rafted downstream to be buried in the channel fill. Possibly concurrent with or shortly after these sediments were deposited, quartz overgrowths formed on many of the quartz grains. Subsequently, certain lenses in the channel fill were cemented by carbonate to form the calcite-cemented sandstone. During the progressive cementation of these lenses, the quartz overgrowths were selectively replaced by carbonate, and the excess silica was moved both laterally and vertically to be redeposited in both the silica-cemented sandstone and the trash-pocket conglomerate.

During Late Cretaceous time the region was deformed and the strata were fractured.

Subsequently, and possibly not more than 80 million years ago, ore-bearing solutions of unknown origin mingled with the ground water and percolated through the Shinarump. These solutions were probably alkaline and when they became entrapped in the Monument No. 1 channel, they deposited primary uranium and vanadium minerals wherever they found reducing conditions, principally in the silica-cemented sandstone and the trash-pocket conglomerate. As a result, the formerly alkaline solutions became less alkaline. Reaction between these solutions and the carbonate of the calcite-cemented sandstone permitted an adjustment of the pH of the solutions, and additional uranium minerals were deposited. The uranium combined with vanadium and phosphorus to form relatively stable insoluble compounds.

Erosion gradually stripped away much of the overlying sedimentary cover, and as the water table dropped, air percolated down through the channel fill and circulated about the moist ore body. The ensuing oxidation has resulted in an ore body marked by a core of low-valent minerals partly surrounded by two sheaths of oxidized minerals.

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