# Heavy Minerals as Guides to Uranium-Vanadium Ore Deposits in the Slick Rock District, Colorado

GEOLOGICAL SURVEY BULLETIN 1107-B

*Prepared on behalf of the U.S. Atomic Energy Commission and published with the permission of the Commission*

# Heavy Minerals as Guides to Uranium-Vanadium Ore Deposits in the Slick Rock District, Colorado

*By* HOWARD E. BOWERS *and* DANIEL R. SHAWE

CONTRIBUTIONS TO THE GEOLOGY OF URANIUM

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UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1961

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington 25, D.C.

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# HEAVY MINERALS AS GUIDES TO URANIUM-VANADIUM ORE DEPOSITS IN THE SLICK ROCK DISTRICT, COLORADO

By Howard E. Bowers and Daniel R. Shawe

## ABSTRACT

Heavy-mineral studies were made of sandstone from the Morrison formation of Late Jurassic age in the Disappointment Valley area, Slick Rock district, San Miguel County, Colo. The studies were made in conjunction with exploratory drilling for the U.S. Geological Survey for uranium-vanadium deposits in the Salt Wash member. Important production has come from the Salt Wash in the district.

The Disappointment Valley area lies in a syncline between two salt anticlines and is bordered on either side by fault zones. One of the fault zones seems to be spatially related to a zone of alteration and to an area that includes almost all the known uranium-vanadium deposits in the district.

Heavy-mineral fractions from about 230 samples of sandstone from the Brushy Basin and Salt Wash members of the Morrison taken from 61 drill holes were studied to determine identity and relative amounts of minerals. Among the heavy minerals recognized are black opaque minerals (which are now principally hematite), zircon, tourmaline, apatite, rutile, garnet, leucoxene, barite, anatase, pyrite, and galena.

Three distinct lithologic types of sandstone were recognized, all of which contain virtually the same heavy minerals, but in different proportions. Light reddish-brown sandstone, which contains no ore deposits and in general is outside the zone of alteration associated with faults, is characterized by the dominance of black opaque minerals. Light-gray carbonaceous sandstone that is not closely associated with ore deposits and is most abundant in the ore-bearing sandstone unit of the Salt Wash member is characterized by abundant black opaque minerals (less than in light reddish-brown sandstone), and a small amount of pyrite. Within the third lithologic type one variant is light-gray sandstone (light buff at the surface where weathered) in the zone of alteration associated with faults, which is characterized by very sparse black opaque minerals, and some pyrite. A second variant is light-gray sandstone near mineralized layers, which also is characterized by very sparse black opaque minerals, and contains more anatase and pyrite than the other types, and minor galena.

Probably shortly after deposition of the Morrison formation and before deep burial, black opaque minerals became oxidized in place, largely to hematite but

in part to leucoxene. Some iron moved locally and was redeposited as hematite films on other detrital grains; although altered, the black opaque minerals were not destroyed. This diagenetic change produced the red beds as such. In places in the Morrison, especially in the ore-bearing sandstone, carbonaceous material inhibited oxidation of black opaque minerals. No hematite films formed on other detrital grains, and the sandstone remained light gray. Nevertheless some black opaques were probably leached and destroyed and iron was redeposited as sparse pyrite, but most of the black opaque minerals remained in the sandstone. This change also is considered to be diagenetic. At a later time, after consolidation of sediments, and after the rocks were faulted, altering solutions moved along the fault zones and converted the light reddish-brown sandstone near the faults to light-gray sandstone by leaching black opaque minerals and the hematite films. This change is considered to be epigenetic. Where the solutions moved through light-gray carbonaceous sandstone in the ore-bearing unit, black opaque minerals were similarly leached. In addition, ore minerals, as well as some anatase, pyrite, and galena, were precipitated because of the chemical interaction of the leaching solutions and the stagnant, reducing solutions surrounding areas containing carbonaceous material.

The almost complete absence of black opaque minerals in light-gray carbonaceous sandstone in the ore-bearing sandstone of the Salt Wash member of the Morrison formation in the Disappointment Valley area is considered to be a positive indication of proximity to mineralized rock.

## INTRODUCTION

Heavy-mineral studies were undertaken as part of an investigation of alteration of host rocks in the vicinity of uranium-vanadium ore deposits in the Salt Wash member of the Morrison formation in the Slick Rock district, San Miguel County, Colo. Heavy minerals might provide clues to the degree of alteration of rocks, and could provide data to help locate new ore bodies as well as elucidate the origin and genesis of the deposits. For these reasons an extensive sampling of drill cores obtained during exploratory drilling for uranium-vanadium deposits in the Slick Rock district was undertaken. Only samples collected in the Disappointment Valley area were used in the present investigation. Study of many drill-core and other samples collected elsewhere in the district has corroborated the results on Disappointment Valley samples, even though many of the other samples have undergone near-surface weathering. D. R. Shawe was responsible for sampling of drill cores and part of the heavy-mineral studies; H. E. Bowers was responsible for most of the detailed studies and evaluation of samples of the drill cores.

Howard E. Bowers, the senior author, died May 13, 1959, at the age of 35, from the effects of multiple sclerosis. He had finished the research for this report, and was preparing the text and illustrations at the time of his death. During the 5-year illness preceding his death, Bowers' productive working time was greatly curtailed by periodic painful crippling attacks of varying degree. When possible, he labored diligently at this and other geologic tasks assigned to him. The junior author completed the report, but it lacks much of the detailed statistical treatment that Bowers was in the process of preparing, and perhaps in part as well, his careful, objective approach.

## ACKNOWLEDGMENTS

We are indebted to many colleagues in the Geological Survey for help in the development of ideas set forth in the text, as well as for methods of presentation of the data. R. A. Cadigan was especially helpful in discussions on statistical treatment of grouped data.

Considerable help in the preparation of samples for study was given by G. C. Simmons, W. B. Rogers, N. L. Archbold, O. T. Marsh, E. L. Boudette, and W. B. Gazdik, all of the Geological Survey.

The work was done on behalf of the Division of Raw Materials of the U.S. Atomic Energy Commission.

## GEOLOGIC SETTING OF THE DISAPPOINTMENT VALLEY AREA

The Disappointment Valley area is in the northern part of the Slick Rock mining district, near the south edge of the salt anticline region of southwestern Colorado and southeastern Utah, and near the eastern boundary of the Colorado Plateau (fig. 1). It occupies a synclinal trough between two northwestward-trending salt anticlines. Rocks exposed in the district are chiefly clastic terrestrial sediments of Mesozoic age, gently folded across the salt anticlines. Important amounts of uranium-vanadium ore have been produced from the Salt Wash member of the Morrison formation of Late Jurassic age.

### STRATIGRAPHY

Sedimentary rocks exposed in the district include a maximum thickness of about 4,700 feet of shale, mudstone, siltstone, sandstone, and conglomeratic sandstone ranging in age from Permian to Late Cretaceous. Except for about 850 feet of marine shale of Late Cretaceous age, virtually all the rocks are of terrestrial origin, and include flood-plain, channel-fill, and windblown dune types.

The Morrison formation overlies the Summerville formation of Late Jurassic age and underlies the Burro Canyon formation of Early Cretaceous age. The Morrison consists of about 275 to 450 feet of lenticular sandstone and mudstone layers of the Salt Wash member and about 300 to 720 feet of bentonitic mudstone and some sandstone and conglomeratic sandstone of the overlying Brushy Basin member.

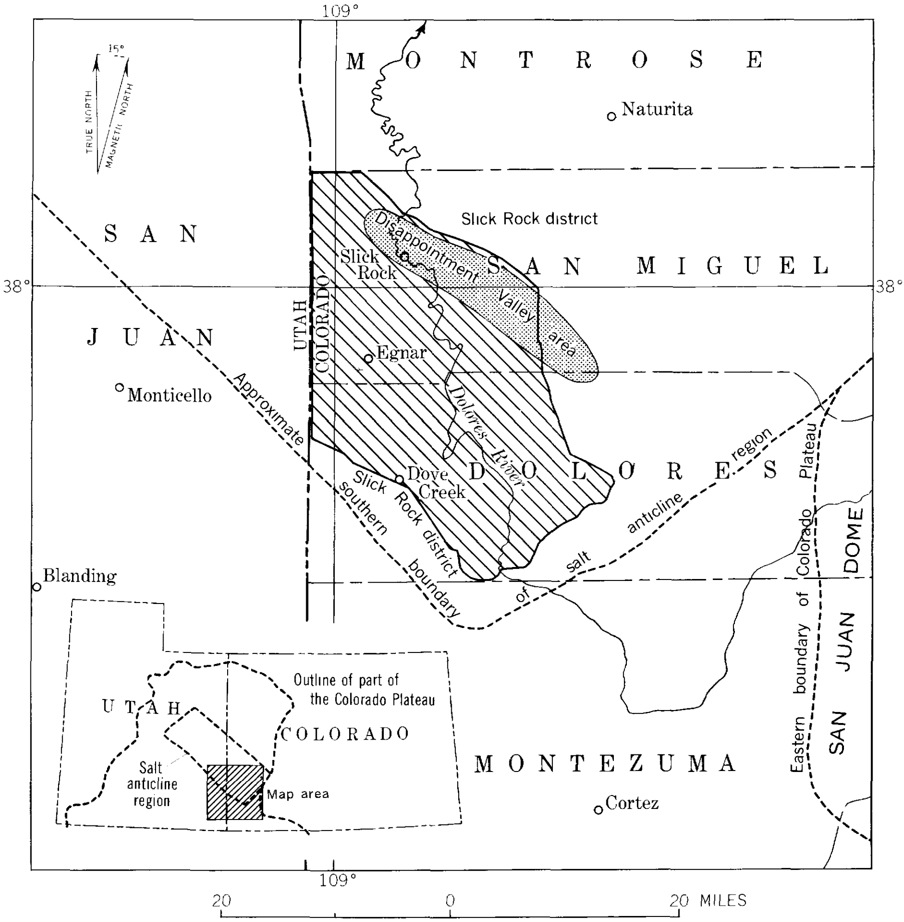


FIGURE 1.—Map showing the Disappointment Valley area in the Slick Rock district, Colorado.

## LITHOLOGY OF THE MORRISON FORMATION

In this and following sections colors of Morrison formation sandstone are referred to chiefly as light reddish brown and light gray, even though the rocks show various shades, values, and hues of these colors. For example, light reddish brown includes, in terms of symbols and names given in the Rock-Color Chart of the National Research Council (Goddard and others, 1948), colors such as 10*R* 6/2 (pale red), 10*R* 8/2 (grayish orange pink), 5*YR* 7/2 (grayish orange pink), 5*YR* 8/1 (pinkish gray), 10*R* 4/2 (grayish red), 5*YR* 6/1 (light brownish gray), and 5*YR* 5/2 (pale brown), as well as combinations of these. Light gray includes colors such as *N* 9 (white), *N* 8 (very light gray), *N* 7 (light gray), 5*GY* 8/1 (light greenish gray), and 5*G* 8/1 (light greenish gray), as well as combinations of these. Some sandstone is light buff to light brown, including colors such as 10*YR* 8/2 (very pale orange) and 5*Y* 8/1 (yellowish gray) in the Rock-Color Chart.

The Salt Wash member consists of light-buff (or light-gray below the water table where unweathered) to light reddish-brown lenticular sandstone layers that show scour-and-fill features and crossbedding typical of channel-type sediments, intercalated with reddish-brown flood-plain-type mudstone layers. Sandstone to mudstone ratios of the member range generally from about 1:1 to 2:1. Sandstone of the Salt Wash is principally quartzose, and cemented by variable amounts of carbonates, silica, and clay. All sandstone layers seem to be more thoroughly cemented at the top and base than in the middle of a layer (Archbold, 1955; 1959). Mudstone in the Salt Wash member appears to be chiefly hydromica and kaolinite clays containing mainly quartz detritus.

The upper part of the Salt Wash member consists of a persistent layer of juxtaposed sandstone lenses. This layer ranges from about 15 to more than 100 feet in thickness; in some places it is a single massive unit and in other places it is divided into as many as three layers by mudstone seams as much as 15 feet thick. The upper part of the member is referred to as the ore-bearing sandstone because nearly all uranium-vanadium production in the district comes from this unit. The ore-bearing sandstone is dominantly buff (where weathered) to light gray (where unweathered), fine to very fine grained, and locally contains abundant carbonaceous material whereas sandstone in the lower part of the member is mainly light reddish brown (where weathered and unweathered), fine to medium grained, and contains sparse carbonaceous material. The ore-bearing sandstone is generally more poorly cemented than sandstone in the rest of the Morrison formation.

The Brushy Basin member consists of bentonitic, reddish-brown and greenish-gray mudstone with interbedded sandstone and conglomeratic sandstone lenses that are more numerous near the base of the member than near the top. Sandstone of the Brushy Basin is similar in composition to that of the Salt Wash, except that sandstone in the upper part of the Brushy Basin contains abundant chert detritus. Like sandstone layers in the Salt Wash, those in the Brushy Basin are more thoroughly cemented at the top and base than in the middle of a layer. Mudstone in the Brushy Basin member seems to be largely bentonitic clay containing mainly quartz and chert detritus.

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## STRUCTURE

The Disappointment Valley area coincides with the Disappointment syncline in the northern part of the Slick Rock district (fig. 2). The syncline is a broad, nearly flat structure which trends about N. 55° W. To the southwest the broad gently folded Dolores anticline lies adjacent and parallel to the syncline; maximum dip of beds between the fold axes is about 9°. To the northeast the more tightly folded Gypsum Valley anticline is also almost parallel to the syncline; maximum dip of beds between the syncline and anticline is about 20°. Both the Dolores and the Gypsum Valley anticlines are underlain by thickened sections of salt in the Paradox member of the Hermosa formation of Pennsylvanian age, and folding of the anticlines was due at least in part to flow of salt into their axial regions from the axial region of the Disappointment syncline. After intrusion of salt beneath the Gypsum Valley anticline, this structure collapsed because of extrusion and solution removal of salt.

A zone of faults trending about N. 55° W. lies just northeast of Disappointment Valley, and forms the southwest edge of the collapsed core of the Gypsum Valley anticline. The Dolores fault zone southwest of Disappointment Valley lies about 2 miles northeast of and parallel to the axis of the Dolores anticline. Individual faults in the

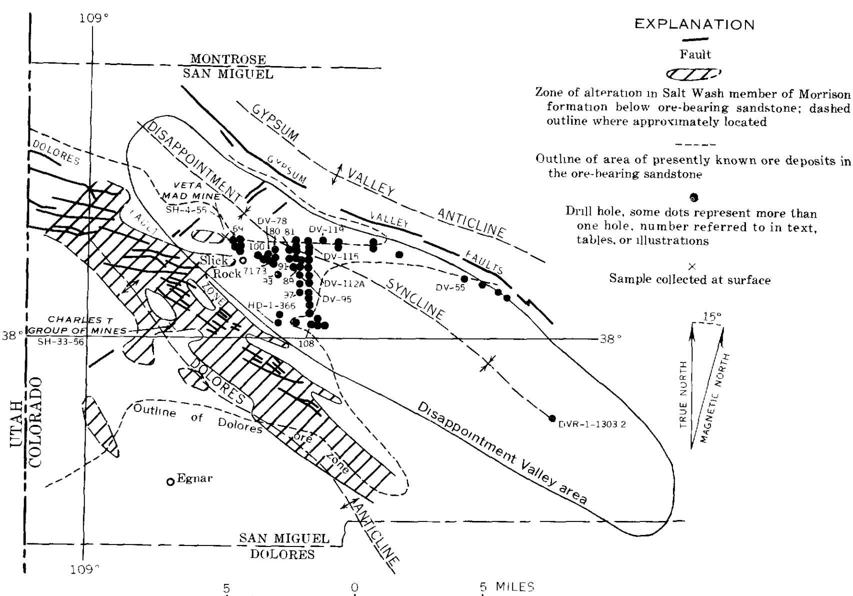



FIGURE 2.—Map showing main structural elements, zones of alteration and ore deposits, and location of drill holes and samples in the Disappointment Valley area, Slick Rock district, Colorado.

zone strike N. 60°–85° W. and form a series of small en echelon grabens. A few faults at the northwest end of Disappointment Valley form a zone almost normal to the Dolores fault zone and to the Gypsum Valley faults.

A persistent set of joints in the Disappointment Valley area is oriented almost parallel to the Dolores and Gypsum Valley faults; a less prominent set approximately parallels the northeastward-trending faults.

## ALTERATION

Color differences in sedimentary rocks in and around the Disappointment Valley area are related to the position of the uranium-vanadium deposits. Much of the sandstone in the Morrison formation in the Slick Rock district is light reddish brown and much of the mudstone is reddish brown. Near ore deposits, however, the sandstone is light buff to light brown where it is weathered, and light gray where it is below the water table and unweathered. The mudstone is light greenish gray. This fact led some geologists to the conclusion that the color differences were caused by alteration (Fischer, 1942, p. 376).

In addition, bleaching or alteration related to structural features in the vicinity of the Disappointment Valley area was recognized many years ago; for example, Coffin (1921, p. 73) described color changes from reddish to whitish or yellowish in faulted regions. In the Slick Rock district bleached sandstone is common near faults and along joints in the area of faults.

Because similar-appearing "altered" rocks are associated with both structural elements and ore deposits, and because some evidence suggests that faults in the district were important in localizing the uranium-vanadium deposits (Shawe and others, 1959, p. 409–410, 414), a study of the distribution of color types within and near the ore-bearing sandstone seemed appropriate in an attempt to clarify the origin of the deposits as well as to develop useful guides to hidden ore deposits.

Throughout this report rocks are described either as "diagenetically" or "epigenetically" altered. Diagenetically altered rocks are arbitrarily considered to be those having undergone any mineralogic change after deposition without gross change in chemical composition. They may have started undergoing change immediately after deposition. Epigenetically altered rocks, on the other hand, are considered to be those having undergone mineralogic change with a gross change in chemical composition resulting from action of extraneous solutions, probably long after deposition, and after consolidation.

At least three types of sandstone in the Morrison formation can be distinguished by color, composition, and geologic occurrence. One type of sandstone is colored light reddish brown. This first type is the most prevalent type in the Disappointment Valley area, is characterized by relatively abundant black opaque heavy minerals, and contains no known uranium-vanadium deposits. The color probably originated by diagenetic processes in the sediment, after deposition but before burial, that resulted in partial oxidation of detrital magnetite and ilmenite and caused precipitation of hematite coatings on other detrital grains, imparting a reddish color to the rock, as described by Miller and Folk (1955).

A second type of sandstone is colored light gray, generally has a moderate content of black opaque heavy minerals, has some pyrite, invariably contains carbonaceous material, and does not contain uranium-vanadium deposits. This second type probably originated diagenetically under reducing conditions associated with local accumulations of carbonaceous material, and although it may have lost some black opaque minerals by action of connate solutions with released iron forming pyrite, no hematite is present as coatings on other detrital grains. Mackin and Schmidt (1956, p. 380) give convincing evidence that magnetite "is dissolved by semistagnant acid water" in modern peat bogs in Idaho, where ilmenite is not so affected.

A third type of sandstone is also colored light gray, but has only a small content of black opaque heavy minerals, has some pyrite, may or may not contain carbonaceous material, and in places contains uranium-vanadium deposits. Where this type of sandstone contains uranium-vanadium deposits it also contains carbonaceous material, and where uranium-vanadium deposits are not known, the type seems merely to be associated with structural elements such as faults and joints, or the axial region of the Dolores anticline. Light-gray sandstone of the third type, although it originally may have been either light gray near carbonaceous material or light reddish brown where faulted or jointed, probably originated from the action of solutions that were largely restricted to fault zones. The solutions leached most of the black opaque minerals from the sandstone, and, where the sandstone was originally reddish, it was bleached by removal of hematite, although no color change occurred where leaching of black opaques took place in rock already gray. Because the ore-bearing sandstone is laterally more extensive and more transmissive than lower sandstone layers, movement of leaching solutions may have been more widepread in it than in the others. The third type seems to be more widespread in the ore-bearing sandstone than in other layers. The leaching solutions may have been responsible for deposition of the ore deposits, which formed only near carbonaceous material.

No apparent change has taken place in reddish sandstone of the first type where it has been exposed to weathering. But in the second and third types exposure to weathering has oxidized pyrite to limonite, imparting a characteristic light-buff to light-brown color to the rock.

The distribution of the three types of sandstone in the Morrison formation in the Disappointment Valley area can be outlined in a general way. Light reddish-brown sandstone is the most widely distributed type in the area. Except near the Dolores fault zone and possibly the Gypsum Valley and other faults, it makes up most of the sandstone of the lower part of the Salt Wash member, and a large part of the sandstone in the Brushy Basin member. Light-gray sandstone of the second type, that is, sandstone whose color may have developed by diagenetic alteration in the vicinity of carbonaceous material, is most prevalent in the upper part of the Salt Wash member. Significantly the upper part, or ore-bearing sandstone, contains most of the uranium-vanadium deposits, and this fact suggests that carbonaceous material played an important part in localizing the ore deposits. The second type is sparsely but widely distributed in the ore-bearing sandstone, chiefly within the area of known ore deposits shown on figure 2, and locally occurs above and below this horizon. Light-gray sandstone of the third type, that which formed by epigenetic alteration including solution leaching of black opaque heavy minerals, in the lower part of the Morrison formation (shown only in the Salt Wash member below the ore-bearing sandstone in fig. 2) is clearly restricted to a zone lying along the Dolores fault zone and extending updip from the faults near the axis of the Dolores anticline (fig. 2). In the ore-bearing sandstone it is prevalent close to the uranium-vanadium deposits which, as earlier stated, seem to be restricted to a zone that includes the fault zone (fig. 2). Presumably this type of sandstone is associated also with the Gypsum Valley faults, although no detailed studies such as those made around the Dolores fault zone have been undertaken to examine this possibility.

Because the Disappointment Valley area lies in the axial region of the syncline, rocks more than about 100 feet below the surface are saturated with ground water, and as most of the Morrison formation here lies at depths of several hundred feet, almost all the samples collected for use in this study were completely unweathered.

Although the Disappointment Valley area actually contains none of the faults of the Dolores fault zone, and therefore seems to be less desirable than an area coinciding with the fault zone for a study of alteration, two reasons suggested the feasibility of the area for such a study. First, we concluded that altered rocks at any place within the area of known deposits which seems to be related to the Dolores fault zone should be representative of the area. Second, samples from the Morrison formation in the Disappointment Valley area are consistently unweathered, unlike a large proportion of samples from the other areas that are coincident with the fault zone.

## ORE DEPOSITS

Most of the known uranium-vanadium deposits in the Disappointment Valley area are in the uppermost (ore-bearing) sandstone unit of the Salt Wash member of the Morrison formation. They occur principally in a belt called the Dolores ore zone lying generally at the southwest edge of the Disappointment Valley area. The zone is irregularly shaped with a narrow extension southeastward paralleling the Dolores fault zone. A narrow neck of the zone extends eastward across Disappointment Valley, where it apparently merges with a similar, though smaller, zone near the Gypsum Valley faults. The ore zone within the Slick Rock district is about 20 miles long from northwest to southeast, 10 to 15 miles wide near the northwest corner of the district and narrows to about 2 miles wide south of Disappointment Valley (fig. 2). The zone lies within and roughly normal to the south end of the Uravan mineral belt as defined by Fischer and Hilpert (1952). Within the Dolores ore zone are narrower zones to which the ore deposits are confined; these zones are a few thousand feet wide and generally trend about N. 70°–90° W., which is almost parallel to sedimentary trends, as well as to the principal faults and joints in the district. The narrower zones, however, do not seem to be directly associated with individual faults.

Uranium-vanadium deposits in the area are chiefly tabular to lenticular and are roughly parallel to the stratification, although some ore bodies, called rolls, are narrow, elongate, and curve sharply across bedding. Tabular deposits seem to be localized in massive sandstone where clay is interstitial, and clay and mudstone are in scattered and streaked gall and pebble accumulations, and in discontinuous lenses, whereas roll deposits seem to be confined to sandstone where clay and mudstone are in numerous thin well-defined interconnecting layers.

The uranium-vanadium deposits occur only in epigenetically altered light-gray sandstone (light-buff to light-brown where weathered) of the third type near carbonaceous material. Mudstone close to ore deposits has been altered and is greenish gray, whereas mudstone in and near ore-bearing sandstone farther from deposits is largely reddish brown. The greatest changes in epigenetically altered sandstone have occurred close to ore bodies. In barren rock on the concave side of rolls extensive solution of quartz grains and partial replacement by barite has occurred, whereas on the convex side of rolls quartz overgrowths on quartz grains are common. Authigenic anatase is much more abundant immediately adjacent to some tabular ore bodies than elsewhere and barite is more abundant in ore than in adjacent unmineralized sandstone. Minute amounts of pyrite, galena, and possibly other sulfide minerals are more evident in the heavy fractions from samples close to the ore deposits than elsewhere in the zones that have undergone epigenetic alteration.

Some minor elements, such as copper, are more abundant close to the Dolores fault zone than farther from the faults, suggesting a possible genetic relation of deposits and the fault zone (Shawe and others, 1959, p. 411).

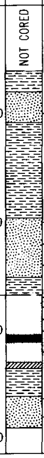
## HEAVY-MINERAL STUDIES

### SAMPLING

Heavy-mineral studies in the Disappointment Valley area consisted almost exclusively of examination and grain counts of heavy minerals in samples of sandstone from the Morrison formation.

Samples are almost all from drill core obtained in 1955 in an exploratory drilling program carried out by the Geological Survey for uranium-vanadium deposits. The drilling program was designed primarily to explore the ore-bearing sandstone unit of the Salt Wash member, so most of the core samples necessarily came from a restricted zone near the base of the Brushy Basin member and near the top of the Salt Wash member. Fifty-six samples of light reddish-brown and light-gray sandstone from the Brushy Basin member and 172 samples of light reddish-brown and light-gray sandstone from the Salt Wash member, averaging about 100 grams each in weight, were obtained from 61 drill cores (fig. 2). Two samples of sandstone for heavy-mineral study were collected from the surface near the Charles T. group of mines (fig. 2).

The sample interval in the drill cores was not rigidly fixed and the number of samples from each drill core ranged from 1 to 17. Samples were taken at intervals of 5 or 10 feet in some drill cores, only at the top, middle, and base of the ore-bearing sandstone in other drill cores, and on opposite sides of the contacts of differently colored sandstone in others. Samples from drill cores that penetrated mineralized rock were taken both near mineralized layers and at a distance from the layers. Figure 3 shows a graphic log, sample points, and the relative abundance of heavy minerals in cores from a drill hole that penetrated mineralized sandstone. Figure 3 may clarify the sampling pro-




| MEMBER OF MORRISON FORMATION | DEPTH, IN FEET | SAMPLE | HEAVY MINERALS PERCENT OF HEAVY FRACTIONS | | | | | | | | | | | | | HEAVY FRACTION, PERCENT BY WEIGHT OF TOTAL SAMPLE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | BLACK OPAQUE | LEUCOXENE | ANATASE | BARITE | PYRITE | ZIRCON | TOURMALINE | APATITE | GARNET | RUTILE | GALENA | SPINEL | UNIDENTIFIED | |
| Brushy Basin | 1000 | 1000 | 69 | 4½ | ½ | 6 | - | 12½ | 5 | 1 | - | Tr | - | - | 1½ | .16 |
| | 1050 | 1050 | 51 | 1 | ½ | 35½ | 1 | 7 | 2 | 1 | - | ½ | - | - | ½ | .11 |
| | | 1060 | 66 | 7 | Tr | 15 | - | 7 | 4 | 1 | - | Tr | - | - | - | 34 |
| | | 1070 | 70 | 7 | 3½ | 5½ | - | 9½ | 1 | ½ | 1 | 1 | - | - | 1 | .23 |
| | | 1085 | 1 | 27 | 1 | 3 | 7 | 52 | 3 | 3 | - | 2 | - | 1 | - | .02 |
| Salt Wash | | 1090 | ½ | 8½ | 8 | 60½ | Tr | 17½ | 1½ | 2 | - | Tr | - | 1½ | - | .06 |
| | | 1095 | 1 | 13½ | 6½ | 47 | 6 | 17½ | 4½ | ½ | 2 | ½ | Tr | - | 1 | .04 |
| | 1100 | 1100 | 1 | 13 | 17½ | 15½ | 2 | 41 | 5 | 2 | 1 | Tr | 1½ | ½ | - | .09 |
| | | 1110 | ½ | 14 | 3½ | 39½ | 2½ | 23½ | 12 | 1 | Tr | 1 | 1 | ½ | 1 | .05 |
| | | 1130 | 59 | 6½ | Tr | 8 | 2½ | 11 | 7½ | 3 | - | ½ | - | - | 2 | .16 |
| | | 1140 | 72 | 5½ | Tr | - | Tr | 14½ | 3 | 1 | - | 3 | - | - | 1 | .07 |
| | 1150 | | | | | | | | | | | | | | | |

EXPLANATION


**FIGURE 3.—Graphic log of drill core from hole DV–115 showing percentage of heavy minerals in heavy-mineral fractions.**

cedure, and the relation of the ore-bearing sandstone to overlying and underlying strata.

The sandstone samples are thought to be representative of the cored interval. In the Salt Wash member the ratio of two light-gray sandstone samples to one light reddish-brown sandstone sample is about equal to the ratio of light-gray to light reddish-brown sandstone cored. In the Brushy Basin member the ratio of one light-gray to one light reddish-brown sandstone sample is also about equal to the ratio of light-gray to light reddish-brown sandstone cored.

## PREPARATION OF SAMPLES AND GRAIN COUNTING

In the field all samples of drill core were wrapped and stored in core boxes. In the laboratory each sample was prepared as shown in figure 4.

The relative abundance of heavy minerals in each grain mount of only the $-150$ mesh size fractions (grain size range about 0.03 to 0.1 mm) were determined, using a petrographic microscope chiefly with a medium-power (16 mm) objective, a mechanical stage, and a cell counter. Each grain mount was traversed at 1-mm intervals until 200 heavy-mineral grains in each mount were counted.

All heavy minerals except carbonate minerals were counted. Because the range of density of carbonate minerals in the sandstone

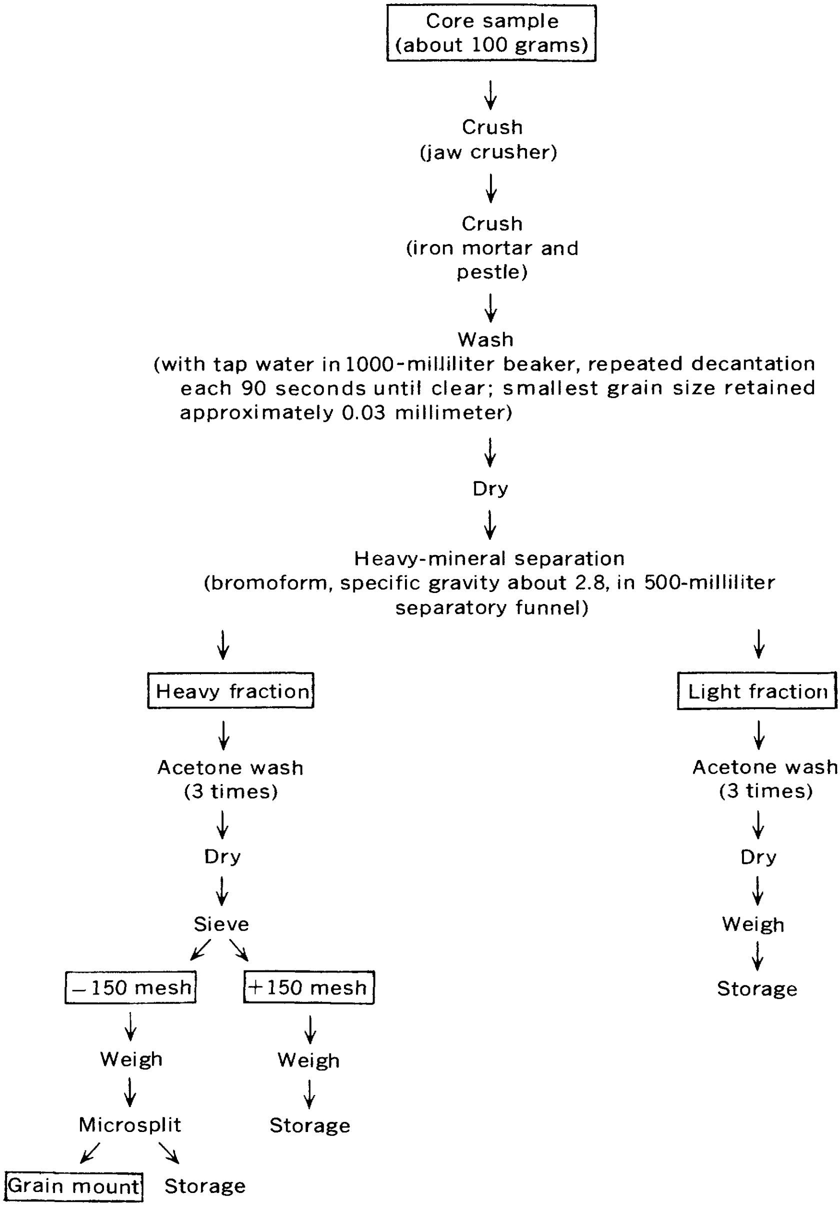



**FIGURE 4.—Flow sheet for preparation of grain mounts.**

samples brackets the density of bromoform used in the separations, carbonate minerals were not consistently brought down in the bromoform separations. Authigenic barite, leucoxene, anatase, pyrite, limonite, and galena in some samples tend to lower and even obscure the relative abundance of detrital minerals, but the inclusion of

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the authigenic minerals in the grain counts provided useful information about alteration processes.

Mineral abundance determined from grain counts is only percentage of grains, and therefore only an approximation to true weight or volume percentage of a certain mineral. However, because each grain count is of the same size fraction, and the sandstone samples are of similar grain size, a grain count is reasonably representative of the total sample, and can be compared with validity to other grain counts.

## DESCRIPTIVE MINERALOGY

The principal detrital heavy minerals in sandstone samples from the Morrison formation are black opaque minerals, zircon, tourmaline, apatite, rutile, garnet, and perhaps leucoxene. The principal authigenic heavy minerals are barite, leucoxene, anatase, pyrite, and galena. Other heavy minerals noted include limonite, spinel, bornite, sphalerite, cassiterite, dahllite(?), and possibly staurolite and brookite.

Heavy-mineral fractions from light reddish-brown and from light-gray sandstone samples in the Morrison formation contain virtually the same minerals. The heavy fractions differ, however, in the relative abundance of minerals. Recalculation of mineral-grain percentage of heavy-mineral fractions to weight percentage of total rock sample (see tables 2 and 3), as shown later, permits a more direct comparison of mineral frequencies among different rock types.

### BLACK OPAQUE MINERALS

Black opaque minerals are present in most of the samples. They range in relative abundance from a trace to almost 80 percent of the heavy fractions. In virtually all the heavy fractions from light reddish-brown sandstone they are the dominant minerals, whereas in the heavy fractions from light-gray sandstone they range from dominance to complete absence. Minerals called black opaques in the heavy fractions actually appear dark reddish brown to reddish black, dark grayish black, or dark brownish black, as well as black, with metallic luster ranging from dull to shiny. Some apparently black grains have coatings of reddish oxide and some, when crushed, show a mixture of reddish and black particles. A few black grains show blue or purple iridescence.

Black opaque mineral grains are commonly well rounded, but many are poorly rounded, and some have sharply angular edges (fig. 5). The only grains showing crystal form among the black opaque minerals are worn octahedra; one or two octahedral faces are common whereas euhedral crystals are rare.

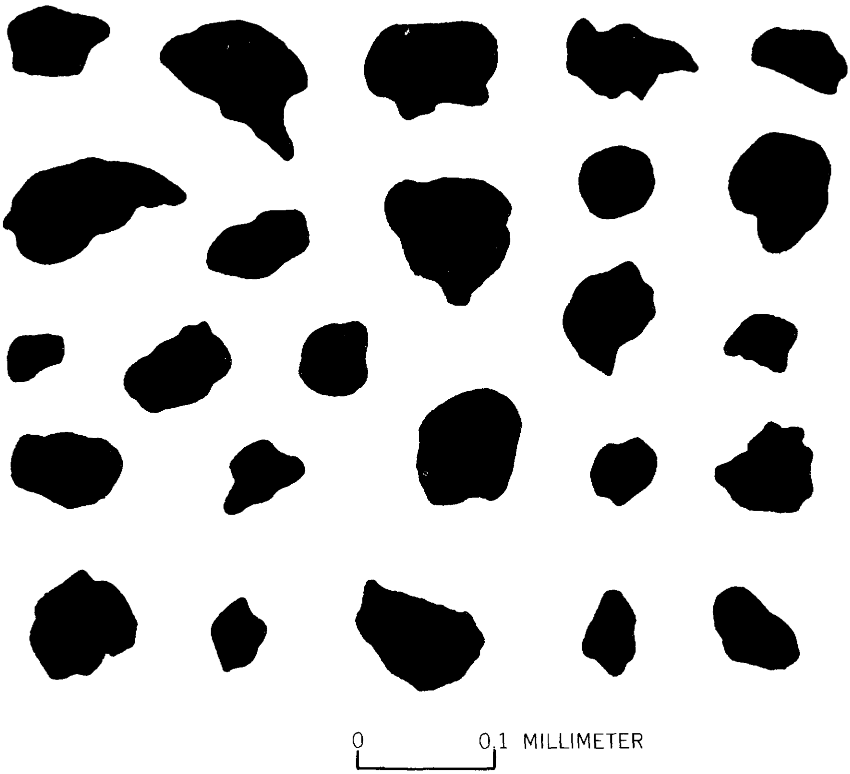


FIGURE 5.—Camera lucida sketches of black opaque mineral grains from sample DV-80-829.1 from the Morrison formation in the Disappointment Valley area, Colorado.

A count of different black opaque minerals was not made to determine the percentage of types, but dark reddish-black moderately rounded grains with dull metallic luster seem to be dominant. Black or grayish-black moderately rounded grains with dull to shiny metallic luster are fairly abundant, whereas dark brownish-black grains are less abundant, and well-rounded grains with very shiny metallic luster are sparse. Many of the dark reddish-black grains contain patches or lamellae of creamy-white to reddish-tan leucoxene.

Most of the dark reddish-black grains with detrital form are readily crushed with a needle point and seem to be porous. Perhaps because of their softness many grains were broken during separation of the samples, accounting for the numerous sharp edges on grains. A few black grains show conchoidal fracture surfaces.

A typical black opaque-rich heavy-mineral fraction from sandstone of the Morrison formation in the Disappointment Valley area can be separated with a hand magnet into ferromagnetic and "nonmagnetic" fractions. The ferromagnetic fractions consist of black opaque minerals that constitute about 5 to 10 percent by weight of the total heavy fraction. These black opaque minerals are probably magnetite or composite grains of other black opaque minerals containing enough magnetite to permit their attraction by a hand magnet. The nonmagnetic fraction of heavy minerals can be further separated in the Frantz isodynamic separator at a field strength of about 0.35 ampere into paramagnetic and nonmagnetic fractions. The paramagnetic fraction constitutes about half the total heavy fraction and contains virtually all the remaining black opaque minerals in the original heavy-mineral fraction, and the nonmagnetic fraction consists almost entirely of minerals other than black opaque minerals.

One such paramagnetic fraction (screened to −200 mesh) from a sandstone sample (SH-4-55) collected just below the ore-bearing sandstone near the Veta Mad mine at the west edge of the Disappointment Valley area (fig. 2) was further separated in the Frantz separator. Two of the fractions so obtained—one attracted at 0.06 ampere (SH-4-55.a) and one at 0.15 ampere (SH-4-55.b)—were analyzed by X-ray and spectrographic methods. The X-ray analyses by Richard P. Marquiss of the Geological Survey showed that the principal mineral present in both fractions is hematite. The semiquantitative spectrographic analyses made by Nancy M. Conklin of the Geological Survey are shown in table 1. The presence of more than 10 percent titanium in the more paramagnetic fraction, and of about 7 percent titanium in the less paramagnetic fraction suggests that the samples probably contain some ilmenite.

From the foregoing facts we conclude that although the black opaque minerals now seem to be chiefly hematite in composition, their apparent porosity, and the presence of some magnetite and ilmenite suggest that these grains as originally deposited were chiefly magnetite and ilmenite, including a large proportion that were intergrowths of magnetite and ilmenite. After deposition and probably before deep burial the magnetite was largely oxidized in place to hematite, and ilmenite was largely altered to leucoxene. The present softness of many of the hematite grains indicates that they could not have been transported in such a fragile state, but probably developed in place, after deposition.

Some well-rounded grains with shiny metallic luster, and some grains that are dark brownish black, may be chromite or a mineral of the spinel group other than magnetite, but these are sparse.

## ZIRCON

Zircon is present in all samples. It ranges in relative abundance from a trace to 70 percent of the heavy fractions; in several samples it is the dominant heavy mineral. Most zircons examined are clear

TABLE 1.—*Semiquantitative spectrographic analyses, in percent, of two samples of paramagnetic black opaque heavy minerals from sandstone in the Morrison formation near the Veta Mad mine, Disappointment Valley area, Colorado*

[Analyses by Nancy M. Conklin, U.S. Geological Survey]

| | SH-4-55.a (−200 mesh, attracted at 0.06 ampere in the Frantz separator) | SH-4-55.b (−200 mesh, rejected at 0.06 ampere and attracted at 0.15 ampere in the Frantz separator) |
|---|---|---|
| Si | 0.7 | 0.7 |
| Al | 1.5 | 1.5 |
| Fe | >10 | >10 |
| Mg | 1.5 | 1.5 |
| Ca | .3 | .3 |
| Ti | >10 | 7 |
| Mn | .7 | .7 |
| Ba | .015 | .015 |
| Cr | .15 | .03 |
| Cu | .007 | .015 |
| Nb | .03 | .015 |
| Ni | .007 | .007 |
| Sc | .007 | (1) |
| Sr | .0015 | .0015 |
| V | .15 | .15 |
| Zr | .3 | .15 |

[1] Not detected.

NOTES TO TABLE

Elements looked for but not found: K, P, Ag, As, Au, B, Be, Bi, Cd, Ce, Co, Dy, Er, Eu, Ga, Gd, Ge, Hf, Hg, Ho, In, Ir, La, Li, Lu, Mo, Nd, Os, Pb, Pd, Pr, Pt, Re, Rh, Ru, Sb, Se, Sn, Sm, Ta, Tb, Te, Th, Tl, Tm, U, W, Y, Yb, Zn.
Elements not looked for: Na, Cs, F, Rb.
Percent figures are approximate midpoints of arbitrary ranges of content; the ranges are bounded by multiples of the logarithmic progression 1.0, 2.2, 4.6, and 10.0. At least 60 percent of the reported contents are in the correct range.

and colorless but a few are pink. A count of 1,000 zircons from 10 core samples from the Salt Wash members (table 2) indicates that almost 95 percent of the zircons are colorless and that only 5 percent are pink. Zircon grains are most commonly well worn and spheroidal or egg shaped. The grain count (table 2) indicates that nearly all colorless as well as pink zircons are well rounded. Worn euhedral and subhedral crystals are fairly common, however, and sharply euhedral crystals appear in some samples. Most of the subhedral to euhedral crystals are simple elongate prisms terminated by pyramids, and a few crystals show both first- and second-order prisms and pyramids. Some crystals are very slender and have length to width ratios of as much as 8:1. Several crystalline aggregates containing two or three crystals were observed. Figure 6 illustrates the appearance of some typical zircons.

Spheroidal and rod-shaped inclusions are common in the zircons, especially in those colorless grains having euhedral outlines. The inclusions are what appear to be minute acicular zircons, unidentified

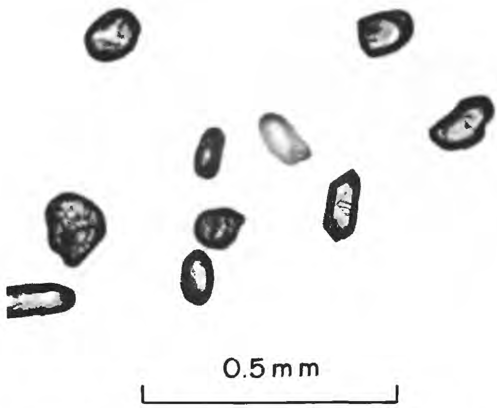


FIGURE 6.—Photomicrograph of zircons from the Morrison formation in the Disappointment Valley area, Colorado.

dark minerals, and clear cavities. In most crystals the inclusions appear to be unoriented, but in some crystals the rod-shaped inclusions are parallel to the *c* crystallographic axis or parallel to the edge of a pyramidal face. A few grains have a dusty appearance caused by swarms of included minute dark minerals.

TABLE 2.—*Relative abundance of zircon varieties in the heavy fractions of 10 core samples from the Salt Wash member*

[Tr., trace]

| Sample No. DV– | Colorless (percent) | | | Pink (percent) | |
|---|---|---|---|---|---|
| | Spheroidal or egg-shaped grains | Worn euhedral or subhedral crystals | Sharply euhedral crystals | Spheroidal or egg-shaped grains | Worn euhedral or subhedral crystals |
| 69–634.1 | 80 | 11 | 6 | 3 | |
| 71–798.0 | 91 | 8 | Tr. | 1 | |
| 91–949.5 | 87 | 10 | 1 | 2 | |
| 93–337.9 | 81 | 7 | 1 | 11 | |
| 93–357.3 | 84 | 9 | 1 | 6 | |
| 95–950.0 | 79 | 10 | 1 | 10 | |
| 97–853.3 | 88 | 6 | 1 | 4 | |
| 112A–1068.0 | 90 | 8 | Tr. | 2 | |
| 112A–1090.0 | 86 | 8 | 1 | 10 | |
| 112A–1115.0 | 92 | 4 | | 3 | 1 |
| Average | 86 | 8 | 1 | 5 | Tr. |

## TOURMALINE

Tourmaline is a common detrital mineral in the samples and ranges in relative abundance from a trace to 23 percent of the heavy fractions. Tourmaline grains are commonly spheroidal or egg shaped (fig. 7); a few elongate grains show the remnants of prism faces.


FIGURE 7.—Photomicrograph of tourmalines from the Morrison formation in the Disappointment Valley area, Colorado.

Most grains are transparent and strongly dichroic, but some of the darker grains are nearly opaque. Yellow-brown or green-brown tourmaline is most common, followed by blue, pink to black, and colorless varieties. The results of a count of 100 tourmaline grains in each of 10 samples from the Salt Wash member are shown in table 3.

TABLE 3.—*Relative abundance of color varieties of tourmaline in the heavy fractions of 10 core samples from the Salt Wash member*

| Sample No. DV– | Color variety (relative abundance in percent) | | | |
|---|---|---|---|---|
| | Yellow brown or green brown | Blue | Pink to black | Colorless |
| 55–1126.2 | 87 | 9 | 4 | ---------- |
| 78–798.5 | 89 | 7 | 3 | 1 |
| 81–911.0 | 83 | 11 | 5 | 1 |
| 89–1074.5 | 87 | 9 | 3 | 1 |
| 91–924.0 | 88 | 9 | 3 | ---------- |
| 93–295.6 | 92 | 3 | 5 | ---------- |
| 100–410.0 | 85 | 7 | 7 | 1 |
| 100–442.0 | 89 | 10 | ---------- | 1 |
| 108–325.5 | 83 | 12 | 5 | ---------- |
| 119–1095.0 | 91 | 5 | 3 | 1 |
| Average | 87 | 8 | 4 | 1 |

TABLE 4.—*Dichroic schemes of tourmaline in the Salt Wash member*

| | E | O |
|---|---|---|
| Yellow-brown | Pale yellow | Dark orange-brown |
| | Yellow-brown | Red-brown |
| Green-brown | Colorless | Green or yellow-green |
| | Pale green | Dark olive-green |
| | Pale brown | Green-brown |
| Blue | Pale gray | Dark blue |
| | Pale blue | Dark blue-green |
| Pink to black | Pale pink | Dark green or black |

The dichroic schemes observed are shown in table 4.

Some tourmaline grains have fractures parallel to the long dimension of the grain, and many grains show irregular fractures. Inclusions are common and comprise colorless cavities, minute apatite crystals, subhedral black magnetite(?) crystals, and swarms of minute unidentified black minerals.

## APATITE

Apatite is present in most samples in amounts ranging from a trace to 7 percent of the heavy fractions. Spheroidal or egg-shaped grains, and elongate worn euhedral and subhedral crystals occur in about equal amounts. Elongate prismatic crystals are commonly broken or cleaved across prism faces. Some worn prismatic crystals have an imperfect cleavage parallel to (0001) and others show an irregular cleavage or parting parallel to the length of the crystal. A few elongate crystals have what appear to be closely spaced striations parallel to the length of the crystal. Worn tabular crystals with the basal pinacoid are rare. Most apatite grains are transparent and colorless and have a vitreous luster, but a few grains are light yellow, light brown, or reddish brown, and dichroic. Several otherwise colorless grains contain patches of brown coloration.

Some apatite grains contain spheroidal or rod-shaped inclusions and cavities. The rodlike inclusions appear to be small clear crystals of apatite and dark-red needles of rutile. Rutile needles have either a random orientation, a radial grouping, or are oriented parallel to the length of the apatite crystal. Spheroidal inclusions are clear cavities and swarms of minute randomly distributed unidentified dark minerals that impart a dusty appearance to the grain. Most brown apatite has this dusty appearance.

## RUTILE

Rutile is a minor detrital constituent of most samples and ranges in relative abundance from a trace to about 4 percent of the heavy-mineral fractions. It commonly occurs as elongate rounded grains, rod-shaped grains, or more rarely, as slender subhedral prismatic crystals. It is also present as inclusions in some apatite grains where it appears as needles and as crystalline aggregates. In plane polarized light rutile grains are red, brown, golden yellow, or opaque. The yellow variety is commonly transparent and dichroic, but some red and brown rutile is opaque or nearly so and best observed in reflected light. No count of rutile was made to determine percentages of color varieties, but the yellow variety seems to be much more common than the red and brown varieties.

## GARNET

Garnet is a minor detrital constituent of many samples and in these it ranges from a trace to 4 percent of the heavy-mineral fractions. It occurs as isotropic, spheroidal or irregularly shaped colorless or pink grains, and as isotropic, platy colorless grains showing conspicuous rectangular or triangular surface patterning (fig. 8), apparently iden-

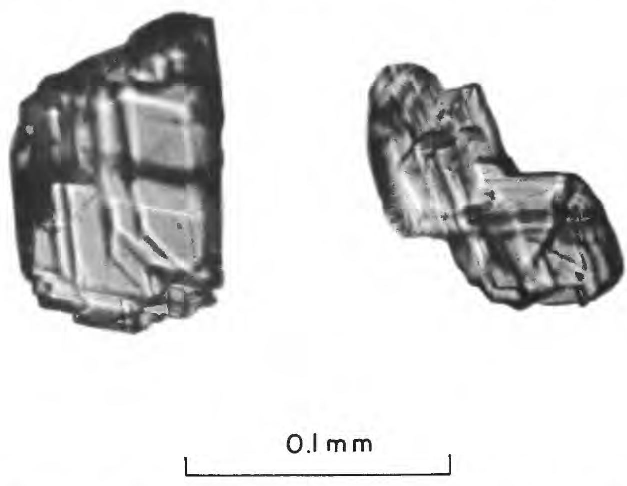


FIGURE 8.—Photomicrographs of typical etched detrital garnet grains from the Morrison formation in the Disappointment Valley area, Colorado.

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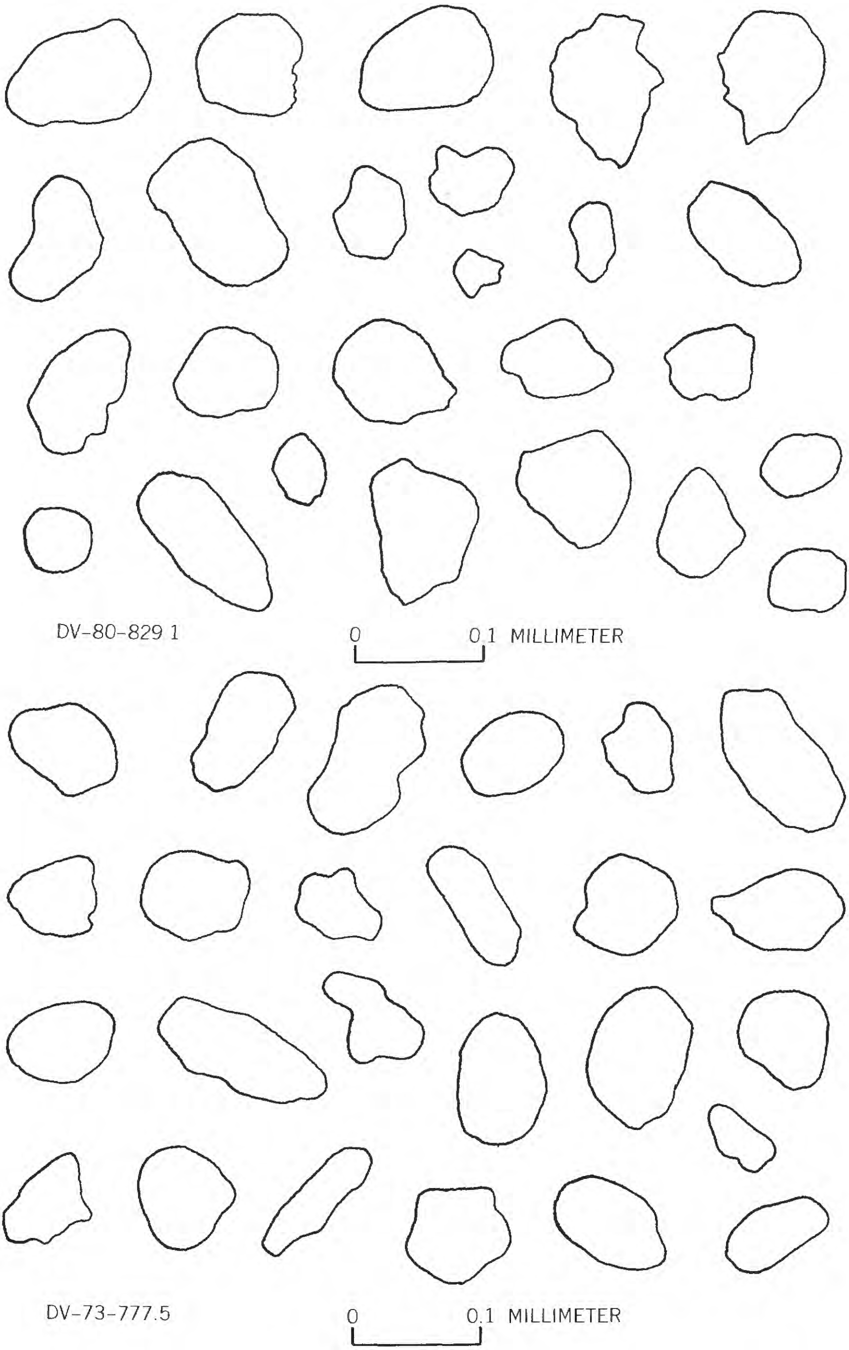


FIGURE 9.—Camera lucida sketches of leucoxene grains from two samples from the Morrison formation in the Disappointment Valley area, Colorado.

tical to that described by M. N. Bramlette (1929) as a result of authigenic etching.

## LEUCOXENE

Leucoxene is present in most samples, and ranges from a trace to 42 percent of the heavy-mineral fractions. It commonly occurs as opaque light-colored spheroidal or irregularly shaped grains (fig. 9), and as a constituent of composite grains that also contain titaniferous dark reddish-black hematite, or ilmenite (fig. 10). Leucoxene grains are white, cream, or tan, and have a dull luster in reflected light. A few grains have a reddish cast suggesting that fine-grained

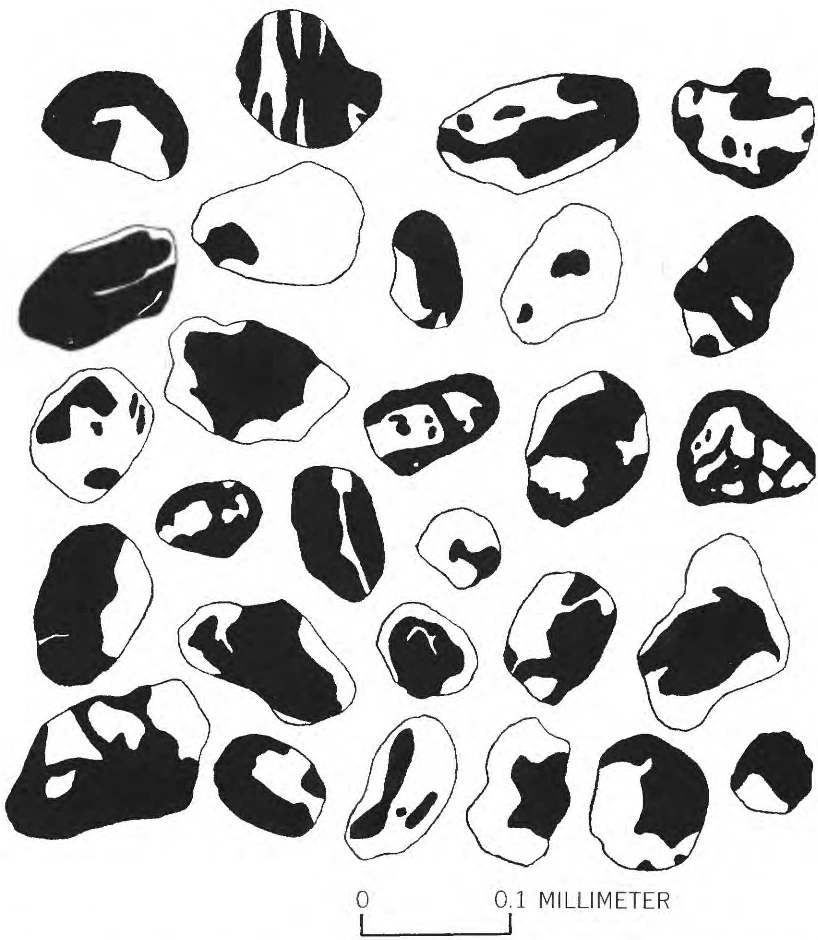


FIGURE 10.—Camera lucida sketches of composite grains composed of leucoxene and titaniferous dark opaque minerals from the Morrison formation in the Disappointment Valley area, Colorado.

hematite may be dispersed in the grains. Some leucoxene grains are soft and are easily crushed with a needle point.

Composite grains that contain both leucoxene and titaniferous dark opaque minerals are common, and grains containing different amounts of leucoxene may represent different stages in the alteration of dark opaque mineral grains to leucoxene (fig. 10). Contacts between dark opaque minerals and leucoxene in composite grains range from sharp to gradational, and the intersection of a contact with the boundary of a grain is generally not indented, suggesting that the grains have not undergone abrasion during transportation since developing their present mineralogic composition. Most composite grains show cores or islands of dark opaque minerals in leucoxene, but a few grains show islands of leucoxene in dark opaque minerals. Some red-brown opaque grains contain narrow parallel stringers of leucoxene suggesting perhaps that the grain was composed, before alteration, of lamellar intergrowths of magnetite and ilmenite, which are now hematite (titaniferous?) and leucoxene, respectively. Perhaps some of the dark-brown to black mineral in composite grains containing leucoxene is pseudobrookite, as suggested by the study of leucoxene by Karkhanavala and others (1959).

If the composite grains were originally magnetite and ilmenite intergrowths, their present compositions probably represent an authigenic change, and because of their abundance suggest that a large proportion of the grains that are wholly leucoxene are also authigenic.

## BARITE

Barite is present as an authigenic mineral in most samples and ranges from a trace to 96 percent of the heavy-mineral fractions. It occurs chiefly as translucent to almost opaque irregularly shaped fragments and less commonly as transparent tabular subhedral to euhedral crystals and aggregates of oriented crystals (fig. 11). Some irregular barite grains have crenate outlines that suggest the original shape of a barite-filled space between rounded detrital grains of other minerals. The irregularly shaped fragments typically contain swarms of tiny opaque minerals (possibly leucoxene inasmuch as they appear white in reflected light) that impart a dusty to almost opaque aspect. Some dusty barite contains abundant minute pyrite crystals.

Most irregularly shaped fragments appear to be rimmed with tiny oriented platelets. Each platelet shows the crystal form of barite that is typically developed in the subhedral and euhedral crystals, and similar to the aggregates of crystals shown in figure 11, but smaller and more numerous. These platelets impart a saw-toothed appearance to the edges of the grain. The platelets are cleared of the dusty

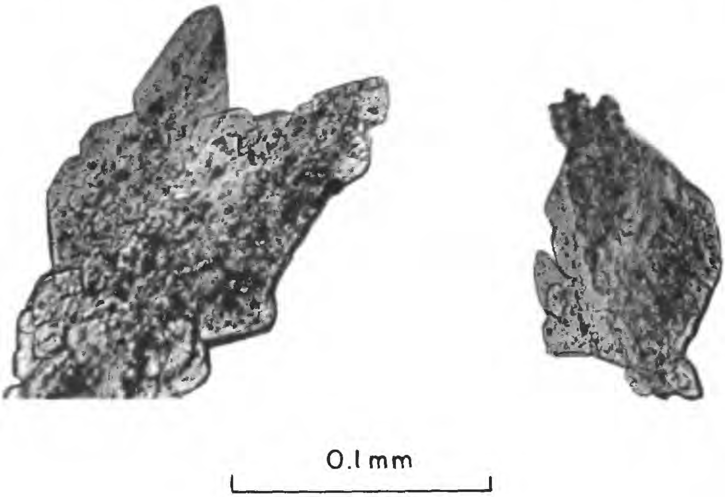


FIGURE 11.—Photomicrographs of aggregates of oriented barite crystals from the Morrison formation in the Disappointment Valley area, Colorado.

inclusions common to irregular barite grains, suggesting that the fragments have started to recrystallize around their edges. Complete gradation from irregular dusty fragments rimmed with clear platelets, to aggregates of oriented small crystals, to single large euhedral clear crystals is shown among barite grains from different samples from the Disappointment Valley area. These grains thus may represent various arrested stages in authigenic recrystallization from irregular dusty fragments to euhedral clear crystals.

The saw-toothed edges of some grains could have resulted from prismatic cleavage. Authigenic recrystallization seems to be the likely cause of most of the crystal forms observed, however, because most euhedral barite is found in light-gray sandstone, especially near ore deposits. The irregular barite is generally found in light reddish-brown sandstone, probably as a diagenetic matrix.

## ANATASE

Anatase is a common authigenic mineral in most samples and ranges from a trace to 27 percent of the heavy-mineral fractions. It commonly occurs as euhedral or subhedral crystals, complex crystalline aggregates, and irregularly shaped masses containing subhedral crystals in a translucent, highly birefringent material that resembles leucoxene. A few dark-colored carbonate grains contain minute euhedral pyramidal crystals of anatase. Anatase also forms minute crystalline outgrowths on some leucoxene grains, and more rarely, on some titaniferous black or brown opaque grains. Figure 12 shows the

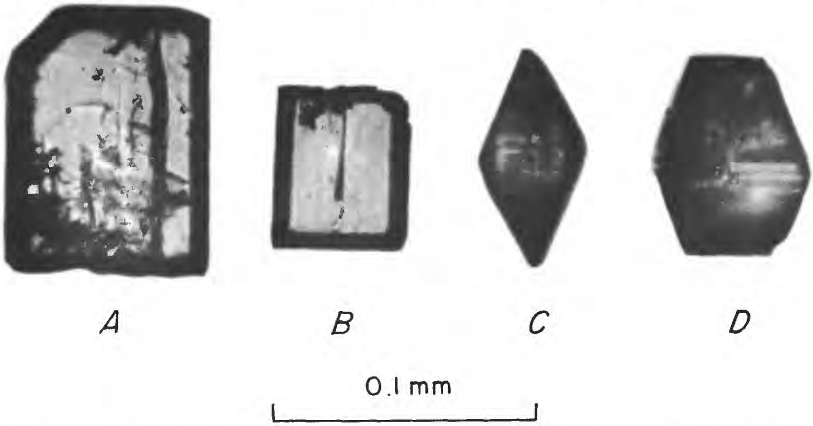


FIGURE 12.—Photomicrographs of anatase crystals of different habit. *A* and *B*, tabular crystals defined by basal pinacoids and a narrow belt of pyramidal faces; *C*, simple pyramids; *D*, pyramids truncated by basal pinacoids; from the Morrison formation in the Disappointment Valley area, Colorado.

three most common crystal habits, which are simple pyramids (*C*), pyramids truncated by basal pinacoids (*D*), and tabular crystals defined by basal pinacoids and a narrow belt of pyramidal faces (*A* and *B*). Some pyramidal crystals are modified by a narrow girdle of prism faces, and a few show two first-order pyramids or both first- and second-order pyramids. Tabular crystals composed of a prism and basal pinacoids are rare.

In plane polarized light some anatase crystals are transparent but others are opaque or nearly opaque. Crystals are commonly colorless, white, or yellow, and less commonly blue, brown, or violet brown. Most samples contain only one or two color varieties of anatase, but a few contain as many as four distinct color varieties. Some colored crystals are weakly dichroic, especially the violet-brown variety. Many crystals appear dusty because of included swarms of minute dark opaque minerals.

Closely spaced striations parallel to the edges of the basal pinacoids are common (fig. 12, *C* and *D*). In reflected light these striations appear as minute grooves, but in transmitted light they appear as black closely spaced lines. The striations cover the pyramidal faces of some crystals, but are restricted on other crystals to a narrow zone at the intersection of pyramidal faces.

## PYRITE

Pyrite is an authigenic constituent in about 40 percent of the samples examined and ranges from a trace to as much as 80 percent of the heavy fractions. Pyrite is commonly in the form of euhedral or subhedral striated cubes or pyritohedrons, irregularly shaped fragments, irregularly shaped fine-grained crystalline aggregates, and rod-shaped replacements of fossil vegetal material. It occurs rarely as tetrahedra or aggregates of tetrahedra. Swarms of minute euhedral pyrite crystals are present in some barite grains, and veinlets of pyrite cut some leucoxene grains. Most crystals of pyrite are relatively unaltered, but fine-grained aggregates commonly are partly altered to dark-brown limonite. Several cubic pseudomorphs of limonite after pyrite were noted.

### GALENA

Galena is an authigenic mineral found in about 10 percent of the samples; the galena content of the heavy-mineral fractions of these samples ranges from a trace to 2½ percent. It is typically seen as bright silvery blue fragments with cubic cleavage and metallic luster.

Galena is found only in samples of light-gray sandstone. Of these, more than 75 percent were collected within a few feet vertically of known mineralized rock, 4 samples were taken within a few hundred feet horizontally of known mineralized rock, and only 1 sample was taken more than 1,000 feet horizontally from known mineralized rock.

### OTHER MINERALS

In addition to the minerals already described, other heavy minerals have been recognized in samples from the Morrison formation in the Disappointment Valley area, but these are sparse and some were seen in only a few samples. Other minerals are limonite, spinel, bornite, sphalerite, cassiterite, dahllite(?), and possibly staurolite and brookite.

The content of limonite ranges from a trace to about 3 percent in fewer than 10 samples, probably as an alteration of pyrite. It occurs typically as yellowish-brown almost opaque irregular fragments.

Spinel was recognized in trace amounts in about 35 samples. It commonly is well rounded, very dark reddish brown to greenish black to opaque, with shiny metallic luster and is isotropic. It was seen predominantly in samples from light-gray (altered) sandstone. In view of the obvious detrital origin of the spinel grains the preferential occurrence in altered sandstone is problematical. Possibly the dearth of other black opaque minerals in these samples made the spinel more conspicuous, and abundance of black opaque minerals in samples from light reddish-brown (unaltered) sandstone may have resulted in less careful examination, and nonrecognition of spinel.

Bornite, sphalerite, cassiterite, and dahllite(?) were recognized as sparse constituents in only a few samples, all of which are from light-gray sandstone. Bornite was observed in only two samples collected respectively a few feet above and below mineralized rock in altered sandstone. It appears as irregular dark bluish-gray grains with metallic luster and "peacock" iridescence. The grains constitute about 1 percent of the heavy-mineral fractions and have the appearance of matrix fragments broken from interstitial spaces during crushing of the sandstone preparatory to mineral separation.

Sphalerite, associated with abundant pyrite and some galena, was seen in only two samples, taken a few feet from mineralized rock in altered sandstone. It makes up respectively ½ and 4 percent of the heavy fractions and consists of isotropic cleavage fragments of light-yellow color and extreme relief.

Cassiterite was identified in only two samples, in trace amounts, as a dark-brown or dark greenish-brown, strongly dichroic, uniaxial positive mineral of very high relief, and detrital aspect. It probably occurs in trace amounts in many other samples, but was not identified in these.

A few samples contain sparse well-rounded, dusty, light brownish-gray almost isotropic grains of moderate relief that may be dahllite. They are probably detrital.

The occurrence of bornite and sphalerite in altered sandstone can be explained as a result of authigenic growth accompanying alteration and probably associated with ore deposition. Cassiterite and dahllite(?) on the other hand are probably detrital and may have been observed merely because a greater number of samples of altered sandstone were studied than samples of unaltered sandstone.

Staurolite and brookite may be present in a few samples in trace amounts, but these were not positively identified.

## HEAVY-MINERAL SUITES

In the following discussion, samples are grouped into suites on the basis of stratigraphic position (Salt Wash member or Brushy Basin member), and lithologic type. Accordingly, suites from the Salt Wash include light reddish-brown sandstone (red-beds type, of diagenetic origin, described in the section on "Alteration," p. 175–176, as (the first type) light-gray unmineralized carbonaceous sandstone (carbon-facies type, of diagenetic origin, described as the second type), and light-gray sandstone adjacent to mineralized layers (mineralized type, of epigenetic origin, described as one variant of the third type). Suites from the Brushy Basin include light reddish-brown sandstone and light-gray sandstone, undifferentiated.

The average relative abundance of heavy minerals in these suites was determined as an arithmetic mean, computed from grain counts of

200 heavy-mineral grains in each grain mount. Use of arithmetic means of heavy minerals in a suite seems permissible because most of the means are close to the medians of the minerals. The average heavy-mineral composition of rocks of a suite (tables 5 and 6) was determined as the product of the abundance of heavy minerals in each heavy-mineral suite and the average total heavy-mineral content of the suite. The average compositions are valid insofar as the assumption is valid that the measured composition of the heavy-mineral fraction is representative of the total amount of heavy minerals in the rock.

## SALT WASH MEMBER

Most samples of sandstone from the Salt Wash member are from the uppermost (ore-bearing) sandstone layer of the member. The samples are divided into three suites: one of 66 samples from light reddish-brown sandstone, one of 74 samples collected within a few tens of feet of mineralized layers in light-gray sandstone, and one of 32 samples of light-gray unmineralized carbonaceous sandstone.

### HEAVY-MINERAL SUITE FROM LIGHT REDDISH-BROWN SANDSTONE

The average relative abundance of minerals in heavy-mineral fractions from 66 samples of light reddish-brown sandstone is shown in table 5. Black opaque minerals are dominant in this suite of samples.

Figure 13 illustrates the frequency distribution of some heavy minerals in 66 heavy-mineral fractions from light reddish-brown sandstone. The histograms suggest a negatively skewed mound-shaped distribution for black opaque minerals, and a positively skewed mound-shaped distribution for zircon, leucoxene, tourmaline, and apatite. The histograms for rutile, barite, and anatase suggest a J-shaped distribution.

The average heavy-mineral content of samples of light reddish-brown sandstone is about 0.31 percent by weight.

### HEAVY-MINERAL SUITE FROM LIGHT-GRAY UNMINERALIZED CARBONACEOUS SANDSTONE

Thirty-two of the heavy fractions from light-gray sandstone (about 30 percent) are from drill core of light-gray unmineralized carbonaceous sandstone believed to be not closer than several hundred feet horizontally and several tens of feet vertically from mineralized layers in the same sandstone unit. Lack of knowledge on the location of all mineralized layers in the Disappointment Valley area precludes any confidence that some of the 32 samples were not collected closer to mineralized rock, and probably a few of them were.

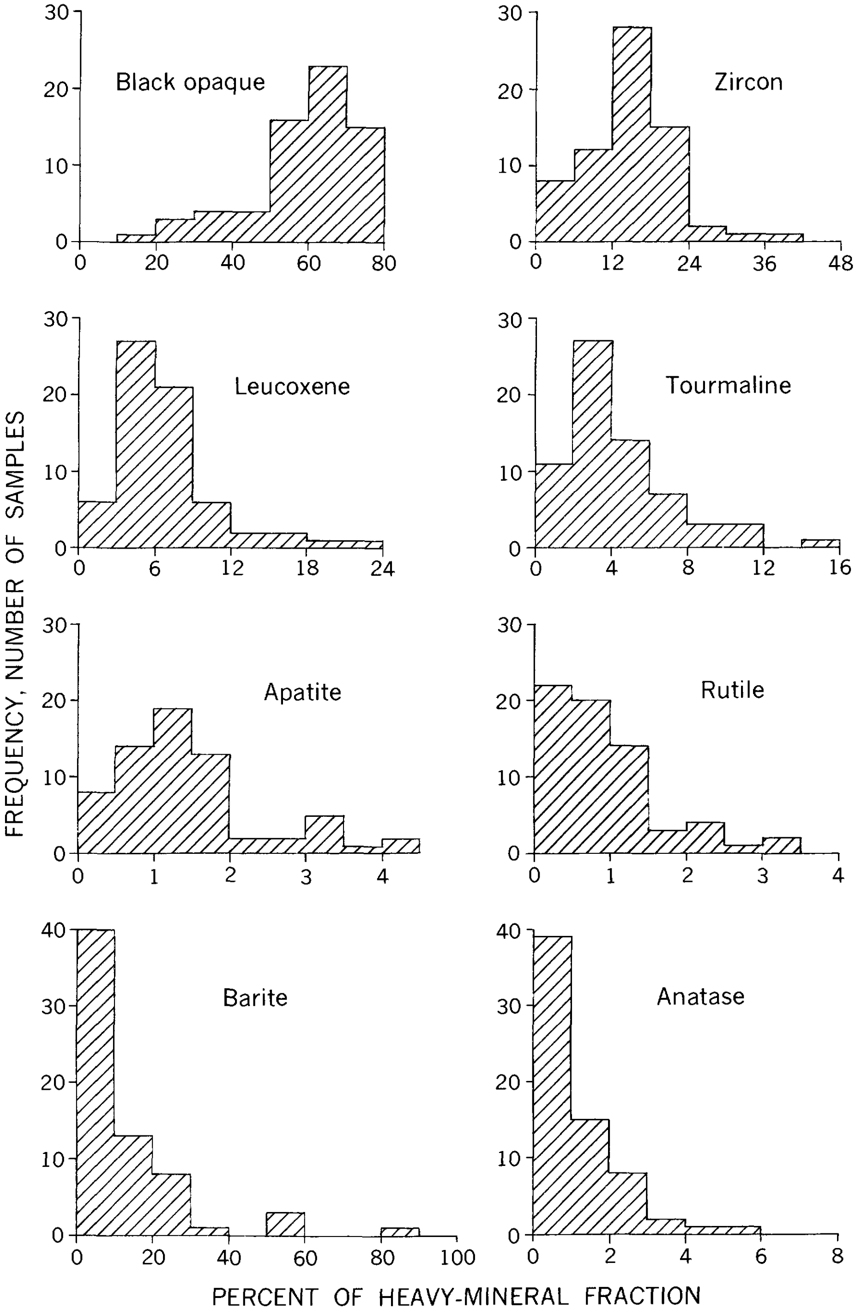


FIGURE 13.—Frequency distribution of some heavy minerals in 66 heavy-mineral fractions from drill-core samples of light reddish-brown sandstone from the Salt Wash member, Disappointment Valley area, Colorado.

TABLE 5.—*Average relative abundance of heavy minerals in drill core samples of sandstone from the Salt Wash member*

[Tr., trace, less than 0.001 percent of total rock, and 0.5 percent of heavy-mineral fraction]

| Mineral | Average relative abundance | | | | | |
|---|---|---|---|---|---|---|
| | Light reddish-brown sandstone<br>First type | | Light-gray unmineralized carbonaceous sandstone<br>Second type | | Light-gray sandstone adjacent to mineralized layers<br>Third type | |
| | Percent of total rock [1] | Percent of heavy-mineral fraction [2] | Percent of total rock [1] | Percent of heavy-mineral fraction [2] | Percent of total rock [1] | Percent of heavy-mineral fraction [2] |
| Black opaque | 0.183 | 59 | 0.067 | 42 | 0.002 | 2 |
| Zircon | .045 | 14.5 | .032 | 20 | .034 | 31 |
| Tourmaline | .012 | 4 | .010 | 6 | .009 | 8 |
| Apatite | .005 | 1.5 | .002 | 1.5 | .002 | 2 |
| Rytile | .003 | 1 | .002 | 1 | .001 | 1 |
| Garnet | Tr. | Tr. | Tr. | Tr. | .001 | .5 |
| Leucoxene | .020 | 6.5 | .014 | 9 | .015 | 13.5 |
| Barite | .037 | 12 | .029 | 18 | .033 | 29.5 |
| Anatase | .003 | 1 | .002 | 1.5 | .004 | 4 |
| Pyrite | Tr. | Tr. | .002 | 1 | .008 | 7 |
| Galena | ------ | ------ | Tr. | Tr. | Tr. | Tr. |
| Limonite | Tr. | Tr. | Tr. | Tr. | Tr. | Tr. |
| Spinel | Tr. | Tr. | Tr. | Tr. | Tr. | Tr. |
| Unidentified | .002 | .5 | Tr. | Tr. | .002 | 1.5 |
| Number of samples | 66 | | 32 | | 74 | |
| Average heavy-mineral content of samples, in weight percent | 0.31 | | 0.16 | | 0.11 | |

[1] By weight.
[2] By grain count.

Table 5 shows the average relative abundance of minerals in the 32 samples, and figure 14 shows the frequency distribution of some heavy minerals in the fractions. A characteristic of the suite is the polymodal distribution of black opaque minerals; fewer than a quarter of the samples contain less than 10 percent black opaque minerals, and the rest contain from 10 to 80 percent black opaque minerals in the heavy-mineral fractions. The frequency distribution of some other heavy minerals in the suite also suggests that more than one lithologic type is present. Histograms for zircon, tourmaline, and barite, and perhaps leucoxene and apatite, show two modes or more. Perhaps this suite represents at least two lithologic types, one with sparse and one with abundant black opaque minerals. It appears to contain a much larger proportion of samples with abundant black opaque minerals than the suite from light-gray sandstone adjacent to mineralized layers (described below); in this respect it resembles the suite from light reddish-brown sandstone.

The average heavy-mineral content of samples of light-gray unmineralized carbonaceous sandstone is about 0.16 percent by weight.

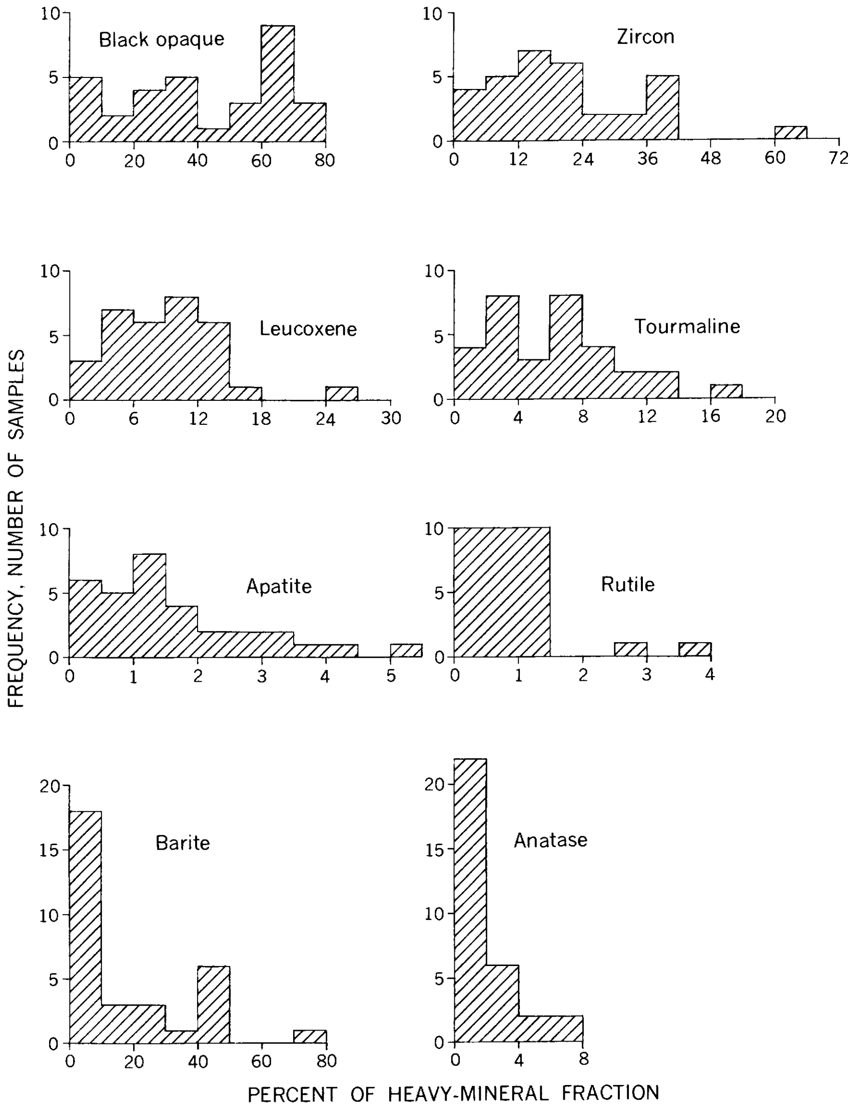


FIGURE 14.—Frequency distribution of some heavy minerals in 32 heavy-mineral fractions from drill-core samples of light-gray unmineralized carbonaceous sandstone from the Salt Wash member, Disappointment Valley area, Colorado.

## HEAVY-MINERAL SUITE FROM LIGHT-GRAY SANDSTONE ADJACENT TO MINERALIZED LAYERS

Seventy-four of the samples from light-gray sandstone are from drill core either above or below mineralized layers in the ore-bearing sandstone near the top of the Salt Wash member.

Table 5 shows the average relative abundance of minerals in the 74 samples, and figure 15 shows the frequency distribution of some heavy minerals in the fractions. Perhaps the most significant characteristics of the suite of samples are the relative scarcity of black opaque minerals, the relative abundance of pyrite, and the common presence of trace amounts of galena. The histogram of black opaque minerals (fig. 15) suggests a J-shaped distribution and shows that all but two samples contain 10 percent or less black opaque minerals in the heavy fraction.

The average heavy-mineral content of samples of light-gray sandstone adjacent to mineralized layers is about 0.11 percent by weight.

### HEAVY MINERALS IN ALTERED AND UNALTERED SANDSTONE NEAR A JOINT

Two samples were collected from a sandstone unit in the Salt Wash member below the ore-bearing sandstone, near the Charles T. group of mines at the west edge of the Disappointment Valley area (fig. 2). One sample (SH–33–56A) is light-buff sandstone, part of a zone of altered rock about 1 foot wide bordering a vertical joint that parallels the Dolores fault zone in the area of epigenetic alteration associated with the fault zone, shown on figure 2. The light-buff sandstone was probably light gray when still deeply buried below the water table, before near-surface weathering. The second sample (SH–33–56B) is light reddish-brown sandstone in the same bedding layer as 56A and about 4 inches laterally from it, part of the unaltered rock which constitutes most of the Salt Wash in the immediate vicinity. Relative abundance of the principal heavy minerals in heavy-mineral fractions separated from the samples is shown in figure 16, graphs *A* and *B*. Graph *C* of figure 16 shows that the principal difference between heavy minerals in altered and unaltered sandstone near the joint is the relative abundance of black opaque minerals. The significance of this fact will be discussed in later sections, pages 211, 212, and 213.

Data from samples of sandstone from the Salt Wash member and from other formations elsewhere in the Slick Rock district corroborate the above relation.

### BRUSHY BASIN MEMBER

Most samples of sandstone from the Brushy Basin member came from the lower part of the member, just above the ore-bearing sandstone layer of the Salt Wash member. The samples are divided into two suites: one of 24 samples from light reddish-brown sandstone and the other of 32 samples from light-gray sandstone, undifferentiated. The total of 56 samples compares to a total of 172 from the Salt Wash

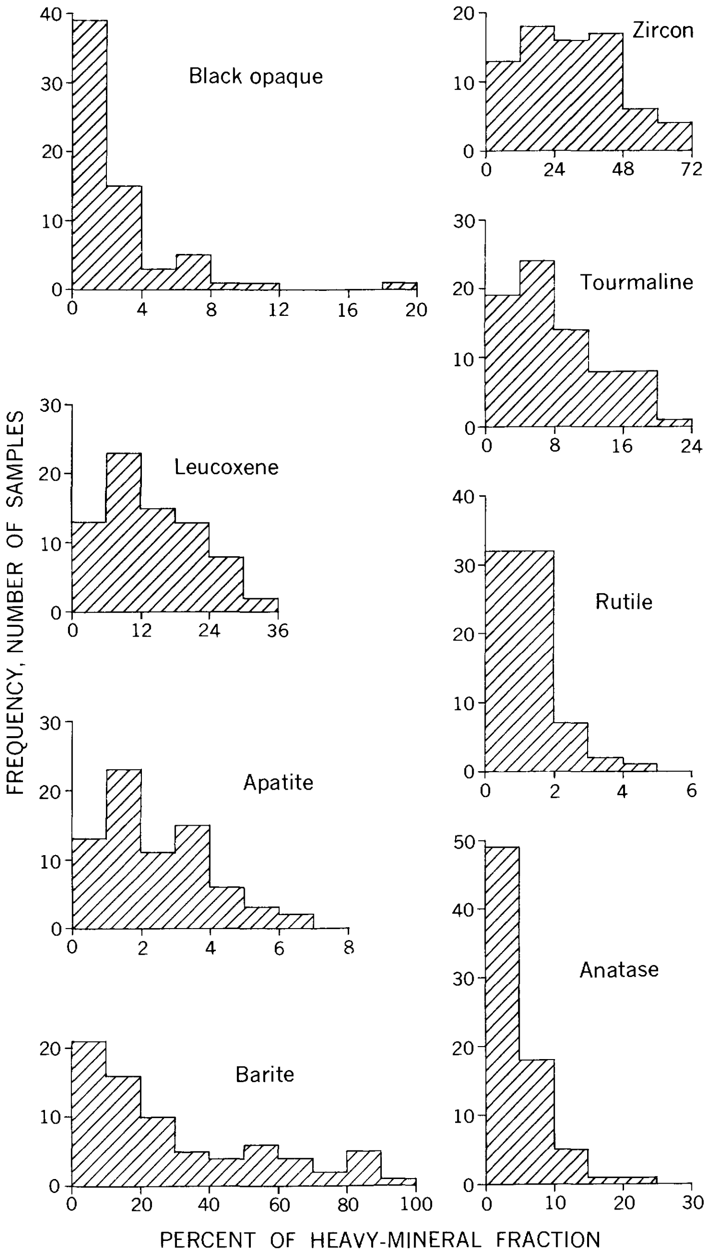


FIGURE 15.—Frequency distribution of some heavy minerals in 74 heavy-mineral fractions from drill-core samples of light-gray sandstone adjacent to mineralized layers in the Salt Wash member, Disappointment Valley area, Colorado.

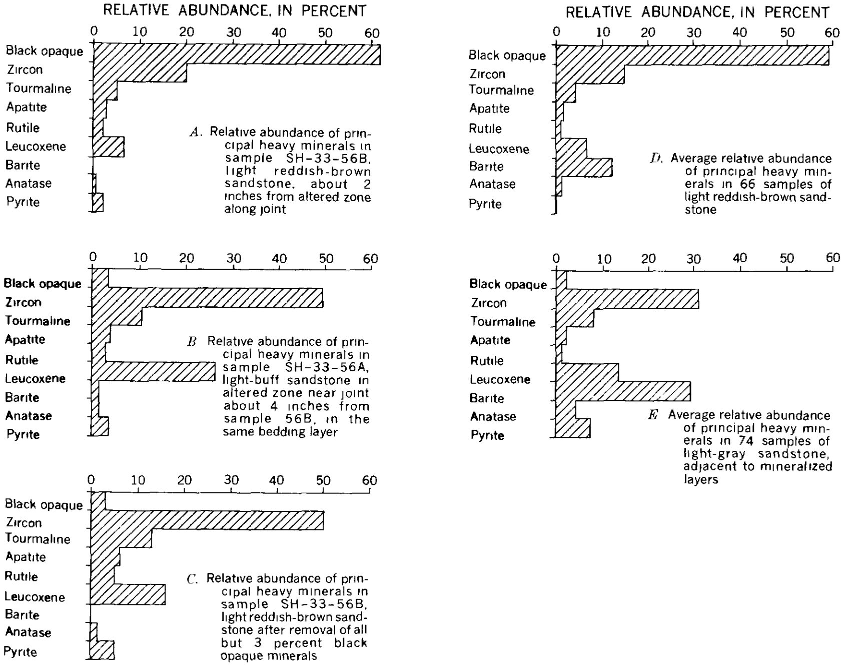


FIGURE 16.—Bar graphs showing average relative abundance of heavy minerals in heavy-mineral suites from some sandstone samples of the Salt Wash member.

member. Similarities with the suites from the Salt Wash member suggest that the suites from the Brushy Basin member may have had a somewhat similar alteration history.

## HEAVY-MINERAL SUITE FROM LIGHT REDDISH-BROWN SANDSTONE

The average relative abundance of minerals in 24 samples of light reddish-brown sandstone is shown in table 6. The data indicate the similarity to the suite from light reddish-brown sandstone of the Salt Wash member, including the dominance of black opaque minerals.

The average heavy-mineral content of samples of light reddish-brown sandstone is about 0.38 percent by weight.

Figure 17 illustrates the frequency distribution of some heavy minerals in 24 heavy-mineral fractions from light reddish-brown sandstone. The histograms suggest a negatively skewed mound-shaped distribution for black opaque minerals, and a positively skewed mound-shaped distribution for zircon and leucoxene. The histograms for tourmaline, apatite, rutile, barite, and anatase suggest a J-shaped distribution.

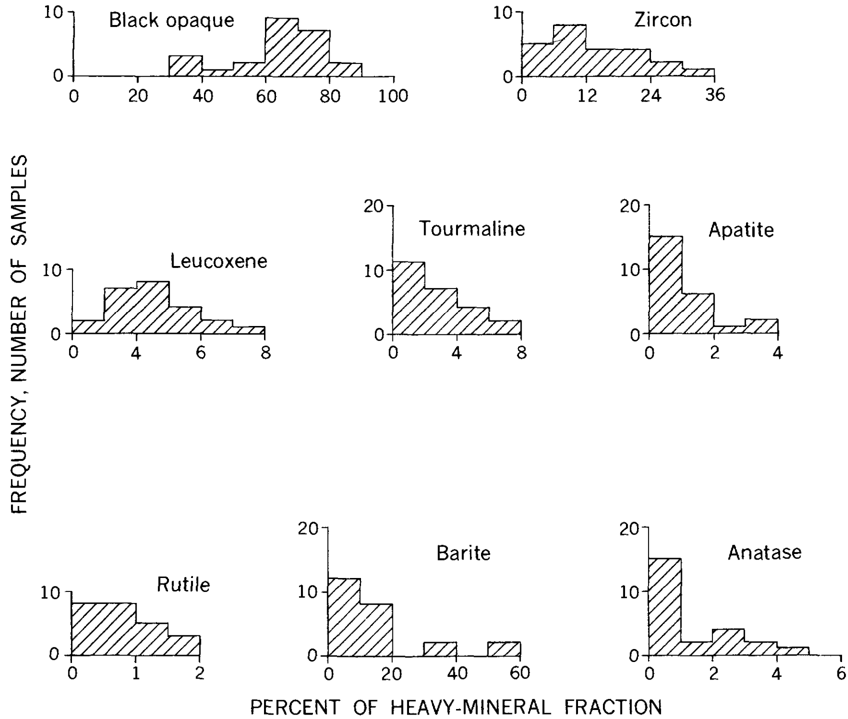


FIGURE 17.—Frequency distribution of some heavy minerals in 24 heavy-mineral fractions from drill-core samples of light reddish-brown sandstone from the Brushy Basin member, Disappointment Valley area, Colorado.

### HEAVY-MINERAL SUITE FROM LIGHT-GRAY SANDSTONE

Heavy-mineral fractions from light-gray sandstone of the Brushy Basin member have a much wider range in the relative abundance of constituents than those from light reddish-brown sandstone. The average relative abundance of heavy minerals in 32 samples of light-gray sandstone is shown in table 6. Characteristics of this suite are the relative scarcity of black opaque minerals and the presence of small amounts of pyrite and trace amounts of galena.

The frequency distribution of some heavy minerals in this suite (fig. 18) has similarities to both the suites from light-gray sandstone adjacent to mineralized layers and light-gray unmineralized carbonaceous sandstone of the Salt Wash member, suggesting the presence of more than one lithologic type.

The average heavy-mineral content of samples of light-gray sandstone is about 0.45 percent by weight.

TABLE 6.—*Average relative abundance of heavy minerals in drill core samples of sandstone from the Brushy Basin member*

[Tr., trace, less than 0.001 percent of total rock, and 0.5 percent of heavy-mineral fraction]

| Mineral | Average relative abundance | | | |
|---|---|---|---|---|
| | Light reddish-brown sandstone | | Light-gray sandstone | |
| | Percent of total rock [1] | Percent of heavy-mineral fraction [2] | Percent of total rock [1] | Percent of heavy-mineral fraction [2] |
| Black opaque | 0.247 | 64 | 0.131 | 29 |
| Zircon | .049 | 13 | .074 | 16.5 |
| Tourmaline | .008 | 2 | .022 | 5 |
| Apatite | .004 | 1 | .007 | 1.5 |
| Rutile | .002 | .5 | .002 | .5 |
| Garnet | Tr. | Tr. | .002 | .5 |
| Leucoxene | .017 | 4.5 | .036 | 8 |
| Barite | .051 | 13.5 | .153 | 34 |
| Anatase | .004 | 1 | .016 | 3.5 |
| Pyrite | Tr. | Tr. | .005 | 1 |
| Galena | ------ | ------ | Tr. | Tr. |
| Limonite | Tr. | Tr. | ------ | ------ |
| Spinel | Tr. | Tr. | Tr. | Tr. |
| Unidentified | .002 | .5 | .002 | .5 |
| Number of samples | 24 | | 32 | |
| Average heavy-mineral content of samples, in weight percent | 0.38 | | 0.45 | |

[1] By weight.
[2] By grain count.

## COMPARISON OF HEAVY-MINERAL SUITES

In the preceding sections heavy-mineral fractions in sandstone samples from the Salt Wash and Brushy Basin members have been divided into several suites. The suites will be compared below in three ways: by the mineral components, by the relative abundance of minerals, and by the percent by weight of the heavy-mineral fractions.

### SALT WASH MEMBER

Heavy mineral suites from sandstone in the Salt Wash member include suites from light reddish-brown sandstone, light-gray unmineralized carbonaceous sandstone, and light-gray sandstone adjacent to mineralized layers.

Heavy-mineral fractions from light reddish-brown and light-gray sandstone contain virtually the same minerals. Galena, however, seems to be restricted to samples from light-gray sandstone. Zircon, tourmaline, and leucoxene are the only heavy minerals present in all samples of light reddish-brown and light-gray sandstone.

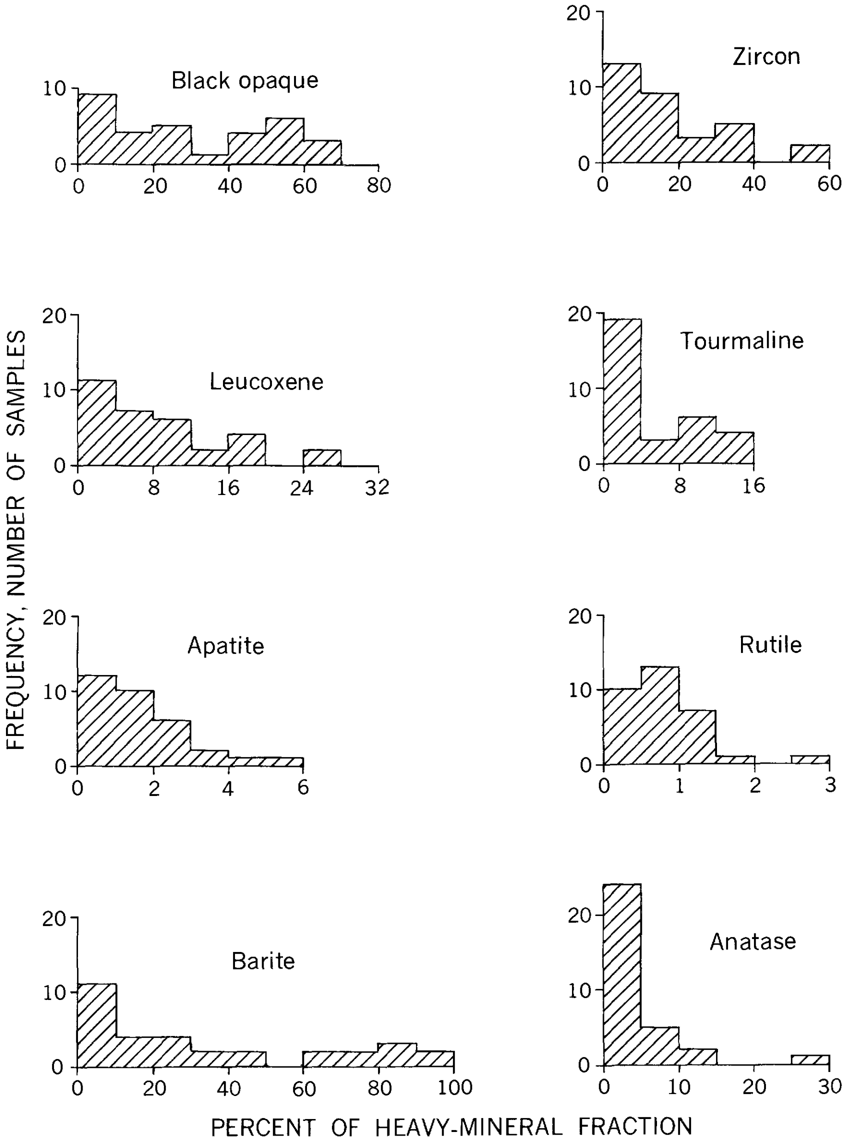


FIGURE 18.—Frequency distribution of some heavy minerals in 32 heavy-mineral fractions from drill-core samples of light-gray sandstone from the Brushy Basin member, Disappointment Valley area, Colorado.

The abundance of the principal heavy minerals in suites from the Salt Wash member is compared graphically in figure 19. The principal difference among the suites is in the abundance of black opaque minerals. Black opaque minerals constitute about 0.183 percent of the average sample from light reddish-brown sandstone (fig. 19,

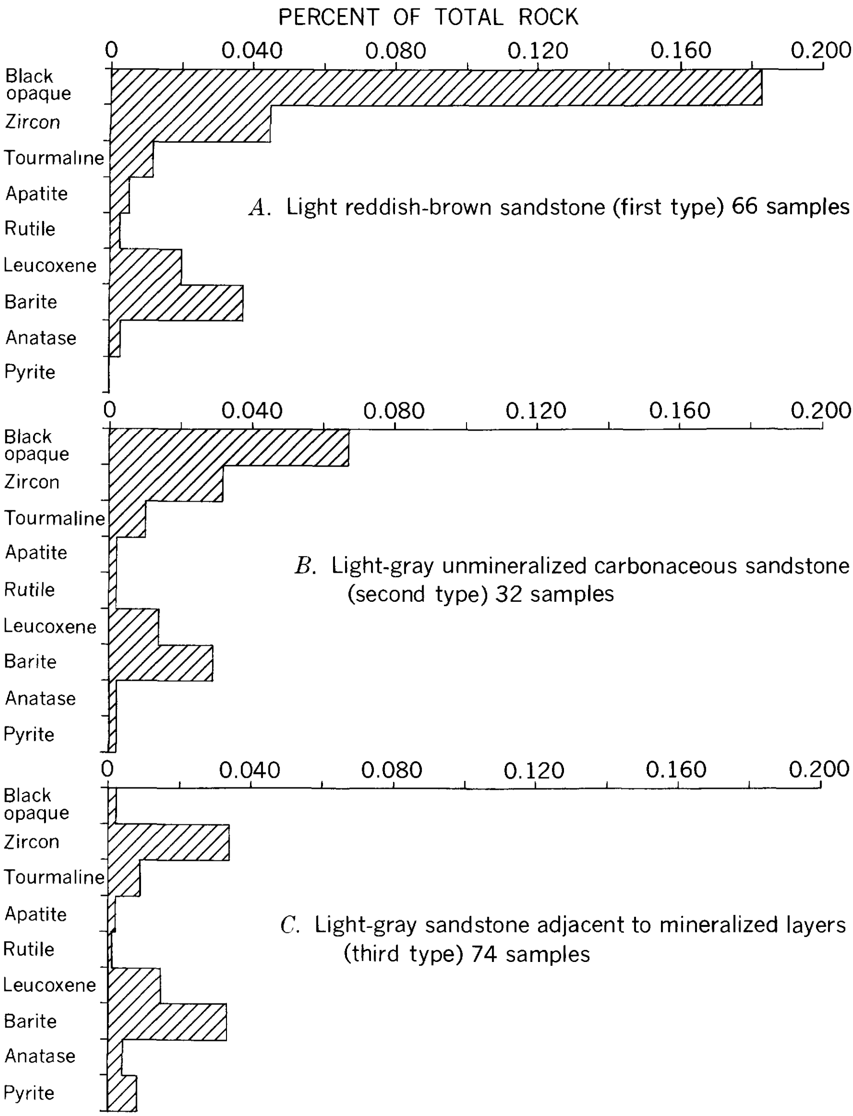


**FIGURE 19.—Bar graphs showing abundance of some heavy minerals in sandstone types of the Salt Wash member.**

graph *A*), about 0.067 percent of the average sample of light-gray unmineralized carbonaceous sandstone (fig. 19, graph *B*), and only about 0.002 percent of the average sample of light-gray sandstone adjacent to mineralized layers (fig. 19, graph *C*). Most minerals, including zircon, tourmaline, rutile, leucoxene, and barite, are roughly of comparable abundance in all suites from the Salt Wash member. Apatite seems to be significantly more abundant in light reddish-brown sandstone (fig. 19, graph *A*) than in light-gray sandstone (fig. 19, graphs *B* and *C*). Anatase seems to be significantly more abundant in light-gray sandstone adjacent to mineralized layers (fig. 19, graph *C*) than in the suites from light reddish-brown sandstone and light-gray unmineralized carbonaceous sandstone (fig. 19, graphs *A* and *B*). Pyrite is essentially absent in the suite from light reddish-brown sandstone (fig. 19, graph *A*) ; it constitutes about 0.002 percent of the average sample of light-gray unmineralized carbonaceous sandstone (fig. 19, graph *B*) and 0.008 percent of the average sample of light-gray sandstone adjacent to mineralized layers (fig. 19, graph *C*).

The average heavy-mineral fraction from light reddish-brown sandstone is about twice as heavy as the average heavy-mineral fraction from light-gray unmineralized carbonaceous sandstone and nearly three times as heavy as the average heavy-mineral fraction from light-gray sandstone adjacent to mineralized layers (table 5), reflecting the higher content of black opaque minerals in light reddish-brown sandstone.

The relative abundance of heavy minerals from altered and unaltered sandstone near a joint is similar to those of two heavy-mineral suites in the Salt Wash already described. The average relative abundance of the principal heavy minerals in 66 samples of light reddish-brown sandstone and in 74 samples of light-gray sandstone adjacent to mineralized layers is plotted on figure 16 (graphs *D* and *E*) to show these similarities. Except for the absence of barite, whose content is highly erratic, and the presence of pyrite, which may have formed during incipient alteration of the sandstone, the relative abundance of heavy minerals from light reddish-brown sandstone of sample SH–33–56B (fig. 16, graph *A*) is very similar to the average relative abundance of heavy minerals from 66 other light reddish-brown sandstones from the Salt Wash. The illustration also shows that relative abundance of the principal heavy minerals in light-buff sandstone of sample SH–33–56A (fig. 16, graph *B*), with the exception of barite, is similar to the average relative abundance of the principal heavy minerals in 74 samples of light-gray sandstone adjacent to mineralized layers.

## BRUSHY BASIN MEMBER

Heavy-mineral suites from sandstone in the Brushy Basin member include suites from light reddish-brown sandstone and from light-gray sandstone (table 6). Both suites contain virtually the same minerals, but in different proportions.

The heavy-mineral suite from light reddish-brown sandstone of the Brushy Basin member (fig. 20) is similar to that from light

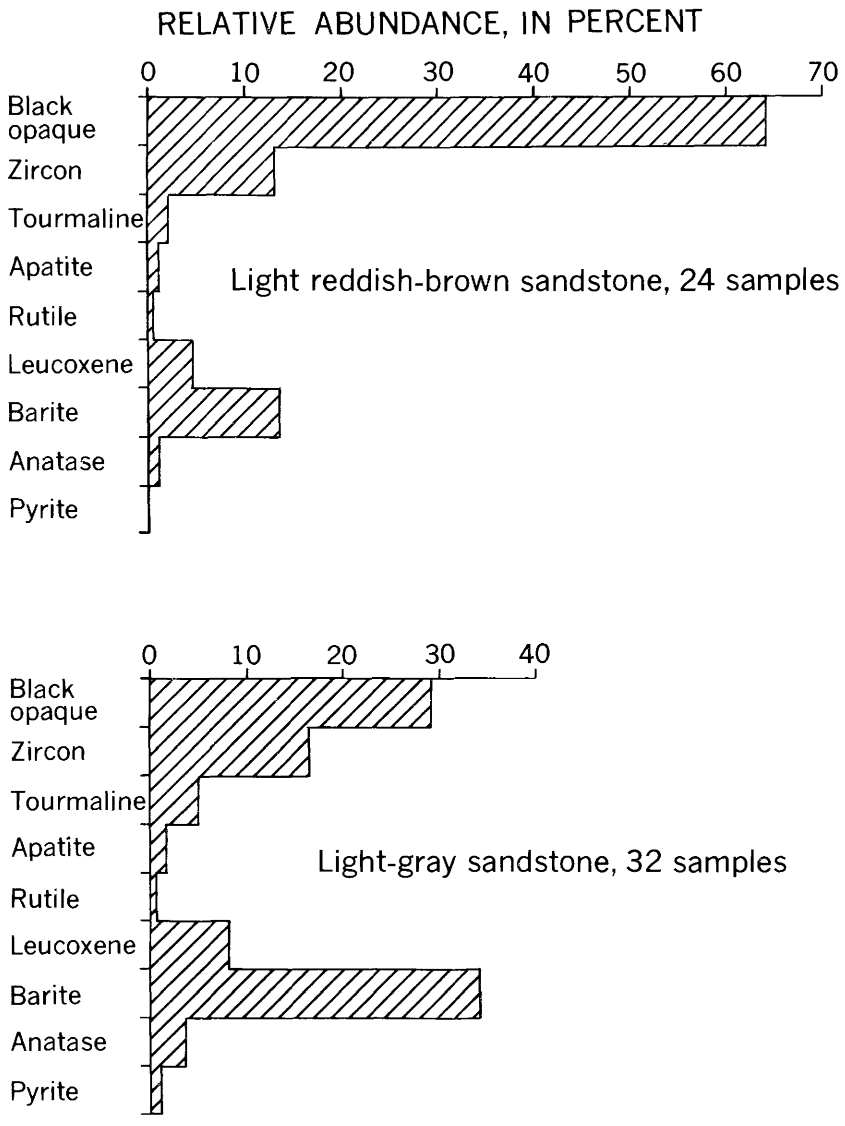


FIGURE 20.—Bar graphs showing average relative abundance of some heavy minerals in heavy-mineral suites from sandstone of the Brushy Basin member.

reddish-brown sandstone of the Salt Wash member. The heavy-mineral suite from light-gray sandstone of the Brushy Basin member (fig. 20) is similar to the heavy-mineral suite from light-gray unmineralized carbonaceous sandstone of the Salt Wash member. However the Brushy Basin suite contains about twice as much barite relative to other minerals as the Salt Wash suite. Inasmuch as a large percentage of the light-gray sandstone in the lower part of the Brushy Basin member is unmineralized carbonaceous sandstone, the similarity of the two heavy-mineral suites is understandable.

Heavy-mineral fractions from light reddish-brown sandstone from the Brushy Basin member constitute about 0.38 percent by weight of the average sample, and this is similar to the percent by weight (0.31) of the average sample of light reddish-brown sandstone from the Salt Wash member. Heavy-mineral fractions from light-gray sandstone from the Brushy Basin make up about 0.45 percent by weight of the average sample, and this is about three times the percent by weight (0.16) of the average sample of light-gray unmineralized carbonaceous sandstone from the Salt Wash member. The anomalously large average weight of heavy-mineral fractions from light-gray sandstone from the Brushy Basin member can be attributed in part to abundant authigenic barite (table 6) and possibly in part to authigenic carbonate minerals which were not counted.

## INTERPRETATION OF HEAVY-MINERAL SUITES

The differences among the various suites of heavy minerals from different types of sandstone that are distinguished on the basis of appearance and geologic occurrence seem to justify the division of suites described in the foregoing pages.

The chief difference among the heavy-mineral suites from the Salt Wash member is the relative abundance of black opaque minerals. Lesser differences are the relative abundance of pyrite, anatase, galena, and apatite. If the geologic evidence is accepted that the heavy-mineral content of all sandstone of the Morrison studied was probably essentially uniform when the sediment was deposited, and that the heavy-mineral content of light reddish-brown sandstone is generally representative of the original content, then we could conclude that where carbonaceous material was deposited with the sandstone the principal mineralogic change in heavy minerals was leaching of some black opaque minerals and redeposition of a small amount of the iron as pyrite. Some iron apparently was removed, or may have been redeposited in authigenic carbonate minerals. A similar relation is noted between the heavy-mineral suites from light reddish-brown sandstone and those from light-gray sandstone from the Brushy Basin member, but in addition, with alteration, some authigenic barite must have been added to light-gray sandstone.

The heavy-mineral suite in light-gray sandstone adjacent to mineralized layers could have resulted merely by leaching most of the black opaque minerals from either light reddish-brown standstone or light-gray unmineralized carbonaceous sandstone. Appreciable iron was redeposited as pyrite, and some authigenic anatase developed, possibly by recrystallization of leucoxene. Some of the iron liberated by leaching of black opaque minerals must have been removed from the sandstone or redeposited in authigenic carbonate minerals or in pyrite in the mineralized layers.

A recalculation of the relative abundance of minerals in a sample of unaltered (light reddish-brown) sandstone near a joint in the Salt Wash member was made for comparison with the relative abundance of minerals in a sample of altered (light-buff) sandstone near the joint. This recalculation was done by subtracting all but 3 percent black opaque minerals and adjusting the remaining minerals to 100 percent. Because these samples came from the same bedding layer the differences in relative abundance of minerals can almost certainly be attributed primarily to alteration. Here the heavy-mineral suite recalculated from that of light reddish-brown sandstone by removal of all but 3 percent of the black opaque minerals is similar to that of the light-buff sandstone (fig. 16, graphs *A*, *B*, and *C*). Perhaps the chief difference is that the suite from light-buff sandstone has about 10 percent more leucoxene relative to other minerals than the recalculated suite; perhaps some of the black opaque minerals were altered to leucoxene rather than completely removed. Some iron must have been removed from the sandstone or redeposited in authigenic carbonate minerals.

As calculated from table 5, the average weight percent of heavy minerals other than black opaque minerals in the suite from light reddish-brown sandstone from the Salt Wash member is 0.13, that in the suite from light-gray sandstone adjacent to mineralized layers is 0.11, and that in the suite from light-gray unmineralized carbonaceous sandstone is 0.09. The close similarity of all of these suggests that the initial heavy-mineral content (excluding authigenic minerals) in all the sandstone in the Salt Wash member was generally uniform. According to data shown in table 6 the average weight percent of heavy minerals other than black opaque minerals in the suite from light reddish-brown sandstone from the Brushy Basin member is 0.14, close to that for the Salt Wash, but the average weight percent in the suite from light-gray sandstone from the Brushy Basin is much higher, 0.32 percent. These data suggest again that an authigenic constituent must have been added during alteration of Brushy Basin sandstone.

Light reddish-brown sandstone below the ore-bearing sandstone in the Salt Wash member near the Charles T. group of mines (sample SH–33–56B, fig. 16, graph *A*) is typical of samples from the suites of light reddish-brown (unaltered) sandstone from the Salt Wash member (fig. 16, graph *D*) as indicated by the dominance of black opaque minerals in the heavy mineral fraction, and the general similarity in relative abundance of other minerals. Light-buff sandstone of sample SH–33–56A (fig. 16, graph *B*) collected near sample SH–33–56B in an altered zone adjacent to a joint is typical of samples from the suite of light-gray sandstone adjacent to mineralized layers in the Salt Wash member (fig. 16, graph *E*) in that it contains very little black opaque minerals in the heavy mineral fraction and is otherwise generally similar in the abundance of other minerals. Even though sample SH–33–56A is not from sandstone close to mineralized layers it is nevertheless strikingly similar mineralogically to those samples which are. Possibly it was altered by the same leaching solutions that affected sandstone near the mineralized layers.

## CONCLUSIONS

The similarity of the actual weight percentage of heavy minerals other than black opaques in most of the suites from the Morrison formation indicates that, when deposited, most of the sandstone of the Morrison had a generally uniform heavy-mineral content, with similar amounts of various species. Geologic and petrologic evidence indicates that the variation in black opaque minerals resulted from alteration after deposition. The uniformity in heavy-mineral content of the original sediment suggests that all the rocks of the Morrison formation studied here had a common source.

Light reddish-brown sandstone in the Morrison formation seems to have escaped the effects of alteration associated with structural elements such as faults and joints, alteration associated with local concentrations of carbonaceous material in sandstone, and alteration associated with the ore deposits. In mineralogic composition it is therefore more nearly like the original sediments than any of the rocks affected by alteration. Even so, some mineralogic changes took place after deposition of light reddish-brown sandstone. Soft, porous grains of leucoxene, sofe hematite pseudomorphs after black opaque minerals, and hematite films on other detrital grains could not have developed before deposition of the grains. Some of the leucoxene could have been originally detrital, but some has probably altered in place from ilmenite, and most of the hematitic black opaque minerals have altered in place from magnetite and ilmenite, or mixtures of the two. Both these mineralogic changes involved oxidation, and because the light reddish-brown sandstone has probably existed in a mildly reducing environment from the time of first saturation with more or less stagnant ground waters upon burial, until the present time, the oxidation must have taken place shortly after deposition and before deep burial. At that time iron was liberated which moved locally and redeposited as hematite films on other detrital grains, imparting the reddish color that gives the red beds their name. The changes just described are considered to be diagenetic.

In places in the sedimentary rocks of the Morrison formation abundant carbonaceous material was deposited, notably in the ore-bearing sandstone. Presumably these rocks almost from the time of deposition existed in a reducing environment. For this reason black opaque minerals probably never were oxidized, as they were oxidized in light reddish-brown sandstone, and no iron was redistributed and deposited as hematite films on other detrital grains. The light-gray color of these rocks as we see it today may be the same color as the original sediments. The sandstone facies discussed here, which could be called the carbon facies, may not be precisely represented by the suite of heavy minerals from light-gray unmineralized carbonaceous sandstone in the Salt Wash member, because that suite may contain samples collected near mineralized rock, but it is probably approximately represented. Even if black opaque minerals are more abundant in light-gray unmineralized carbonaceous sandstone than indicated by the suite, probably some of the black opaque minerals were dissolved in the reducing environment, as suggested by the presence of a small amount of pyrite. The destruction of black opaque minerals and redeposition of iron as pyrite may have taken place over a long period of time; they probably started, however, almost at the time of deposition and the changes are considered to be diagenetic.

Probably long after deposition of the sediments, after consolidation and faulting of the beds, light reddish-brown sandstone in the Morrison formation near the Dolores fault zone was attacked by altering solutions that were localized there because of the channeling effect of the shattered and more permeable rocks along the fault zone. The chief effects of the alteration were almost total removal of black opaque detrital minerals, removal of all interstitial hematite dust and hematite in the form of films coating other detrital grains, and redeposition of some of the iron as pyrite. A light-gray rock resulted. These changes probably involved actual removal of iron from the sandstone. Because iron was removed and because the fault-controlled alteration started long after deposition of the sediments, the changes which manifest the alteration are considered to be epigenetic.

The alteration that was associated with both faults and ore deposits probably resulted from the same geologic processes. This is suggested partly by the close similarity of the heavy minerals in altered sandstone near faults and joints to the suite in light-gray sandstone adjacent to mineralized layers, partly by the coincidence in general distribution of the ore deposits and the zone of epigenetic alteration associated with the faults, and partly by the zoning of metals in the deposits relative to the faults. The heavy minerals in altered sandstone close to faults and in light-gray sandstone adjacent to mineralized layers differ principally in the relatively greater abundance of anatase and pyrite, both authigenic minerals, close to the deposits. Possibly these minerals are abundant there because of conditions for precipitation which also induced deposition of ore minerals. Because of the implied relation of the deposits to epigenetic alteration in the fault zone, and because of geologic evidence to suggest that the deposits were formed long after deposition of the sediments, the alteration that was related to uranium-vanadium deposits is believed to be epigenetic.

On the basis of the foregoing hypothesis, the conclusion is reached that at some time after deposition of the sediments of the Morrison formation in the Disappointment Valley area, after consolidation and after faulting of the beds, solutions flowed through the fault zone, causing alteration of sandstone close to faults and joints. In the Salt Wash member below the ore-bearing sandstone the zone of alteration was generally about 2 or 3 miles wide, but in the laterally more continuous, and initially more permeable, ore-bearing sandstone itself the zone of alteration was much wider. In the ore-bearing sandstone the contact of the altering fluid with pockets of stagnant water, where strongly reducing conditions already existed close to carbonaceous material, resulted in precipitation of minerals in the uranium-vanadium deposits.

We propose that the differences among the heavy minerals, especially the amount of black opaque minerals, in suites from different types of sandstone from the Morrison formation can be usefully applied as guides to the location of hidden uranium-vanadium deposits. For example, the almost total absence of black opaque minerals in light-gray sandstone that contains carbonaceous material is thought to be a positive indication of proximity to mineralized rock.

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