Vanadium-Uranium Deposits of the Rifle Creek Area, Garfield County, Colorado

GEOLOGICAL SURVEY BULLETIN 1101

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

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By RICHARD P. FISCHER

With a section on MINERALOGY

By THEODORE BOTINELLY

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VANADIUM-URANIUM DEPOSITS OF THE RIFLE CREEK AREA, GARFIELD COUNTY, COLORADO

By Richard P. Fischer

ABSTRACT

One of the largest vanadium-uranium deposits in the Colorado Plateau region is in the Navajo(?) and Entrada sandstones in the Rifle Creek area. This deposit is well exposed by mine development and therefore suited to the study and interpretation of structural features, ore habits, and geochemical relations. Small deposits also occur in the Morrison formation, but as they are poorly developed they have not been studied in detail.

The Rifle Creek area is on the Grand Hogback monocline where this fold has a structural relief of about 15,000 feet and exposes rocks ranging in age from Precambrian to Cenozoic. However, only strata of late Paleozoic and Mesozoic ages and landslide debris of Quaternary(?) age are exposed in the area of detailed study.

The strata of late Paleozoic and early Mesozoic ages are about 4,000 feet thick and mainly red shale and sandstone. The top few hundred feet of this sequence resembles the Chinle formation of Triassic age.

The Navajo(?) sandstone of Jurassic and Jurassic(?) age overlies the Chinle formation. The Navajo(?) is 30 to 75 feet thick and is composed of clean, fine-grained, light-brown sandstone conspicuously layered with torrential crossbedding. It is hard and crops out as a rough vertical cliff. Above the Navajo(?) is the Entrada sandstone of Jurassic age. The Entrada also consists of clean fine-grained sandstone, but it is light gray, tangentially crossbedded, and soft enough to form rounded cliffs or steep slopes. It is 75 to 125 feet thick.

The Morrison formation, also Jurassic, overlies the Entrada; it consists of two poorly defined units. The lower unit is 150 feet thick and is composed of gray sandstone interbedded with gray and red mudstone. Small vanadium-uranium deposits occur in sandstone beds in the middle and upper parts of this unit. The upper unit is 350 feet thick and consists dominantly of gray and maroon mudstone.

The Dakota sandstone is above the Morrison and is of Cretaceous age. It is about 80 feet thick and consists of shale and sandstone. It is overlain by a few thousand feet of Mancos shale, also Cretaceous.

Landslides of Quaternary(?) age have spread a thin cover of debris over parts of the area.

The Rifle Creek area is bounded on the north and south by structural terraces of flattish dip, but between these terraces the rocks mostly dip southward at angles ranging from 15° to 30°. Fractures, some with displacement along them, are abundant and are grouped into three sets—two sets that dip at high angles and one of low-angle dip. One set of high-angle fractures trends generally eastward, approximately along the strike; it is the stronger set and evidently the older one. The second set strikes northwestward. The low-angle fractures are bedding-plane slips of small displacement.

Deformation forming the Grand Hogback monocline probably began about the start of Tertiary time but most of the folding is generally considered to be of late Eocene age.

The Rifle Creek area has yielded about 750,000 tons of vanadium-uranium ore, mostly from the deposit in the Navajo(?) and Entrada sandstones. This deposit has been mined for 7,000 feet along its trend in the Rifle mine and for several hundred feet in the Garfield mine. Its ore contains 1 to 3 percent V_2O_5 and several hundredths percent U_3O_8; ore from the Morrison formation has about the same vanadium content but a little more uranium.

Primary vanadium minerals in the Rifle-Garfield deposit consist dominantly of micaceous silicates with a small amount of montroseite, an oxide. They mainly occupy the sandstone pores but also partly replace the sand grains. Secondary vanadium minerals are sparse. The only uranium minerals recognized are secondary.

The ore occurs in three tabular layers, called No. 1, No. 2, and No. 3 "veins" in ascending order. Each layer lies nearly parallel to the major bedding but cuts across crossbedding in many places, and two of the layers even cross formational contacts. No. 1 vein underlies the entire deposit; it is mostly in the Navajo(?) but in a few places along the south side of the Rifle mine it crosses into the Chinle formation, and it is in the Chinle beneath the Garfield mine. No. 2 vein forms several separate ore bodies. One of these is in the Navajo(?) and joins No. 1 vein in the east end of the Rifle mine; the others are in the Entrada, and one of these joins No. 3 vein along the northwest side of the Garfield mine. No. 3 vein is known only in the Garfield mine, where it is wholly in the Entrada. If the separate ore bodies in No. 2 vein are connected by some imagined link, the three layers have a broad S-shaped pattern about 80 feet high and 10,000 feet long.

Each ore layer is bordered on one side by a thin layer, generally about ⅛ inch thick, containing fine grains of a solid-solution mixture of galena and clausthalite. This layer in turn is bordered by a 1- to 2-foot thick layer of greenish sandstone containing a micaceous chromium-bearing mineral. The galena-clausthalite and chromium-bearing layers lie above No. 1 and No. 3 veins but below No. 2 vein.

The east half of the deposit in the Rifle mine trends eastward, almost parallel to the strike, but the west half curves southwestward and rakes down the dip. All faults displace and brecciate the ore.

The writer has failed to recognize the controls that localized the deposit and he cannot suggest an explanation supported by evidence for its origin. Field relations, however, seem to require the contemporaneous formation of all three ore layers under conditions that selectively mineralizd a small part of a nearly homogeneous host and permitted the fractionation of the five elements—vanadium, uranium, lead, selenium, and chromium—that are enriched in the ore layers. Reactions at the interface of two solutions might satisfy these requirements. There is no recognized evidence to suggest the source of the mineralizing solution or the contained elements.

The only practical suggestion that can be offered to guide prospecting for another deposit relates to an altered zone at the top of the Chinle formation and its apparent association with the Rifle-Garfield deposit. This zone extends beyond the limits of the deposit and would offer a larger target for exploration than the ore itself.

Deposits in the Morrison formation occur in shaly sandstone beds containing carbonized plant fossils. Recognized ore minerals are micaceous and clayey vanadium minerals and secondary uranium minerals. They form tabular ore bodies 1 to 3 feet thick and a few yards across. These deposits show no physical continuity with the deposit in the Navajo(?) and Entrada formations.

INTRODUCTION

Deposits of vanadium and uranium in sandstone are numerous in the Colorado Plateau region and they have many common characteristics. In the Rifle Creek area (fig. 1) the principal deposit, which is developed by the Rifle and Garfield mines, has most of the characteristics common to the deposits of the region as well as a few unique features. Moreover, this deposit is well suited to the

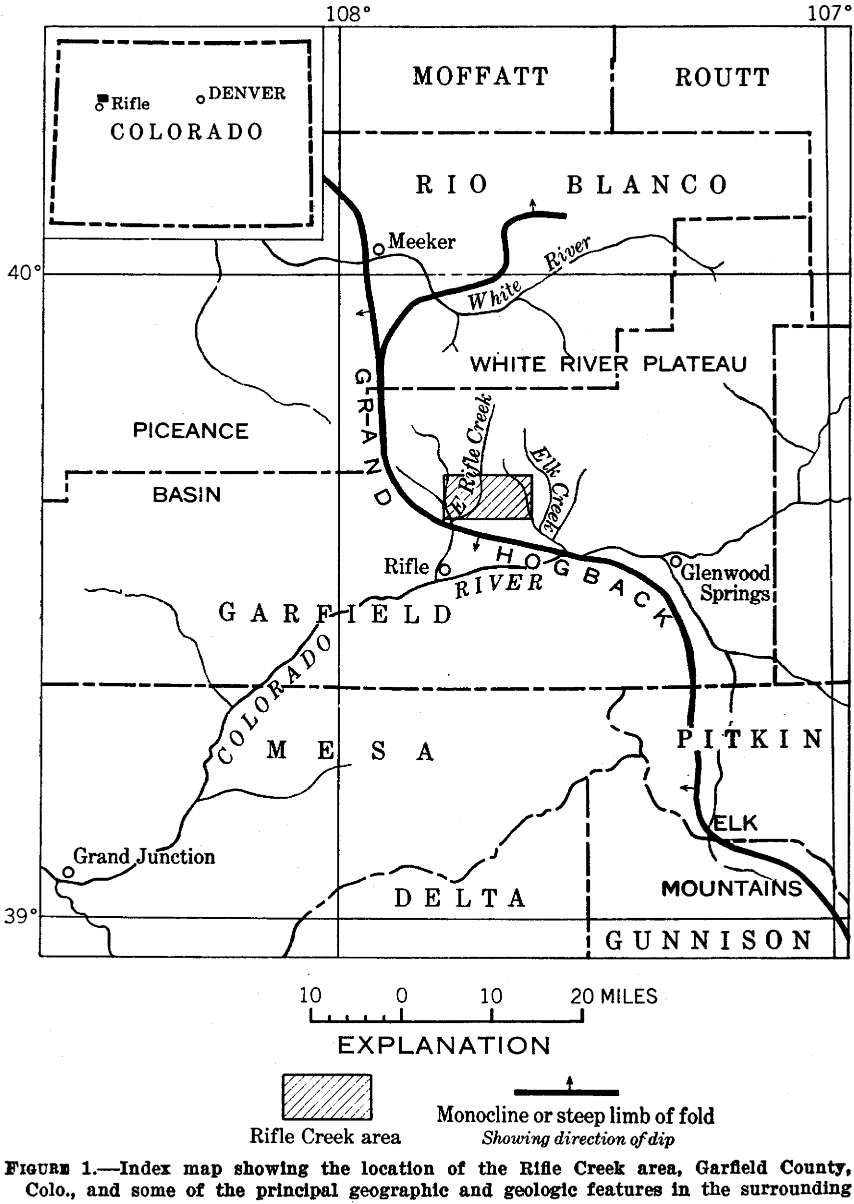


FIGURE 1.—Index map showing the location of the Rifle Creek area, Garfield County, Colo., and some of the principal geographic and geologic features in the surrounding region.

study and interpretation of structural features, ore habits, and geochemical relations—not only is this deposit well exposed at the outcrop and in these two mines, so the character of the host rock and the ore bodies can be readily observed, but also the ore habits are more consistent than in many of the other deposits in the region. In addition, this deposit is one of the larger ones in the Colorado Plateau region. This report is mainly focused on the description of this deposit.

The Rifle-Garfield deposit is partly in the Entrada sandstone of Jurassic age and partly in an underlying sandstone to which the name Navajo(?) is tentatively applied; the true Navajo is probably Jurassic and Jurassic(?) age. Both formations are composed entirely of clean fine-grained sandstone; they lack the abundant shaly and carbonaceous materials that occur in the sandstone host of most other ore-bearing formations in the Colorado Plateau region. This deposit, like those in the Entrada near Placerville, Rico, and Durango, Colo., has been worked mainly for vanadium—the uranium content of the ore is so low that it has had only byproduct value. Nevertheless, the Rifle-Garfield ore has the same general suite of minerals and accessory elements as many other sandstone deposits in which uranium and vanadium are of coproduct value, and like those other deposits the ore minerals also mainly occupy the sandstone pores and form tabular ore bodies.

The Morrison formation of Jurassic age also contains vanadium-uranium deposits in the Rifle Creek area. These deposits have a higher average content of uranium than the deposit in the Entrada and Navajo(?), and they are in sandstone that contains abundant shaly and carbonaceous material. All the known deposits in the Morrison, however, are small, and this formation is probably not a favorable host for large deposits in this area. There is no obvious physical continuity between the deposits in the Morrison and the one in the Entrada and Navajo(?).

LOCATION AND ACCESS

The Rifle and Garfield mines are on East Rifle Creek about 13 miles northeast of Rifle, Garfield County, Colo. The mines are in secs. 34 and 35, T. 4 S., R. 92 W., sixth principal meridian. Access to these mines is by State Route 13 for 3 miles north of Rifle and thence northeastward on State Route 325.

East Rifle Creek flows southward through the center of the mapped area, which extends to Middle Rifle Creek, about 4 miles west of East Rifle Creek, and to West Elk Creek, about 4 miles east of East Rifle Creek. Secondary roads follow these creeks and are connected by a road along the south border of the mapped area (pl. 1).

FIELDWORK

The mines and surrounding area were studied and mapped by the writer, assisted by W. L. Stokes and L. E. Smith, in the summer of 1944. The area was revisited in 1954, to bring the geologic map of the mine workings up to date; during 1954 the writer was assisted for intervals of several days each by D. C. Hedlund, E. B. Ekren, R. T. Chew 3d, H. S. Johnson, Jr., and D. D. Haynes.

The geologic map and its topographic base (pl. 1) were compiled by a combination of planetable and photogrammetric methods. A base line was measured near the southeast corner of the map. An elevation was carried to this base line by planetable traverse from a sea-level datum bench mark established by the U.S. Bureau of Reclamation on the Harvey Gap Reservoir about 1¼ miles south of the base line. From this base line a planetable triangulation net with vertical control was established over the area to be mapped. This net was tied by planetable traverses to two section corners of the township survey. All of these planetable control points were also located by inspection on airphotos.

A map base comprising the triangulation net and the township survey was compiled and on it the horizontal positions of photo centers and additional points were established by radial-line plot from airphotos; planimetry between these control points was sketched from the airphotos. Many points of vertical control were then established by occupying with the planetable several locations recognizable on the airphotos, reading vertical angles to triangulation stations, and reading vertical angles to all nearby locations recognizable on the airphotos. The correct horizontal positions of the planetable stations and the locations shot from them were then transferred to the base map by the radial-line method. The elevations of the points occupied were then calculated. Contours were sketched between these points by stereoptic inspection of the airphotos. Geology was also transferred from airphotos by radial-line plot and inspection.

ACKNOWLEDGMENTS

The fieldwork in 1944 in the Rifle Creek area was done as part of the wartime strategic minerals program of the U.S. Geological Survey. The fieldwork in 1954, and the preparation of this report are a part of the U.S. Geological Survey work that is being done on behalf of the Division of Raw Materials of the U.S. Atomic Energy Commission. The generous aid of all the claim owners and operators in the area facilitated the fieldwork. The staffs of the Union Carbide Nuclear Co. (formerly the United States Vanadium Co.), which operates the Rifle mine, and the Garfield Vanadium Corp., owner of the Garfield mine, were especially helpful.

GEOLOGY

STRATIGRAPHY

The Rifle Creek area lies on part of the Grand Hogback monocline, a fold that flanks the south and west sides of the White River Plateau uplift. Rocks ranging from Precambrian to Cenozoic in age and having a total thickness of about 15,000 feet are exposed across this fold. Only rocks of late Paleozoic and Mesozoic ages and landslide debris of Quaternary(?) age, however, are exposed in the area mapped and will be described in this report; their lithologic characteristics are summarized in the following generalized section.

Generalized section of late Paleozoic, Mesozoic, and Quaternary(?) strata in the Rifle Creek area, Garfield County, Colo.

System	Formation or unit	Thickness (feet)	Lithologic character
Quaternary(?)	Landslide debris	0–250±	Mostly material of the Morrison formation and Dakota sandstone, in jumbled masses.
Cretaceous	Mancos shale	5, 000±	Gray shale.
	Dakota sandstone	80	Brown and gray sandstone and brown carbonaceous shale.
Jurassic	Morrison formation	500	Gray and red mudstone and light-gray medium-grained sandstone; sandstones in the lower part contain small deposits of vanadium and uranium.
	Entrada sandstone	75–125	Sandstone, light-gray fine-grained, massive and crossbedded; contains part of the vanadium-uranium deposit in the Rifle and Garfield mines.
Jurassic and Jurassic(?)	Navajo(?) sandstone	30–75	Sandstone, light-brown, fine grained, massive and crossbedded; contains part of the vanadium-uranium deposit in the Rifle and Garfield mines.
Triassic, Permian, and Pennsylvanian	Red beds	4, 000±	Red shales, arkosic sandstones, and conglomerates.

PENNSYLVANIAN, PERMIAN, AND TRIASSIC SYSTEMS

RED BEDS

The oldest rocks in the Rifle Creek area are a sequence of red beds composed dominantly of shale and sandstone. They crop out along the north edge of the area mapped and to the north. Their total thickness is about 4,000 feet. These rocks were not mapped, nor were they studied for the purpose of correlating formational units or recognizing stratigraphic limits. Their lithologic characteristics are briefly described, however, and the correlations suggested by other geologists are given.

The name Maroon formation has been applied to the lower three-fourths of the red-beds sequence in this part of Colorado. Brill (1944, p. 628) shows the Maroon to be 2,700 feet thick in his section at Rifle Falls (East Rifle Creek) and assigns it to the Pennsylvanian system; Bass and Northrup (1950, p. 1547) give a thickness of 3,000 feet for this formation a few miles east of the Rifle Creek area, and assign it to the Pennsylvanian and Permian ages. In the Rifle Creek area, the lowest part of the Maroon consists of several hundred feet of gypsum and gray and brown shale and limestone. The upper two-thirds of the Maroon consist of shale and feldspathic and conglomeratic sandstone, all dominantly red though some of the sandstone beds are gray and have a conspicuous amount of petroleum residue.

Above the Maroon formation is a unit that Brill (1944, p. 628) called Weber quartzite of probable Pennsylvanian age; Thomas, McCann, and Raman (1945) called this unit Weber sandstone in their Elk Creek section and also assigned it to the Pennsylvanian. It is about 150 feet thick and consists of soft gray coarse-grained sandstone with lenses of quartz-pebble conglomerate. Petroleum residue abundantly contaminates these beds. Feldspar grains also occur but in smaller quantities than in some of the sandstones of the Maroon formation.

Because of the quartz pebbles in the conglomerate, some local prospectors have correlated this unit with the uranium-bearing Shinarump member of the Chinle formation (Triassic) of Utah and Arizona, and they have prospected for uranium deposits along the outcrop of this unit in the Rifle Creek area. It does resemble the Shinarump in appearance, but both Brill (1944) and Thomas, McCann, and Raman (1945) place the horizon of the Shinarump about 150 feet above this unit.

Brill (1944, p. 638) correlates the unit above his Weber quartzite with the Dinwoody or the Moenkopi formation of Triassic age, whereas Thomas, McCann, and Raman (1945) apply the name Phosphoria (Permian) to the unit above their Weber sandstone; perhaps these are also the beds considered possibly equivalent to the Moenkopi by Bass and Northrup (1950, p. 1547). This unit, which is poorly exposed, is about 150 feet thick. It consists mainly of soft argillaceous sandstone, gray to brownish in color; the sand grains are dominantly fine although some beds have coarse grains. Some of the finer grained beds are micaceous.

The next higher stratigraphic unit is a few hundred feet thick and extends to the base of the Navajo(?) sandstone. It has been called Chinle by Thomas, McCann, and Raman (1945) and by Bass and Northrup (1950), and its lithologic characteristics closely resemble those of the Chinle formation of Triassic age in southwestern Colorado and eastern Utah. It consists of shale, siltstone, and fine-grained sandstone. Most or all of these rock types, but especially the finer grained ones, are calcareous; intraformational conglomerates of limestone pebbles occur in places though not abundantly. These rocks weather blocky, and at the outcrop they appear indistinctly bedded, whereas in fresh exposures in the Rifle mine the rocks are rather well bedded in layers a few inches to a few feet thick. The entire unit is brick red except where altered to gray; this color change occurs in small irregularly shaped spots throughout the formation, along fractures, and in the upper few feet of the formation near the vanadium-uranium deposit in the Rifle and Garfield mines.

JURASSIC AND JURASSIC(?) SYSTEM

NAVAJO(?) SANDSTONE

Immediately above the red beds and below the overlying Entrada sandstone is a fine-grained light-brown cliff-forming sandstone that is host to much of the ore in the Rifle mine. N. Wood Bass and John R. Donnell suggest that this unit is equivalent to the Navajo sandstone, and they say this name is in common usage by oil geologists in northwestern Colorado (written communication, 1957). For these reasons the name Navajo is used in this report, but because its usage is based on the unpublished work of others, a question mark is attached to the name.

Other formation names have been applied to this unit previously. Baker, Dane, and Reeside (1936, fig. 5) combined this unit with the Entrada sandstone in their East Rifle Creek section. Thomas, McCann, and Raman (1945) tentatively correlated this unit with the Wingate sandstone in the section they measured on Elk Creek a few miles east of the Rifle Creek area. Craig and Holmes (1951) suggested it may be the southeastward extension of the Nugget sandstone of northeastern Utah and southwestern Wyoming. As the Nugget is considered to be a direct equivalent of the Navajo sandstone (Baker, Dane, and Reeside, 1936, p. 3), the name Navajo is just as applicable.

Regardless of the ultimate correlation or naming of this unit, for the purpose of this report it is important only to recognize that the unit is distinct from the underlying red beds and the overlying Entrada, and that both contacts of the unit do represent breaks in sedimentation.

This unit is of Jurassic and Jurassic(?) age if it is Navajo, of Early Jurassic age if it is Nugget, of Late Jurassic age if it is Entrada, or of Late Triassic age if it is Wingate.

The Navajo(?) in the Rifle Creek area ranges in thickness from about 30 to 75 feet. It consists of clean fine-grained light-brown sandstone. The sand grains are quartz associated with a small amount of weathered feldspar and a trace of heavy minerals; calcite and secondary silica cement the sandstone. No fossil plant material has been found, and the only argillaceous material that is megascopically visible occurs as clay films along bedding planes. The sandstone is well bedded and each bed is characterized by conspicuous torrential crossbedding, the original inclination of which was dominantly southward. Most beds range from 5 to 10 feet in thickness, but in one stope in the Rifle mine individual planes of crossbedding sweep through the entire 35 feet of exposed Navajo(?) (pl. 4, section *F-F′*). The sandstone is hard and brittle and conspicuously jointed. It is well exposed in a rough vertical cliff (pl. 5) throughout the area.

The color, crossbedding, and hardness of the Navajo(?) readily distinguish it from the overlying Entrada. These two formations, however, are mapped together (pl. 1), for the Navajo(?) commonly crops out as a vertical cliff under the steep slope of the Entrada, and thus in many places its outcrop band is too narrow to show separately on the map.

The contact of the Navajo(?) with the underlying red beds is sharp and even; the contact with the Entrada is equally sharp, but it is uneven due to erosion before deposition of the Entrada. This erosion is mainly responsible for local variations in thickness of the Navajo(?) in the Rifle Creek area, and also for a general thinning of the unit eastward through the area. The Navajo(?) is cut out altogether by pre-Entrada erosion a short distance east of the area (fig. 2), and it has not been reported any farther east or south.

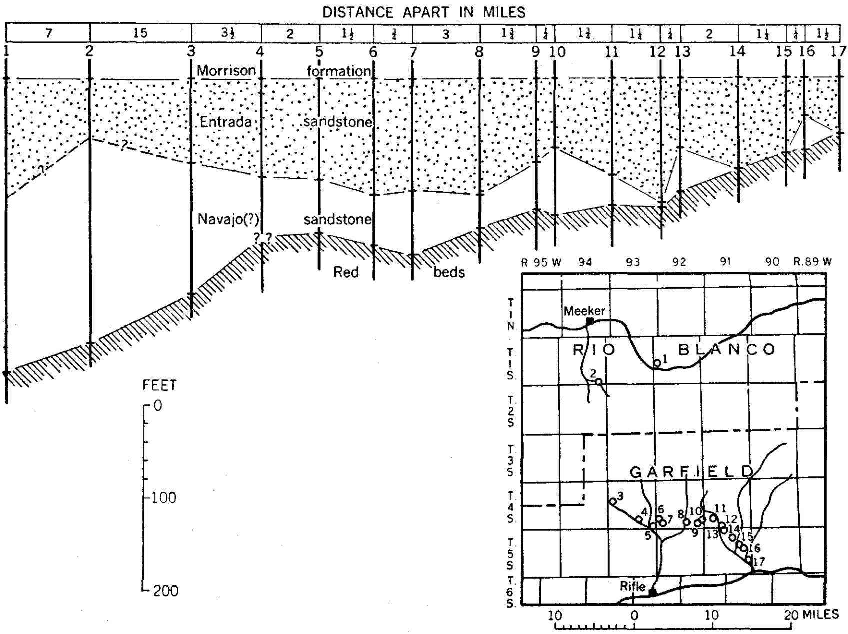


Figure 2.—Measured sections of the Navajo(?) and Entrada sandstones, Rio Blanco and Garfield Counties, Colo.

Figure 2 also shows the thickening of the Navajo(?) northward from the Rifle Creek area.

JURASSIC SYSTEM

ENTRADA SANDSTONE

The Entrada sandstone is like the Navajo(?) in many respects, which perhaps is significant from the standpoint that both formations are host to the vanadium-uranium deposit developed by the Rifle and Garfield mines. The Entrada, nevertheless, does have its own distinguishing characteristics. The Entrada is dominantly white to pale gray, and it is uniformly soft and weathers to rounded cliffs or steep slopes, in contrast to the light-brown blocky cliffs of the Navajo(?). Like the Navajo(?), the Entrada is composed mainly of fine sand grains that are predominantly quartz, but the lower two thirds of the formation also contains larger, well-rounded grains of quartz and dark-colored chert and jasperoid like those that are so characteristic of the Entrada elsewhere in western Colorado and eastern Utah. The finer grains average about 0.1 mm across, the coarser grains about 0.3 or 0.4 mm across (pl. 7*A*). The Entrada is a clean sandstone, as is the Navajo(?), and it contains no recognized fossil plant material and no argillaceous material other than clay films along bedding planes. The Entrada sandstone is also conspicuously crossbedded, at least in the lower part, but the crossbedding is curved and tangential; the upper part is evenly bedded although indistinctly so. Petroleum residue occurs in places in the upper part of the Entrada.

In the Rifle Creek area the Entrada ranges from about 75 to 125 feet in thickness (fig. 2); the observed variations in thickness are due partly to the uneven surface of Navajo(?) sandstone on which the Entrada was deposited. This surface bevels the bedding of the Navajo(?), and in many places the contact is sharp enough to be pinpointed even though it is commonly less conspicuous than many bedding and crossbedding planes in either formation. The contact of the Entrada with the overlying Morrison seems to be a plane surface showing no angular discordance.

The Entrada generally thins in both a southeasterly and a northwesterly direction from the Rifle Creek area (fig. 2).

MORRISON FORMATION

The Morrison formation is about 500 feet thick and consists mainly of mudstone and sandstone with a small amount of limestone and conglomerate. It is divisible into two poorly defined parts.

The lower part of the Morrison consists of lenses of pale-gray and greenish-gray sandstone interbedded with gray and red mudstone. The sandstone beds contain scattered grains of a green mineral that resembles glauconite, and they also contain fairly abundant petroleum residue; some contain carbonized and silicified plant fossils and a few are conglomeratic. A few thin beds of gray dense limestone are present in the mudstone. The lower part of the Morrison is about 150 feet thick, and except for the lower 20 to 25 feet, which consists of alternating thin beds of fine-grained gray sandstone and dark-gray shale, it vaguely resembles the Salt Wash member of the Morrison in southwestern Colorado (Craig and others, 1955). Several small deposits of vanadium and uranium have been found in sandstone near the top and middle of this part of the Morrison in the Rifle Creek area; these deposits are in shaly sandstone that contains plant fossils.

The upper part is composed dominantly of gray, green, and maroon mudstone, but it also contains thin beds of limestone and sandstone and lenses of chert-pebble conglomerate. This part of the Morrison is about 350 feet thick, and it resembles the Brushy Basin member in southwestern Colorado and adjoining States (Craig and others, 1955).

The following stratigraphic section was measured near the Rifle mine and it shows in detail the lithologic characteristics of the lower part of the Morrison formation.

Section of the lower part of the Morrison formation along the Harvey Gap Reservoir ditch just south of the Rifle mine, sec. 34, T. 4 S., R. 92 W.

	Feet
Upper part of Morrison formation:	
Mudstone, dominantly gray, but some maroon; contains abundant thin beds of gray limestone, and some beds of gray sandstone as much as 5 ft thick	350±
Lower part of Morrison formation:	
Sandstone, pale-gray, fine- to medium-grained, massive hard	8
Mudstone and siltstone, gray and red; contains a few layers of limy nodules	35
Limestone, gray, dense and hard, poorly bedded	6
Mudstone and siltstone, light-red and gray; with thin layers of hard limy sandstone	45
Sandstone, gray due to petroleum residue or greenish-gray due to small fragments of greenish clay and grains of glauconite(?), thinly and irregularly bedded, soft	15
Mudstone and fine-grained sandstone interbedded, dominantly red but some gray; bedding is thin and contorted	9
Sandstone, pale- to light-gray, medium- to fine-grained, massive or crossbedded; contains clay pebbles and scattered grains of glauconite(?)	23
Sandstone and shale, interbedded and thin-bedded; sandstone light-gray to greenish-gray, fine-grained; shale gray to red, finely sandy	5
Sandstone, light-gray to buff, fine-grained, crossbedded, hard	3
Sandstone and shale, thinly and irregularly bedded, all light-gray	3
Sandstone, light-gray to buff, fine-grained, crossbedded, hard	5
Sandstone and shale, thinly and irregularly interbedded; sandstone light-gray to greenish-gray, fine-grained; shale reddish to dominantly gray, sandy	6
Shaly sandstone, olive-drab, dominantly fine grained but some coarse sand grains	1
Total thickness of lower part of Morrison formation	164
Entrada sandstone:	
Sandstone, pale-gray with slightly darker streaks due to petroleum residue, fine-grained, massive or indistinctly evenbedded.	

CRETACEOUS SYSTEM

DAKOTA SANDSTONE

The Dakota sandstone is about 80 feet thick in the Rifle Creek area. The upper and lower parts of the formation are composed of light-brown and light-gray, fine- to coarse-grained, partly conglomeratic sandstone that weathers dark and forms cliffs and dip slopes. The middle part of the formation consists of brown to dark-gray carbonaceous shale.

MANCOS SHALE

The Mancos shale consists of a few thousand feet of gray, thin-bedded shale. It crops out in a broad valley along the south side of the area. Only the basal part of this formation is in the mapped area, and none of the formation was studied in detail.

QUATERNARY(?) SYSTEM

Landslides, probably of Pleistocene or Recent age, have spread a thin cover of debris over parts of the area, especially between Middle Rifle and East Rifle Creeks (pl. 1). The debris forms a rough topography of mud and jumbled blocks of sandstone mostly from the Morrison and Dakota formations. It may be as much as 250 feet thick in places. The map pattern for this landslide debris is superimposed on the patterns showing bedrock geology (pl. 1).

STRUCTURE

The Grand Hogback monoclinal structure extends about 20 miles northwest of the Rifle Creek area and about 40 miles to the southeast; belts of related deformation extend even beyond these limits (fig. 1). The trend of the folds is curved—in the Rifle Creek area the trend is slightly north of west, but just west of the area it curves northward, whereas east of the area it swings to the south. The fold has a structural relief of about 15,000 feet, some of which is due to displacement by faulting. Rather than being a simple fold, the monocline comprises several units or structural terraces of low dip separated from each other by steeper dips or faulting, as shown by a generalized section (fig. 3) across the fold. Deformation form-

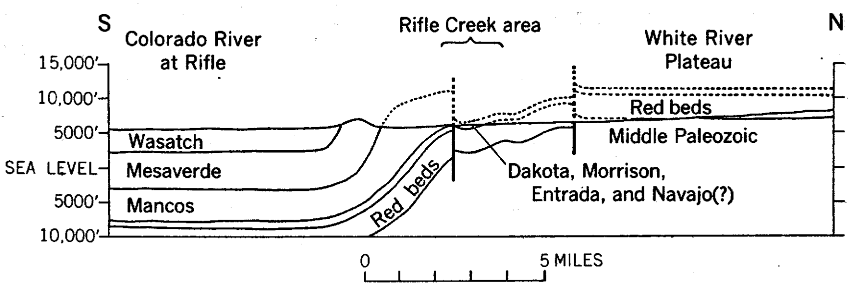


FIGURE 3.—Generalized structural relations across the Grand Hogback monocline (in part after Kelley, 1955a, fig. 2).

ing the monocline evidently began about the beginning of Tertiary time, but most of the deformation must have been nearer the middle of the Tertiary. The structural irregularities of the fold and the long period of deformation complicate interpreting the sequence of tectonic events and the relations of ore deposits to tectonic features.

The rocks in the central part of the Rifle Creek area mostly dip southward at angles ranging from 15° to 30°. In other parts of the area, however, this general attitude is modified along faults and minor flexures, so that locally the dips may range from horizontal to vertical and in places the beds even dip northward. These structural relations are shown in plate 1. The ore deposit in the Navajo(?) and Entrada formations is also plotted by plan projection on the structure map (pl. 1) to show its structural environment. More detailed structural relations and smaller scale tectonic features observed in the Rifle and Garfield mines are shown on plate 2.

FLEXURES

Structural terraces of flattish dip bound the northern and southern limits of mapping in the Rifle Creek area (pl. 1). An anticlinal flexure borders the north side of the area between West Elk and East Rifle Creeks; another anticline, nearly along the same trend but actually echelon in position, crosses Middle Rifle Creek. Shallow, complementary synclines lie just north of these anticlines. Southward from the north structural terrace the southerly inclination of the beds increases to about 30° and then flattens again toward a complex belt of synclinal flexures and faults along the south edge of the area. The faults that are south of the synclinal axes in this belt in effect displace or camouflage anticlinal axes, for the beds dip northward on the north sides of these faults and dip southward on the south sides (pl. 1).

Structural terraces on the Grand Hogback monocline (fig. 3) are not unique to the Rifle Creek area. MacQuown (1945, pl. 3) shows one, comprising a narrow anticline and its complementary syncline, along the Grand Hogback near Glenwood Springs, about 20 miles east of the Rifle Creek area. Kelley (1955a, fig. 2) also shows an anticlinal-synclinal terrace along the Grand Hogback from Glenwood Springs to a point about 20 miles northwest of the Rifle Creek area. More detailed mapping along the monocline will be required to show if either the north or south terraces of the Rifle Creek area correlate with the terrace shown by MacQuown and that shown by Kelley.

FRACTURES

The rocks in the Rifle Creek area are intensively and complexly fractured. The fractures (both joints and faults) can be grouped into 3 sets; 2 are high-angle fractures, the other dips at low angles. One set of high-angle fractures trends generally eastward, approximately along the strike of the beds; it is the stronger set and evidently the older one. The other set trends northwestward. The low-angle fractures are bedding-plane slips of small displacement.

JOINTS

Joints are abundant in the hard sandstones, such as the Navajo(?) and Dakota, but less numerous in shale units and soft sandstones such as the Entrada (pl. 5). Even where abundant, individual joints are not particularly strong—many do not extend far, either vertically or horizontally, and nowhere in the area do joints have a conspicuous topographic expression.

Joints of the so-called eastward-trending set range in trend from northeast to slightly south of east; generally their trends correspond rather closely to the local strike of the rocks. Most of them dip from 60° to 80° N., and thus they are nearly perpendicular to bedding, for the beds mainly dip 15° to 30° S. Joints of the northwestward-trending set are fairly consistent in their northwesterly trend, but their dip ranges from northeast to southwest.

FAULTS

The largest fault in the area trends slightly north of west, nearly parallel to the regional strike. Its maximum displacement is in the south part of sec. 34, T. 4 S., R. 92 W., and is about 500 feet. It was traced for 6 miles in the area (pl. 1), and it probably continues farther to the southeast. This fault and those associated with it are components of the structural terrace along the south side of the area. Exposures are not good enough to determine the exact attitude of these fault planes, but most planes seem to be vertical and all are projected vertically on the structure map and sections (pl. 1). In the Rifle and Garfield mines, on the other hand, most of the eastward-trending faults dip northward. They are downthrown to the south, however, and hence in their present attitude are high-angle reverse faults, but if the beds were restored to a flat dip, many of these fault planes would be rotated enough to have southerly dips and the faults would then have the attitude of high-angle normal faults. Thus the direction of movement relative to the present atttiude of these faults does not necessarily indicate thrusting by compressional forces.

Northwestward-trending faults with displacements large enough to be shown on the areal geologic map (pl. 1) are not common in the area; none have displacements exceeding 150 feet, and none were traced more than a mile. The faults of this set are uniform in strike direction, but some tend to be complex zones of movement and jointing rather than planes of simple displacement; for example, the fault shown in NE¼ sec. 35, T. 4 S., R. 92 W. (pl. 1) is in reality the swarm of faults shown near coordinate 16,000 E. in the Rifle mine (pl. 2). Even some of the fractures mapped as individual faults on the large scale of the mine map are actually complex zones of displacement like that shown in plate 6*A*. Most of the faults of the northwestward-trending set are normal, though a few have the attitude of high-angle reverse faults. Some of the northwestward-trending faults tend to turn or jog with offset in the right-lateral direction on eastward-trending fractures; good examples of this jogging are seen near coordinate 14,000 E., plate 2. This relationship suggests that the eastward-trending fractures are older than the displacement on the northwest ones.

The low-angle fractures are merely bedding-plane slips in response to folding. They probably occur along bedding planes in all formations, but they are easily seen only in the more massive and crossbedded sandstone, like the Navajo(?) and Entrada. In these formations the planes show as tight fractures, commonly with a paper-thin white layer of crushed quartz, and where the movement is commonly evident from the displacement of crossbedding planes and high-angle fractures. Maximum observed displacement along these low-angle faults is about 1 foot, but most have a displacement of less than an inch. All strike approximately parallel to the regional strike. The displacement of all of them in the Rifle and Garfield mines and immediate vicinity is in the reverse or thrust direction, as would be expected along the lower, flattening part of the structural slope between an anticline and syncline (fig. 3 and pl. 1, section *B-B'*). These low-angle thrusts are clearly younger than and displace the ore (pl. 6*B*), as well as the vertical fractures.

INTRODUCED MINERALS AND ALTERATION ALONG FRACTURES

Although some of the high-angle joints and faults are tight, like the fault shown in plate 6*A*, many stand open and are partly filled with exotic material. Fractures in shale beds or soft sandstone like the Entrada are less apt to stand open or contain fracture-filling material than hard sandstones like the Navajo(?). Fractures of the northwestward-trending set are more apt to be open than those that are eastward-trending, but only the eastward-trending ones contain much introduced material. Many openings or fracture fillings are only a small fraction of an inch across, but in places they are as much as several inches across. The low-angle faults are all tight and contain no introduced material.

Calcite and marcasite, both coarse grained, are the common minerals in these fractures. Although widespread, they have a spotty distribution in small patches. Either may occur alone or in contact with one another. A small amount of sphalerite is intergrown with or replaces marcasite in places. A few fractures in the Navajo(?) and Chinle formations in the Rifle mine are filled with unconsolidated sand resembling the Entrada; they are as much as several inches wide. No vanadium or uranium minerals have been observed along fractures except adjacent to ore, where secondary minerals such as tyuyamunite or carnotite may occur; all faults displace and brecciate the ore. The introduced minerals and sand cement or engulf any fragments of wallrock breccia, either barren or ore bearing, that may be in the fracture.

Fractures in fine-grained red sediments like the Chinle are commonly bordered by a narrow and irregular zone of altered rock in which the color has been changed from red to gray; patches of calcite and iron minerals may also occur along these fractures. No alteration is observed along fractures in light-colored sandstone.

HISTORY OF DEFORMATION

The Mancos shale and Mesaverde formation, both of Late Cretaceous age, dip steeply along the Grand Hogback (fig. 3), and they are involved in the folding; regional relations suggest that these formations were deposited before any deformation of this structure. The Wasatch and Green River formations of Eocene age are also steeply upturned along the flank of the monocline (Duncan and Denson, 1949), but evidently some deformation was in progress during their deposition. Merriam (1954) shows that the two formations have a combined thickness of only a few thousand feet along the flank of the fold, whereas several miles westward toward the center of the Piceance basin (fig. 1) their combined thickness is nearly 9,000 feet; he also reports that the Wasatch is coarser grained along the hogback than to the west. Bradley (1931) reports that the Green River formation is thinner and coarser grained along the extension of the Grand Hogback structure northwest of Meeker than in the basin to the west.

These relations suggest a broad tilting of the region during the deposition of the Wasatch and Green River formations. The greatest sinking occurred in the Piceance basin and a moderate amount along the Grand Hogback and near the Rifle Creek area. General uplift and erosion of country occurred somewhere to the east, perhaps near the Park Range about 60 miles east of Rifle Creek. Evidence is lacking to show definitely whether or not the Grand Hogback monocline began at this time as a wrinkle on this tilted block. The major elevation of the White River uplift and the coincident folding of the monocline, however, must have occurred after deposition of the Green River formation, and are probably late Eocene (Kelley, 1955a, p. 85), therefore in the later part of the Laramide deformation.

Monoclines like the Grand Hogback are common in the Colorado Plateau region. Presumably they formed by the draping of the sedimentary cover over deep-seated flexures or faults; the latitude of structural analysis permits the concept of formation by either tensional or compressional forces (Kelley, 1955b, p. 798, 802). The oldest and perhaps the simplest explanation used is that of normal faulting in basement rocks. In contrast, Baker (1935, p. 1501–1504) favors the idea of compressive faults of the thrust or steep reverse type in the basement rocks, but he points out that the folded sedimentary cover would be under tension and thus normal faults parallel to the strike might be expected in these beds.

A modification of these concepts is offered by Vanderwilt (1937, p. 89 and fig. 7) to explain the origin of the Elk Mountain thrust zone, which is the continuation of the Grand Hogback structure about 50 miles southeast of the Rifle Creek area. He suggests that a simple monoclinal fold first was formed by vertical uplift, and some normal faulting occurred along it in places. As uplift continued the normal faults were rotated to the attitude of reverse faults, and the vertical force generated a large horizontal component that caused thrust motion on these faults. N. Wood Bass (oral communication, 1956) also has mapped thrust faulting along the south side of the White River uplift near Glenwood Springs. Kelley (1955a, fig. 10) infers southwestward compressive forces in northwestern Colorado during Laramide time.

Not enough information is available to select an explanation for the origin of the Grand Hogback and the flexures or structural steps along it in the Rifle Creek area. The structural features shown in figure 3 could have been formed by draping and displacing the cover of sedimentary formations over large deep-seated faults of either the normal or thrust type. It is even possible to explain the observed strike faults in the area as the upward-dying extensions of deep-seated ones of either type. Perhaps it is also possible, though it seems unlikely to the writer, that the structural steps and the associated faults resulted from some kind of tensional sagging after the main uplift. At any rate, late but relatively minor movement in a direction opposite to the major displacement on exposed and buried faults may be necessary to form the synclinal-anticlinal couples along the north and south edges of the area. Such movement is probable in view of the large anomalous drag along the fault bordering the White River Plateau (fig. 3).

The relative age of the smaller scale structural features to one another and to the Rifle-Garfield deposit can be determined in part, but it is not easy to relate these smaller structures to the larger ones. Of the two sets of vertical fractures, individual fractures of the eastward-trending or strike set generally extend farther laterally and vertically than do those of the northwest set. When the eastward-trending set formed, or sometime later, joints in the Navajo(?) sandstone in places opened as much as several inches wide and long enough to be filled with unconsolidated Entrada-like sand or with coarse-grained calcite and some marcasite and sphalerite. The northwestward-trending set of fractures seems to be younger, for some of the faults turn or jog on the eastward-trending joints; furthermore, even though many fractures of the northwest set stand open, they contain hardly any vein filling. The low-angle fractures, or bedding plane slips, which presumably resulted from adjustments between beds during folding, displace the high-angle fractures. All faults, both high and low angle, displace the ore.

When intensive folding of the Grand Hogback began after the Green River formation was deposited, the Entrada and Navajo(?) sandstones in the Rifle Creek area must have been buried from 10,000 to 15,000 feet. Strike joints may have formed as folding began, but whether or not joints at this depth would open to allow fracture-filling is an unsolved problem. Likely the northwest set of fractures, as well as the bedding-plane slips, formed as folding continued, though possibly both could have formed much later under conditions of tension, sag, and squeezing.

ORE DEPOSITS

The principal vanadium-uranium deposit in the Rifle Creek area is in the Navajo(?) and Entrada sandstones and is developed by the Rifle and Garfield mines; it is one of the largest vanadium-uranium deposits in the Colorado Plateau region. It is similar in many characteristics to other sandstone deposits of vanadium and uranium ore in the region, but it is especially like these deposits in the Entrada sandstone near Placerville, Rico, and Durango, Colo.

The Rifle-Garfield deposit is at least 10,000 feet long, if it is extended across the canyon of East Rifle Creek, as seems likely, and averages several hundred feet in width (pl. 1). The ore consists of fine-grained minerals that impregnate the sandstone host; it contains about 1 to 3 percent V_2O_5 and several hundredths percent U_3O_8. The ore minerals color the rock gray, and the color darkens as the vanadium content increases. The ore occurs in three tabular layers that partly overlap. Although these layers lie nearly parallel to the formation contacts, they are not concordant with the bedding in detail. Each layer of ore is accompanied by a thin layer of finely disseminated grains of galena and clausthalite, and by another layer containing a finely micaceous chromium-bearing mineral. All faults displace and brecciate the ore and accompanying layers.

The deposits in the Morrison formation in the Rifle Creek area as much like those in the Morrison elsewhere on the Colorado Plateau, though only small deposits have been found in the Rifle Creek area. The ore minerals are fine grained; they impregnate shaly sandstone and replace fossil plant material and form thin tabular ore bodies. The ore as mined has averaged 1 to 2 percent V_2O_5 and and a few tenths percent U_3O_8.

Because the known deposits in the Morrison in the Rifle Creek area are small, they have not been intensively developed, and they are not suited to geologic study of their origin and the conditions that influenced their localization. For this reason, only a brief description of them is presented. The Rifle-Garfield deposit in the Navajo(?) and Entrada formations, on the other hand, is well exposed, and it is described in detail.

HISTORY AND PRODUCTION

Vanadium ore in the Navajo(?) sandstone was discovered at the outcrop along the east side of East Rifle Creek about 1909 (Burwell, 1932). In 1922, H. K. Thurber and associates acquired ownership of the ground and organized the Vanadium Corp. of Colorado (Hess, 1925, p. 576). In 1924 the claims were leased by A. H. Bunker and associates, who organized the United States Vanadium Co. and built a mill at Rifle (Hess, 1927, p. 470). This mine and mill were bought in 1926 by the Union Carbide and Carbon Co., who established the United States Vanadium Corp. as a subsidiary (Hess, 1929, p. 270). Operations continued until 1932.

The Rifle mine was idle from 1933 through 1939, but yielded a small amount of ore in 1940 and 1941. Large-scale ore production was resumed in 1942, when the mill at Rifle was rebuilt, and these operations, part of which were on claims leased from Messrs. Corlett and Coulter, were continued until 1948. No ore was produced in 1949 and 1950, but development work and some mining was done in 1951, 1952, and 1953; the mine was shut down again in 1953.

The claims of the Garfield Vanadium Corp. on the west side of East Rifle Creek were located in 1929 (R. A. Pitts, Garfield Vanadium Corp., oral communication). In the midthirties these claims were leased to the Rifle Vanadium Co., who built a small mill at the mine; a small tonnage of ore was treated, but there is no published record of production. Mining in the Garfield mine was resumed in 1942 and continued to 1945, during which time a moderate tonnage was obtained. Only small-scale operations and development work have been done since 1946.

Most of the productive claims filed to cover deposits in the Morrison formation in the Rifle Creek area were located early in World War II. Some of these claims yielded ore during the war years, and some have produced ore since 1949, but none have been operated except on a small scale and in a desultory manner.

Total production of vanadium-uranium ore from the Rifle Creek area, from 1925 through 1954, is about 750,000 tons, containing about 25 million pounds of V_2O_5.

DEPOSIT IN THE NAVAJO(?) AND ENTRADA FORMATIONS

MINERALOGY

By THEODORE BOTINELLY

The minerals of the Rifle-Garfield deposit can be arranged into three groups, which have simple relations to one another. The first group comprises the minerals that form the host sandstone, the second includes those minerals that contain the ore metals and accessory elements enriched in the deposit, and the third consists of the minerals that occupy fractures in barren and mineralized rock. Secondary ore minerals are few and too rare to be of economic importance.

The following description of the minerals in the Rifle-Garfield deposit is brief; readers interested in more detail on the habits and geochemical relations of these minerals should refer to a report by Botinelly and Fischer (1959).

MINERALS OF THE HOST SANDSTONE

The Navajo(?) and Entrada sandstones are composed dominantly of quartz grains with a small amount of weathered feldspar, chert, and jasperoid, and a trace of heavy mineral grains; detrital particles of clay minerals form films on bedding planes and are sparsely disseminated through the beds. Carbonate and secondary silica are the principal cementing minerals in these formations; both are sparse in ore and fairly abundant in the barren sandstone, and perhaps both were largely or wholly deposited after the ore minerals. These detrital and cementing minerals are the only ones that can be classified as gangue minerals in this deposit.

ORE AND ACCESSORY MINERALS

The principal ore minerals are vanadium-bearing silicates of a micaceous habit; they color the rock gray. They have been identified by X-ray analyses as the vanadium mica roscoelite and as unnamed varieties of a mixed layer mica-montmorillonite and a chlorite (John Hathaway, written communication, 1955). These minerals are extremely fine grained, and as it has not yet been possible to distinguish among them by megascopic or microscopic methods, the distribution and relative amounts of each are not known. These minerals mainly occupy the spaces between sand grains (pl. 8), suggesting growth in open pores, but partial replacement of the sand grains is also likely in places (pl. 9*A*).

In roscoelite [$(K,Na)Al_2(Al,V)Si_3O_{10}(OH,F)_2$], vanadium substitutes for aluminum in the tetrahedral layer (Heinrich and Levinson, 1955); the mineral may contain as much as 17 percent V_2O_3 (Wells and Brannock, 1946). Not much is known about vanadium-bearing varieties of mixed layer mica-montmorillonite or chlorite, but by analogy to roscoelite they presumably contain V_2O_3 in substitution for Al_2O_3.

Montroseite [VO(OH)] is also a vanadium ore mineral, though quantitatively of little importance in this deposit. It is black and opaque, with a high luster, and forms minute bladed crystals or radial aggregates that occupy the spaces between sand grains and partly replace the sand grains. Montroseite is widely distributed below the zone of oxidation, but only in ore of average grade or higher; it is mostly disseminated through the ore in small amounts (pl. 9*B*), but it is the principal ore mineral in small masses of the highest grade ore. If montroseite differs in age from the vanadium silicates, the evidence of this difference has not been recognized.

Vanadium in montroseite and the vanadium-bearing silicates has a valence of +3, which is the lowest valence state of vanadium found in nature. Evans (1959) suggests that minerals containing V^{+3} compounds probably were deposited under reducing conditions, but the present environment of the deposit is an oxidizing one, in which montroseite is unstable. This mineral has been destroyed in the ore near the outcrop; the vanadium has either been removed by solution or perhaps combined with uranium in tyuyamunite or carnotite, although no depletion or enrichment of vanadium is recognizable near the outcrop, for the average amount of montroseite in the ore is so small. In the deeper parts of the Rifle mine the present oxidation of montroseite is evident from the efflorescent coating of pascoite (a hydrous calcium vanadate) and similar vanadium salts on masses of ore rich in montroseite. The vanadium silicates, on the other hand, are stable in the present oxidizing environment, so the bulk of the ore shows no change in character from the surface to below the zone of oxidation.

Tyuyamunite [$Ca(UO_2)_2V_2O_8 \cdot nH_2O$] or carnotite [$K_2(UO_2)_2V_2O_8 \cdot nH_2O$] and bayleyite [$Mg_2(UO_2)(CO_3)_3 \cdot 18H_2O$] are the only uranium minerals recognized; all are secondary minerals. Tyuyamunite or carnotite occur as small crystals on fracture walls and are disseminated in open pores of the sandstone; they are sparse throughout the deposit although slightly more abundant at and near the outcrop than in the deeper parts of the mines. Bayleyite forms a sparse efflorescent coating on mine walls in a few places.

No low-valence uranium minerals have been found, but it is likely that uraninite occurs though so finely disseminated in the ore that it is not recognized.

Lead, selenium, and chromium are also enriched in this deposit and form accessory minerals that are concentrated in thin layers bordering one side of each of the three layers of vanadium-uranium ore. Below the zone of complete oxidation, lead and selenium are combined in minute grains that have been identified by R. G. Coleman (written communication, 1955) as a solid-solution mixture of galena (PbS) and clausthalite (PbSe). X-ray analyses, by J. R. Houston, of concentrates of this galena-clausthalite mixture show that the clausthalite content ranges from 25 to 74 percent, and chemical analyses by Maryse Delevaux of these concentrates show that the selenium content ranges from 7.09 to 18.0 percent. The galena-clausthalite grains occupy the sandstone pores; they do not exceed 0.2 mm across. Most of them are concentrated in layers only a small fraction of an inch thick (pl. 7*A*), though they are also sparsely disseminated in the chromium-bearing layer and in the vanadium-uranium ore. On oxidation, the galena-clausthalite grains alter to cerussite ($PbCO_3$), some of which has a reddish internal reflection that might be caused by native selenium. A reddish bloom of native selenium is conspicuous where the galena-clausthalite layer is exposed in mine walls.

Several other metallic minerals are present in small amounts in the galena-clausthalite layer. Chalcopyrite ($CuFeS_2$) occurs as grains by itself, or it is intergrown with sphalerite (ZnS) or with galena-clausthalite and an unknown mineral that resembles eskebornite (FeSe·CuSe). A few grains of pyrite and marcasite (both FeS_2) are also present. These same minerals are also disseminated in the ore and chromium-bearing layers but only in very sparse amounts. Pyrite and marcasite are more abundant in the ore than chalcopyrite, sphalerite, and galena-clausthalite. Most mineral grains are extremely fine and all of them occupy the sandstone pores; some grains of pyrite and marcasite have grown slightly larger than the available pore space, partly replacing the adjacent sand grains and tending to form euhedral outlines. A few grains of pyrite and marcasite are cracked and veined by the other metallic minerals, showing some age differences among these minerals, but the writer has no criteria to determine the relative ages of the metallic accessory minerals and the nonmetallic ore minerals.

The chromium-bearing layer is light green to grayish green, and it contains a green micaceous fine-grained material that fills the sandstone pores. This micaceous material does not alter in the zone of oxidation. It has not been completely identified, but X-ray analyses of the clay-size material from this layer show it to be dominantly a mixed layer mica-montmorillonite with a small amount of chlorite. This chromium-bearing sandstone closely resembles the chromium-bearing layer associated with the vanadium-uranium deposits at Placerville, Colo.; Hess (1913, p. 148) suggested that the chromium-bearing mineral at Placerville is mariposite.

MINERALS IN FRACTURES

Many open fractures in the mineralized and barren sandstone are partly filled with minerals that in composition or habit are exotic to the ore. Coarse-grained calcite, with crystals as much as an inch or more across, is the most common fracture-filling material, but it is not abundant and is localized in small patches along fractures. Marcasite, also moderately coarse grained, is likewise localized in small patches, either with or without calcite. In most places where calcite and marcasite are together, the marcasite coats the fracture walls and fragments of sandstone breccia and in turn is coated by calcite, but in other places marcasite is on calcite crystals. A small amount of sphalerite is intergrown with or replaces some of the marcasite.

One fracture in the southwestern part of the Rifle mine has a small pocket of material containing an assemblage of minerals that is unique in the deposit. The pocket is exposed for a length of only 6 feet where the fracture is tangent to a pillar, and the observable vertical extent of the pocket is no more than 4 feet. The minerals are mainly galena, sphalerite, and marcasite; a small amount of argentite (Ag_2S) and native silver are also present, as are traces of pyrite and chalcopyrite and an unknown mineral determined by R. G. Coleman (oral communication, 1956) to have the optical properties and an X-ray pattern resembling rammelsbergite ($NiAs_2$). These metallic minerals and a small amount of associated calcite fill the fracture and cement a breccia of both barren and vanadium-bearing sandstone derived from the wallrock. The fracture-filling minerals are coarse grained—some of the galena crystals are an inch across. This galena contains only 0.009 percent selenium, in contrast to the galena-clausthalite grains associated with the vanadium-uranium ore and which contain from 7 to 18 percent selenium (Botinelly and Fischer, 1959). The fracture containing this pocket of minerals extends across the mine stope, but only small patches of marcasite are visible along it, as is common with many other fractures in the mine.

Some fractures in the eastern part of the Rifle mine are filled with a soft light-colored sand that is fine grained but contains abundant coarse-grained, well-rounded quartz, chert, and jasperoid grains similar to those characteristic of the overlying Entrada. This sand fills in around fragments of wallrock breccia and also masses of calcite, marcasite, and sphalerite where these minerals coat the walls and breccia fragments.

Small blebs of asphaltite are scattered along fracture walls in a few places. One sample of this material has the properties shown in table 1, on the basis of which the analyst (Norman Davidson) judged the material to be similar to the albertite member of the asphaltic pyrobitumens.

Spectrographic analysis of the ash of this material showed 1 to 10 percent uranium and 0.1 to 1.0 percent vanadium (K. J. Murata, analyst, 1946).

TABLE 1.—*Properties of asphaltic material from a fracture in the Garfield mine*

[Norman Davidson, analyst, 1946]

	Properties
Color in mass	Black
Fracture	Hackly
Lustre	Bright
Streak	Brown
Specific gravity (27° C)	1.10
Hardness (Moh's scale)	2
Fusing point	Infusible at 220° C (the highest temperature measured).
Soluble in CS_2 percent	<1
Nonmineral matter insoluble in CS_2 do	98
Mineral matter do	2
Fixed carbon do	35

GEOLOGIC HABITS OF ORE

RELATIONS OF THE ORE MINERALS TO THE HOST ROCK

Although the Navajo(?) and Entrada formations are stratigraphically distinct, they are similar in lithologic characteristics, and each is nearly uniform throughout its thickness. Both are clean and composed dominantly of subangular to rounded fine quartz grains that average about 0.1 mm across and which are moderately well sorted. Carbonate and secondary silica cement both formations; carbonate is more abundant in the Entrada and silica in the Navajo(?). Each formation has low porosity and permeability, partly due to the addition of cement, and also to the partial destruction of the sand grains by solution, which in places dissolved the grains enough that they fit together in a tight mosaic pattern. The solution of the sand grains, and the addition of silica and carbonate cement, are generally more common in the barren sandstone than in that which is ore bearing.

The ore minerals are so fine grained that their habits and manner of growth have not been determined with complete confidence. In low- and medium-grade ore, relations are reasonably clear—the minerals mainly occupy the spaces between sand grains, suggesting growth in open pores, although some replacement of the sand grains might have occurred in places. Relations in the richer ore, where the sand grains have been partly destroyed either by solution or replacement, are especially difficult to decipher. These habits are not unique to this deposit, however, but rather are nearly identical with the relations of the vanadium minerals to the sand grains in other vanadium-uranium deposits on the Colorado Plateau, relations which are well illustrated by Waters and Granger (1953).

The micaceous vanadium minerals (roscoelite and the vanadium-bearing mica-montmorillonite and chlorite) are the principal ore minerals in the Rifle-Garfield deposit and mainly occupy pore spaces. Where mineralization was weak (low grade), they form a coating of minute flakes standing perpendicular to the original surfaces of the sand grains, growing into the pore spaces but only partly filling the pores (pl. 8, right side, see also fig. 4). In places calcite occupies the central part of the pore spaces, and in places where vanadium mineralization was especially weak, the micaeous minerals that formed sparsely on the original surface of the sand grains are engulfed by secondary quartz overgrowths (fig. 5, top part). These relations can

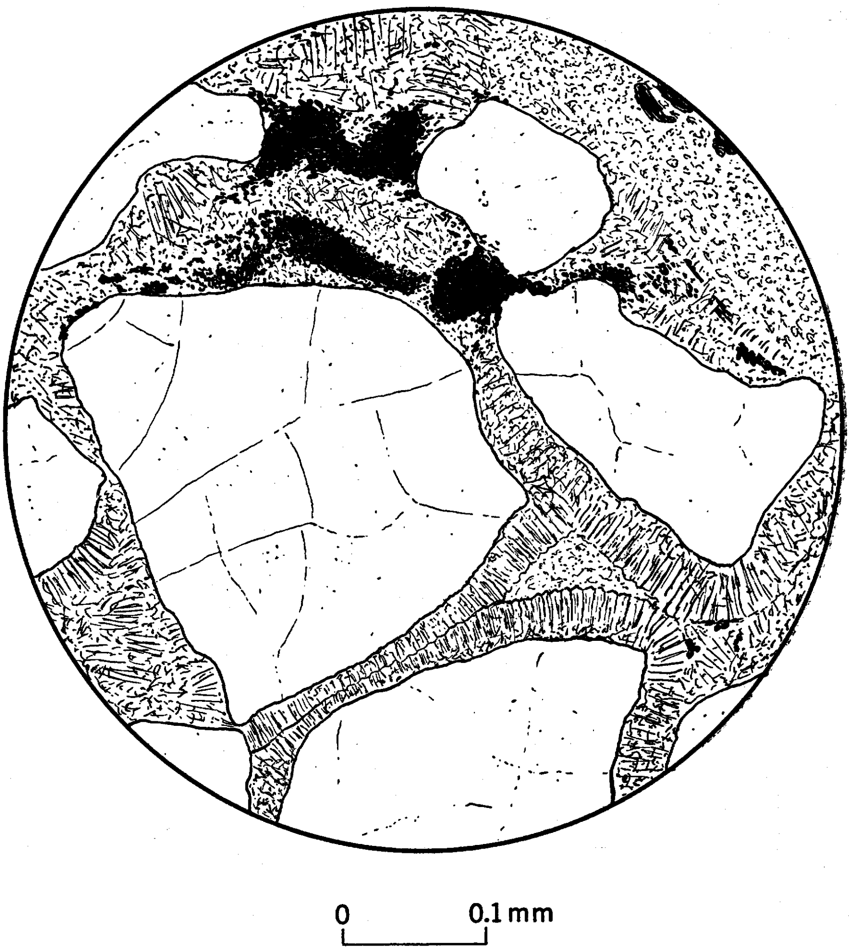


FIGURE 4.—Clear quartz grains surrounded by vanadium clay dusted with unidentified uranium-bearing(?) mineral (black). Reproduced from Waters and Granger (1953, fig. 11).

be interpreted as replacement of the calcite or quartz overgrowths by the vanadium minerals growing along the original surfaces of the sand grains, as interpreted by Waters and Granger (1953, p. 15), but in the opinion of the writer the evidence is better interpreted as filling by carbonate or silica after mineralization. Quartz overgrowths have not been seen by the writer where the micaceous vanadium minerals insulate the original quartz grain with a coat as dense as that shown in even the low-grade part of plate 8 (right side).

Where mineralization was moderate, or of average ore grade, the micaceous flakes form a felted mass that completely fills the pore spaces (pl. 8, center and left side, and fig. 4); there is no positive evidence that an earlier pore-filling mineral has been replaced, and the original surfaces of the sand grains show little or no etching or replacement.

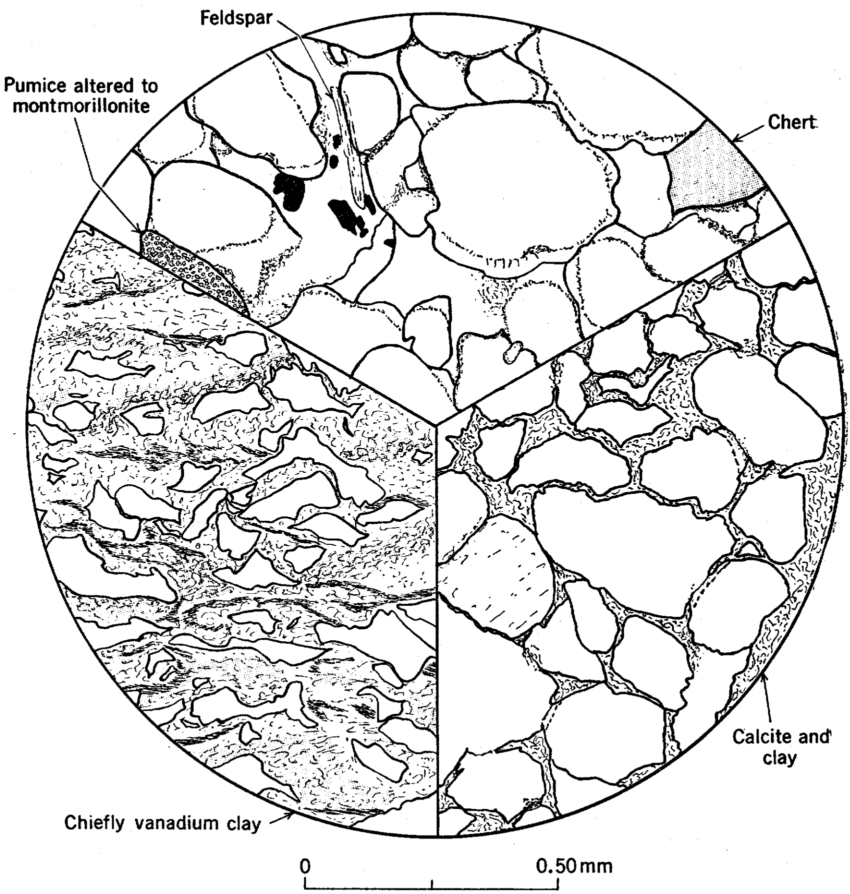


Figure 5.—Authigenic overgrowths and solution features on quartz grains shown on different parts of a single thin section of ore. Salt Wash sandstone member of the Morrison formation. Reproduced from Waters and Granger (1953, fig. 9).

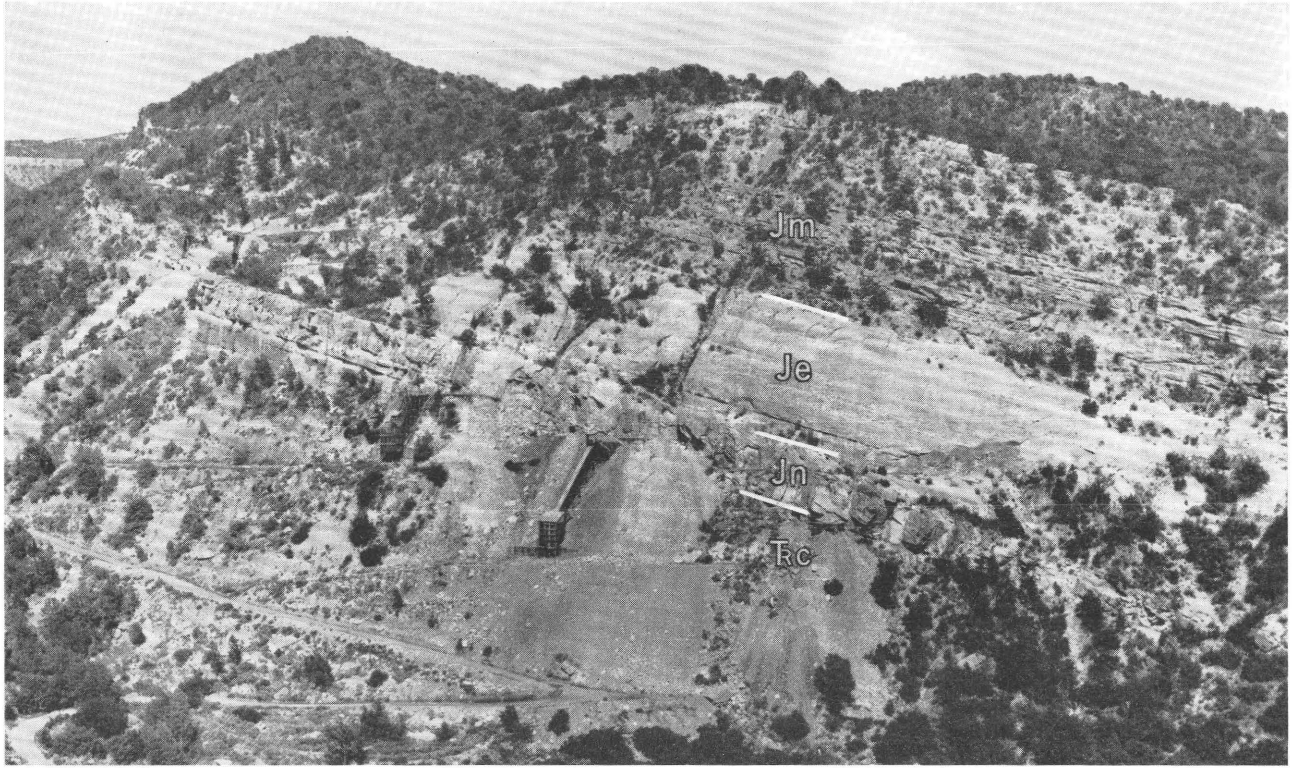
In high-grade ore, and also where rich concentrations have occurred along favorable bedding planes such as those shown in plate 7*B*, the sand grains have been partly destroyed (pl. 9*A* and fig. 5, lower left part). This phenomenon might be considered by some geologists as a replacement of the sand grains by the micaceous vanadium minerals. Waters and Granger (1953, p. 20), however, suggest solution of the quartz grains during mineralization; the writer favors their suggestion, but he also considers that the solution might have occurred after mineralization, in which case the locally rich concentrations of vanadium minerals would be in part a residual concentration.

Study of oriented thin sections shows that typically the sand grains have been destroyed in one direction, leaving elongate remnants oriented roughly parallel to bedding. Destruction begins with the formation of a microscopic stylolite between sand grains at their point of vertical contact, suggesting that solution was localized at pressure points, and it may continue until the sand grains are largely or wholly destroyed, leaving a rich accumulation of the micaceous vanadium minerals in a relatively thin "shaly" seam. Such seams contain as much as 10 percent V_2O_5. The formation of the stylolites was noted by Waters and Granger (1953, p. 15) as well as by Fischer (1942, p. 380), who also recognized slumping along these shaly seams, apparently due to a volume decrease with the removal of quartz.

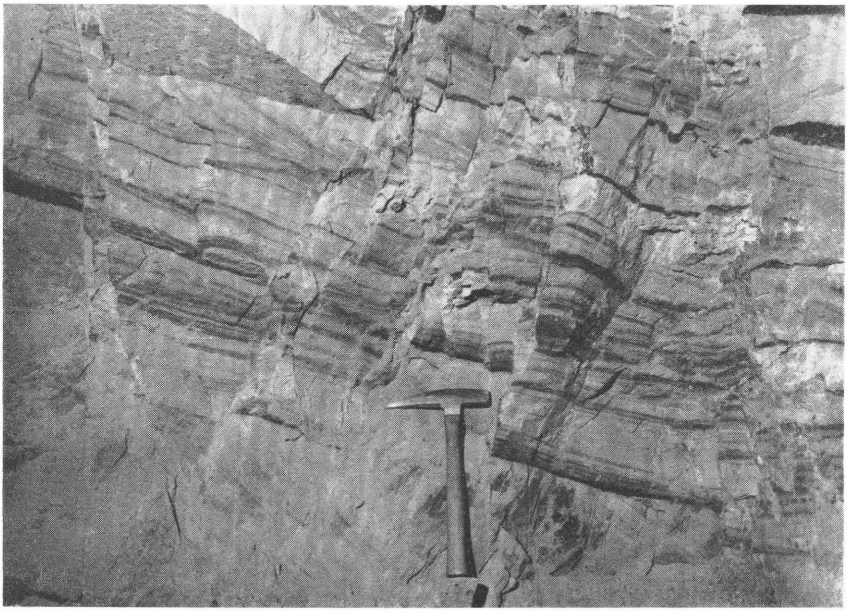
As an ore mineral, the vanadium oxide montroseite is only of minor importance. It is sparsely disseminated through much of the ore in the Rifle mine, forming small bladed crystals or radial aggregates. These grains mainly occupy the sandstone pores and are intergrown with or replace the micaceous vanadium minerals (pl. 9*B*), but they also seem to penetrate and replace the quartz grains. Where montroseite is abundant, as in small masses of rich ore, it completely fills the spaces between sand grains, and it even replaces the grains enough that they are no longer in contact with one another. No controlling feature has been observed for the localization of these rich masses of ore.

ORE LAYERS

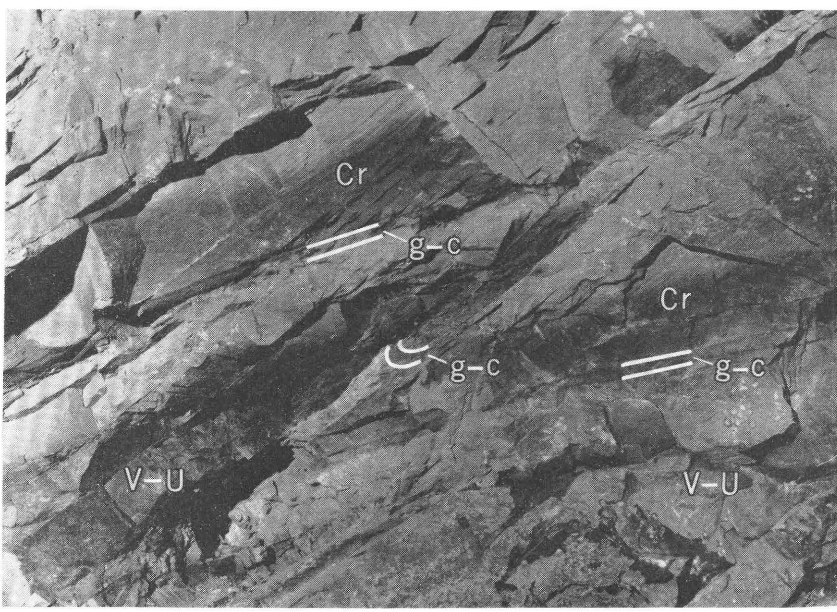
The Rifle-Garfield deposit comprises three ore layers, which the miners call the No. 1, No. 2, and No. 3 "veins" in ascending order. As No. 1 and No. 2 veins join in the eastern part of the deposit and the No. 2 and No. 3 veins join in the western part, the vertical arrangement of these layers along the length of the deposit is S-shaped, though one that is incomplete, for No. 2 and No. 3 veins are spotty rather than continuous. Both No. 1 and No. 3 veins are



Photograph showing outcrop of the Chinle (T̶Rc), Navajo(?) (Jn), Entrada (Je), and Morrison (Jm) formations at the west end of the Rifle mine, east side of East Rifle Creek.

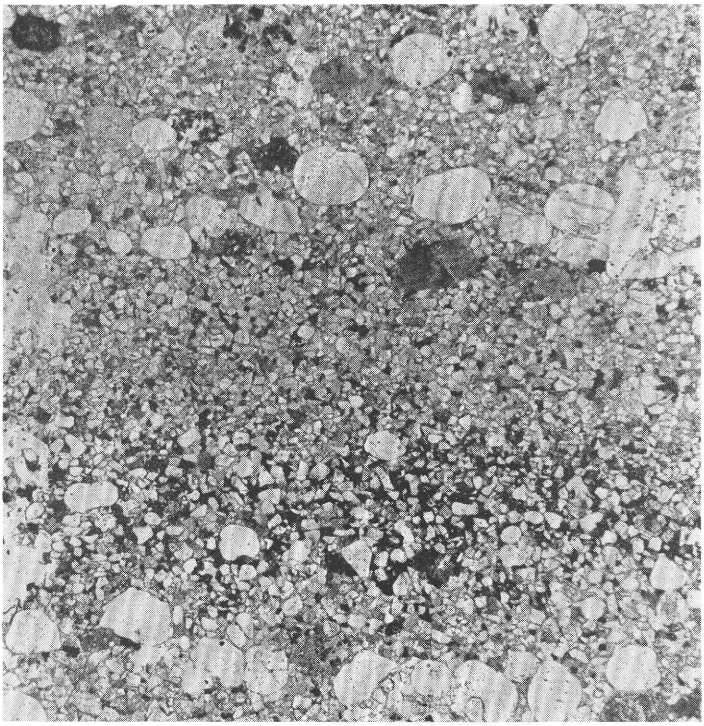


A. Complex fault displacing banded ore.



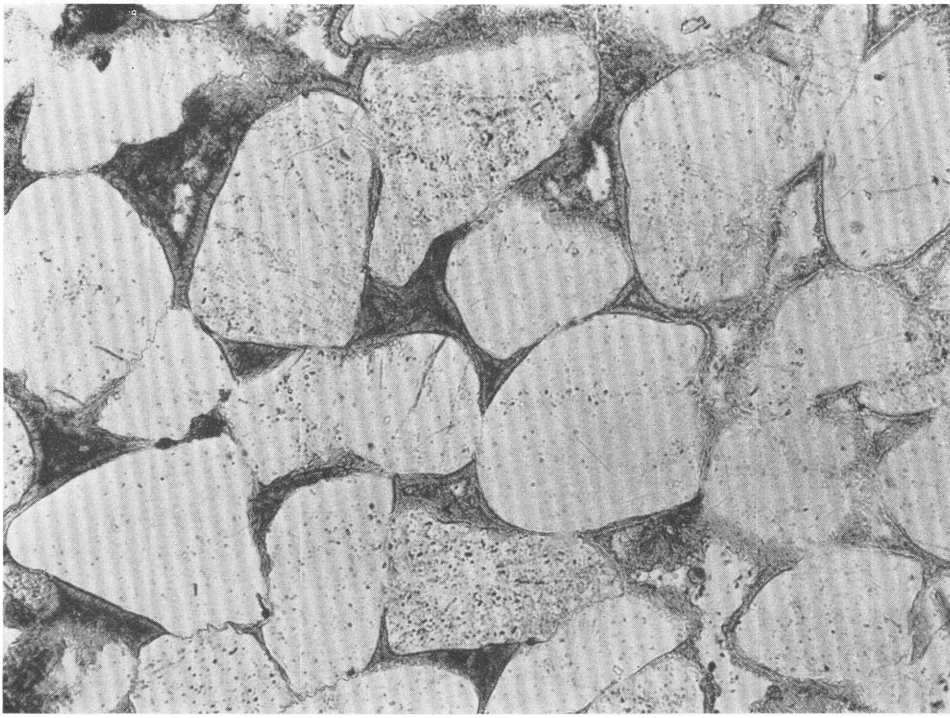
B. Low-angle double fault of reverse movement along bedding planes, showing displacement of vanadium-uranium ore (V-U), the galena-clausthalite layer (*g-c*), and the chromium-bearing layer (*Cr*); displacement is about 1 foot, No. 1 vein.

PHOTOGRAPHS OF FAULTS AT RIFLE MINE



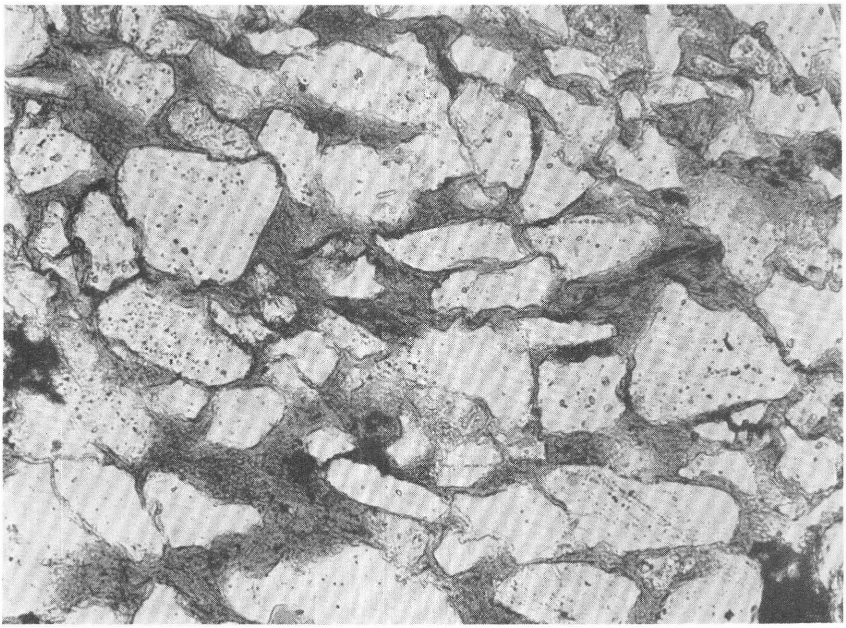
A. Photomicrograph of a thin section across a galena-clausthalite layer. The galena-clausthalite grains (black), which occupy the sandstone pores and perhaps partly replace the sand grains, are concentrated in a layer only about one-twentieth of an inch thick. ×16. Entrada sandstone, No. 2 vein, Garfield mine.

B. Photograph of ore-bearing sandstone with relatively rich concentrations along favorable bedding planes (dark). Rifle mine.

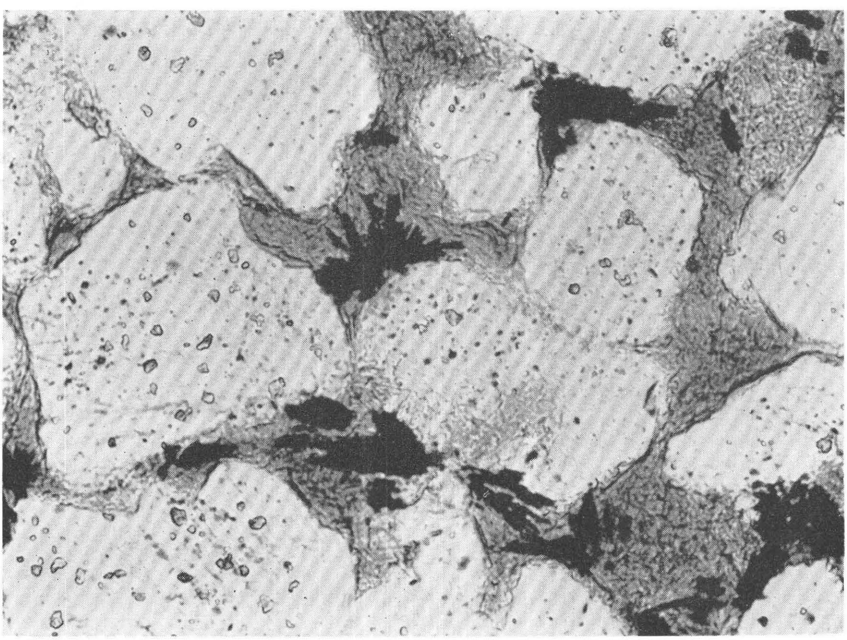


PHOTOMICROGRAPH SHOWING LOW-GRADE AND MEDIUM-GRADE ORE

In the low-grade ore (right part of picture), flakes of a micaceous vanadium mineral form a single layer and stand perpendicular to the original surfaces of the sand grains, having grown into the pore spaces but only partly filling the pores. In the medium-grade ore (central and left parts of picture), the sandstone pores are completely occupied by the vanadium mineral. Intermediate stages of pore filling are also evident. Note also that microstylolitic seams are beginning to form at a few places where the quartz grains are in contact. In a few places, especially along the top and right sides of the picture, the contacts of the sand grains and the coating of the vanadium mineral are fuzzy; these places may show replacement, but the writer believes they merely show the original surfaces of the quartz grains beveled at a low angle by the thin section. $\times 140$.



A. Photomicrograph of high-grade ore, showing partial destruction of the sand grains either by replacement or solution along microstylolitic seams between grains. ×140.



B. Photomicrograph of ore with bladed montroseite crystals (black) in the pore spaces between sand grains and intergrown with or replacing a micaceous vanadium mineral. ×300.

Photograph of No. 3 vein showing the upper part of the vanadium-uranium ore layer (V-U), the galena-clausthalite layer, the thin, faintly dark line at the tip of leader (*g-c*), and the chromium-bearing layer (*Cr*) where they cut across bedding. The scale of the photograph is indicated by the 6-inch ruler on the right side. Garfield mine.

overlain by the galena-clausthalite and chromium-bearing layers, and No. 2 vein is underlain by these accessory layers.

STRATIGRAPHIC AND SPATIAL RELATIONS

The No. 1 vein (the lowest ore layer) underlies the entire deposit. It forms the principal ore body in the Rifle mine, where it has been mined for more than 7,000 feet (pl. 3). It is mostly in the lower part of the Navajo(?) sandstone, but in at least two places the layer thickens enough so the upper part of the ore extends upward a few feet into the Entrada sandstone. (See pl. 4, section *F-F'*.) No. 1 vein also crosses into the uppermost foot of the underlying Chinle formation at a few places along the south edge of the Rifle mine (pl. 4, section *G-G'*). It is also in the top of the Chinle along the outcrop on the west side of East Rifle Creek and at the Garfield mine. It seems likely this layer was continuous across the canyon of East Rifle Creek before erosion cut it.

No. 2 vein is not as well exposed by mining as No. 1 vein, so its distribution is not as well known. But instead of forming a continuous layer as does No. 1 vein, the No. 2 vein seems to form several small- to moderate-size ore bodies that are not connected to one another by vanadium-bearing sandstone.

In the southern part of the workings at the east end of the Rifle mine No. 2 vein is in the upper part of the Navajo(?) sandstone, and it seems to join No. 1. The exact character of this connection is not clear at the present stage of mine development, but one point of connection is shown in plate 4, section *A-A'*. Elsewhere No. 2 vein is in the Entrada sandstone, and it becomes progressively higher in the formation westward through the Rifle mine—at coordinates 10,830 N. and 15,180 E. (pls. 2 and 3) it is about 6 feet up into the Entrada; at coordinates 10,770 N. and 13,690 E. it is about 15 feet up in the Entrada (pl. 4, section *C-C'*); and at 10,250 N. and 10,375 E. it is about 25 feet up in the Entrada (pl. 4, section *G-G'*). In the Garfield mine No. 2 vein is about 25 to 40 feet above the base of the formation (pl. 4, sections *I-I'* and *H-H'*).

No. 3 vein is known only in the Garfield mine (pls. 2 and 3). It is connected to No. 2 vein along the northwest edge of the mine, but eastward it is separated from No. 2 vein by an increasing thickness of barren sandstone (pl. 4, section *I-I'*); at the outcrop east of the mine, No. 3 vein is about 20 feet above No. 2 vein.

Thus, if the separate ore bodies in No. 2 vein are connected by some imagined link, and if No. 1 is projected across East Rifle Creek, the vertical pattern of the three layers in the Rifle-Garfield deposit is broad, flat, S-shaped, and about 10,000 feet long and 80

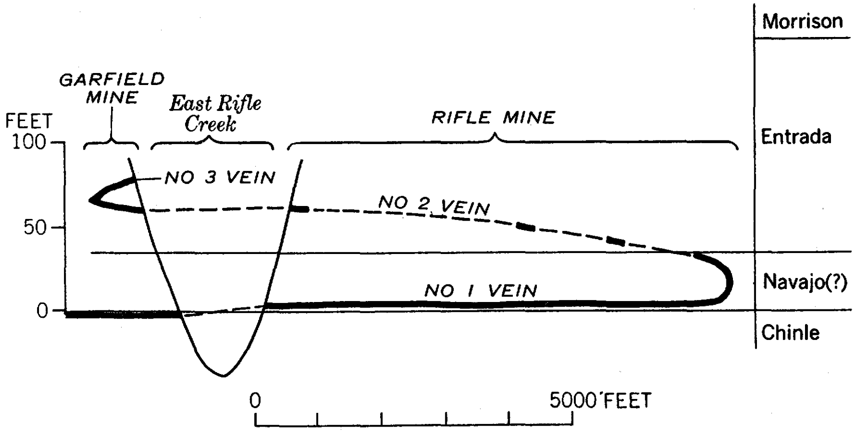


FIGURE 6.—Generalized cross section of the Rifle-Garfield deposit, showing the three ore layers with a broad flat S-shaped pattern about 10,000 feet long and 80 feet high. The observed parts of the layers are shown with heavy lines, the inferred connections are dashed.

feet high. The observed vertical relations and imagined projections are shown in the diagrammatic cross section, figure 6.

A plan projection of the known ore bodies in the three layers suggests a tendency for the ore bodies in each higher layer to be marginal or satellitic to ore in the layer below (pl. 3). Except along the northwest edge of the Garfield mine, where No. 2 and No. 3 join, there is no known place where ore bodies of commercial grade and thickness in two different layers directly overlap, although the fading or thinning edge of an ore body may overlap or underlie ore in another layer. No reason for this horizontal pattern is evident, and admittedly not a great deal of confidence can be placed in this picture at the present time, for the number of examples are few.

BEDDING RELATIONS

In gross aspect the lower edge of No. 1 in the Rifle mine is a remarkably plane surface, although in detail it is somewhat undulant, and instead of being a sharply defined contact it is a gradational zone several inches thick. This edge of ore is mostly 5 to 15 feet above the base of the Navajo(?) along the north side of the ore body; southward this edge is generally lower in the formation, and at many places along the south side of the mine this edge rests on the Chinle and in a few places is actually in the Chinle, as shown in plate 4, sections *B-B′*, *C-C′*, and *G-G′*. Thus this edge dips southward at an angle slightly greater (but only about 1° greater) than does the formation contact. The Navajo(?), however, is strongly crossbedded, dominantly of the torrential type, and most of the crossbedding had an initial dip of 10° to 20° southward.

Therefore the lower edge of ore, as well as the entire ore layer, is conspicuously discordant to the more steeply dipping crossbedding (pl. 4).

Like the Navajo(?), the Entrada is also crossbedded, but dominantly sweeping or tangential with sets as much as several tens of feet across. No. 2 and No. 3 veins, though somewhat undulant in detail, in general lie nearly parallel to the formation contacts, and they cut across the crossbedding with little or no regard to it (pls. 4 and 10).

THICKNESS AND GRADE RELATIONS

The approximate thickness of the ore layers is shown by isopach lines on plate 3. The data from which this map was compiled consist in part of channel samples taken by the miners and in part of measurements and estimates by the writer.

In the southwestern part of the Rifle mine the ore is a well-defined, blanketlike layer that ranges from 2 to 5 feet in thickness in the stopes and tapers to less than 2 feet beyond the stope walls. Throughout this area the grade of the ore layer is fairly uniform and averages slightly higher than the grade of ore for the entire deposit. The ore layer is mostly 5 to 15 feet above the base of the Navajo(?) sandstone, but in several places along the south edge of the workings the layer is at the bottom of the sandstone and in at least 2 places it crosses into the top of the Chinle formation.

East of coordinate 11,000 E., northeastward-trending pods of thick ore are the conspicuous feature of the deposit, and in general there is a striking asymmetry in thickness and grade of ore from north to south across the ore body. Most of the pods are in the northern half of the body, and much of the ore along the north edge of the workings is more than 5 feet thick. The grade of the thick ore averages less than the deposit as a whole, and as the grade decreases northward the limit of mining in that direction is an assay wall of about 1 percent V_2O_5 or slightly less. Through the southern half of the ore body, on the other hand, the layer thins gradually southward, but the average grade of the thin ore is moderately high, commonly more than 2 percent V_2O_5, so that the south limit of stoping is controlled mainly by a thickness cutoff of about 2 feet rather than a grade factor.

The ore thickens mainly by the top of the layer rising stratigraphically, though in places an increase in thickness is also attained as the bottom of the ore layer curves downward. Where either the top or the bottom of the ore layer changes stratigraphic position abruptly, the edge of ore is commonly a well-defined and smoothly curved surface, which in places steepens to the vertical or may even be slightly overturned as a C- or S-shaped curve (pl. 4, sections *D-D′*

and *E-E'*). The surface of the ore cuts across bedding without regard to the laminae, and there is no obvious control for the localization of this surface. Surfaces of conspicuous curvature resemble the "rolls" so commonly found in the vanadium-uranium deposits in the Morrison formation in other parts of Colorado and Utah (Fischer, 1942, p. 383–384). The positions and dip directions of the more conspicuous curved surfaces, or rolls, in the Rifle mine are shown on plate 3; their characteristics in cross section and their relation to bedding is shown in the cross sections on plate 4.

Most of the pods of thick ore, as well as the associated rolls, trend between N. 60° E. and due east, and the average trend is about N. 75° E. (See pl. 2, radial diagrams.) Between coordinates 11,000 E. and 11,800 E. these pods are in a broad mass of ore (pl. 3). Between coordinates 11,800 E. and 13,000 E., however, the ore body is relatively narrow and trends about N. 75° E., and the pods and rolls within it trend about the same. From 13,000 E. to 16,000 E. the ore body trends nearly due east, but most of the pods and rolls trend about N. 75° E. and have an echelon pattern. East of 16,000 E. the ore body seems to trend about due east, as do the pods and rolls, but this part of the mine is not completely developed so the true relations may not be accurately depicted. There is no observed reason for the localization of these pods of ore nor for the pattern they form.

A pod of ore nearly 10 feet thick has been mined from No. 3 vein in the westernmost workings in the Garfield mine, and a pod of about the same thickness, and which was formed by the joining of No. 2 and No. 3 veins, has been mined from the stope along the northwest edge of the mine (pl. 3). Both of these pods trend about N. 45° E., and they have an echelon arrangement. The ore in No. 2 vein has a maximum thickness of about 10 feet at the east end of the Rifle mine near the junction of No. 1 and No. 2 veins. Elsewhere the ore bodies in the No. 2 and No. 3 veins average only a few feet in thickness, and they taper to a few inches in thickness along their edges.

GEOCHEMICAL RELATIONS

In addition to the ore metals, vanadium and uranium, three other elements—lead, selenium, and chromium—have accumulated in the Rifle-Garfield deposit. Each of these five elements is concentrated in fairly distinct sheets within or adjoining each of the three ore layers, forming three mineralized zones that are asymmetric vertically in composition. Each zone has the same asymmetry, but the middle zone, which contains No. 2 vein of ore, is a mirror image (or upside down) with respect to the lower and upper zones, which contain No. 1 and No. 3 ore veins, respectively. The asymmetric characteristics of these zones are described below, and the grade distribu-

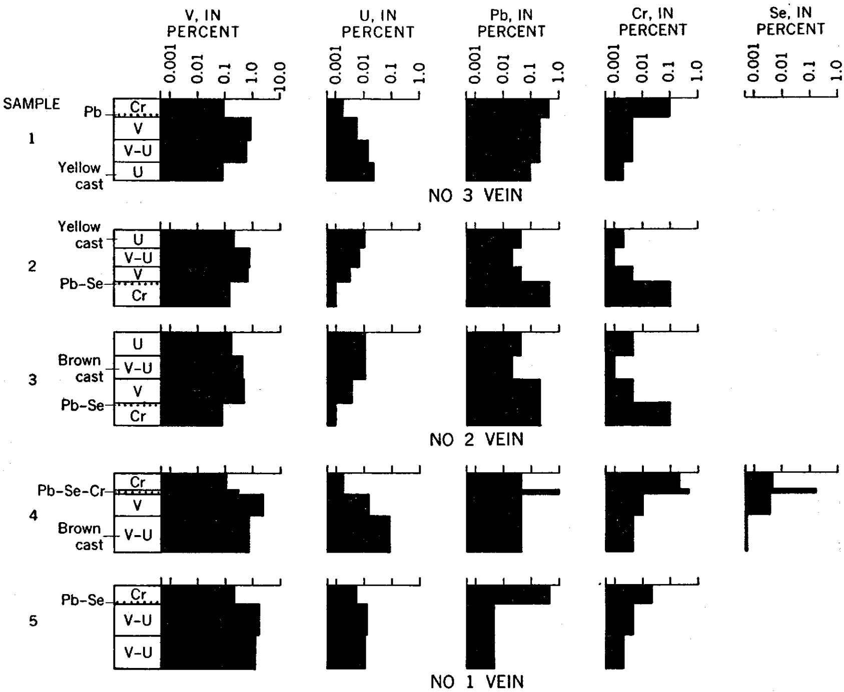


FIGURE 7.—Grade distribution of vanadium, uranium, lead, chromium, and selenium, as determined by chemical and spectrographic analyses of channel samples across the three ore layers. The left-hand column shows the sample intervals and the elements of relatively large concentration in each interval.

tion of these elements as determined by chemical and spectrographic analyses of 5 channel samples across the 3 zones is shown graphically in figure 7. The photograph, plate 10, shows part of the mineralized zone containing No. 3 vein; channel sample 1 (fig. 7) was taken at the same place as this photograph.

At most places in the Rifle and Garfield mines, scintillometer readings across the lower and upper mineralized zones (No. 1 vein and No. 3 vein respectively) indicate a little more radioactivity in the lower part of the ore layers and the sandstone immediately below them than in the rest of the mineralized rock. In the middle zone (the No. 2 vein) the greatest radioactivity is in the upper half of the ore and the adjacent overlying sandstone. A similar distribution of uranium is shown by chemical analyses of channel samples 1, 2, 3, and 4 (fig. 7). Commonly the more radioactive part of the rock has a light-brownish or yellow cast, which seems to be more conspicuous as the radioactivity increases; the color, however, is not obviously due to a uranium-bearing mineral.

Vanadium minerals color the rock gray which darkens as the vanadium content increases. Where the layer of vanadium ore is thick it is generally lower in grade than average, and commonly its vertical limits are not well defined; where the ore layer is thin and rich, it has well-defined limits and consistent characteristics. In No. 1 and No. 3 veins the upper part (approximately the upper half) is generally slightly higher in grade, and the upper edge of the ore is commonly almost as sharp as that shown in plate 10. The lower part of the vanadium ore generally has a brownish cast, and the ore fades out through an interval a few inches thick at the lower edge. No. 2 vein has the same habits but in a reverse vertical sequence. The nearly barren sandstone (part of the uranium-bearing layer) on one side of the ore and the chromium-bearing layer on the other side both contain about 0.1 to 0.2 percent vanadium, which is considerably less than the ore but which is much more than the spectrographic trace in the truly barren sandstone away from the deposit.

All parts of the mineralized zone are relatively rich in lead, which ranges from a few hundredths to a few tenths percent in most samples analyzed, but lead is most abundant in a thin layer on the side of the vanadium ore opposite the uranium-bearing layer—the lead layer is above No. 1 and No. 3 veins, below No. 2 vein. In this layer lead occurs as a solid-solution mixture of galena and clausthalite, which form minute grains in the sandstone pores. (See page 23 and pl. 7*A*.) The greatest concentration is in a sheet ⅛ to ¼ inch thick; commonly this sheet is separated from the ore by about half an inch of nearly barren sandstone, as shown in plate 10, but in places it lies immediately adjacent to ore. A small sample cut down to the thickness of the sheet itself assayed 3.05 percent lead (E. Mallory and D. Skinner, analysts). Galena-clausthalite grains are also disseminated in the adjoining part of the chromium-bearing layer, decreasing in amount through an interval a few inches thick; a 3-inch sample of this interval was taken separately in channel sample 4, and it assayed nearly 1 percent lead (fig. 7). Isotopic analysis shows the lead from the galena-clausthalite zone to be mainly common lead with only a small amount of radiogenic lead (Lorin R. Stieff, oral communication).

Of the 5 channel samples across the ore layer, only sample 4 was analyzed for selenium; it showed 4 ppm (parts per million) (0.0004 percent) in the lower half of the ore layer, 40 ppm (0.004 percent) in the upper half, 1,800 ppm (0.18 percent) in the galena-clausthalite layer, and 50 ppm (0.005 percent) in the chromium-bearing layer (fig. 7). The widespread distribution of selenium in the galena-clausthalite layer, however, is shown by the analyses of samples collected from the Rifle and Garfield mines by Robert G. Coleman (Botinelly and Fischer, 1959), and it can also be visually recognized by the reddish bloom of native selenium that has formed on the walls throughout the Rifle and Garfield mines.

Chromium is concentrated in a poorly defined layer, generally about 1 to 2 feet thick, above veins 1 and 3 and below No. 2. The chromium-bearing layer in the Entrada sandstone is light to pale green. In the Navajo(?) it is dominantly greenish gray, but in places it has about the same color as the layer in the Entrada. The chromium-bearing mineral has not been completely identified; it is micaceous and occupies the pore spaces of the sandstone, as do the micaceous vanadium minerals. Samples of the chromium-bearing zone contain from a few hundredths to a few tenths percent chromium.

Although several other elements have accumulated in this deposit in amounts greater than is common in barren sandstone, none of these show a systematic distribution within the mineralized zones. Zinc, which has a high threshold of detection spectrographically (about 0.01 percent), is not reported in many samples but is as high as a few tenths percent in others; thin and polished sections of the ore show small blebs of sphalerite erratically distributed. Copper occurs consistently in samples in small amounts, ranging from 0.001 to 0.01 percent; minute grains of chalcopyrite are scattered through the ore. Nickel and cobalt are also consistently reported but mostly in traces, only rarely exceeding 0.001 percent. Both silver and molybdenum range from 0.001 to about 0.02 percent in the metallic mineral concentrates from the galena-clausthalite layer, but they are both less than 0.001 percent in all ore samples analyzed, and in most samples they are in amounts below the limit of spectrographic detection. Only 3 ore samples have been analyzed chemically for arsenic, and these range from 30 to 50 ppm (0.003 to 0.005 percent).

The following tabulation gives the results of semiquantitative spectrographic analyses of a sample obtained by combining splits of assay pulps from several hundred tons of ore.

TABLE 2.—*Semiquantitative spectrographic analyses of a composite sample of ore from the Rifle mine, Garfield County, Colo.*

[Analyst, R. G. Havens]

	Percent[1]		*Percent*[1]
Si	XX.	B, Cr	0. 00X+
Al	X.	Cu, Sr	. 00X
K, V	X. −	Mo, Ni	. 000X +
Ca, Fe, Mg, Na	. X+	Co	. 000X
Mn, Zn	. 0X+	Ag	. 0000X
Ba, Pb, Zr	. 0X−		

[1] The concentrations of the elements as determined by semiquantitative spectrographic analysis are bracketed into groups each of approximately one-third of an order of magnitude, X+ indicating the higher portion (10 to 5 percent), X the middle portion (5 to 2 percent), and X− the lower portion (2 to 1 percent). Comparisons of this type of semiquantitative results with those obtained by quantitative methods, either chemical or spectrographic, show that the assigned group includes the quantitative value in about 60 percent of the analyses.

Looked for but not detected: As, Au, Be, Bi, Cd, Ce, Dy, Er, Ga, Gd, Ge, Hf, Hg, In, Ir, La, Li, Nb, Nd, Os, P, Pd, Pt, Re, Rh, Ru, Sb, Sc, Sm, Sn, T, Te, Th, Tl, U, W Y, Yb.

Colorimetric analyses of the same sample are given in the following tabulation:

Colorimetric analyses of a composite sample of ore from the Rifle mine, Garfield County, Colo.

[Analysts, H. E. Crowe, R. R. Bein, J. S. Wahlberg, W. D. Goss, H. H. Lipp, and R. E. Cox]

	Parts per million
As	50
Sb	<1
Se	75
Zn	300

RELATIONS OF ORE TO TECTONIC STRUCTURES

The Rifle Creek area is on the Grand Hogback monocline where this fold flanks the south side of the White River Plateau uplift; the fold has a structural relief of 15,000 feet. The fold comprises several structural terraces of flattish dip separated from each other by steeper dips or faulting (fig. 3). The area mapped in this study forms a structural unit or block that spans the interval between two terraces. The terrace to the north is one of low-angle dip, in places bowed enough to form a gentle anticline and a shallow complementary syncline; faulting is absent or negligible along this terrace. To the south the terrace comprises a complex belt of synclinal flexures and faults. The vanadium-uranium deposit in the Navajo(?) and Entrada sandstones is localized about midway between these terraces (pl. 1), in rocks that have a moderate dip, are intensively fractured, but are only slightly disturbed by faulting.

ATTITUDE OF BEDS

The structural block that forms the Rifle Creek area trends slightly north of west, and has an average inclination of 10° to 15° S. (pl. 1, cross sections). Both west of the Garfield mine and east of the Rifle mine the structure contours bend southward (pl. 1), indicating southward-plunging flexures or cross anticlines imposed on this structural block; the intervening area, which contains the deposit, is therefore relatively depressed. These structural relations are more clearly seen if the present southerly inclination of this block is removed by an imaginary tilting of the area northward. As shown in figure 8, the depressed area is a shallow westward- or northwestward-trending basin, and at this selected angle of tilt (12½° N. 7° E.), which virtually flattens the block, the ore deposit occupies the north flank of the basin. Note that the deposit roughly follows the 1,400-foot contour (datum arbitrarily selected) on the northwest side of this basin. If this deposit actually formed in such a basin, ore might have formed somewhere else around the basin at approximately the same level. The size and shape of this basin, and the position of its low point, however, changes with the

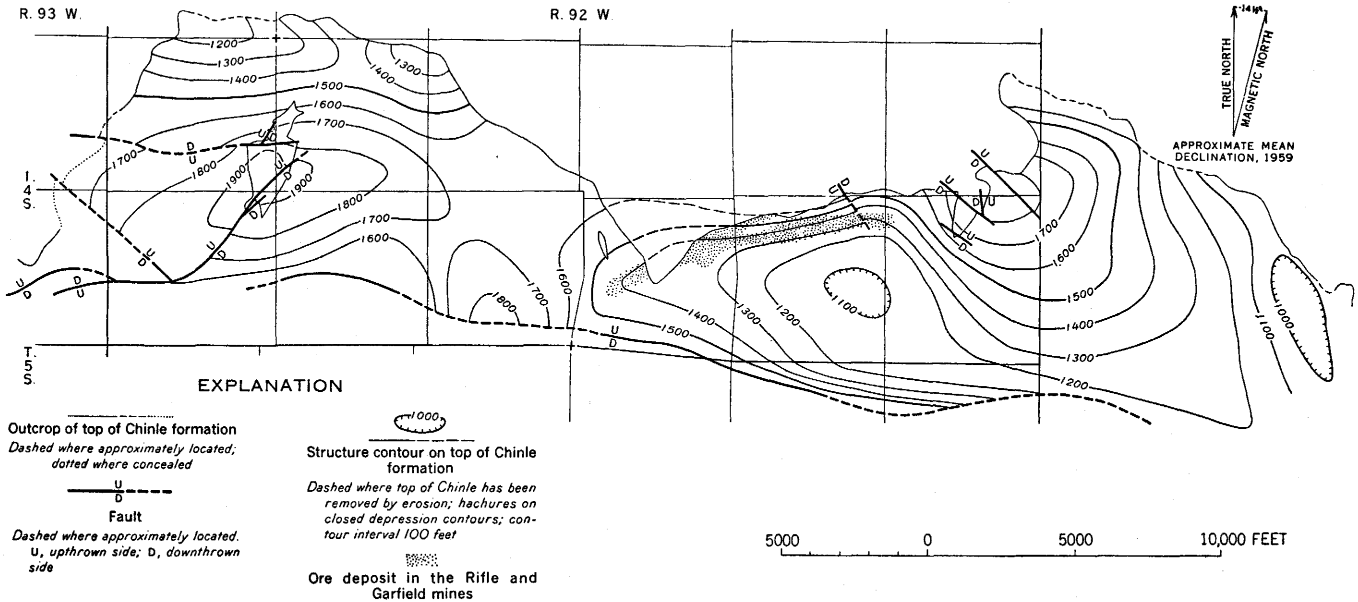


Figure 8.—Structural setting of the Rifle-Garfield deposit as shown by contours on the top of the Chinle formation after removing the regional southerly dip by imaginably tilting the area 12½° N. 7° E. and adjusting to an arbitrarily selected datum.

angle and direction of tilt selected to remove the true inclination of the block, but nevertheless the ore deposit remains somewhere within the basin—for example, if the block is tilted northward 22½°, compensating for the approximate average dip of beds in the Rifle mine, the low point of the basin shifts northward to the east end of the deposit. As the writer has no evidence for dating these cross anticlines relative to the time of formation of the Rifle-Garfield deposit or of the Grand Hogback monocline, he cannot state positively that this basin had an influence on the localization of this deposit.

The detailed relations of the ore in the Rifle mine to the dip and strike of the host rock are shown in detail by the structure contours on plate 2. In the western part of the mine the ore body is a broad tabular layer, whose outlines show a vague northeasterly trend and which contains a few thick masses of ore that trend about N. 75° E. The beds strike due east, and the southerly dip gradually increases from about 15° along the south edge of the workings to about 30° along the north edge (pl. 2). Eastward the ore body is elongate and relatively narrow, the trend swinging from about N. 75° E. to about due east in the central part of the mine; through this interval the beds retain their easterly strike and have a dip of 25° to 30° S. In the east part of the mine the strike is about N. 85° E., which is also about the local trend of the ore body. At the east end of the mine the strike swings slightly and the dip lowers to about 20°; the trend of the ore body at the east end of the mine is not clearly shown at the present stage of mine development, but it seems to be either due east or somewhat north of east.

In the Garfield mine the rocks strike about N. 80° E. and dip between 15° to 20° S. The trend of the deposit is more southerly than is the strike of the beds, and the deposit rakes down the dip; two rolls of ore in the western part of the mine trend about N. 45° E., and the northwest edge of the ore also probably trends northeast.

FRACTURES

In the Rifle Creek area the hard and brittle sandstones like the Navajo(?) are intensively fractured, whereas the softer sandstones like the Entrada are sparsely fractured. Three sets of fractures are recognized; two sets dip at high angles, the other at low angles. These fractures have been studied and mapped in detail only in the Rifle and Garfield mines, but they seem to have much the same habits and abundance in barren ground away from this ore deposit.

The pattern of the high-angle joints and faults in the Rifle and Garfield mines is shown in plate 2. The base of this map is a plan of the inclined mine workings projected to a horizontal plane. The fractures were plotted from the roof or backwall of the workings, and in relation to the detailed characteristics of the mine walls and pillars rather than by the conventional method of compass readings. Thus all fractures are shown in true positions with respect to the workings, but only the fractures that trend about parallel to the regional strike (about due east), or those that dip vertically, have a map plot that corresponds with their true strike. The map does not show the exact true strike of fractures that trend at moderate angles to the strike of the beds and are inclined somewhat from the vertical, such as many of the northwestward-trending fractures. This method of plotting also results in the abrupt changes in trend or zigzags shown where an inclined fracture is connected between a stope at one stratigraphic position and a haulage drift at another horizon.

Joints are abundant in the Navajo(?) sandstone in the Rifle mine (pl. 2), but not many individual breaks extend more than a few tens of feet, either horizontally or vertically. Along their trend they may curve or split, losing their identity as they join or cross other breaks, or they may merely die, perhaps in juxtaposition to the start of another break a few inches away. They have the same irregularities vertically, and many do not even extend directly across bedding planes, but rather their continuations are set off a few inches. In general, the individual lines shown as joints on plate 2 represent a group of closely spaced breaks that have moderate continuity instead of representing a single break. In some places the lines shown are wholly schematic and merely record the trend and relative abundance of fractures. Joints belonging to the eastward-trending set of fractures generally are better defined and have greater extent than do those of the northwestward-trending set.

The eastward-trending fractures are uniformly distributed throughout the Rifle mine (pl. 2), but the northwestward-trending ones are mostly grouped in three swarms. One swarm is between coordinates 10,000 E. and 11,000 E., a second between 13,500 E. and 15,000 E., and the third near 16,000 E. (pl. 2). Some of the northwestward-trending faults turn or jog with offset in the right-lateral direction on eastward-trending joints; good examples of this jogging are seen near coordinate 14,000 E. This relationship suggests that the eastward-trending fractures are older than the northwest ones.

Some of the high-angle faults are tight, and these may be either single planes of movement or complex zones like that shown in plate 6*A*. Other faults are open and rubbly or else are partly or wholly filled with exotic material (see p. 24–25).

The low-angle set of fractures are merely bedding-plane slips in response to folding. The fracture planes are tight and commonly show a paper-thin white layer of crushed quartz. Movement is evident from the displacement of crossbedding planes, high-angle fractures, and the ore (pl. 6*B*). Maximum observed displacement is about 1 foot, but most fractures have moved less than 1 inch; displacement is in the reverse or thrust direction.

The movement on all three sets of fractures has clearly brecciated and displaced the ore, and, except for the presence of secondary minerals such as tyuyamunite, there is no recognized evidence of vanadium and uranium mineralization along these faults nor has there been any obvious enrichment or leaching of ore in the rock adjacent to these faults. In a like manner, individual joints show no influence on mineralization. Nevertheless, there is a coincidence in the local strike of the eastward-trending joints and the trend of the deposit in the Rifle mine. In the western part of the mine, west of coordinate 11,800 E., the deposit trends about N. 70° E., and most of the eastward-trending joints plot between N. 50° and 80° E. (See pl. 2, diagram *A*.) Between coordinates 11,800 E. and 13,400 E. the deposit has a well-defined trend of about N. 75° E. and most of the eastward-trending joints plot between N. 80° E. and due east (pl. 2, diagram *B*). East of coordinate 13,400 E. most of the eastward-trending joints plot between N. 80° E. and S. 80° E. (pl. 2, *C*), whereas the deposit extends due east or slightly north of east. Diagram *D* is a composite of *A*, *B*, and *C*.

These radial diagrams also show the plot of the trend of ore rolls or thick pods of ore in the deposit, and the trend of faults. The ore rolls are consistent in trend in all parts of the mine; nearly all plot between N. 60° E. and due east and the dominant trend is N. 70°–80° E. The faults displace the rock and the thick pods of ore; in places the joints and ore rolls are coincident in trend but elsewhere they cut across one another with no suggestion that either influenced the position of the other.

RELATIONS OF ORE TO FRACTURE-FILLING MATERIAL

Fracture-filling material consists of patches of coarse-grained calcite and marcasite with a small amount of sphalerite, scattered small blebs of asphaltite, and, in a few fractures, unconsolidated sand. (See p. 16–17 and 24–25.) These minerals and the sand cement or engulf any fragments of wallrock breccia in the fracture. No vanadium or uranium minerals, except those in breccia fragments from the adjacent mineralized wallrock or those that are clearly secondary, have been found in these fractures.

RELATION OF ORE TO ALTERATION IN THE CHINLE FORMATION

The Chinle formation, which immediately underlies the Navajo(?), is brick red except where altered to gray, a color change that has occurred in small spots throughout the formation, in narrow bands along fractures, and in the upper part of the formation near the vanadium-uranium deposit in the Rifle and Garfield mines. As the alteration in spots and along fractures seems to be distributed throughout the area, no meaningful association with the ore deposit is apparent. The altered zone at the top of the Chinle, on the other hand, has an areal distribution that suggests a genetic relationship to the ore and permits the concept that it may be a guide to ore. Observation of the Chinle altered zone in the Rifle Creek area suggested the idea that the altered mudstone associated with the ore-bearing sandstone in the Morrison formation in southwestern Colorado and eastern Utah might be a valuable prospecting guide, which it has proved to be (Fischer, 1949).

The altered zone at the top of the Chinle has its maximum thickness of 4 to 7 feet along the outcrop near the Garfield mine and the western part of the Rifle mine (pl. 1). Along the outcrop northwest of the Garfield mine the altered zone thins gradually and disappears about 2,000 feet away, and no altered zone is seen from that point westward to Middle Rifle Creek. In the east half of the Rifle mine the altered zone ranges from 1 to 4 feet in thickness and from 2 to 4 feet in thickness along the outcrops north of the mine. Outcrops in the northern part of sec. 36, T. 4 S., R. 92 W., about 2,000 feet east of the eastern heading of the Rifle mine, show only small discontinuous lenses of the altered zone ranging from 0 to about 6 inches in thickness. Logs of holes drilled a few hundred feet south of the Rifle mine report only a thin altered zone or none at all, and only thin discontinuous lenses of altered material were seen in exposures on the east side of East Rifle Creek south of the Rifle mine. Because of lack of exposures, no information is available regarding the extent of the altered zone west or southwest of the Garfield mine. These relations suggest that this altered zone is roughly centered with the deposit—it apparently extends 1,000 to 2,000 feet north of the deposit and perhaps about the same distance to the east, but south of the deposit the zone dies out within a few hundred feet. The difference between the extension of the altered zone north and south of the deposit may be related in some manner to the north-south asymmetry of the ore body. (See p. 31.)

The geochemical character of the altered zone in the Chinle has not been studied in detail, but what is known suggests this alteration was of the same nature as that which altered the mudstone associated with the ore-bearing sandstone of the Morrison formation elsewhere on the Colorado Plateau. Where fresh the rock of the altered zone in the Chinle is greenish gray and contains disseminated fine-grained cubic crystals of pyrite; the contact with the unaltered rock beneath is well defined but uneven and crosses bedding. Where weathered the altered rock is buff. Thin sections of the altered and unaltered rock show no obvious differences except color. Analyses (table 3) of channel samples cut through the altered zone average 0.50 percent FeO and 1.52 percent Fe_2O_3, whereas similar samples from unaltered rock average 0.40 percent FeO and 1.74 percent Fe_2O_3. The altered rock samples average 0.015 percent V_2O_5 and the unaltered 0.02 percent, which is a common amount of vanadium in shale; the uranium content of both the altered and unaltered rock is negligible.

TABLE 3.—*Partial chemical analyses (in percent) of channel samples of altered and unaltered rock in the upper part of the Chinle formation, Rifle Creek area.*

[Analyst, Norman Davidson, 1946.]

Sample	Thickness (feet)	V_2O_5	FeO	Fe_2O_3	Total Fe as Fe_2O_3 (calculated)
		Altered			
120	0. 5	0. 01	0. 51	2. 68	3. 25
165a	4. 0	. 02	. 37	1. 07	1. 48
168a	7. 5	[1] . 18	. 63	. 82	1. 52
Average		0. 015	0. 50	1. 52	2. 07
		Unaltered			
63	2. 0	0. 04	0. 54	2. 08	2. 68
165b	3. 0	. 01	. 39	1. 01	1. 44
166	8. 0	. 01	. 27	1. 50	1. 80
168b	5. 5	. 02	. 49	1. 88	2. 42
176	4. 0	. 01	. 29	2. 21	2. 53
Average		0. 02	0. 40	1. 74	2. 18

[1] Top 1–2 feet of this sample contains the No. 1 vein, which at this locality is in the Chinle formation rather than the Navajo(?) sandstone. This assay is not included in the average.

Weeks (1951) found that the altered mudstone associated with uranium-vanadium deposits in the Morrison formation of southwestern Colorado also contains more FeO than the unaltered mudstone, whereas the content of Fe_2O_3 as well as total iron is greater in the unaltered material. No other differences except color were noted between the two types of material; even vanadium and uranium showed no significant enrichment, the samples averaging a few hundredths percent V_2O_5 and a few thousandths percent uranium.

LOCALIZATION AND ORIGIN

The deposit in the Rifle and Garfield mines has many features in common with other sandstone deposits containing vanadium and uranium on the Colorado Plateau—the primary and secondary ore minerals and the accessory minerals are largely the same; these minerals mainly occupy the sandstone pores; and the ore bodies are tabular layers that lie nearly parallel to the major bedding but do not follow beds in detail. The ore differs from that in most deposits principally in the lithologic characteristics of the host rock—the Navajo(?) and Entrada are clean massive sandstones without plant fossils in contrast to the conspicuous amount of argillaceous and carbonaceous material in ore-bearing sandstones like those in the Morrison and Chinle formations. Perhaps the uniform host rock and the lack of plant fossils are responsible for the well-defined and consistent habits of the Rifle-Garfield deposit and its relatively low uranium content.

It was hoped that an intensive study of this well-exposed deposit would reveal ore controls and origin of this deposit in particular and other deposits of the Colorado Plateau in general. Although the controls and origin were not determined, factors pertinent to them are reviewed.

SUMMARY OF RELATIONS CONSIDERED PERTINENT

1. The host sandstone units are similar in composition though different in crossbedding characteristics—the crossbedding of the Navajo(?) is dominantly torrential, whereas the crossbedding in the Entrada is of the unsystematic tangential type. The ore layers are nearly parallel to the major bedding and formational contacts and cut across the crossbedded units; they are not obviously influenced by bedding or any other small-scale sedimentary structure.
2. In other parts of the Colorado Plateau region many deposits in the Morrison formation are near the middle of sandstone lenses (Fischer, 1949, p. 11) and many deposits in the Shinarump member of the Chinle formation are in sandstones that fill channels cut in underlying rocks (Witkind, 1956, p. 233; Trites, Finnell and Thaden, 1956, p. 282); it is commonly suggested that these sedimentary structures played some part in localizing these deposits. In the Rifle Creek area both the Navajo(?) and Entrada sandstones vary in thickness, but if these variations influence the position of the Rifle-Garfield deposit, exposures do not show the relations.
3. The deposit is on the Grand Hogback monocline, about midway between two structural terraces, and in a basin of slight depression relative to small cross flexures. Dips in the ore-bearing rocks range from 15° to 30°; the deposit has a curved trend, which in part parallels the regional strike and in part rakes across the strike at a small to moderate angle.

   Fractures are abundant in the hard Navajo(?) sandstone and relatively sparse in the soft Entrada, and they seem to have the same general habits and abundance in the barren as well as the ore-bearing rocks. The ore has been brecciated and displaced along all fractures on which there has been movement, and except for secondary minerals, there is no recognized vanadium and uranium mineralization along these faults nor has there been any obvious enrichment or leaching of ore in rock adjacent to these faults. Joints also break the ore, and likewise they show no evidence of ore mineralization (except secondary minerals) nor any enrichment or leaching. These relations suggest fracturing after mineralization, but on the other hand, there is a coincidence in the trend of the deposit in the Rifle mine and the strike of the eastward-trending set of joints (see p. 40) that might suggest to some geologists fracturing before mineralization and tectonic influence on the localization of the deposit. Most of the ore rolls and thick pods of ore, on the other hand, trend about N. 75° E.—only along a small part of the deposit are they coincident in trend with the eastward-trending set of joints; elsewhere they cut across one another with no suggestion that either influenced the position of the other.

Some of the fractures are partly filled with introduced material. Calcite is most abundant, but some marcasite and a small amount of sphalerite occur in a few places; a few fractures in the Navajo(?) are filled with unconsolidated sand like that which forms the overlying Entrada. Where breccia of the mineralized or barren wallrock occurs in these fractures, it is either cemented by or engulfed in the exotic material.

Tectonic structures are not lacking at the site of the deposit, but if any of them influenced the localization of the deposit the evidence of such control is too subtle or unusual to be recognized by the writer.

4. In the barren parts of the Navajo(?) and Entrada the sand grains are partly destroyed by solution and are tightly cemented with silica and carbonate. In contrast, solution or replacement of the sand grains in the ore-bearing rock is clearly evident only in rich ore, and secondary silica and carbonate occur in pore spaces only in weakly mineralized sandstone; in most of the ore the minerals fill the pore spaces and seem to have grown on the original surfaces of the sand grains. Although relations are admittedly difficult to decipher with confidence because the ore minerals are so fine grained, the writer has no evidence that these minerals have replaced an earlier pore-filling mineral, nor any indication that the ore-bearing sandstone was specially prepared to receive and localize the minerals. Without evidence to the contrary it seems likely that little or nothing other than ordinary dia-

genesis happened to the sandstone before the ore was introduced.

5. The ore has well-defined habits and geochemical relations that are consistent throughout the deposit. It occurs in three layers that partly overlap. The lowest layer, No. 1 vein, is continuous and underlies the entire deposit. No. 2 vein forms several separate ore bodies, one of which joins No. 1 vein in the southern part of the workings at the east end of the Rifle mine, and another that joins the overlying No. 3 vein along the northwest side of the Garfield mine. If the several separate ore bodies in No. 2 vein are joined by an imaginary link, the 3 layers form a vertical S-shaped pattern about 10,000 feet long and 80 feet high.

   Five elements—vanadium, uranium, lead, selenium, and chromium—have accumulated in the deposit, and these five elements are concentrated in fairly distinct sheets within or adjoining each of the three ore layers. The sheets associated with the middle ore layer are in reverse vertical sequence with respect to their arrangement in the other two ore layers, conforming to the S-shaped pattern.

   The lowest ore layer contains the largest ore body, one that is more than 7,000 feet long and as much as several hundred feet wide. This ore body is asymmetric in cross section—on the north side the bottom of the ore is 5 to 15 feet above the base of the Navajo(?) sandstone, and the ore averages about 10 feet in thickness and decreases in grade northward to an assay wall; on the south side the ore is at or near the base of the Navajo(?) and actually passes into the underlying Chinle formation in a few places, it thins gradually to a tapering edge, and the grade is generally higher than average for the deposit as a whole.

6. In the vicinity of the deposit the top few feet of the underlying Chinle formation is altered from red to gray. This altered zone extends about two thousand feet north of the deposit and a few hundred feet south of it. Possibly this asymmetric distribution is related in some manner to the north-south asymmetry of ore in the No. 1 vein.

INFERENCES

The ore minerals crystallized from solution, at some time after the accumulation of the ore-bearing rocks and almost certainly before displacement on any fractures. Field relations would also seem to require contemporaneous formation of all three ore layers, by some pervading influence, under conditions that selectively mineralized a small part of a nearly homogeneous host and permitted the fractionation of the five elements enriched in the ore layers. Evidently the ore-bearing solution was nearly in chemical equilibrium with the host rock, for it did not alter the sandstone conspicuously, and it merely removed a small amount of iron and reduced the state of oxidation of part of the remaining iron in the underlying Chinle formation.

There is no evidence that the ore minerals replaced some earlier minerals that had selectively mineralized the host rock, nor that the ore-bearing solutions were restricted solely to the mineralized part of the rock. Mineralization was probably due to reactions within a solution that penetrated the ore-bearing formations. Changes in temperature or pressure of a solvent could cause reactions that would precipitate elements from solution at the critical point of a temperature or pressure gradient, and such a reaction might even permit fractionation of the elements. It is not easy for the writer, however, to imagine conditions that would distribute critical changes in gradient over the area of the deposit and with the pattern of the ore layers. Reactions at the interface of two fluids could also cause the precipitation of elements from one fluid or both, and such an interface might be obtained if one fluid that filled the pores of the ore-bearing formations was being displaced by another fluid. But could this interface obtain the distribution pattern of the ore layers, and could it be maintained long enough to form the minerals in and associated with the ore layers? The writer cannot answer these questions, but the concept of mineralization at the interface of two fluids seems more compatible with observed field relations.

There is no recognized evidence to suggest the source of the mineralizing solution or the elements it contained.

SUGGESTIONS FOR PROSPECTING

The only known accumulation of vanadium in the Navajo(?) and Entrada sandstones in the Rifle Creek area is in the deposit developed by the Rifle and Garfield mines. This deposit is large, and may have contained as much as 40 to 50 million pounds of V_2O_5 before mining and erosion removed part of the ore. Many geologists will doubt that a deposit so large would form completely by itself. Furthermore, other deposits of vanadium and uranium on the Colorado Plateau typically occur in clusters, a habit often observed, but best documented by the map compiled by Finch (1955). These thoughts permit some optimism that other deposits may occur in the Navajo(?) and Entrada sandstones in the vicinity. With the steep southerly dips along the Grand Hogback, however, the ore-bearing strata are deeply buried 1 or 2 miles south of the outcrop of the Navajo(?) and Entrada, so the area of feasible prospecting even for a large deposit is limited.

Lacking evidence regarding controls that localized the Rifle-Garfield deposit, the only practical suggestions for prospecting relate to the altered zone at the top of the Chinle formation and its apparent association with this deposit. The deposit offers a fairly large target for subsurface exploration, but the altered zone extends 1,000 to 2,000 feet north of the deposit and a few hundred feet south of it, thereby offering a still larger target. For example, if the Rifle-Garfield deposit had been completely buried, a pattern of drill holes spaced about half a mile apart would almost certainly have found the deposit itself or the associated altered zone in the Chinle. A pattern of holes spaced at this interval should also find indication of another deposit of like size, if one is present nearby and if it is associated with a similar altered zone.

Prospecting efforts might first be focused in the eastern part of the area, for the outcrop of the top of the Chinle in the NE¼ sec. 32, T. 4 S., R. 91 W., unsurveyed, shows discontinuous lenses of altered material ranging from 0 to about 6 inches in thickness (pl. 1). This material might indicate a deposit southwest of this outcrop, a possibility that could be tested with a few drill holes, but of course this altered material could be related to a deposit that was northeast of the outcrop and now is eroded away.

Outcrops at the top of the Chinle formation were examined at several places east of West Elk Creek and northwest of Middle Rifle Creek, but no evidence of alteration was found. These lines of outcrop, however, were not followed continuously, and thus the possibility of finding patches of altered material is not completely eliminated. At these places also the Navajo(?) and Entrada formations commonly have some sandstone beds that are reddish, a color that was not observed in these formations in the Rifle Creek area; in the opinion of the writer this reddish sandstone and that associated with it is not a likely host for large deposits.

As described on pages 36 and 38 and shown in figure 8, the Rifle-Garfield deposit is in a relatively depressed area between two minor cross flexures on the Grand Hogback monocline. If an imaginary tilt is made northward in the Rifle Creek area to compensate for the regional southerly dip, the deposit lies within a basin, the size and shape of which changes with the angle and direction of tilt selected to remove the true inclination of the beds. At the angle of tilt selected in preparing figure 8, the deposit roughly follows the 1,400-foot contour (datum arbitrarily selected) on the northwest side of the basin. Although the writer has no evidence for dating this basin relative to the time of formation of the Rifle-Garfield deposit or of the Grand Hogback monocline, if a basin actually existed when the deposit was formed and influenced its localization, ore might have formed somewhere else around the basin at approximately the same level as the Rifle-Garfield deposit. If economic conditions in the future should justify wildcat exploration for another vanadium deposit in this area, a few drill holes would test this possibility.

DEPOSITS IN THE MORRISON FORMATION

The Morrison formation in the Rifle Creek area is divisible in two poorly defined parts. The upper part is about 350 feet thick and comprises gray, green, and maroon sandstone, thin beds of limestone and sandstone, and lenses of chert-pebble conglomerate. The lower part is 150 feet thick and consists of gray and greenish-gray sandstone and gray and red mudstone; this unit contains small deposits of vanadium and uranium ore in beds of shaly sandstone 50 to 140 feet above its base. The locations of the mines and prospects on the known deposits in the Rifle Creek area are shown on plate 1. Another deposit in the Morrison was found by a drill hole near the Rifle mine, but not enough ore has yet been cut by adjacent drilling to encourage the development of this deposit. Similar deposits in the same stratigraphic interval have been prospected and mined along the outcrop eastward toward Glenwood Springs and northward toward Meeker.

The recognized ore minerals consist of micaceous and clayey vanadium minerals and tyuyamunite or carnotite. They are mainly disseminated in the sandstone, but they also partly replace some of the carbonized plant fossils that are scattered through the rock, and some of the tyuyamunite or carnotite coats joint surfaces. These ore minerals are localized in thin tabular layers, mostly only a few inches thick, but which locally thicken to form ore bodies 1 to 3 feet thick and as much as several yards across. These layers and the ore bodies lie nearly parallel to the bedding of the sandstone, but are not concordant in detail. The ore as mined has averaged 1 to 2 percent V_2O_5 and a few tenths percent U_3O_8.

RELATIONS AMONG DEPOSITS

The deposit in the Navajo(?) and Entrada sandstones and the deposits in the Morrison formation all belong to the same family. They all have the same ore metals, much the same mineralogic composition, and similar habits. Their differences need not have genetic significance—the smaller size of the known deposits in the Morrison might be due to the diverse lithologic character of the host rock, and the higher grade of uranium in the ore from the Morrison might be due to the presence of carbonized plant fossils. Yet in spite of their sameness, no physical continuity among these deposits has been observed. They are not joined by any obvious throughgoing channel way for solutions, such as a fault or a conspicuous joint system. Neither is there any obvious clustering of deposits in the Morrison near the deposit in the Navajo(?) and Entrada; rather the distribution of the known deposits in the Morrison in the Rifle Creek area and along the outcrops east and north of the area seems almost haphazard.

These relations would seem to require either the introduction of ore-bearing solutions through many channel ways or else a general invasion of the rocks by these solutions. There is no observed evidence to show the pathways along which the solutions moved, there are no recognized relations that seem to explain clearly the localization of any deposit at its exact position, and there is no available evidence to determine whether the several deposits formed at a single period of mineralization or more than one.

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