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GEOLOGY OF THE BULL CANYON QUADRANGLE, MONTROSE AND SAN MIGUEL COUNTIES, COLORADO

By Fred W. Cater, Jr.

Trace Elements Memorandum Report 692

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UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

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AEC - 569/4

Dr. Phillip L. Merritt, Assistant Director
Division of Raw Materials
U. S. Atomic Energy Commission
P. O. Box 30, Ansonia Station
New York 23, New York

Dear Phil:

Transmitted herewith is one copy of TEM-692, "Geology of the Bull Canyon quadrangle, Montrose and San Miguel Counties, Colorado," by Fred W. Cater, Jr., December 1953.

On May 14, 1952, Mr. Hosted approved our plan to publish this report in the Survey's Quadrangle Map Series.

Sincerely yours,

Douglas M. [signature]

for W. H. Bradley
Chief Geologist

Geology and Mineralogy

This document consists of 25 pages, plus 1 figure. Series A

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

GEOLOGY OF THE BULL CANYON QUADRANGLE, MONTROSE AND SAN MIGUEL COUNTIES, COLORADO*

By

Fred W. Cater, Jr.

December 1953

Trace Elements Memorandum Report 692

This preliminary report is distributed without editorial and technical review for conformity with official standards and nomenclature. It is not for public inspection or quotation.

*This report concerns work done partly on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission.

USGS - TEM-692

GEOLOGY AND MINERALOGY

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GEOLOGY OF THE BULL CANYON QUADRANGLE, MONTROSE AND SAN MIGUEL COUNTIES, COLORADO*

By Fred W. Cater, Jr.

ABSTRACT

The Bull Canyon quadrangle is one of eighteen 7 1/2-minute quadrangles covering the principal carnotite-producing area of southwestern Colorado. The geology of these quadrangles was mapped by the U. S. Geological Survey for the Atomic Energy Commission as part of a comprehensive study of carnotite deposits. The rocks exposed in the eighteen quadrangles consist of crystalline rocks of pre-Cambrian age and sedimentary rocks that range in age from late Paleozoic to Quaternary. Over much of the area the sedimentary rocks are flat lying, but in places the rocks are disrupted by high-angle faults and northwest-trending folds. Conspicuous among the folds are large anticlines having cores of intrusive salt and gypsum.

Most of the carnotite deposits are confined to the Salt Wash sandstone member of the Jurassic Morrison formation. Within this sandstone, most of the deposits are spottily distributed through an arcuate zone known as the "Uravan Mineral Belt". Individual deposits range in size from irregular masses containing only a few tons of ore to large, tabular masses containing many thousands of tons. The ore consists largely of sandstone selectively impregnated and in part replaced by uranium and vanadium minerals. Most of the deposits appear to be related to certain sedimentary structures in sandstones of favorable composition.

INTRODUCTION

The U. S. Geological Survey mapped the geology of the Bull Canyon quadrangle, Colo., as part of a comprehensive study of carnotite deposits. The study, covering the principal carnotite producing area in southwestern Colorado, included detailed examination of mines and geologic mapping of eighteen 7 1/2-minute quadrangles, of which the Bull Canyon quadrangle is one. Work was started in the area in 1939 as a cooperative project with the State of Colorado Geological

Survey Board and the Colorado Metal Mining Fund, and was continued through 1945 as a wartime strategic minerals project. Since 1947 the Geological Survey has been continuing these geologic studies on behalf of the Division of Raw Materials of the Atomic Energy Commission. A small part of the Bull Canyon quadrangle was mapped in 1944; the rest was mapped in 1947.

The Bull Canyon quadrangle covers about 59 square miles in Montrose and San Miguel Counties, Colo., and lies in the Canyon Lands division of the Colorado Plateau physiographic province. The western part of the quadrangle is a rugged area of mesas and canyons, whereas the eastern part is relatively flat and featureless. Total relief within the quadrangle is about 1,900 feet; altitudes range from about 5,250 feet in the canyon of the Dolores River to 7,175 feet on Wedding Bell Mountain. The Dolores River and its tributaries drain all the area except Dry Creek Basin in the eastern part of the quadrangle.

No accurate rainfall information is available, but the annual precipitation is probably between 10 and 15 inches; the area is semiarid and supports a moderate growth of juniper and piñon on rocky terrain, and abundant sagebrush where soils are thick. Cacti of several varieties and sparse grass are widely distributed. Most of the quadrangle is accessible over a system of dry-weather roads.

REGIONAL GEOLOGY

Rocks exposed in the area covered by the eighteen 7 1/2-minute quadrangles consist of crystalline pre-Cambrian rocks and sedimentary rocks that range in age from late Paleozoic to Quaternary. Crystalline rocks crop out only in the northeastern part of the area along the flanks of the Uncompahgre Plateau; the rest of the area is underlain by sedimentary rocks. The latest Paleozoic and earliest Mesozoic beds wedge out northeastward against the crystalline pre-Cambrian rocks. The sedimentary beds are flat lying over most of the region, but in places they are disrupted by high angle faults or are folded into northwest-trending monoclines, shallow synclines and strongly developed anticlines. The largest of the folds is the Uncompahgre Plateau uplift, a fold nearly 100 miles long that traverses the northeastern part of the area. Well-developed anticlines having intrusive cores of salt and gypsum underlie Sinbad Valley, Paradox Valley, and Gypsum Valley in the central part of the area; the Dolores anticline in the southwestern part of the area probably has a similar salt-gypsum core, although it is not exposed.

STRATIGRAPHY

The oldest rocks exposed in the Bull Canyon quadrangle are of Pennsylvanian age and are exposed in a small outcrop in Paradox Valley. Next oldest are Triassic rocks which are exposed only on the sides of Gypsum Valley and Paradox Valley. Jurassic rocks crop out along the sides of Gypsum Valley and Paradox Valley and in the canyon walls and on the benches and slopes below the mesas. Cretaceous rocks cap the mesas and underlie the floor of Dry Creek Basin. Recent deposits of wind-blown material and sheet wash are widely distributed on top of the mesas, along the benches, and on the valley floors.

The stratigraphic sequence is similar to that studied by Baker (1933) and Dane (1935) in nearby areas in Utah; most of the formations can be traced continuously from the Bull Canyon quadrangle into Utah.

Hermosa formation

Paradox member

Gypsum beds of the Paradox member of the Hermosa formation crop out in Paradox Valley a short distance northeast of the lower end of the aerial tramway from the Jo Dandy mine. The outcrop is small and is composed of massive, sandy, cellular gypsum. In exposures elsewhere outside the Bull Canyon quadrangle, the Paradox contains considerable black shale and gray sandstone; at depth, below the zone of leaching, salt is the most abundant single constituent. Baker (1933, p. 17-18) and Dane (1935, p. 27-29) assigned the Paradox beds to the lower Pennsylvanian. None of the upper limestone member of the Hermosa formation is exposed within the quadrangle.

Chinle formation

The Chinle formation of Upper Triassic age consists of red to orange-red siltstone, with interbedded red fine-grained sandstone, shale, and limestone-clay pellet conglomerate. These lithologic units are lenticular and discontinuous. The lower part of the formation contains numerous lenses of a very distinctive limestone pebble and clay pellet-conglomerate; in places the lowermost lenses contain quartz pebbles or consist of a relatively clean quartz grit. These quartz-bearing lenses are probably the stratigraphic equivalents of the Shinarump conglomerate, which is so widely distributed in eastern Utah and northern Arizona. Much of the Chinle formation consists of indistinctly bedded red siltstone that breaks into angular fragments; evenly bedded shale is rare. The sandstone layers vary in bedding characteristics; some layers are massive whereas others are cross-bedded, and still others are markedly ripple-bedded. Almost everywhere the formation crops out as a steep slope broken in places by more resistant ledges of sandstone and conglomerate.

The base of the Chinle formation is not exposed in the Bull Canyon quadrangle. The thickness, as projected from adjoining quadrangles, probably ranges from 475 feet to 525 feet, except where it thins abruptly on the flanks of the Gypsum Valley and Paradox Valley anticlines.

Glen Canyon group

The Glen Canyon group comprises in ascending order, the Wingate sandstone, the Kayenta formation, and the Navajo sandstone.

Wingate sandstone

The Wingate sandstone conformably overlies the Chinle formation. The sandstone is a massive, fine-grained rock composed of clean, well-sorted quartz sand. It typically crops out as an impressive red or dark brown wall, stained and streaked in places with red and black desert varnish. Vertical joints cut the sandstone from top to bottom; the spalling of vertically jointed slabs largely causes the recession of the cliff. The sandstone is divided into horizontal layers by extensive bedding planes spaced 2 to 50 feet apart. Within each horizontal layer the sandstone is cross-bedded on a magnificent scale; great sweeping tangential cross-beds of eolian type, in places extending across the entire thickness of the horizontal layer, are disposed in all directions. The sandstone is rather poorly cemented and crumbles easily; this quality probably accounts for the readiness with which the rock disintegrates in faulted areas.

In the Bull Canyon quadrangle the Wingate sandstone ranges in thickness from 290 to 325 feet, except along the walls of Gypsum Valley, where it thins to 200 feet, and Paradox Valley, where it thins to as little as 50 feet.

Kayenta formation

The Kayenta formation conformably overlies the Wingate sandstone; the contact between the two formations is gradational in most places. The formation is notable for its variety of rock types. Sandstone, red, buff, gray, and lavender in color, is the most abundant type; but the formation also contains considerable quantities of red siltstone, thin-bedded shale, and conglomerate. The conglomerate contains pebbles of sandstone, shale, and limestone. The sandstone is composed of rounded to subrounded quartz grains and minor quantities of mica, feldspar, and dark minerals. Most of the sandstone is thin-bedded, cross-bedded in part, and flaggy; some is massive. Individual sandstone beds are lenticular, discontinuous, and interfinger with shale, and in places, with conglomerate. The Kayenta typically crops out in a series of benches and ledges; the ledges in many places overhang recesses where softer beds have eroded back. The lower part of the formation is more firmly cemented and forms resistant thick ledges that protect the underlying Wingate sandstone from erosion.

The thickness of the Kayenta formation in the Bull Canyon quadrangle ranges from 190 to 230 feet, except on the wall of Paradox Valley below the Jo Dandy mine where the formation wedges out entirely. Abrupt local changes in thickness of 10 to 20 feet are common. The irregular bedding, channel filling, and range of thickness all indicate a fluviatile origin.

Navajo sandstone

The Navajo sandstone conformably overlies the Kayenta formation. The Navajo is a gray to buff massive fine-grained clean quartz sandstone. Tangential cross-beds of tremendous size leave little doubt of the eolian origin of the sandstone. The sandstone weathers by disintegration and tends to develop rounded topographic forms where exposed on slopes or benches and vertical cliffs where protected by overlying rocks.

The Navajo sandstone ranges from a maximum thickness of more than 200 feet in the southwestern part of the quadrangle to a knife-edge in the east and north and is absent in the area between Wild Steer Canyon and the walls of Paradox Valley.

San Rafael group

In this area the San Rafael group, of Middle and Late Jurassic age, comprises in ascending order the Carmel formation (Middle and Upper Jurassic), the Entrada sandstone (Upper Jurassic), and the Summerville formation (Upper Jurassic). The group crops out in a narrow band along the canyon walls and on the sides of buttes and mesas. The Carmel formation and the Entrada sandstone were mapped as a single unit because in most places they form a narrow outcrop.

Carmel formation and Entrada sandstone

The Carmel formation consists largely of red or buff, nonresistant, horizontally bedded siltstone, mudstone, and sandstone. In some localities the basal beds consist of reworked Navajo sandstone. Pebbles and angular fragments of white and gray chert, as much as an inch across, are scattered rather abundantly through the lower part of the formation and less abundantly through the upper part. These chert pebbles and angular fragments are sufficiently abundant locally to form layers of conglomerate. Included in these layers are scattered greenish-gray, red, or yellow quartzite pebbles and cobbles as large as 5 by 8 inches. In many places the upper part of the formation contains scattered barite nodules as much as an inch across.

In the Bull Canyon quadrangle the Carmel formation ranges from 10 feet or less to 90 feet in thickness. This range in thickness appears to be due to deposition on irregular, eroded surfaces of Navajo sandstone or beds of the Kayenta formation. No definite evidence indicates that the Carmel of this area is of marine origin as is the Carmel of central Utah, but the probabilities are that the Carmel of southwestern Colorado was deposited in shallow water marginal to a sea.

The Carmel formation grades upward, in most places without a prominent break, into the Entrada sandstone. The Entrada sandstone, known locally as the "slick rim", is, perhaps, the most picturesque of all the formations in the plateau region of Colorado. The smoothly rounded, in places bulging, orange, buff, and white Entrada cliffs are a distinctive and scenic feature of the region. Horizontal rows of pits resulting from differential weathering and ranging from a few inches to a foot or more across are characteristic of these cliffs. The Entrada consists of alternating horizontally bedded units and sweeping, eolian-type cross-bedded units. The horizontally bedded units are most common in the basal part and in the uppermost, lighter colored part of the Entrada, whereas the cross-bedded units are dominant in the middle part. The Entrada sandstone differs from the somewhat similar Wingate sandstone and Navajo sandstone by the sorting of sand into two distinct grain sizes. Subrounded to subangular quartz grains mostly less than 0.15 mm in diameter make up the bulk of the sandstone. The sandstone also contains larger grains which are well-rounded, have frosted surfaces, and range from 0.4 to 0.8 mm in diameter; most of these grains are of quartz, but grains of chert are scattered among them. Most of the large grains are distributed in thin layers along bedding planes.

The Entrada sandstone in the Bull Canyon quadrangle is 130 to 150 feet thick, except along the flanks of the Gypsum Valley and Paradox Valley anticlines, where it thins to less than 100 feet.

Summerville formation

The Summerville formation generally crops out as a steep, debris-covered slope, with very few good exposures. Where exposed the Summerville exhibits a remarkably even, thin horizontal bedding. Beds are predominantly red of various shades, although some beds are green, brown, light yellow, or nearly white. Sandy and silty shale are the most abundant kinds of rock, but all gradations from claystone to clean, fine-grained sandstone are interbedded with them. Well-rounded amber quartz grains with frosted or matte surfaces are disseminated throughout most of the formation including beds consisting almost entirely of claystone. Thin beds of authigenic red and green chert are widespread. A thin discontinuous bed of dark-gray dense fresh-water limestone occurs in the upper part of the formation. Sandstone beds are thicker and sandstone is more abundant in the lower part of the formation than in the upper part. Commonly the sandstone beds are ripple-marked, and in places they show small-scale low-angle cross-bedding.

The Summerville formation rests conformably on the Entrada sandstone, and although a sharp lithologic change marks the contact, no cessation of deposition separated the two formations. The upper contact of the Summerville is uneven and channeled, and the channels are filled by the overlying basal sandstone of the Morrison formation. Locally, however, the contact is difficult to determine because the overlying shales and mudstones of the Morrison formation are similar to beds of the Summerville.

In the Bull Canyon quadrangle the Summerville formation has a moderately uniform thickness of about 105 feet except where it thins on the flanks of the Gypsum Valley and Paradox Valley anticlines.

Morrison formation

The Morrison formation of Upper Jurassic age is of special interest economically because of the uranium- and vanadium-bearing deposits it contains. The formation comprises two members in this area; the lower is the Salt Wash sandstone member, and the upper is the Brushy Basin shale member. The thickness of the Morrison formation in the Bull Canyon quadrangle varies from place to place but generally ranges from 700 to 800 feet. The Salt Wash sandstone and the Brushy Basin shale members in general are of approximately equal thickness. In some areas, however, their thicknesses vary independently of one another, whereas in other areas a thinning in one is accompanied by a thickening in the other.

Salt Wash sandstone member

The Salt Wash sandstone member ordinarily crops out above the slope-forming Summerville formation as a series of thick resistant ledges and benches. Sandstone predominates and ranges from nearly white to gray, light buff, and rusty red. Interbedded with the sandstone are red shale and mudstone and locally a few thin lenses of dense gray limestone. Sandstone commonly occurs as strata traceable as ledges for considerable distances along the outcrop, but within each stratum individual beds are lenticular and discontinuous; beds wedge out laterally, and other beds occupying essentially the same stratigraphic position wedge in. Thus, any relatively continuous sandstone stratum ordinarily consists of numerous interfingering lenses, with superposed lenses in many places filling channels carved in underlying beds. Lenses are separated in places by mudstone and contain mudstone seams. Most of the sandstone is fine- to medium-fine-grained, cross-bedded, and massive; single beds or lenses may attain a maximum thickness of 120 feet. Ripple marks, current lineations, rill marks, and cut-and-fill structures indicate that the Salt Wash member was deposited under fluviatile conditions.

The sandstone consists largely of subangular to subrounded quartz grains, but orthoclase, microcline, and albite grains occur in combined amounts of 10 to 15 percent. Chert and heavy mineral grains are accessory. Considerable quantities of interstitial clay and numerous clay pellets occur in places, especially near the base of some of the sandstone lenses. Fossil wood, carbonaceous matter, and saurian bones occur locally.

In the Bull Canyon quadrangle the Salt Wash sandstone member ranges from 320 to 400 feet in thickness and, unlike the underlying formations, the Salt Wash does not thin along the flanks of the Gypsum Valley and Paradox Valley anticlines. Local thickness changes of as much as 30 feet are common.

Brushy Basin shale member

The Brushy Basin shale member contrasts strongly in overall appearance with the underlying Salt Wash sandstone member. Although the lithologic differences are marked, nevertheless the contact between the two members is gradational. The mapped contact, taken is the base of the lowermost layer of conglomerate lenses, is arbitrary in many respects, and probably does not mark an identical stratigraphic horizon in all localities.

The Brushy Basin shale member consists predominantly of varicolored bentonitic shale and mudstone, with intercalated beds and lenses of conglomerate, sandstone, and a few thin limestone layers. Because of the high proportion of soft, easily eroded bentonitic shale and mudstone, the Brushy Basin member forms smooth slopes covered with blocks and boulders weathered from the more resistant layers and from the overlying formations. The shales and mudstones are thin-bedded, and range from pure white to pastel shades of red, blue, and green. Exposed surfaces of the rock are covered with a loose, fluffy layer several inches thick caused by the swelling of the bentonitic material during periods of wet weather. Scattered through the shale and mudstone are thin beds of fine-grained, hard silicified rock that break with a conchoidal fracture. The silica impregnating these beds may have been derived from the devitrification of volcanic debris in adjacent beds. Beds of chert pebble-conglomerate, a few inches to 25 feet thick, occur at intervals throughout the member. These conglomerate beds are commonly dark rusty red and form conspicuous resistant ledges. Silicified saurian bones and wood are much more abundant in the Brushy Basin than in the Salt Wash sandstone member, especially in some of the conglomerate beds.

The Brushy Basin shale member, like the Salt Wash sandstone member, undoubtedly was deposited under fluviatile conditions. The conglomerate and sandstone lenses mark stream channels that crossed flood plains on which were deposited the fine-grained sediments now represented by the mudstone and shales.

The thickness of the Brushy Basin shale member in the Bull Canyon quadrangle ranges from 350 to 500 feet; erratically distributed local variations in thickness of 20 to 30 feet are prevalent throughout the quadrangle.

Burro Canyon formation

The name Burro Canyon formation was proposed by Stokes and Phoenix (1948) for the heterogeneous sequence of Lower Cretaceous conglomerate, sandstone, shale, and thin limestone lenses that overlies the Morrison formation. The Burro Canyon characteristically crops out as a cliff or a series of thick, resistant ledges. The bulk of the formation consists of white, gray, and red sandstone and conglomerate that form beds up to 100 feet thick. These beds are massive, irregular and lenticular. Cross-bedding and festoon-bedding are prevalent throughout the formation. The sandstone is poorly sorted and consists of quartz and lesser amounts of chert. The conglomerate consists largely of chert pebbles, but intermixed are pebbles of quartz, silicified limestone, quartzite, sandstone, and shale. In places beds are highly silicified. A considerable part of the formation consists of bright-green mudstone and shale, and locally these predominate over sandstone and conglomerate. Thin discontinuous beds of dense gray limestone crop out in a few scattered localities. The formation was undoubtedly deposited under fluviatile conditions. The lower contact is indistinct in many places and appears to interfinger with the upper part of the Brushy

Basin; elsewhere local erosion surfaces intervene and the contact is sharp. The upper contact is an erosion surface of regional extent.

The Burro Canyon formation in the Bull Canyon quadrangle attains a maximum thickness of about 200 feet.

Dakota sandstone

The Dakota sandstone of Early and Late Cretaceous age consists principally of flaggy gray, yellow, and buff sandstone; less abundant are conglomerate, carbonaceous shale, and impure coal. Because of its resistance to erosion, the Dakota crops out extensively as the capping beds on Wild Steer and Monogram Mesas and on the floor of Dry Creek Basin. Some of the sandstone is fine-grained and thin-bedded, but much of it is coarse-grained and cross-bedded. Scattered through the sandstone are irregular, discontinuous beds and lenses of conglomerate containing chert and quartz pebbles as much as 2 inches across. Interfingering with the sandstone beds are thinly bedded gray and black carbonaceous shales and thin coal seams and beds. Plant impressions abound in both the sandstone and shale. The entire thickness of the Dakota sandstone is not exposed in the quadrangle; the remaining beds under Dry Creek Basin in the eastern part of the quadrangle are probably about 150 feet thick.

Quaternary deposits

Extensive deposits of light-red, sandy and silty material of Quaternary age mantle the benches and mesa tops. This material appears to be mostly wind deposited, although much of it has been reworked by water and intermixed with sheet wash. These deposits have not been mapped where they are unusually spotty, discontinuous, or less than 1 foot thick; the greatest observed thickness in some dry washes on mesa tops is about 10 feet.

The floors of Gypsum and Paradox Valleys are covered with soils that, generally, differ markedly from the wind-deposited material on the mesas. These valley soils are derived not only from wind-blown material but also from the disintegration of the rocks exposed on the valley walls and floors. Very little gravel and alluvium occur in any of the stream beds. Considerable talus covers many of the steeper slopes.

Landslides consisting largely of Brushy Basin shale are prominent along the sides of Paradox Valley in the northeastern part of the quadrangle. Because the alluvium, talus, wind-deposited material, and sheet wash are difficult to differentiate in some places, they have not been separated on the geologic map.

STRUCTURE

Regional setting

Many geologic structures on the Colorado Plateau are so large that a 7 1/2-minute quadrangle covers only a small part of any complete structural unit. The larger structural units consist of salt anticlines, 45 to 80 miles long; uplifted blocks bounded by monoclinal folds, 50 to 125 miles long; and domical uplifts, 8 to 20 miles across, around stocklike and laccolithic intrusions.

The salt anticlines trend northwesterly and lie in a group between eastward-dipping monoclines on the west side of the Plateau and westward-dipping monoclines on the east side of the Plateau. The cores of these anticlines consist of relatively plastic salt and gypsum, derived from the Paradox member of the Hermosa formation and intruded into overlying late Paleozoic and early Mesozoic rocks. All the anticlines are structurally similar in many respects, but each exhibits structural peculiarities not common to the rest; furthermore, all are more complex than their seemingly simple forms would suggest. Faults, grabens, and collapse and slump structures alter the forms of the anticlines. Erosion has removed much of the axial parts of these anticlines, leaving exposed large intrusive masses of the Paradox member, and forming valleys such as Sinbad Valley, Paradox Valley, Gypsum Valley in Colorado, and similar valleys in Utah. Alternating with these anticlines are broad, shallow, simple synclines such as that underlying Dry Creek Basin in the eastern part of the Bull Canyon quadrangle.

Structure in Bull Canyon quadrangle

Most of the rocks in the Bull Canyon quadrangle are either flat lying or dipping at angles of less than 2°; only near the edges of Gypsum Valley and Paradox Valley do the dips steepen appreciably. The Dry Creek Basin syncline, of which only the northwest end lies within the quadrangle, is a simple downfold rimmed by cuestas of Cretaceous sandstone. The rocks marginal to Gypsum Valley and Paradox Valley are upturned sharply along the flanks of the anticlines that underlie these valleys. The pre-Morrison formations thin against the salt-gypsum cores of these anticlines, and the older formations dip more steeply; however, these relations are more clearly seen in nearby areas outside the quadrangle.

Complex systems of faults cut the sides of Gypsum Valley and Paradox Valley. In general the blocks and slivers formed by these faults are downthrown toward the valleys, but some blocks form small horsts. Immediately southwest of the Monogram group of mines a small graben, about 1,000 feet wide and several miles long, separates the intensely faulted walls of Paradox Valley from the long dip slopes that form Monogram and Skein Mesas.

Structural history

In order to understand the structural history of the Bull Canyon quadrangle, it is necessary to understand the structural history of the adjoining part of southwestern Colorado. Parts of this history are still in doubt, because no clear evidence remains of some events; the record of other events, although legible, is subject to different interpretations.

Weak compressive forces which probably began in early Pennsylvanian time gently warped the region. This warping gave rise to the ancestral Uncompahgre highland, an element of the ancestral Rocky Mountains, and to the basin in which the Paradox member of the Pennsylvanian Hermosa formation was deposited. These major structural features controlled the pattern and prevailing northwest-trending grain of the smaller structures later superimposed on them. The boundary between the highland and the basin, which is closely followed by the southwest margin of the present day Uncompahgre Plateau, was a steep northwest-trending front, possibly a fault scarp, along which were deposited arkosic fanglomerates during late Pennsylvanian and Permian times. The older fanglomerates interfinger with Pennsylvanian marine sedimentary rocks of the Hermosa formation. The bulk of the fanglomerates probably is of Permian age and belongs to the Cutler formation. Intrusion of salt from the Paradox member, probably initiated by gentle regional deformation, began sometime during deposition of the Permian Cutler formation.

Isostatic rise of salt ruptured the overlying Hermosa and Cutler formations and, after the Cutler was deposited, salt broke through to the surface. From then until flowage ceased, late in the Jurassic, the elongate salt intrusions such as those in Paradox Valley and Gypsum Valley stood as actual topographic highs at one place or another along their lengths. The rate of upwelling of additional salt, perhaps accelerated by the increase of the static load of the sediments accumulating in the surrounding areas, balanced or slightly exceeded the rate of removal of salt by solution and erosion at the surface. Consequently, all the Mesozoic formations to the base of the Morrison formation wedge out against the flanks of the salt intrusions. Salt flowage was not everywhere continuous or at a uniform rate; rather, in many places it progressed spasmodically. Local surges of comparatively rapid intrusion gave rise to cupolas at different times and in different places along the salt masses. At the beginning of deposition of the Morrison sediments finally covered the salt intrusions, perhaps because the supply of salt underlying the areas between the intrusions was exhausted. Relative quiescence prevailed throughout the remainder of the Mesozoic and probably through the early part of the Tertiary.

The second major period of deformation occurred in the Tertiary, probably during the Eocene (Hunt, C. B., written communication). The region of the salt intrusions was compressed into a series of broad folds, guided and localized by the pre-existing salt intrusions. Although salt flowage was renewed, it seems unlikely that any considerable amount of new salt was forced into the intrusions; flowage probably consisted largely of redistribution of the salt already present. By the end of this period of deformation these folds had attained approximately their present structural form, except for modifications imposed by later collapse of the anticlines overlying the salt intrusions. Owing to the mobility of the rocks in the cores of the anticlines, normal faulting took place along the crests of the anticlines, probably during relaxation of compressive stresses after folding ceased. At this time the crests of the anticlines in places were dropped as grabens several hundred to a few thousand feet. A period of crustal quiescence followed during which the highland overlying the anticlines and domes were reduced by erosion and topographic relief became low throughout the area.

Then during the middle Tertiary, the entire Colorado Plateau was uplifted. This uplift rejuvenated the streams and increased ground-water circulation. The crests of the anticlines were breached, and the underlying salt was exposed to rapid solution and removal. With the abstraction of salt, renewed collapse of anticline began. Although much of the collapse was due directly to removal of salt by solution, it seems unlikely that all the collapse can be attributed to this process, as was believed by earlier workers in the area. Rather, much of the collapse was apparently caused by flowage of salt from the parts of the anticlines still overlain by thick layers of sediments to the parts from which the overlying sediments had been removed. Once the crests of the anticlines had been breached, the relatively plastic salt offered little support for the beds overlying the Paradox member of the Hermosa formation in the flanks of the anticlines; consequently these essentially unsupported beds slumped, probably along fractures and joints formed during earlier flexures. Small faults and folds in Quaternary deposits may indicate that collapse and local readjustments are still continuing.

MINERAL DEPOSITS

The only commercially important mineral deposits in the Bull Canyon quadrangle are those that contain uranium, vanadium, and radium. Although deposits containing these metals were discovered in 1899 near Roc Creek, about 15 miles north of the Bull Canyon quadrangle, intensive mining of these ores did not begin in the Plateau region until 1911. Thereafter the ores were mined primarily for their radium content until 1923, when the Belgium Congo pitchblende deposits began to supply radium. The mines were mostly idle from 1923 until 1937, but since 1937 they again have been exploited intensively, first for vanadium and in more recent years for both vanadium and uranium.

Most of the deposits are restricted to the upper layer of sandstone lenses in the Salt Wash sandstone member, but within this layer the deposits have a spotty distribution. Ore bodies range from small, irregular masses, containing only a few tons of ore, to large tabular masses, containing many thousands of tons; most are small and contain only a few hundred tons. The ore consists mainly of sandstone inpregnated with uranium- and vanadium-bearing minerals.

Mineralogy

The most common ore minerals are carnotite and a fine-grained, vanadium-bearing, micaceous mineral. Carnotite ($K_2(UO_2)_2(VO_4)_2 \cdot 3H_2O$), is a yellow fine-grained earthy or powdery material.

Tyuyamunite ($Ca(UO_2)_2(VO_4)_2 \cdot nH_2O$), the calcium analogue of carnotite, is also present and is nearly indistinguishable from carnotite. The micaceous vanadium mineral, which formerly was thought to be roscoelite, is now considered to be related to the nontronite or montmorillonite group of clay minerals. It forms aggregates of minute flakes coating or partly replacing sand grains and filling pore spaces in the sandstone. It colors the rock gray. Other vanadium ore minerals present are montroseite ($nFeO \cdot nV_2O_4 \cdot nV_2O_3 \cdot nH_2O$), corvusite ($V_2O_4 \cdot 6V_2O_5 \cdot nH_2O$), and hewettite ($CaO \cdot 3V_2O_5 \cdot 9H_2O$). Corvusite and montrosite occur together, forming compact masses of bluish-black ore, whereas hewettite commonly forms stringers and veinlets along joints and fractures. Recent deeper drilling and mining in the Plateau have indicated that below the zone of oxidation black oxides of uranium and vanadium, accompanied by pyrite and perhaps other sulfides, are more abundant, and uranyl vanadates are scarce or absent.

Ore bodies

The ore consists mostly of sandstone selectively impregnated and in part replaced by uranium and vanadium minerals, but rich concentrations of carnotite and the micaceous vanadium clay mineral are also associated with thin mudstone partings, beds of mudstone pebbles, and carbonized fossil plant material. Many fossil logs replaced by nearly pure carnotite have been found. In general the ore minerals were deposited in irregular layers that roughly followed the sandstone beds. In most deposits the highest grade concentrations of ore minerals occur in sharply bounded, elongate concretionary structures, called "rolls" by the miners. These rolls are encompassed by rich, vein-like concentrations of the micaceous vanadium-bearing clay mineral that curve across bedding planes. Within these rolls this mineral generally is distributed as diffusion layers, the richer layers commonly lying nearer the margins of the rolls. The distribution of carnotite in the rolls is less systematic. Margins of ore bodies may be vaguely or sharply defined. Vaguely defined margins may have mineralized sandstone extending well beyond the limits of commercial ore; on the other hand, sharply defined margins, such as occur along the surfaces of rolls, ordinarily mark the limits of both the mineralized sandstone and the commercial ore.

Although many rolls are small and irregular, the larger ones are elongate and may extend with little change of direction for more than 100 feet. The elongate rolls in an ore body or group of ore bodies in a given area generally have a common orientation. This orientation is roughly parallel to the elongation of the ore bodies.

Origin of ore

The origin of the uranium-vanadium ores in the Morrison formation is uncertain and controversial. In some respects the deposits are unique, and much of the evidence concerning the genesis of the ore is either not conclusive or appears to be contradictory. In this brief account only a small amount of evidence can be presented and the hypotheses can only be summarized.

Most of the deposits are closely associated with certain sedimentary features. Layers of ore lie essentially parallel to the bedding; most of the deposits occur in the thicker parts of the sandstone lenses, commonly near the base of the sandstone lenses; the trend of the long direction of the deposits and the trend of the ore rolls in the sandstone are roughly parallel to the trend of the fossil logs in the sandstone and to the average or resultant dip of the cross-bedding in the sandstone. These relations strongly suggest that primary structures in the sediments were instrumental in localizing most of the ore deposits.

Recent investigations have revealed new data bearing on the origin of the ores (Waters and Granger, 1953). Below the zone of oxidation some of the ore consists chiefly of oxides, such as pitchblende and low-valent oxides of vanadium, and small quantities of sulfides such as pyrite, bornite, galena, and chalcopyrite; fully oxidized and fully hydrated minerals are either rare or nonexistent. A hard variety of uraninite, previously reported only from hydrothermal deposits, has been found in the Gray Daun mine in San Juan County, Utah (Rasor, 1952), and in the Happy Jack mine in White Canyon, Utah. Studies of lead-uranium ratios in ores from the Colorado Plateau indicate that, regardless of where or in what formation found, all the ores are of roughly the same age, and this age is no older than latest Cretaceous (Stieff and Stern, 1952). Some geologists believe field relations in pre-Morrison formations at White Canyon (Benson, and others, 1952) and Temple Mountain in Utah, indicate that the deposits may be genetically related to faults and fractures. At the Rajah mine near Roc Creek, in Colorado, ore occurs along a fault and horsetails out into the wall rock.

The main hypotheses have arisen to explain the origin of the ores. The oldest and probably the most widely held is the hypothesis that the ores are penesyngenetic and were formed soon after the enclosing rocks were deposited (Coffin, 1921; Hess, 1933; Fischer, 1937, 1942, 1950; and Fischer and Hilpert, 1952). Later movements of ground water may have dissolved and reprecipitated the ore constituents, but the essential materials were already present in the host rocks or in the waters permeating them. Although this hypothesis offers a reasonable explanation for the relation of ores to sedimentary features, it faces some difficulty in explaining: (1) the discrepancy between the age of the uranium and the age of the enclosing rock; (2) the broad stratigraphic distribution of uranium occurrences and association of ores with fractures in some localities; and (3) the hydrothermal aspect of the mineral suites in some ores. The second hypothesis, and the one the author favors, is essentially a telethermal hypothesis and assumes the ore to have originated from a hypogene source. Proponents of this hypothesis believe that ore-bearing solutions, originated at depth from an igneous source and ascended along fractures. After these solutions mingled with circulating ground waters, the minerals were precipitated in favorable beds as much as several miles from fractures. This hypothesis explains more readily the difficulties inherent in the penesyngenetic hypothesis but poses two other difficulties, namely: (1) the hypothetical location of igneous source rocks and (2) the difficulty of proving the connection between fractures and faults and the ore deposits. A third hypothesis, advanced by some geologists, suggests that the source of the ore metals was the volcanic material in the beds overlying the ore-bearing sandstone and that these metals were subsequently leached and redeposited in the beds that now contain the ore. This hypothesis encounters not only most of the difficulties in the penesyngenetic hypothesis, but it presents some additional ones of its own.

Suggestions for prospecting

Regardless of the actual origin of the deposits, certain habits of the deposits--habits that have been recognized through geologic mapping and exploration experience--are useful as guides for finding ore (Weir, 1952). In southwestern Colorado most of the deposits are in the uppermost sandstone stratum in the Salt Wash member of the Morrison formation. Generally the central or thicker parts of the sandstone lenses are more favorable--many deposits are in sandstone that is 40 feet or more thick; few deposits are in sandstone less than 20 feet thick. Cross-bedded, relatively coarse-grained sandstone is more favorable than thinly or evenly bedded, fine-grained sandstone. Light yellow-brown sandstone speckled with limonite stain is more favorable than red or reddish-brown sandstone. Sandstone that contains or is underlain by a considerable amount of gray, altered mudstone is more favorable than sandstone containing and underlain by red, unaltered mudstone--this guide is perhaps the most useful in diamond-drill exploration. If the deposits have a hypogene origin, then localities where favorable host rocks are near or are coextensive with areas of more intense deformation may be especially favorable for finding ore.

The mines

Jo Dandy group

The most productive mines in the Bull Canyon quadrangle are those of the Jo Dandy group. All the mines of this group are in one large deposit that ranges from a few inches to 15 feet in thickness and is essentially continuous along the outcrop through a distance of about 3,000 feet. In a number of respects this deposit is unique among deposits in the Morrison formation. Associated with the usual micaceous vanadium mineral are commercially important quantities of the commonly less abundant vanadium minerals, corvusite and hewettite. Not much carnotite is visible, although the ore contains considerable uranium. Gypsum saturates the sandstone as a cement and as fracture fillings. Considerable pyrite is disseminated through the ore or occurs as clusters of crystals; these clusters are 2 to 6 inches across.

The deposit consists of an essentially continuous layer of rather uniformly distributed, low-grade, disseminated ore. The margins of the ore body are indefinite, and rolls are rare. In general neither lenses of mudstone pebbles nor fossil logs are as richly mineralized as they commonly are in other deposits. Some of the richest ore consists of concentrations of corvusite in small, spherical masses 4 to 12 inches across.

The zone of collapse faulting that borders Paradox Valley cuts through the ore body, and some of the faults in the zone offset the ore as much as 50 feet.

Monogram group

The ore deposits at the Monogram group of mines are more or less typical of other deposits in the Salt Wash sandstone member. The ore minerals are carnotite and the micaceous vanadium mineral. The minor vanadium minerals, so abundant in the Jo Dandy area, are either rare or nonexistent. The ore bodies are sharply defined, irregular tabular masses as much as 600 feet long and 350 feet wide. Rolls and fossil logs are common, although the logs generally are not richly mineralized. The ore-bearing sandstone is split into an upper and a lower unit by a mudstone lens as much as 25 feet thick. Deposits occur in the base of the upper sandstone unit, and both near the top and near the base of the lower unit. Numerous faults with a displacement of a few feet cut the deposits.

Wild Steer mine

The ore body at the Wild Steer mine is unusual in that it lies only 10 to 20 feet above the base of the Salt Wash sandstone member. In addition to carnotite and the micaceous vanadium mineral, the ore also contains considerable amounts of corvusite, especially in the higher-grade ores. Copper stains are common. Fairly well-developed rolls and numerous erratically distributed high-grade lenses and "pockets" containing corvusite are characteristic of the deposit.

Tea Pot Dome mines

The Tea Pot Dome mines are the largest in the area. The deposits are in a thick channel sandstone that trends about N. 75° W. The ore minerals are carnotite and the micaceous vanadium mineral; these occur as low-grade disseminations in the sandstone, or as higher-grade concentrations confined largely to numerous rolls. The rolls curve slightly, but most have a common trend of about N. 75° W., parallel to the trend of the enclosing lens of channel sandstone. Additional ore might be found by exploring the ground southeast of the mine along the projected extension of the thick channel sandstone.

About half a mile south of Fawn Springs promising new deposits have been discovered in another thick lens of sandstone. These deposits appear to be very similar to the Tea Pot Dome deposits.

Other mines and prospects

Many other small mines and prospects are scattered along the outcrops of the Morrison formation, especially in the Bull Canyon area and along the rim of Paradox Valley. In the Bull Canyon area, although most of the larger deposits occur in the uppermost sandstone beds of the Salt Wash sandstone member, deposits are not as closely confined to those beds as is common elsewhere in western Colorado. One of the more productive mines, the Ground Hog mine, is in the conglomeratic bed in the lower part of the Brushy Basin shale member. In general, deposits in the lower part of the Salt Wash are small and consist of irregular masses of relatively high-grade ore. These deposits characteristically contain copper stains; deposits in higher beds rarely, if at all, contain any visible copper minerals.

On the rim of Paradox Valley between the Jo Dandy and Monogram groups are a number of mines known as the Opera Box group. The geologic features of the Opera Box deposits are intermediate between those of the Jo Dandy and the Monogram. Carnotite and the micaceous vanadium mineral are the important ore minerals, but corvusite and hewettite are present, as are gypsum and pyrite. Rolls are common.

Southwesterly from the Monogram mines on the Gray and Black Point claims a number of small deposits have been mined from a conglomeratic lens in the lower part of the Brushy Basin shale member. The deposits were mostly low-grade and the mineralization spotty and irregular.

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