GEOLOGY OF THE URAVAN QUADRANGLE, MONTROSE COUNTY, COLORADO

By Fred W. Cater, Jr., A. P. Butler, Jr., and E. J. McKay,
with a section on "The mines" by Robert L. Boardman

Trace Elements Memorandum Report 707

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

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IN REPLY REFER TO:

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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-707, "Geology of the Uravan quadrangle, Montrose County, Colorado," by Fred W. Cater, Jr., A. P. Butler, Jr., and E. J. McKay, with a section on "The mines" by Robert L. Boardman, March 1954.

We are asking Mr. Hosted to approve our plan to publish this report in the Survey's Quadrangle Map Series.

Sincerely yours,

for W. H. Bradley
Chief Geologist

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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 URAVAN QUADRANGLE, MONTROSE COUNTY, COLORADO*

By

Fred W. Cater, Jr., A. P. Butler, Jr., and E. J. McKay, with a section on "The mines" by Robert L. Boardman

March 1954

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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-707

GEOLOGY AND MINERALOGY

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By Fred W. Cater, Jr., A. P. Butler, Jr., and E. J. McKay
with a section of "The mines" by Robert L. Boardman

ABSTRACT

The Uravan 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 Uravan 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 Uravan quadrangle is one. Parts of the texts accompanying these maps have been standardized; these parts comprise some descriptions of geologic formations and general descriptions of regional structural setting, geologic history, and ore deposits. A comprehensive report presenting in greater detail the geologic features of the entire area and interpretations of these features is in preparation. 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 this geologic study on behalf of the Division of Raw Materials of the Atomic Energy Commission. The Uravan quadrangle was mapped in 1941 and 1948.

The Uravan quadrangle covers about 59 square miles in Montrose County, Colo., and lies in the Canyon Lands division of the Colorado Plateau physiographic province. The quadrangle is largely a rugged area of mesas and canyons, but considerable areas on the larger mesas and in Paradox Valley are relatively flat and featureless. Total relief within the quadrangle is about 1,900 feet; altitudes range from about 4,940 feet in the canyon of the San Miguel River to 6,849 feet on the northeast rim of Paradox Valley. The San Miguel River and its tributaries drain all the area except Paradox Valley which is drained by East Paradox Creek.

No accurate information on rainfall 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 and sparse grass are widely distributed. Most of the quadrangle is accessible over Colorado Highway 141 and a system of dry-weather roads.

REGIONAL GEOLOGY

Rocks exposed in the 18 quadrangles mapped 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, but later Mesozoic units were deposited on top of the pre-Cambrian rocks. Over most of the region the sedimentary beds are flat lying, but in places they are disrupted by high-angle faults, or 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 salt-gypsum core, although it is not exposed.

The quadrangle lies in the east-central part of the 18-quadrangle area, about eight miles southwest of the Uncompahgre Plateau; the southwest corner of the quadrangle is traversed by the edge of Paradox Valley.

STRATIGRAPHY

The oldest rocks exposed in the Uravan quadrangle are Upper Triassic beds that crop out along the sides and on the floor of Paradox Valley. Rocks of Pennsylvanian and Permian age, although not exposed within the quadrangle, crop out extensively in adjacent quadrangles. Jurassic rocks crop out along the sides of Paradox Valley and in the canyon walls and on the benches and slopes below the mesas. Cretaceous rocks cap the mesas. 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. Terrace gravels occur along the San Miguel River at various altitudes as much as 700 feet above the present river level.

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 Uravan quadrangle into Utah.

Chinle formation

The Upper Triassic Chinle formation consists of red to orange-red siltstone, with interbedded red fine-grained sandstone, shale, and limestone pebble and clay pellet-conglomerate. These lithologic units are lenticular and discontinuous. The lower part of the formation contains numerous lenses of a highly distinctive limestone pebble and clay pellet-conglomerate; in places the lowermost lenses contain quartz pebbles or consist of a relatively clean quartz grit. These lenses are probably the stratigraphic equivalent of the Shinarump conglomerate, which is 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 differ in bedding characteristics;

some layers are massive, whereas others are cross-bedded, and still others are conspicuously 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 Uravan quadrangle. The formation, as projected from adjoining quadrangles, probably ranges from 375 to 425 feet in thickness, except where it thins abruptly on the flanks of the Paradox Valley anticline.

Glen Canyon group

The Glen Canyon group, of Jurassic (?) age, 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 a surficial 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 from 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 layers, 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 Uravan quadrangle the Wingate sandstone, where exposed, ranges in thickness from 160 to 240 feet, a thickness somewhat less than normal because of thinning on the flanks of the Paradox Valley anticline.

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 and 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 Kayenta formation in the Uravan quadrangle ranges in thickness from 190 to 210 feet. 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 eastern edge of the Navajo sandstone follows an irregular course through the westernmost part of Colorado, and the only Navajo in the Uravan quadrangle is part of a fairly large disconnected lens that crops out around the town of Uravan. The Navajo, which conformably overlies the Kayenta formation, is a massive, fine-grained, gray to buff, clean quartz sandstone. Tangential cross-beds of tremendous size leave little doubt of the eolian origin of the sandstone, although around Uravan cross-beds are not so large, and horizontal bedding planes are more common than in other areas. The sandstone is friable and weathers to rounded topographic forms where exposed on slopes or benches and vertical cliffs where protected by overlying rocks. It reaches a maximum thickness in the quadrangle of 40 feet.

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 San Miguel River in the northwest part of the quadrangle and the northeast side of Paradox Valley. 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 to buff, soft, 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. Locally these chert pebbles and angular fragments are sufficiently abundant to form layers of conglomerate. In many places the upper part of the formation contains scattered barite nodules as much as an inch across.

In the area of the Uravan quadrangle the Carmel formation ranges from less than 10 feet to 20 feet in thickness. This range appears to be due chiefly to deposition on irregular, eroded surfaces of Navajo sandstone or beds of the Kayenta formation. No definite evidence indicates that the Carmel formation 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 prominent breaks, into the Entrada sandstone. The Entrada sandstone, known locally as the "slick rim" because of its appearance, is perhaps the most strikingly picturesque of all the formations in the plateau region of Colorado. The smoothly rounded, in places bulging, orange, buff, and white cliffs formed by this sandstone 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 larger grains are distributed in thin layers along bedding planes.

The Entrada sandstone is 90 to 110 feet thick in the Uravan quadrangle.

Summerville formation

The Summerville formation generally crops out as a steep, debris-covered slope, with a 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-colored 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. Regionally the upper part of the Entrada and the lower part of the Summerville intertongue, and the contact does not occur everywhere at the same stratigraphic horizon. The upper contact of the Summerville is uneven and channeled, and the channels are filled by the overlying basal sandstones 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 Uravan quadrangle the Summerville formation is about 100 feet thick.

Morrison formation

The Morrison formation, of Late 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. In the Uravan quadrangle the Morrison formation ranges in thickness from 600 to 750 feet. The Salt Wash sandstone member and the Brushy Basin shale member in general are of approximately equal thickness. In some areas, however, their thicknesses vary independently, whereas in other areas a thinning in one member 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 in color 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.

The Salt Wash sandstone member ranges from 300 to 360 feet in thickness and, unlike the underlying formations, does not thin along the flanks of the Paradox Valley anticline. Local changes in thickness 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, the contact between the two members is gradational. The mapped contact, taken as 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 and sandstone, and a few thin layers of limestone. Because of its 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 of the member and from the overlying formations. The shales and mudstones are thin-bedded and range in color from pure white to pastel tints of red, blue, and green. Exposed surfaces of the rock are covered with a loose, fluffy layer of material 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 breaks with a conchoidal fracture. The silica impregnating these beds may have been released during 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 shale member 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 floodplains on which were deposited the fine-grained sediments now represented by the mudstone and shale.

Within the quadrangle the Brushy Basin shale member ranges from 300 to 500 feet in thickness; local variations in thickness of 20 to 30 feet are common.

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 lenses of limestone 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 as much as 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 the 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 shale member; 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 Uravan quadrangle is 160 to 200 feet thick; abrupt local variations in thickness of 10 to 30 feet are common.

Dakota sandstone

The Dakota sandstone of Early and Late Cretaceous age crops out extensively as capping beds on the mesas northeast of the San Miguel River because of its resistance to erosion. The Dakota consists principally of gray, yellow, and buff flaggy sandstone; less abundant are conglomerate, carbonaceous shale, and impure coal. 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 thin-bedded gray and black carbonaceous shales and thin coal seams and beds. Plant impressions abound in both the sandstone and the shale. The entire thickness of the Dakota sandstone is not exposed in the quadrangle, the upper beds have been stripped off by erosion, but as much as 100 feet of Dakota beds are preserved in a few places.

Quaternary deposits

The deposits of Quaternary age consist of wind-deposited material, alluvium, talus, and terrace gravel. Entensive deposits of light-red sandy and silty material 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 a foot thick; the greatest observed thicknesses in some dry washes on mesa tops is about 10 feet. The floor of Paradox Valley is covered with soils that generally differ markedly from the wind-deposited material on the mesas. These valley soils are derived not only from windblown material but also from the disintegration of the rocks exposed on the valley walls and floors. Gravel and alluvium cover the floor of the San Miguel River valley. Considerable talus covers many of the steeper slopes. Terrace gravel, containing pebbles and cobbles of various intrusive and extrusive rocks from the headwater areas of the river in the San Juan Mountains, occurs along the San Miguel River at several altitudes as much as 700 feet above the stream. Because these various deposits, other than the terrace gravel, 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, 50 to 125 miles long, bounded by monoclinal folds; 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 Pennsylvanian 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, and Gypsum Valley in Colorado and similar valleys in Utah. Alternating with these anticlines are broad, shallow, simple synclines.

Structure in Uravan quadrangle

The Uravan quadrangle lies near the southeast end of the system of salt anticlines and is crossed by the northeast flank of the Paradox Valley anticline. The San Miguel syncline crosses the northeast part of the quadrangle. Most of the rock strata in the quadrangle either are horizontal or dip at angles of less than 2°; only near the edge of Paradox Valley do the dips steepen appreciably. The rocks marginal to Paradox Valley are upturned sharply along the flanks of the anticline that underlies the valley. The pre-Morrison formations thin against the salt-gypsum cores of these anticlines, and the older pre-Morrison formations dip more steeply than the younger; however, some of these relations can be seen more clearly in nearby areas outside the quadrangle.

Particularly striking are the complex systems of faults that cut the sides of Paradox Valley. In general the blocks and slivers formed by these faults are downthrown toward the valleys, but some blocks form small horsts. These faults formed with collapse of the anticline because abstraction of the underlying salt, by both solution and plastic flowage, left the overlying beds unsupported. The two faults of small displacement that cut Second and Third Parks probably also reflect a gravity adjustment to the abstraction of salt.

Structural history

In order to understand the structural history of the Uravan 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 record remains of some events; the record of other events, although legible, is subject to different interpretations. All the events described in the following discussion affected the Uravan quadrangle either directly or indirectly, although the evidence for some of them is not visible within the quadrangle boundaries.

Weak compressive forces which probably began in early Pennsylvanian times, 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 Hermosa formation of Pennsylvanian age was deposited. These major structural features controlled the pattern and the 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 time. 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 formation and at the end of Cutler deposition 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 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, 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 highlands overlying the anticlines and domes were reduced by erosion and topographic relief became low throughout the area.

During 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 the anticlines 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 apparently was 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 Uravan quadrangle are those that contain uranium, vanadium, and radium. Although deposits containing these metals were discovered in 1899 near Roc Creek, about 10 miles northwest of the Uravan 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 Belgian 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, but most ore bodies are relatively small and contain only a few hundred tons. The ore consists mainly of sandstone impregnated 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 mineral. 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 montroseite 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 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, veinlike 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 and 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.

Two 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 a few 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 the 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: 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 sandstone 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 considerable amounts of or is underlain by a considerable thickness 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 coextensive with areas of more intense deformation may be especially favorable for finding ore.

In the Uravan quadrangle the most likely area for finding ore, because of the presence of favorable host rocks, is the part north of Paradox Valley and west of a line roughly between the Bitter Creek mines and Spring Creek Mesa. The largest mines are in the Long Park area, an area cut by many joints and relatively close to the faults paralleling Paradox Valley. The faults northeast of the San Miguel River are in areas of generally unfavorable host rocks.

The mines

By Robert L. Boardman

Numerous deposits are scattered over the west half of the Uravan quadrangle, and several of the mines have been among the larger ore producers on the Colorado Plateau. Most of the deposits are in the uppermost layer of sandstone lenses of the Salt Wash sandstone member of the Morrison formation.

Recently, extensions of old deposits and new discoveries have been found by extensive drilling programs in the southwestern quarter of the Uravan quadrangle. Most of the exploration near old workings and in areas where the ore zone is relatively shallow in depth has been conducted by private industry; however, in areas where the ore zone is deeper and where the cost of drilling has been too great for private concerns, the exploration has been undertaken by the Geological Survey on behalf of the Atomic Energy Commission,

Long Park No. 6 mine

The Long Park No. 6 mine is one of the most productive in the area. The ore is erratically distributed through two ore layers in a relatively thin sandstone lens in the upper part of the Salt Wash. The lens is 20 to 25 feet thick, whereas the other large deposits in the Long Park area are in sandstone lenses more than 30 feet thick. Some of the ore bodies are lenticular, others are tabular; rolls occur in both types. The chief ore minerals are carnotite and the micaceous vanadium clay mineral; these occur as disseminations in the sandstone. Carnotite is also present along mudstone seams and in "trash pockets". Local concentrations of corvusite, hewettite, and montroseite form scattered high-grade pockets commonly associated with fossil logs or other carbonaceous material. The trend of the ore bodies, mineralized logs, and rolls is east to northeast.

Black Dinah mine

The Black Dinah mine is one of the oldest large producers in the Long Park area. The deposits are in the upper part of the Salt Wash in a sandstone stratum 30 to 35 feet thick, consisting of three large overlapping lenses of ore. The ore in these lenses consists of sandstone impregnated with disseminated carnotite and the micaceous vanadium clay mineral. The few scattered rolls and mineralized logs trend east to northeast. Small amounts of corvusite and hewettite occur locally.

Bitter Creek mines

Deposits in the Bitter Creek mines are large, extensive, and of unusual mineralogic interest. They occur in the uppermost Salt Wash in a sandstone lens about 50 to 60 feet thick that dips about 15° to the northeast. The ore bodies near the outcrop consist of broad rolls and lenticular masses associated with abundant gypsum seams of an inch or more in thickness. The ore is relatively low-grade in this part of the mine, and consists predominantly of the micaceous vanadium clay mineral disseminated in the sandstone. Carnotite occurs in relatively small amounts as stainings along fractures and in association with mudstone seams. The ore bodies down dip remote from the outcrop are predominantly high-grade pockets erratically distributed in a gray sandstone devoid of limonite stains. Less gypsum is found at depth, but the ore commonly is associated with finely disseminated pyrite and with carbonaceous material. The ore minerals are corvusite, hewettite, vanadium clay, montroseite, and one or more unidentified black uranium minerals. The rich pockets become smaller and more erratically distributed with increasing depth. Some widely scattered mineralized logs are present in the lower workings. The logs and rolls in the Bitter Creek group generally trend northeast.

Other deposits

Elsewhere in the western half of the Uravan quadrangle, a large number of small deposits have been worked. Most of these are similar to the larger deposits but are generally of lower grade.

The Rock Raven mine, a small mine in the northwestern corner of the quadrangle, is unique in that the ore occurs in a conglomeratic sandstone lens of the Brushy Basin shale member of the Morrison formation, about 100 feet above the uppermost sandstone stratum of the Salt Wash sandstone member. The ore occurs in tabular, irregular, and lenticular masses; rolls are poorly defined and mineralized logs are absent. Ore minerals are micaceous vanadium clay and carnotite. Some of the carnotite occurs in mudstone seams and along bedding planes of the sandstone.

The Rambler workings in the Club group of mines expose large, essentially tabular ore bodies. Ore also occurs in numerous large rolls and as high-grade replacement of fossil trees or in halos surrounding fossil wood and trash. Ore minerals are predominantly carnotite and micaceous vanadium clay. The ore bodies and better developed rolls are oriented in a general northeasterly direction.

Recently, drilling by the Geological Survey on behalf of the Atomic Energy Commission has partially outlined large ore bodies a few thousand feet northeast of the Black Dinah mine. These deposits are in the uppermost Salt Wash sandstone stratum in a lens about 40 feet thick. The sandstone appears gray and unoxidized in the drill core. The ore apparently is associated with pyrite and gypsum, and is composed of vanadium clay minerals and one or more unidentified black uranium minerals.

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