GEOLOGY OF THE NATURITA NW QUADRANGLE, COLORADO

By Fred W. Cater, Jr.,
with a section on "The Mines" by J. D. Vogel

Trace Elements Memorandum Report 702

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

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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-702, "Geology of the Naturita NW quadrangle, Colorado," by Fred W. Cater, Jr., with a section on "The Mines" by J. D. Vogel, November 1953.

On November 27, 1953, Mr. Hosted approved our plan to publish this report in the Quadrangle Map Series.

Sincerely yours,

Dwight M. Lemmon

for W. H. Bradley
Chief Geologist

Geology and Mineralogy

This document consists of 27 pages,
plus 1 figure.
Series A

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

GEOLOGY OF THE NATURITA NW QUADRANGLE, COLORADO*

By

Fred W. Cater, Jr.,

with a section on "The Mines"

by J. D. Vogel

November 1953

Trace Elements Memorandum Report 702

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 on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission.

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GEOLOGY OF THE NATURITA NW QUADRANGLE, COLORADO

By Fred W. Cater, Jr.
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ABSTRACT

The Naturita NW 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 on behalf of 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 Naturita NW 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 Naturita NW 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 Naturita NW quadrangle was mapped in 1948.

The Naturita NW 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 southwestern part of the quadrangle is a fairly smooth, sloping surface, and the floor of Paradox Valley is relatively flat, but the walls of Paradox Valley and the canyon of Dry Creek are rough and precipitous. Total relief within the quadrangle is about 1,850 feet; altitudes range from about 5,520 feet in Paradox Valley to 7,360 feet on the south rim of the Valley. Dry Creek and East Paradox Creek drain all the quadrangle except Sawtooth Ridge which drains directly into the San Miguel River a short distance north of the quadrangle.

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 90 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 northeast 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 southwest part of the area probably has a salt-gypsum core, although it is not exposed.

The Naturita NW quadrangle lies in the east-central part of the area, about 12 miles southwest of the Uncompahgre Plateau. The quadrangle lies astride the east end of Paradox Valley.

STRATIGRAPHY

The oldest rocks exposed in the Naturita NW quadrangle are of early Pennsylvanian age and are exposed in Paradox Valley and in the canyon of Dry Creek. Rocks of late Pennsylvanian age crop out in Paradox Valley and rocks of Permian age crop out in the canyon of Dry Creek. Rocks of Triassic and Jurassic age are exposed along the sides of Paradox Valley and in Dry Creek, whereas rocks of Cretaceous age underlie most of the rest of the quadrangle. 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, and landslides cover large areas on the southwest side of Paradox Valley.

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 Naturita NW quadrangle into Utah.

Hermosa formation

The Pennsylvanian Hermosa formation comprises two members in this area; these are the lower or Paradox member, consisting largely of intrusive salt and gypsum, and the upper or limestone member.

Paradox member

The Paradox member, where exposed, consists largely of cellular and earthy gypsum and minor amounts of limestone, sandstone, and black shale. At depth more than half the member is rock salt. All known surface occurrences of the Paradox are intrusive, and the beds are completely folded and contorted. The true, undisturbed thickness of the member is not known, but a well drilled in the center of Paradox Valley in the northwest corner of the quadrangle penetrated over 10,800 feet of intrusive beds without reaching pre-Paradox rocks. Baker (1933, p. 17-18) and Dane (1935, p. 27-29) assigned the Paradox beds to the lower Pennsylvanian.

Limestone member

Presumably the upper or limestone member of the Hermosa formation conformably overlies the Paradox member. The beds mapped in Paradox Valley as belonging to the limestone member may possibly be limestones of the Paradox member. In other areas, where well-exposed, the limestone member consists almost entirely of gray thick-bedded marine limestone. Data from bore-holes in nearby areas indicate the member is 2,000 to 2,300 feet thick. The member is probably of late Pennsylvanian age.

Cutler formation

Less than 200 feet of the uppermost beds of the Permian (?) Cutler formation are exposed in the Naturita NW quadrangle. These beds consist of maroon, purple, red, and mottled light-red arkosic conglomerate and conglomeratic sandstone and reddish-brown sandy mudstone. Beds are poorly sorted, rudely cross-laminated, and lenticular. The source of the material in the formation was the mass of crystalline pre-Cambrian rocks forming the ancestral Uncompahgre Highland which lay to the northeast.

Moenkopi formation

Less than 100 feet of beds belonging to the Lower Triassic Moenkopi formation are exposed in the quadrangle. These beds unconformably overlie the Cutler formation and are probably part of the lower member of the Moenkopi. The beds consist of poorly sorted reddish-brown mudstone with scattered sandstone and arkosic sandstone beds. The middle and upper members were removed by erosion prior to deposition of the overlying Chinle formation.

Chinle formation

The Upper Triassic Chinle formation consists of red to orange-red siltstone, with interbedded red fine-grained sandstone, shale, and limestone pebble-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-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 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 Chinle formation where exposed in the canyon of Dry Creek is about 520 feet thick. Toward the center of Paradox Valley it thins and over the top of the salt-gypsum core of the anticline it disappears.

Glen Canyon group

The Glen Canyon group, of Jurassic (?) age, comprises, in the Naturita NW quadrangle, the Wingate sandstone and the Kayenta formation.

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 layer, are disposed in all directions. The sandstone is poorly cemented and crumbles easily; this quality probably accounts for the readiness with which the rock disintegrates in faulted areas.

In the Naturita NW quadrangle the Wingate sandstone attains a maximum exposed thickness of 240 feet. It thins to a vanishing edge along the walls of Paradox Valley.

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 Naturita NW quadrangle has a maximum exposed thickness of 220 feet, but it wedges out entirely on the south wall of Paradox Valley. 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.

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), and Entrada sandstone (Upper Jurassic), and the Summerville formation (Upper Jurassic). The group crops out in a narrow band along canyon walls and on the sides of Paradox Valley. The Carmel formation and the Entrada sandstone were mapped together 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. These chert pebbles and angular fragments are sufficiently abundant locally to form layers of conglomerate. The upper part of the formation contains scattered barite nodules as much as an inch across.

The Carmel formation has a maximum thickness of 10 feet, but in many places it is very thin or missing. The variations in thicknesses and absence of the formation locally appears to be due chiefly to deposition on irregular, eroded surfaces of the Kayenta formation. No definite evidence indicates that the Carmel formation of this area is of marine origin as is the Carmel formation of central Utah, but the probability is 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 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 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 100 feet thick, except along the flanks of the Paradox Valley anticline, where it thins and possibly wedges out.

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-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.

The Summerville formation in the Naturita NW quadrangle has a moderately uniform thickness of about 105 feet except where it thins on the flanks of the Paradox Valley anticline.

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 Naturita NW quadrangle the Morrison formation ranges in thickness from 600 to 800 feet. Commonly the Salt Wash sandstone member is somewhat thinner in the Naturita NW quadrangle than the Brushy Basin shale member. In some areas the thicknesses of the two members 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 broad 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. Features indicative of fluviatile origin, such as ripple marks, current lineations, rill marks, and cut- and-fill structures, are abundant.

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 280 to 340 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 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 layer of loose, fluffy 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 very 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 flood plains on which were deposited the fine-grained sediments now represented by the mudstone and shale.

The Brushy Basin shale member ranges from 320 to 480 feet in thickness; 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 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 forms 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 Naturita NW quadrangle is 160 to 250 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 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 total thickness of the Dakota sandstone where exposed on Dry Creek is about 195 feet, but the upper beds have been stripped off by erosion over much of the quadrangle.

Mancos shale

The Upper Cretaceous Mancos shale is a soft, homogeneous, dark-gray fissile rock. It crops out in the downwarped area beyond the southeastern end of Paradox Valley. Only the basal 50 feet of the formation is exposed in the area.

Quaternary deposits

The deposits of Quaternary age consist of lithified fanglomerate, wind-deposited material, alluvium, talus, and landslides. A hard, thoroughly cemented fanglomerate crops out on a low hill in Paradox Valley. The fanglomerate consists of a poorly sorted, rudely bedded accumulation of sand and angular fragments and boulders derived from the older formations in the walls of the valley. The age of this deposit is uncertain but it may possibly be as old as Pliocene. Extensive deposits of light-red sandy and silty material mantle the long dip slopes northeast and southwest of Paradox Valley. 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 thickness 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 wind-blown material but also from the disintegration of the rocks exposed on the valley walls and floors. Gravel and alluvium cover some of the stream beds. Considerable talus has accumulated on many of the steeper slopes. Because these various deposits are difficult to differentiate in some places, they have not been separated on the geologic map. Great landslides consisting largely of Brushy Basin debris blanket parts of the southwest side of Paradox Valley.

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 northwest 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, and Gypsum Valley in Colorado and similar valleys in Utah. Alternating with these anticlines are broad, shallow, simple synclines.

Structure in Naturita NW quadrangle

The Naturita NW quadrangle lies across the Paradox Valley salt anticline near its southeastern end. This anticline, which is the dominant structural feature in the quadrangle, is asymetrical and its axial plane dips steeply southwest. The salt core of the anticline consists of two distinct but connected segments. The southeast segment is offset more than a mile to the northeast. A similar offset is apparent in the Gypsum Valley salt anticline which lies a few miles to the southwest. The crest of the anticline over each of these segments has collapsed, but the form of the collapse structures over the two segments differ. The strata in the crest of the northwest segment have been stripped away by erosion, and the rocks in the valley walls are cut by complex systems of faults resulting from removal of the underlying salt by solution and from foundering of the rocks in the flanks of the anticline into the relatively plastic salt. On the other hand, strata overlying the crest of the southeast segment have sagged to form a simple basin-like downwarp, rimmed on the southwest and northeast by faulted anticlines. The northwest edge of the downwarp coincides with the line of offset and is marked by a complex system of faults and sharp fold. The difference in the collapse structures reflects the difference in their manner of development. Probably, collapse of the northwest segment occurred first when the ancestor of East Paradox Creek breached the crest of the anticline and exposed the underlying salt to rapid solution and removal. With removal of the strata overlying the northwest segment, a pressure differential was established between the two segments of the salt core, and the salt was squeezed from the southeast segment into the northwest segment where it was carried away in solution. Eventually a state of comparative isostatic equilibrium was reached, and the surface of the basin in the southeast segment, which is floored with heavier beds, lies about 100 feet below the floor of the northwest segment in Paradox Valley.

Structural history

In order to understand the structural history of the Naturita NW 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 Naturita NW quadrangle either directly or indirectly, although the evidence for some of them is not visible within the boundaries of the quadrangle.

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 closely followed 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 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 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 the Morrison deposition in the area, 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), but the date cannot be determined accurately. 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.

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 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 Naturita NW quadrangle are those that contain uranium, vanadium, and radium. Although deposits containing these metals were discovered in 1899 near Roc Creek, about 15 miles northwest of the Naturita NW 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 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, 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 the ores are found, all are of roughly the same age, and this age is no older than latest Cretaceous (Stieff and Stern, 1952). In pre-Morrison formations at White Canyon (Benson, and others, 1952) and Temple Mountain in Utah, some geologists believe field relations indicate that the deposits may be genetically related to faults and fractures. At the Rajah mine near Roc Creek, Colo., 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 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; (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 sandstones 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 coextensive with areas of more intense deformation may be especially favorable for finding ore.

The largest known deposits in the Naturita NW quadrangle lie in an area where favorable host rocks are traversed by a zone of more intense deformation. This area, which lies on the southwest side of Paradox Valley north of Monogram Mesa, is also the most likely area in which to search for new deposits. Monogram Mesa may be underlain by favorable host rocks and should be explored by deep drilling. Elsewhere in the quadrangle the host rocks, where exposed, are generally unfavorable.

The mines

by J. D. Vogel

Thunderbolt mine

The ore deposits at the Thunderbolt mine are in the uppermost sandstone stratum of the Salt Wash sandstone member of the Morrison formation and in the basal conglomeratic sandstone layer of the Brushy Basin shale member. The upper sandstone layer of the Salt Wash, the ore-bearing layer, is split into three separate units by mudstone lenses as much as 15 feet thick. Only the two upper units are mineralized. The deposits consist of irregular, tabular masses of disseminated ore as much as 600 feet long and 300 feet wide. These deposits are unusual, in that commercially important quantities of the vanadium minerals montroseite and corvusite are associated with the usual micaceous vanadium clay mineral. Disseminated carnotite is common locally, but high-grade concentrations are rare, although the ore contains considerable uranium. Gypsum is fairly common as a cement and as fracture fillings. Abundant pyrite is scattered through the rock. Only a few rolls and fossil logs have been found, and the logs are rarely mineralized. The deposits are cut by a number of recent faults having displacements of a few feet.

Oversight claim

The Oversight claim is on the large Jo Dandy ore body, most of which lies in the adjacent Bull Canyon quadrangle. This ore body is similar in most respects to the deposits in the Thunderbolt mine except that it is much larger. The ore body is an essentially continuous layer of rather uniformly distributed low-grade disseminated ore. The margins of the ore body are indefinite, and rolls are rare. Micaceous vanadium clay, montroseite, and corvusite are the most abundant ore minerals; carnotite is rare although the deposit contains considerable uranium.

Other deposits

Recent exploration by the U. S. Geological Survey on behalf of the Atomic Energy Commission has discovered another large deposit between the Thunderbolt mine and the west edge of the quadrangle north of the Oversight claim. The deposit ranges from a few inches to 15 feet in thickness and has a known length of 3,000 feet and a width of 2,000 feet. It is possible the deposit connects with the Jo Dandy deposit. Diamond-drill information indicates the deposit is similar to the Jo Dandy and the Thunderbolt deposits.

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List of patented claims

1. Oversight

2. Paradox D

3. Paradox C

4. Paradox B

5. Paradox A

6. Great Western

7. Great Eastern

8. Canary Bird No. 2

9. Thunderbolt

10. J. J.