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GEOLOGY OF THE PARADOX QUADRANGLE, MONTROSE COUNTY, COLORADO

By C. F. Withington

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Trace Elements Memorandum Report 703

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

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IN REPLY REFER TO:

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DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
WASHINGTON 25, D. C.

MAR 3 1 1954

AEC - 687/4

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

Dear Phil:

Transmitted herewith is one copy of TEM-703, "Geology of the Paradox quadrangle, Montrose County, Colorado," by C. F. Withington, January 1954.

On February 3, 1954, 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 28 pages, plus 1 figure.
Series A

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

GEOLOGY OF THE PARADOX QUADRANGLE, MONTROSE COUNTY, COLORADO*

By

C. F. Withington

January 1954

Trace Elements Memorandum Report 703

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

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ILLUSTRATION

Preliminary geologic map and section of the Paradox Quadrangle, Colorado . . . . . In envelope

GEOLOGY OF THE PARADOX QUADRANGLE, MONTROSE COUNTY, COLORADO*

By C. F. Withington

ABSTRACT

The Paradox 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 Paradox 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 Paradox quadrangle is one. Parts of the texts accompanying these maps have been standardized; these parts include some descriptions of geologic formations and general descriptions of regional structural setting, geologic history and ore deposits. Comprehensive reports presenting in greater detail the geologic features are 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 Paradox quadrangle was mapped in 1948.

The Paradox quadrangle covers about 59 square miles in Montrose County, Colo., and lies in the Canyon Lands division of the Colorado Plateau physiographic province. Much of the quadrangle is a rugged area of mesas and canyons, but Paradox Valley, which traverses the northeastern part of the quadrangle is relatively flat and featureless. Total relief within the quadrangle is about 2,360 feet; altitudes range from about 4,940 feet at the Dolores River in the eastern part of the quadrangle in Paradox Valley to about 7,300 feet on Wray Mesa in the western part of the quadrangle. The Dolores River and its tributaries drain the area.

Precipitation, as measured in the town of Paradox, averages about 11 inches a year. The area is semiarid and supports a moderate growth of juniper and piñon on rocky terrain and abundant sagebrush and salt bush where the soils are thick. Cacti and sparse grasses are widely distributed. Some tamarisk, willow, and cottonwood trees grow along the Dolores River in Paradox Valley. Fruit and truck produce are grown in the irrigated parts of Paradox Valley.

Paradox Valley and the western part of La Sal Creek are accessible by Colorado Highway 90, which traverses the valley and crosses into the La Sal Creek Canyon in the western part of the quadrangle. The lower part of La Sal Creek Canyon and part of the Dolores River canyon are accessible by dry weather roads. The mesa tops are accessible only by stock trails.

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 Paradox quadrangle lies in the western part of the area mapped, about 12 miles southwest of the Uncompahgre Plateau, and about 3 miles east of the Colorado-Utah state line. The settlements of Bedrock and Paradox are in Paradox Valley, within the boundary of the quadrangle.

STRATIGRAPHY

The oldest rocks exposed in the Paradox quadrangle are of Pennsylvanian age. They are exposed together with rocks of Permian (?), Triassic, and lower Jurassic (?) age in scattered outcrops on the floor of Paradox Valley. Triassic and Jurassic rocks are exposed along the flanks of the valley, in the canyon walls and on benches and mesas. Cretaceous rocks occur in scattered outcrops on the high mesas in the western and southeastern parts of the quadrangle. Quaternary fanglomerates occur on the floor of the valley in isolated outcrops near Bedrock. Recent deposits of wind-blown material and sheet wash are widely distributed on the mesa tops, along the benches, and on the valley floor.

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 Paradox quadrangle into Utah.

Hermosa formation

The Hermosa formation of Pennsylvanian age 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 is exposed in the quadrangle in scattered outcrops in the center of the Paradox Valley. It consists of cellular sandy gypsum, limestone, and gray-black shale. Below the zone of leaching, salt is the most abundant single constituent. The beds in the Paradox member are highly contorted and, therefore, neither stratigraphic sequence nor thickness can be determined. The log of the Wilcox number 2 well, which was drilled in the northeast part of the quadrangle in the floor of the valley, shows that at least 5,000 feet of the Paradox member were drilled before the well was abandoned. (Barb, 1946, p. 285-286).

The Paradox member has been assigned to the lower Pennsylvanian by Baker (1933, p. 17-18) and Dane (1935, p. 27-29).

Limestone member

The upper or limestone member of the Hermosa formation consists of gray fossiliferous limestones, shales, and arkosic sandstones. It crops out on the floor of the valley in small exposures. No complete section of the limestone member has been measured in the valley, but a well drilled 2 miles south of Bedrock on the Dolores River penetrated about 1,800 feet of the limestone member of the Hermosa formation.

Cutler and Rico formations

The Permian (?) Cutler formation consists of maroon, purple, red, and mottled light-red arkosic sandstone and conglomerate, and small quantities of reddish-brown sandy mudstone. The arkosic beds are derived largely from pre-Cambrian crystalline rocks that formed the ancestral Uncompahgre highland, a site now occupied in part by the Uncompahgre Plateau. The poorly sorted, rudely bedded layers and lenses consist of grains and pebbles of quartz, fresh feldspar, and dark minerals, and pebbles of granite, gneiss, schist, and quartzite. Interlayered with the arkosic material are thin irregular beds of sandy mudstone. At the base of the formation where it is in undisturbed contact with the Hermosa formation, beds of marine limestone and arkosic material alternate. These beds are lithologically similar to beds of the Rico formation in the San Juan Mountains and occupy relatively the same stratigraphic position. Because the sequence is thin and the age uncertain, it has been mapped with the Cutler formation. The maximum thickness of the Cutler formation in this area is about 3,500 feet, as determined from surface exposures and oil-well logs. Only the top 600 feet of Cutler formation is exposed in the Paradox quadrangle. The formation thickens to the northeast before wedging out on the southwest flank of the Uncompahgre Plateau.

Moenkopi formation

The Lower Triassic Moenkopi formation unconformably overlies the Cutler formation. In the exposures on the northeast wall of Paradox Valley in the Paradox quadrangle, the formation consists of three members; a lower member of poorly sorted sandy mudstone, a middle member characterized by arkosic conglomerate and conglomeratic sandstone, and an upper member of thinly bedded shale and lesser amounts of fine-grained sandstone.

The lower member of the Moenkopi formation consists entirely of brick-red, poorly sorted sandy mudstone and silty sandstone in which grains range in size from clay particles to granules as much as 3 mm across. The base of the member contains seams of gypsum and, in a few places, thin beds of gypsum.

The middle member of the Moenkopi formation consists of purple and reddish-brown ledge-forming beds of arkosic conglomerate and conglomeratic sandstone, separated by beds of reddish-brown and chocolate-brown sandstone and shale. The conglomeratic beds are cross-laminated fill channels cut in underlying beds, and show current lineations and ripple marks. Shale beds show fossil mud cracks.

The upper member of the Moenkopi formation consists predominantly of reddish-brown and chocolate-brown shale and sandstone. The shale is micaceous; some bedding planes are sheeted with minute flakes of mica. Individual laminae in the shale are paper-thin and ripple-bedding is pervasive. Thin beds of coarse-grained sandstone are scattered throughout the member.

The lithologic characteristics of the formation suggest the lower member of the formation was deposited by dumping of material in a body of standing water, the middle member by deposition under fluviatile conditions, and finally, in the upper member, a return to deposition in a shallow body of water. The Moenkopi formation attains a maximum thickness in the northeast corner of the Paradox quadrangle of about 450 feet, about equally divided among the three members.

In the exposures in the southwest wall of the valley at the Dolores River, no differentiation between the members has been made as there is no complete exposure of the formation. About 500 feet of the Moenkopi formation, as determined from an oil-well log, occurs near the Dolores River about 2 miles south of Bedrock.

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 Chinle formation ranges from about 425 feet in thickness in the southern part of the quadrangle to about 535 feet in thickness in the exposures on the northeast wall of the valley. The formation thins abruptly on the flanks of the 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 Paradox quadrangle the Wingate sandstone ranges in thickness from 250 to 300 feet. The formation thins abruptly on the flanks of the valley to about 100 feet.

Kayenta formation

The Kayenta formation conformably overlies the Wingate sandstone; the contact between the two formations is gradational in most places. The formation is notable for its variety of rock types. Sandstone, red, buff, gray, and lavender in color, is the most abundant type; but the formation also contains considerable quantities of red siltstone, thin-bedded shale, and conglomerate. The conglomerate contains pebbles of sandstone, shale, and limestone. The sandstone is composed of rounded to subrounded quartz grains, and minor quantities of mica, feldspar, and dark minerals. Most of the sandstone is thin bedded, cross-bedded in part, and flaggy; some is massive. Individual sandstone beds are lenticular 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 over-hang 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 Paradox quadrangle ranges in thickness from 180 feet to 260 feet. The formation is thinnest where it is exposed on the wall of the valley. Thin seams of gypsum are interspersed with the shale beds on the walls of the valley.

Navajo sandstone

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

The maximum thickness of the Navajo sandstone in the southern part of the quadrangle is about 180 feet. On the southwest wall of the valley, the formation lenses out and is truncated by the overlying beds. The pinchout is both depositional and erosional. A few beds of water-laid thin green sandy shale are interspersed with the eolian-type sandstone.

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

In the area of the Paradox Quadrangle the Carmel formation ranges from less than 10 feet to 90 feet in thickness. This large 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 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 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.

Over most of the area the Entrada sandstone is 130 to 150 feet thick, except along the flank of the Paradox Valley anticline, where it thins to less than 100 feet.

Summerville formation

The Summerville formation generally crops out as a steep, debris-covered slope, with very few good exposures. Where exposed the Summerville exhibits a remarkably even, thin, horizontal bedding. Beds are predominantly red of various shades, although some beds are green, brown, light yellow, or nearly white. Sandy and silty shale are the most abundant kinds of rock, but all gradations from claystone to clean, fine-grained sandstone are interbedded with them. Well-rounded amber-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 Paradox Quadrangle has a moderately uniform thickness which ranges from 85 to 100 feet except where it thins on the flanks of the Paradox Valley anticline.

Morrison formation

The Morrison formation of Upper Jurassic age is of special interest economically because of the uranium- and vanadium-bearing deposits it contains. The formation comprises two members in this area; the lower is the Salt Wash sandstone member, and the upper is the Brushy Basin shale member. In the Paradox quadrangle the Morrison formation ranges in thickness from 700 to 800 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 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. 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 only complete sections of the Salt Wash sandstone member in the Paradox quadrangle are on Skein and Wray Mesas, where the thickness of the member ranges from 325 to 350 feet. On Nyswonger Mesa only the basal 50 to 100 feet remain.

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 400 feet in thickness, and erratically distributed 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.

In the Paradox quadrangle, the thickness of the Burro Canyon formation on both Wray and Skein Mesas is about 100 feet.

Dakota sandstone

The Dakota sandstone of early and late Cretaceous age unconformably overlies the Burro Canyon formation. The formation consists of predominantly yellow, medium- to coarse-grained sandstone, containing masses of gray chert up to 1 foot in diameter. Thin carbonaceous shale and impure coal are interbedded with the sandstone. The entire thickness of the Dakota sandstone is not exposed in the quadrangle, the upper beds have been stripped off by erosion, but the beds that remain attain a maximum thickness of about 50 feet on Skein and Wray Mesas.

Quaternary deposits

The deposits of Quaternary age consist of wind-deposited material, alluvium, gravel, fanglomerate, talus, and landslide debris. A light-red sandy and silty mantle which lies on benches and mesa tops, is mostly wind-deposited, although much of it has probably been reworked by water and intermixed with sheet wash. The greatest observed thickness, in some dry washes on mesa tops, is about 10 feet. These deposits have not been mapped where they are commonly spotty, discontinuous, or less than a foot thick. The soils which cover the floor of the valley differ somewhat from the wind-deposited material on the mesas. These valley soils are derived from the rocks exposed on the Valley walls and floor, as well as wind-blown material and sheet wash. Thickness of the fill in Paradox quadrangle is over 30 feet, as seen in the cut banks of West Paradox Creek.

Quaternary fanglomerates occur in scattered deposits on the floor of the valley. The fanglomerates are made up of pebbles and boulders of the rocks which make up the valley walls and floor. These deposits are well-indurated with a calcitic matrix and consist of moderately well-sorted rudely bedded subangular to subrounded boulders, as much as 4 feet in diameter, which grade upward to conglomeratic sandstone. Terrace gravels occur along the Dolores River in beds as much as 15 feet thick. The gravels are made up of pebbles and boulders consisting of several varieties of igneous rock, quartzitic rock, and sandstone. Most of the pebbles originated in the San Juan Mountains to the east. Considerable talus covers many of the steeper slopes, and landslide material, consisting largely of Brushy Basin debris, occurs on Wray and Skein Mesas.

The fanglomerates and terrace gravels have been plotted separately on the geologic map, but inasmuch as the alluvium, wind-deposited material, valley fill, talus and landslide debris are difficult to differentiate in some places, they have not been separated on the 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 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 of Paradox quadrangle

The Paradox quadrangle covers part of the northwest end of Paradox Valley and the adjacent area to the south. The rock strata in the southern part of the quadrangle have dips of less than 2°. On the walls of the valley, the dips increase sharply along the flanks of the salt core which underlies the valley. The pre-Morrison formations thin against the salt-gypsum core, and the older pre-Morrison formations dip more steeply than the younger. These relations can be seen more clearly in Gypsum Valley, which lies southeast of the area covered by the quadrangle.

Along the walls of Paradox Valley, a complex system of faults has down-thrown blocks and slivers toward the floor of the valley. In places, graben structures, as much as a half a mile long and 500 feet wide, have formed along the southwest wall of the valley.

Structural history

In order to understand the structural history of the Paradox 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 Paradox 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 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 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) 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.

An additional system of normal faults was developed during the early Tertiary. These faults are northeast-trending, roughly normal to the axis of the salt-gypsum cores. They die out at the edges of the anticlines. The faults are mineralized with copper and silver minerals, which suggest that they are probably deep-seated.

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 commercially important mineral deposits in and adjacent to the Paradox quadrangle are those that contain uranium, vanadium, and radium and those that contain copper and silver.

Uranium, vanadium, and radium deposits

Although deposits containing uranium, vanadium, and radium were discovered in 1899 near Roc Creek about 5 miles north of the Paradox 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.

The deposits are commonly restricted to the upper layer of sandstone in the Salt Wash sandstone member, but a few deposits have been mined from the middle and lower layer of sandstone lenses. Within these layers of sandstone, the deposits have a spotty distribution. Throughout the Colorado Plateau, the ore bodies may range from small irregular masses containing only a few tons of ore to large tabular bodies containing many thousands of tons. In the Paradox quadrangle, the deposits lie exclusively in the upper layer of Salt Wash sandstone and contain only a few tons of ore each. 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 rougly 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 the 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 pitch-blende 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 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 minerals were already present in the host rocks or in the waters permeating them. Although this hypothesis offers a reasonable explanation for the relation of ores to sedimentary features, it faces some difficulty in explaining: (1) the discrepancy between the age of the uranium and the age of the enclosing rock; (2) the broad stratigraphic distribution of uranium occurrences and association of ores with fractures in some localities; and (3) the hydrothermal aspect of the mineral suites in some ores. The second hypothesis, and 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: (1) the hypothetical location of the igneous source rocks and (2) the difficulty of proving the connection between fractures and faults and the ore deposits. A third hypothesis, advanced by some geologists, suggests that the source of the ore metals was the volcanic material in the beds overlying the ore-bearing sandstone and that these metals were subsequently leached and redeposited in the beds that now contain the ore. This hypothesis encounters not only most of the difficulties in the penesyngenetic hypothesis, but it presents some additional ones of its own.

Suggestions for prospecting

Regardless of the actual origin of the deposits certain habits of the deposits--habits that have been recognized through geologic mapping and exploration experience--are useful as guides for finding ore (Weir, 1952). In southwestern Colorado most of the deposits are in the uppermost sandstone stratum in the Salt Wash member of the Morrison formation. Generally the central or thicker parts of the sandstone lenses are more favorable; many deposits are in the sandstone that is 40 feet or more thick; few deposits are in the 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 in the vicinity of areas of more intense deformation may be especially favorable for finding ore. In the Paradox quadrangle, however, none of the exposed host rocks appears to be especially favorable, although on Wray Mesa where large areas of the Salt Wash sandstone member are covered by later deposits, deep drilling may discover favorable host rock. With careful prospecting, some deposits may be found in the Brushy Basin shale member.

Copper and silver deposits

The copper and silver deposits on La Sal Creek were discovered about 1885 and were worked intermittently until 1945. About 350,000 ounces of silver and 1,700,000 pounds of copper have been produced from the La Sal Creek district (Vanderwilt, 1947).

The deposits are found in normal faults that trend roughly northeast. All the ore has come from the faulted zone in the Wingate sandstone. The Cashin mine, the largest in the area, lies in a fault that trends N. 40° E. and dips 65° NW. The maximum displacement on the fault is about 40 feet.

The Cliff Dweller mine is along a fault that trends N. 26° E. and dips 65°-70° E. The displacement on this fault is about 20 feet. The faults die out to the northeast on the flank of Paradox Valley.

About 20,000 ounces of silver and traces of gold have been recovered from La Sal Creek by placer mining (Vanderwilt, 1947).

Mineralogy

The ore minerals (Fischer, 1936) consist chiefly of chalcopyrite and native copper. Some bornite, covellite, and luzonite are also present. The silver occurs in argentiferous covellite. The gangue minerals are barite, calcite and dolomite. Sphalerite and galena have also been identified from mines, though production of zinc and lead from the area indicates these minerals are not important.

Ore bodies

The ore, as reported by Fischer (1936) consists of replacements of sand grains by chalcopyrite, brecciated chalcopyrite cemented by dolomite, and native copper occurring in veins cemented with barite and calcite. The native copper also occurs in masses of as much as 500 pounds each. Such masses have been reported toward the bottom of the vein. The vein ranges in width from 1 to 20 feet and extends in depth more than 275 feet.

Origin of ore

The mineralized material is attributed by Fischer (1936) to low temperature hydrothermal solutions, with colloids playing an important part in the formation of the minerals. The age of the deposits is not known. The faults along which the mineralizing solutions traveled probably were formed during the late Cretaceous or early Tertiary folding of the area. The early Tertiary intrusions in nearby areas, such as in the La Sal Mountains, probably played an important part in originating the ore-bearing solutions.

Suggestions for prospecting

Although most of the faults have been prospected on the surface, both the Cashin and the Cliff Dweller faults disappear under the alluvium and incompetent sediments on Wray Mesa. Prospecting in the area where the faults apparently join might turn up a body similar to that of the Cashin mine. Drill holes of about 1,000 feet would be required to test the Wingate sandstone in this area.

The mines

Uranium, vanadium, and radium

A small number of prospects containing a few tons of ore each have been located on the Paradox quadrangle. Most of these are on Wray Mesa, though a few have been located on Skein Mesa. These occur as isolated bodies of low grade uranium and vanadium.

Cashin and Cliff Dweller mines

Both the Cashin and the Cliff Dweller mines are located in the faulted Wingate sandstone. The Cashin mine extends into the Wingate sandstone about 3,000 feet and a winze has been driven 225 feet downward. A raise has been driven from the main adit to the surface, a distance of about 100 feet. The lower workings in the mine are inaccessible because of water. The Cliff Dweller mine is about three-quarters of a mile up La Sal Creek from the Cashin mine. It consists of an upper and lower adit, the upper one about 900 feet long, and the lower one about 500 feet long. Both these adits are now inaccessible because of caving.

Several small prospects have been dug in the wall of Paradox Valley on the extension of the Cashin fault. Little mineralized material was found, and no production has been reported.

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