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GEOLOGY OF THE JUANITA ARCH QUADRANGLE, MESA COUNTY, COLORADO

By Eugene M. Shoemaker

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Mr. Jesse C. Johnson, Director
Division of Raw Materials
U. S. Atomic Energy Commission
16th and Constitution Avenue, N. W.
Washington 25, D. C.

Dear Jesse:

Transmitted herewith is one copy of TEM-701, "Geology of the Juanita Arch quadrangle, Mesa County, Colorado," by Eugene M. Shoemaker, May 1954.

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

Sincerely yours,

Andrew Brown

for W. H. Bradley
Chief Geologist

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UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

GEOLOGY OF THE JUANITA ARCH QUADRANGLE, MESA COUNTY, COLORADO*

By

Eugene M. Shoemaker

May 1954

Trace Elements Memorandum Report 701

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

*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 JUANITA ARCH QUADRANGLE, MESA COUNTY, COLORADO

By Eugene M. Shoemaker

ABSTRACT

The Juanita Arch 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 sandstone of favorable construction.

INTRODUCTION

The U. S. Geological Survey mapped the geology of the Juanita Arch quadrangle, Colo., in connection with 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 Juanita Arch 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 U. S. Atomic Energy Commission. The Juanita Arch quadrangle was mapped in 1949.

The Juanita Arch quadrangle covers about 59 square miles in Mesa County, Colo., and lies in the Canyon Lands division of the Colorado Plateau physiographic province. The quadrangle is a rugged area of mesas and canyons. Total relief within the quadrangle is about 3,300 feet; altitudes range from about 4,600 feet in the canyon of the Dolores River to 7,898 feet on Cone Mountain. The Dolores River and its tributaries drain the area.

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. Part of the quadrangle is accessible over Colorado Highway 141 and a system of dry-weather roads, but Sewemup Mesa in the southern part is only accessible on foot.

REGIONAL GEOLOGY

Rocks exposed in the 18 quadrangles mapped consist of crystalline rocks of pre-Cambrian age 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 beds. The latest Paleozoic and earliest Mesozoic beds wedge out northeastward against the crystalline pre-Cambrian rocks, but later Mesozoic beds 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 Juanita Arch quadrangle lies in the northern part of the 18-quadrangle area, about 5 miles southwest of the Uncompahgre Plateau. The southwest corner of the quadrangle includes part of Sinbad Valley.

STRATIGRAPHY

The oldest rocks exposed in the Juanita Arch quadrangle are of Pennsylvanian age and are exposed in the floor of Sinbad Valley. Rocks of Permian (?) age crop out in and along the sides of Sinbad Valley and in the canyons of the Dolores River and its tributaries. Jurassic rocks crop out along the sides of Sinbad Valley, in the canyon walls, and on the benches, slopes, and mesas. Cretaceous rocks cap two mesas. Recent deposits of wind-blown material and sheet wash are widely distributed along the benches and on the valley floors. The high terrain at the northwestern part of the quadrangle is mantled with extensive landslide debris.

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 Juanita Arch quadrangle into Utah.

Paradox member of the Hermosa formation

Crumpled beds of the Paradox member, the lower member of the Hermosa formation, of Pennsylvanian age, crop out on the floor of Sinbad Valley. The outcrops include gypsum, micaceous sandstone, arkose, limestone, limestone breccia and conglomerate, and carbonaceous shale. At depth, below the zone of leaching, salt is the most abundant single constituent. Beds of the Paradox member are so highly contorted that neither the stratigraphic sequence nor the true thickness can be determined accurately. Baker (1933, p. 17-18) and Dane (1935, p. 27-29) assigned the Paradox to the lower Pennsylvanian. The upper limestone member of the Hermosa formation is not exposed within the quadrangle.

Rico formation

The Rico formation crops out on the east side of Sinbad Valley in a small narrow strip near the southern boundary of the quadrangle. The beds consist of red arkose, red-brown mudstone, and gray limestone. Fossils collected from the Rico on the southwest side of Sinbad Valley, outside of the quadrangle, and from Paradox Valley show that the Rico in this area is Upper Pennsylvanian and is correlative with beds included in the Rico formation near Moab, Utah (Henbest, 1948) and in Gypsum Valley, Colo. (Stokes and Phoenix, 1948). In nearby quadrangles, where the base of the Rico is exposed, the Rico lies conformably on the Hermosa formation. About 50 feet of the uppermost part of the Rico formation is exposed in the Juanita Arch quadrangle.

Cutler formation

The Cutler formation of Permian(?) age comprises a sequence of maroon and purple conglomerate and arkose, and red-brown sandy mudstone that lies conformably on the Rico formation. Conglomerate and arkose beds contain grains of fresh feldspar and dark minerals, and pebbles and boulders of granite, gneiss, schist, and quartzite--materials derived almost entirely from the pre-Cambrian rocks that underlie the Uncompahgre Plateau. Rude cross-bedding, channeling, and ripple marks are common features of the formation.

The Cutler formation thickens from a knife-edge on the flank of the Uncompahgre Plateau to several thousand feet a few miles southwest of the uplift. A well drilled in the canyon of the Dolores River near the town of Gateway, Colo., a few miles north of the Juanita Arch quadrangle and about 4 miles southwest of the edge of the Culter, penetrated over 7,800 feet of red arkose before reaching the pre-Cambrian basement. It seems probable that this thick sequence of beds includes not only rocks of Permian(?) age, but of Pennsylvanian as well. Abrupt thinning of the formation toward its source area, coarseness of the material, and rude cross-bedding indicate the Cutler in this area was deposited as a fanglomerate.

Only a small section of the upper part of the Cutler formation is exposed in the Dolores River Canyon in the Juanita Arch quadrangle; a faulted section 500 feet thick is exposed against the side of an upthrust mass of beds of the Paradox member of the Hermosa formation in Sinbad Valley.

Moenkopi formation

The Moenkopi formation of Lower and Middle(?) Triassic age in Colorado is divided into three lithologic units: 1) a lower member, composed chiefly of poorly sorted sandy mudstone; 2) a middle member, characterized by beds of conglomerate and conglomerate sandstone; and 3) an upper member, composed chiefly of fine-grained sandstone and shale. The formation in the Juanita Arch quadrangle ranges in thickness from 300 feet along the Dolores River to 1,000 feet in Sinbad Valley.

Lower member

The lower member of the Moenkopi formation unconformably overlies the Cutler formation. It characteristically crops out as a smooth steep slope or a nearly vertical cliff. It consists almost entirely of brick-red poorly sorted sandy mudstone and silty sandstone in which the grains range from clay size to granules with a maximum diameter of 3 mm. A bed of massive white gypsum as much as 6 feet thick is present locally at the base of the member; in other places the gypsum bed is separated from the underlying Cutler formation by a conglomerate bed composed of reworked Cutler detritus. The gypsum bed at the base of the member, together with even bedding, lack of sorting, and uniform thickness of the member, suggests an initial ponding of the area at the beginning of Moenkopi deposition followed by rapid dumping of sediments in a body of standing water. Toward the Uncompahgre Plateau the lower member wedges out both by truncation at the top and by onlap.

In the Juanita Arch quadrangle the lower member ranges in thickness from 200 feet in Sinbad Valley to 220 feet along the Dolores River Canyon.

Middle member

The middle member of the Moenkopi formation overlies the lower member unconformably. It consists of purplish and red-brown conglomeratic arkosic ledge-forming beds of sandstone separated by interbedded red-brown and chocolate-brown silty shale and thin layers of fine- and coarse-grained sandstone. Near the Uncompahgre Plateau the ledge-forming sandstone beds are more conglomeratic and constitute the dominant part of the member. Sandstone beds are cross-laminated and show channeling, current lineation, and abundant ripple marks. Shale beds are marked in places by mud cracks. These features suggest fluviatile deposition. The undersurfaces of the thicker sandstone beds are marked by convoluted patterns of small ridges and knobs due to compaction of underlying shale and are a diagnostic feature of the middle member of the Moenkopi formation.

The middle member of the Moenkopi formation ranges in thickness from about 100 feet along the east side of the Dolores River to 250 feet in Sinbad Valley. A short distance north of the Juanita Arch quadrangle the middle member is cut out entirely on the east side of the Dolores River.

Upper member

The upper member of the Moenkopi formation lies conformably on the middle member and grades from red-brown and chocolate-brown shale and sandstone at the base to light-brown sandstone and gypsiferous brown shale at the top. Thin beds of light-maroon coarse-grained sandstone are scattered throughout the member; these are commonly highly gypsiferous. The relatively abundant gypsum gives rise to a fluffy soil which gives the whole member a light-brown color when viewed from a distance. Bedding is uniform except for small-scale cross-lamination in some of the thin sandstone beds; ripple marks are abundant. A predominance of shales and uniformity of bedding suggests that the upper Moenkopi was deposited in a body of shallow water perhaps marginal to a sea.

In the Juanita Arch quadrangle the thickness of the upper member of the Moenkopi formation ranges from a featheredge along the Dolores River to 575 feet in Sinbad Valley. Along the Dolores River the upper member is cut out toward the Uncompahgre Plateau by an angular unconformity, as great as 7°, at the base of the overlying Chinle formation.

Chinle formation

The Chinle formation of Upper Triassic age consists of bright-red and red-brown mudstone, siltstone, sandstone, and limestone-pebble and mudstone-pebble conglomerate. The formation forms steep slopes. A discontinuous unit of maroon and lavender coarse-grained pebbly sandstone, which locally reaches a thickness of 60 feet, is present in places at the base of the formation. Thin purple limestone beds and lenses of limestone-pebble and mud-pebble conglomerate are commonly interbedded with red mudstone and siltstone in the lower half of the Chinle. Fine-grained sandstone beds, common in the upper part of the formation, are thicker and closer spaced toward the top. The

Chinle grades in places into the overlying Wingate sandstone, although the break in slope between the cliff-forming Wingate and the slope-forming Chinle is generally abrupt. In contrast to the uniform bedding in the Moenkopi formation, the bedding in the Chinle is irregular, and individual sandstone beds cannot be traced more than a few hundred feet along the outcrop.

The Chinle formation thins progressively to the northeast from a maximum thickness in Sinbad Valley of about 750 feet to 300 feet along the Dolores River. All thinning is intraformational. Northeast of the Juanita Arch quadrangle the Chinle thins still more but continues across the crest of the Uncompahgre Plateau.

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 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 Juanita Arch quadrangle the Wingate sandstone ranges in thickness from 275 feet along the Dolores River Canyon below Tenderfoot Mesa to about 350 feet along the rim of Sinbad 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 Juanita Arch quadrangle ranges in thickness from 180 feet in Maverick Canyon to 300 feet on Sewemup Mesa. Abrupt local changes in thickness of 10 to 20 feet are common. The irregular bedding, channel filling, and range of thickness all indicate a fluviatile origin.

Navajo sandstone

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

The Navajo sandstone ranges in thickness from a featheredge in Maverick Canyon to a maximum thickness of 260 feet on the northern rim of Sinbad Valley.

San Rafael group

In this area the San Rafael group, of Middle and Late Jurassic age, comprises, in ascending order, the Carmel formation (Middle and Upper Jurassic), the Entrada sandstone (Upper Jurassic), and the Summerville formation (Upper Jurassic). The group crops out in a narrow band along the sides of the mesas. 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, nonresistant, horizontally bedded siltstone, mudstone, and sandstone. In some localities the basal beds consist of reworked Navajo sandstone. Pebbles and angular fragments of white and gray chert, as much as an inch across, are scattered rather abundantly through the lower part of the formation and less abundantly through the upper part. These chert pebbles and angular fragments are sufficiently abundant locally to form layers of conglomerate. Included in these layers are scattered greenish-gray, red, and yellow quartzite pebbles and boulders 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.

The Carmel formation ranges from less than 10 feet to 90 feet in thickness. No definite evidence indicates that the Carmel formation of this area is of marine origin as is the Carmel of central Utah, but the probabilities are that the Carmel of southwestern Colorado was deposited in shallow water marginal to a sea.

The Carmel formation grades upward, in most places without prominent breaks, into the Entrada sandstone. The Entrada sandstone, known locally as the "slick rim" because of its appearance, is perhaps the most 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, cross-bedded units. The horizontally bedded units are most common in the basal part and in the uppermost, lighter-colored part of the Entrada, whereas the cross-bedded units are dominant in the middle part. The Entrada sandstone differs from the somewhat similar Wingate sandstone and Navajo sandstone by the sorting of sand into two distinct grain sizes. Subrounded to subangular quartz grains mostly less than 0.15 mm in diameter make up the bulk of the sandstone. The sandstone also contains larger grains, which are well-rounded, have frosted surfaces, and range from 0.4 to 0.8 mm in diameter; most of these grains are of quartz, but grains of chert are scattered among them. Most of the larger grains are distributed in thin layers along bedding planes.

The combined thickness of the Entrada sandstone and Carmel formation ranges from less than 100 feet in Maverick Canyon to 220 feet on the northern rim of Sinbad Valley.

Summerville formation

The Summerville formation generally crops out as a steep, debris-covered slope, with 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 those 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. In the Juanita Arch quadrangle near the base of the Summerville formation is a bed of fine-grained sandstone 30 to 45 feet thick which forms a prominent ledge. To the northwest this bed can be traced into the Moab tongue of the Entrada formation, and to the south and east it grades into interbedded sandstones and shales of the lower part of the Summerville formation. In this report this bed is included in the Summerville.

The Summerville formation rests conformably on the Entrada sandstone, and, although a sharp lithologic change marks the contact, no cessation of deposition separated the two formations. The upper contact of the Summerville is uneven and channeled, and the channels are filled by the overlying basal 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 ranges in thickness from 100 feet in Maverick Canyon to 130 feet on Sewemup Mesa.

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 Juanita Arch 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. The ripple marks, current lineations, rill marks, and cut-and-fill structures indicate that the Salt Wash member was deposited under fluviatile conditions.

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

The Salt Wash sandstone member ranges from 280 to 360 feet in thickness in the quadrangle.

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 shale and mudstone 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 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 floodplains on which were deposited the fine-grained sediments now represented by the mudstone and shale.

The Brushy Basin shale member ranges from 330 to 450 feet in thickness.

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 up to 100 feet thick. These beds are massive, irregular, and lenticular. Festoon-bedding is 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 predominant 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 is 200 feet thick in the Juanita Arch quadrangle.

Dakota sandstone

Thin remnants of the lowermost part of the Upper Cretaceous Dakota sandstone occur along the northwestern edge of the quadrangle. These remnants are red and brown thin-bedded conglomeratic sandstone with minor amounts of interbedded carbonaceous shale.

Quaternary deposits

Quaternary deposits include narrow strips of alluvium and colluvium along the bottoms of the Dolores River Canyon and Salt Creek Canyon, a rather extensive cover of alluvium on the floor of Sinbad Valley, terrace gravels and dissected and Recent talus slopes in the Dolores River Canyon, scattered patches of cemented terrace gravels in Sinbad Valley, and extensive landslide debris on the high area in the northwest part of the quadrangle. Scattered patches of sandy silt, present on the mesas and benches, are designated alluvium on the map, but may be largely wind-deposited. Some of the talus along the Dolores River as well as terrace gravels in Sinbad Valley are cemented with calcareous material and were probably stabilized during a dry period, during the Wisconsin or before the post-Wisconsin pluvial maximum.

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 stock-like and laccolithic intrusions.

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

Structure in Juanita Arch quadrangle

The Juanita Arch quadrangle lies between the northeastern-most member of the group of salt anticlines and the Uncompahgre uplift. The principal structural feature of the quadrangle is the Dolores River syncline whose axis trends northwest across Flat Top Mesa to the edge of Tenderfoot Mesa where it turns and trends roughly parallel to the Dolores River. Dips in the broad axial part of the syncline are generally less than 4°. To the southwest, on the rim of Sinbad Valley, the dips increase to more than 12°, as the beds rise more steeply to form one limb of the Sinbad Valley anticline. The axial part of the anticline has been eroded away leaving exposed a large intrusive mass of the Paradox member of the Hermosa formation in Sinbad Valley. This intrusive mass is a composite of several distinct plugs (Shoemaker, 1951), two of which are partly included within the quadrangle boundaries.

A graben, in which Salt Creek Canyon is carved, extends 3 1/2 miles to the northeast from the edge of the intrusive mass of the Paradox member of the Hermosa formation. The faults bounding the graben are complex zones of the fracture containing many slices and wedges. Downward displacement is greatest at the southwest end of the graben near the intrusive mass and dies out toward the northeast near the Dolores River. The graben trends at right angles to the axis of the Sinbad Valley anticline and is located opposite the center of the composite intrusive mass, which forms the core of the anticline. As revealed by the structure contours, the strata have been domed around the intrusive core. These facts suggest that the graben was formed during stretching of the rocks that may have accompanied the process of doming.

Structural history

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

Mild compressive forces, which probably began in early Pennsylvanian time, gently warped the region. This warping gave rise to the ancestral Uncompahgre highland, an element of the ancestral Rocky Mountains, and to the basin in which the Paradox member of the Pennsylvanian Hermosa formation was deposited. These major structural features controlled the pattern and 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 at the end of Cutler deposition salt broke through to the surface. From then until flowage ceased, late in the Jurassic, the elongate salt intrusions such as those in Paradox Valley and Gypsum Valley stood as actual topographic highs at one place or another along their lengths. The rate of upwelling of additional salt, perhaps accelerated by the increase of the static load of sediments accumulating in the surrounding areas, balanced or slightly exceeded the rate of removal of salt by solution and erosion at the surface. Consequently, all the Mesozoic formations to the base of the Morrison formation wedge out against the flanks of the salt intrusions. Salt flowage was not everywhere continuous and 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 Morrison deposition 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 probably occurred in the early Tertiary. 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 forms, 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 groundwater 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 was apparently due to 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 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

Mineral deposits mined in the Juanita Arch quadrangle include uranium-vanadium deposits and copper-silver deposits. The uranium-vanadium or so-called carnotite deposits have been the more important.

Uranium-vanadium deposits

Uranium and vanadium were discovered in copper prospects near Roc Creek, a few miles south of the Juanita Arch quadrangle in 1899. Intensive mining of the uranium-vanadium 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.

All known uranium-vanadium deposits within the quadrangle are in the Morrison formation. Most of the deposits are in the uppermost sandstone stratum of the Salt Wash sandstone member, but one deposit in the lower part of the Salt Wash sandstone has been mined, and small scattered deposits are known in the conglomeratic sandstone lenses at the base of the Brushy Basin shale member of the Morrison.

Mineralogy

The most common ore minerals are carnotite and a fine-grained, vanadium-bearing micaceous mineral. Carnotite $[K_2(UO_2)_2(UO_4)_2 \cdot 3H_2O]$, is a yellow, fine-grained, earthy or powdery material. Tyuyamunite $[Ca(UO_2)_2(UO_4)_2 \cdot nH_2O]$ 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 directions 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 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 crossbedding in the sandstone. These relations strongly suggest that primary structures in the sediments were instrumental in localizing most of the ore deposits.

Recent investigations have revealed new data bearing on the origin of the ores (Waters and Granger, 1953). Below the zone of oxidation some of the ore consists chiefly of oxides, such as pitchblende and low-valent oxides of vanadium, and small quantities of sulfides such as pyrite, bornite, galena, and chalcopyrite; fully oxidized and fully hydrated minerals are either rare or nonexistent. A hard variety of uraninite, previously reported only from hydrothermal deposits, has been found in the Gray Daun mine in San Juan County, Utah (Rasor, 1952), and in the Happy Jack mine in White Canyon, Utah. Studies of lead-uranium ratios in ores from the Colorado Plateau indicate that, regardless of where or in what formation found, all the ores are of roughly the same age, and this age is no older than latest Cretaceous (Stieff and Stern, 1952). Some geologists believe field relations in pre-Morrison formations at White Canyon (Benson, and others, 1952) and the 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 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 rocks; (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, namely: (1) the hypothetical location of igneous source rocks and (2) the difficulty of proving the connection between fractures and faults and the ore deposits. A third hypothesis, advanced by some geologists, suggests that the source of the ore metals was the volcanic material in the beds overlying the ore-bearing sandstone and that these metals subsequently leached and redeposited in the beds that now contain the ore. This hypothesis encounters not only most of the difficulties in the penesyngenetic hypothesis, but it presents some additional ones of its own.

Suggestions for prospecting

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

In the Juanita Arch quadrangle the ground, underlain by the Salt Wash sandstone member of the Morrison formation that appears to be the most favorable for the occurrence of uranium-vanadium ore, includes Flat Top Mesa and the area along the eastern edge of the quadrangle near the Maverick mines. This ground has been fairly well prospected and explored. The ground underlain by Salt Wash sandstone in the northwest part of the quadrangle is believed to be less favorable for ore on the basis of geologic criteria. On the other hand, the northwestern part of the quadrangle has been less accessible in the past and has been less thoroughly prospected than the areas of close-spaced mines in the eastern part of the quadrangle. Outcrops of Salt Wash sandstone south of Cone Mountain and near the fault system bounding the northwest side of the Salt Creek Canyon graben may be worthy of further exploration.

The mines

Maverick mines

Part of the Maverick mines, at the head of Maverick Canyon, are included in the Juanita Arch quadrangle. In addition to carnotite and the micaceous vanadium mineral, corvusite and montroseite constitute an important part of the Maverick ores. Some of the ore is unusually rich in uranium, although carnotite is not conspicuously abundant; part of the uranium may be contained in the oxide form in corvusite-montroseite masses. The ore bodies, up to 500 feet long, tend to be crescent-shaped in plan and contain many closely spaced rolls. The boundaries of the ore bodies are generally sharply defined.

Depression mines

The Depression mines, on the northwest side of Flat Top Mesa, are developed in a group of thin blanket-like ore bodies 100 to 300 feet across. The micaceous vanadium mineral is the dominant ore mineral, and the deposits are unusually rich in vanadium but only average in uranium content. The ore is in layers a few inches to 2 feet thick, some of the layers tend to follow shaly sandstone beds or mudstone-pebble beds in the sandstone. Rolls are only moderately developed.

Other mines

Small scattered deposits have been mined along Maverick Canyon and also west of the Dolores River. A deposit near the head of Cave Canyon consists of two layers of low-grade ore connected by rolls and extends for

100 feet along the outcrop. A deposit north of North Cottonwood Canyon occurs in the lower part of the Salt Wash sandstone member. Other small deposits have been discovered recently and worked on Calamity Mesa south of Little Maverick Canyon. Deposits in the Brushy Basin shale member have been opened up by prospectors, one near the head of Cave Canyon, but it is doubtful whether any ore has been shipped from them.

Copper-silver deposits

Copper-silver deposits were first discovered and worked in Sinbad Valley sometime in the 1870's or 1880's. They have been worked intermittently since that time, principally during the period 1905 to 1916, when a small leach plant was built in western Sinbad Valley to treat the ores. The recorded production from Sinbad Valley consists only of sporadic shipments of a few tons of high-grade ore.

Only vein deposits of copper ore have been found within the Juanita Arch quadrangle, although both disseminated deposits and vein deposits have been found in nearby parts of Sinbad Valley. The Copper Rivet mine is in a vein in the Wingate sandstone. The vein is as much as 2 feet wide and is composed chiefly of calcite and sparse copper minerals. The primary ore consists of chalcopyrite, luzonite (enargite), and small masses of chalcocite that carry minute grains of chalcopyrite and bornite (Fischer, 1936). Most of the ore has been oxidized to form copper carbonates, some of which have impregnated the sandstone wall several feet out from the vein. Although the ore is relatively rich in silver, silver minerals are rare, and most of the silver is apparently contained in the copper minerals.

Traces of copper minerals are present along other faults in the Salt Creek Canyon graben system near the base of the Wingate sandstone. A deposit consisting of copper carbonates lies in a fault breccia in the Moenkopi formation on the main fault system bounding the southeast side of the Salt Creek Canyon graben.

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