GEOLOGY OF THE PINE MOUNTAIN QUADRANGLE, MESA COUNTY, COLORADO

By Fred W. Cater, Jr.

Trace Elements Memorandum Report 704

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

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

Dear Phil:

Transmitted herewith is one copy of TEM-704, "Geology of the Pine Mountain quadrangle, Mesa County, Colorado," by Fred W. Cater, Jr., August 1953.

Mr. Hosted approved on August 27, 1953 our plan to publish this report in the Survey's Quadrangle Map Series.

Sincerely yours,

for W. H. Bradley
Chief Geologist

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Geology and Mineralogy

This document consists of 30 pages, plus 1 figure.
Series A.

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

GEOLOGY OF THE PINE MOUNTAIN QUADRANGLE, MESA COUNTY, COLORADO*

By

Fred W. Cater, Jr.

August 1953

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

USGS - TEM-704

GEOLOGY AND MINERALOGY

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by Fred W. Cater, Jr.

ABSTRACT

The Pine Mountain quadrangle is one of eighteen 7½-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.

GEOLOGY OF THE PINE MOUNTAIN QUADRANGLE, MESA COUNTY, COLORADO

by Fred W. Cater, Jr.

INTRODUCTION

The U. S. Geological Survey mapped the geology of the Pine Mountain 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 7½-minute quadrangles, of which the Pine Mountain 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 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 Pine Mountain quadrangle was mapped in 1949.

The Pine Mountain quadrangle covers about 58 square miles in Mesa County, Colo., and lies in the Canyon Lands division of the Colorado Plateau physiographic province. Much of the quadrangle is a precipitous land, deeply and complexly carved into canyons, cliffs, and steeply sloping mesas; only on a lobe of the Uncompahgre Plateau in the northeastern part are there any extensive relatively flat areas. The total relief within the quadrangle is about 3,620 feet; altitudes range from about 5,800 feet on Ute Creek to 9,400 feet or more a short distance west of Far Pond. The entire quadrangle is drained by tributaries of the Dolores River.

No accurate information on rainfall is available, but the annual precipitation is probably between 10 and 20 inches, depending upon altitude; the area is semiarid in the lower country and supports a moderate growth of juniper and piñon on rocky terrain and abundant sagebrush where soils are thick. Quaking aspen, ponderesa pine, and fir grow at higher altitudes, where precipitation is greater. Cacti and sparse grass are widely distributed. Most of the quadrangle is accessible over a system of dry-weather roads and 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 area 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 Pine Mountain quadrangle lies in the northeast corner of the 18-quadrangle area and includes a part of both the summit and the monoclinal southwest flank of the Uncompahgre Plateau.

STRATIGRAPHY

The oldest rocks in the Pine Mountain quadrangle are crystalline rocks of pre-Cambrian age exposed along Ute Creek and in the cliffs and steep slopes in the eastern and northern parts of the quadrangle. Overlapping these crystalline rocks are sedimentary rocks of Permian(?) and Triassic age. Early Triassic rocks are shown on the structure cross-section; although they are exposed in nearby areas, they do not crop out within the quadrangle. Upper Triassic rocks crop out along Ute Creek, around a lobe of the Uncompahgre Plateau in the eastern part, and on the steep "flatirons" in the southeastern part of the quadrangle. Rocks of Jurassic age crop out extensively on the "flatirons", in the canyons, on mesas and benches flanking the canyons, and on the upland surface of the Uncompahgre Plateau. Recent deposits of wind-blown material and sheet wash are widely distributed on the tops of mesas, and alluvium covers the floors of some of the valleys.

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 Pine Mountain quadrangle into Utah.

Pre-Cambrian rocks

A complex of crystalline pre-Cambrian rocks is exposed in the eastern and northern parts of the quadrangle. No attempt was made to outline on the map the various rocks in the complex because of the exceedingly intricate interrelations of the different types. Most abundant of the rocks is a gray medium-grained gneissic granite. The foliation of this granite strikes in all directions, but the dips are mostly vertical. Engulfed in this granite are small masses of quartzite and hornblende and biotite schists and gneisses that have undergone varying degrees of assimilation. Intruded into this gneissic granite are dikes and irregular-shaped bodies of pink coarse-grained granite and dikes of pegmatite, aplite, and dark colored rock altered largely to chlorite. The older, more abundant gneissic granite has been considerably altered in places, with the dark minerals being replaced by chlorite and epidote, whereas the younger, pink granite appears to be essentially fresh. The entire complex has been sheared, faulted, and crushed.

Schist and gneiss, probably belonging to the same series as the masses engulfed in the gneissic granite, are exposed in Unaweep Canyon a few miles north of the quadrangle; Peale (1877) believed these rocks to be of Archean age. Hunter (1925), in the nearby Gunnison River area, assigned similar rocks to the Archean and the granitic intrusions to the Algonkian or early Paleozoic.

Cutler formation

The Permian (?) Cutler formation consists of maroon, purple, red, and mottled light-red cross-bedded arkosic sandstone and conglomerate, and small quantities of reddish-brown sandy mudstone. It crops out over a small area on the western edge of the quadrangle between Ute Creek and Pine Mountain and in the southeastern part of the quadrangle on Indian Creek. Grains of fresh feldspar and dark minerals, pebbles and boulders of granite, gneiss, schist, and quartzite--materials derived almost entirely from the pre-Cambrian--are mixed together in poorly sorted, rudely cross-bedded layers and lenses. Small amounts of reddish-brown sandy mudstone are distributed through the coarser material as thin, irregular seams that serve to delineate the otherwise obscure bedding.

The Cutler formation rests directly on pre-Cambrian rocks in the Pine Mountain quadrangle and forms a wedge between the pre-Cambrian rocks and the overlying Triassic beds. The formation thickens from a knife-edge near Pine Mountain and Indian Creek on the flank of the Uncompahgre Plateau to several thousand feet a few miles to the southwest. A well drilled about 4 miles southwest of the edge of the Cutler in the canyon of the Dolores River near the town of Gateway, Colo., penetrated more than 7,800 feet of red arkoses before reaching the Pre-Cambrian basement. The upper beds were beveled by erosion before the beds of the overlying Triassic were deposited. 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 bedding all indicate that the Cutler in this area was deposited as a fanglomerate.

Chinle formation

Throughout most of the Colorado Plateau, beds of the Upper Triassic rest unconformably on older rocks. This relationship is strikingly evident in the Pine Mountain quadrangle and adjacent areas. As the Uncompahgre Plateau is approached from the west, the Upper Triassic Chinle formation rests, in turn, first on the Lower Triassic Moenkopi formation, then on the Cutler formation, and finally, on the Plateau, on pre-Cambrian rocks. Except for disturbances incident to later faulting and uplift, this erosion surface below the Chinle in the vicinity of the Uncompahgre Plateau is remarkably flat.

The 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 very distinctive limestone-pebble and clay pellet-conglomerate; in places the lowermost lenses contain quartz pebbles or consist of a relatively clean quartz grit. These quartz-bearing lenses are probably the stratigraphic 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 vary 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 sand-and conglomerate. In the Pine Mountain quadrangle the formation ranges in thickness from 120 feet to 220 feet.

Glen Canyon group

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

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 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. In general, the sandstone is rather poorly cemented and crumbles easily, and this quality probably accounts for the readiness with which the rock disintegrates in faulted areas, but in the area extending from the vicinity of Big Pond northwest to Turner Gulch the sandstone is highly silicified, brittle, and breaks with a conchoidal fracture.

In the Pine Mountain quadrangle the Wingate sandstone ranges in thickness from 220 feet to at least 420 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 limestone, shale, and sandstone. 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 recessions 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.

In the Pine Mountain quadrangle and southeastward over a distance of at least 25 miles, the featheredge of the Kayenta formation coincides rather closely with the southwest front of the Uncompahgre Plateau; thus, on Wolf Hill on the eastern edge of the quadrangle, the Kayenta is missing, and the Entrada sandstone rests directly on the Wingate sandstone. Southwest from its featheredge the Kayenta thickens to a maximum of about 170 feet within the quadrangle. Abrupt local changes in thickness of 10 to 20 feet are common. The irregular bedding, channel filling, and range of thickness all indicate a fluviatile origin.

San Rafael group

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

Carmel formation and Entrada sandstone

The Carmel formation consists largely of red to buff, soft, horizontally bedded siltstone, mudstone, and 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, 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 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 5 feet or less to 15 feet in thickness. This range appears to be due chiefly to deposition on irregular, eroded surfaces of the Kayenta formation. No definite evidence indicates that the Carmel formation of this area is of marine origin as is the Carmel of central Utah, but the probabilities are that the Carmel of southwestern Colorado was deposited in shallow water marginal to a sea.

The Carmel formation grades upward, in most places without a prominent break, into the Entrada sandstone. The Entrada sandstone, known locally as the "slick rim" 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 Entrata consists of alternating parallel-bedded units and sweeping, eolian-type cross-bedded units. The parallel-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 planes of bedding and lamination.

The Entrada sandstone is about 140 feet thick in the western part of the quadrangle; eastward it thins to about 80 feet along Ute Creek.

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 is the most abundant rock, but all gradations from shale to clean, fine-grained sandstone are interbedded in the unit. Well-rounded amber-colored quartz grains with frosted or matte surfaces are disseminated throughout most of the formation, including these beds consisting almost entirely of claystone. Thin beds of autochthonous 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, in the absence of the basal sandstones of the Salt Wash, the shale and mudstone of the Morrison formation are similar to beds of the Summerville.

The Summerville formation in the Pine Mountain quadrangle ranges in thickness from about 85 feet to 110 feet.

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 Pine Mountain quadrangle no complete sections of the Morrison formation remain because the upper part of the Brushy Basin shale member has been stripped off by erosion. In nearby areas outside the quadrangle the Brushy Basin shale member in general is somewhat thicker than the Salt Wash sandstone member.

Salt Wash sandstone member

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

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

In the Pine Mountain quadrangle the Salt Wash sandstone member is 300 to 320 feet thick.

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 several inches thick, caused by the swelling of the bentonitic material during periods of wet weather. Scattered through the shale and mudstone are thin beds of fine-grained very hard silicified rock that breaks with a conchoidal fracture. The silica impregnating these beds may have been released during the devitrification of volcanic debris in adjacent beds. Beds of chert pebble-conglomerate a few inches to 25 feet thick occur at intervals throughout the member. These conglomerate beds are commonly dark rusty-red and form conspicuous resistant ledges. Silicified saurian bones and wood are much more abundant in the

Brushy Basin shale member than in the Salt Wash sandstone member, especially in some of the conglomerate beds.

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

Less than 100 feet of the Brushy shale member is preserved within the quadrangle.

Quaternary deposits

Quaternary deposits consist of a single outcrop of fanglomerate and widespread wind-deposited material, alluvium, and talus debris. The fanglomerate caps a low ridge on the western edge of the quadrangle and consists of a light-red heterogeneous, poorly sorted accumulation of silt, sand, pebbles, and boulders derived almost entirely from the mesozoic formations. The material has been slightly indurated and stands in vertical cut banks 30 to 50 feet high. The fanglomerate was deposited as sheet wash and talus debris on an irregular, sloping surface possibly during early pleistocene time. More recent talus debris differs from the fanglomerate by its lack of induration and its relatively high content of material derived from the Permian (?) Cutler formation and from pre-Cambrian rocks. Extensive deposits of light red sandy and silty material mantle the benches and mesa tops. This material appears to be mostly wind-deposited, although much of it has been reworked by water and intermixed with sheet wash. Gravel and alluvium occur in some of the stream beds.

STRUCTURE

Regional setting

Many geologic structures on the Colorado Plateau are so large that a 7½-minute quadrangle covers only a small part of any complete structural unit. The larger structural units consist of salt anticlines, 45 to 80 miles long; uplifted blocks, 50 to 125 miles long, bounded by monoclinal folds; and domical uplifts, 8 to 20 miles across, around stocklike and laccolithic intrusions.

The salt anticlines trend northwest and lie in a group between eastward-dipping monoclines on the west side of the Plateau and westward-dipping monoclines on the east side of the Plateau. The cores of these anticlines consist of relatively plastic salt and gypsum, derived from the Paradox member of the 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 Pine Mountain quadrangle

The dominant structural feature that crosses the Pine Mountain quadrangle is the monoclinal fold fronting the Uncompahgre Plateau uplift. In this quadrangle the sharpest part of the flexure has been greatly modified by a large graben, which has been named the Ute Creek graben. Beds in the southwestern part of the quadrangle in general dip 2° to 8° SW., away from the Ute Creek graben. The Ute Creek graben is 1 to 2½ miles wide and trends northwest diagonally across the quadrangle. The southwest side of the graben is bounded by a fault having a maximum displacement below the north end of Pine Mountain of at least 850 feet. To the southeast the displacement decreases, and the fault dies out a few miles southeast of the quadrangle. A number of subsidiary faults either parallel or branch off this main fault. The fault bounding the northeast side of the graben follows a more irregular northwesterly course from the head of Cow Creek to where it leaves the quadrangle near Turner Gulch. The displacement along this fault also increases to the northwest and attains a maximum displacement of about 1,000 feet. Several associated branching faults have lesser displacements. The floor of the southeastern end of the graben is cut by numerous minor faults, one of which trends east nearly transverse to the trend of the graben. The Ute Creek graben formed after the main uplift of the Uncompahgre Plateau, probably as an adjustment following relaxation of stresses responsible for the uplift.

In addition to the faults associated with the graben four other faults cut the rocks in the quadrangle. Two of these, about 2 miles south of Pine Mountain, are minor, northwestward-trending faults with only a few feet of displacement. The third fault, just west of Pine Mill in the southeast corner of the quadrangle, strikes north and is cut off by the graben-faulting. The fourth fault, in the head of South Lobe Creek, trends N. 20° E. and drops the rocks west of the fault about 300 feet.

Rocks on the Uncompahgre Plateau in the northeastern part of the quadrangle are relatively flat-lying, and in much of the area dips do not exceed 2°.

Structural history

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

Weak compressive forces, which probably began in early Pennsylvanian times, gently warped the region. This warping gave rise to the ancestral Uncompahgre highland, an element of the ancestral Rocky Mountains, and to the basin in which the Paradox member of the Hermosa formation of Pennsylvanian age was deposited. These major structural features controlled the pattern and the prevailing northwest-trending grain of the smaller structures later superimposed on them. The boundary between the highland and the basin, which is closely followed by the southwest margin of the present-day Uncompahgre Plateau, was a steep northwest-trending front, possibly a fault scarp, along which were deposited arkosic fanglomerates during late Pennsylvanian and Permian time. The older fanglomerates interfinger with Pennsylvanian marine sedimentary rocks of the Hermosa formation. The bulk of the fanglomerates probably is of Permian age and belongs to the Cutler formation. Intrusion of salt from the Paradox member, probably initiated by gentle regional deformation, began sometime during deposition of the Permian (?) Cutler formation. Isostatic rise of salt ruptured the overlying Hermosa and Cutler formation, and 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 these 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 locally 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 in the area, sediments finally covered the salt intrusions, perhaps because the supply of salt underlying the area 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 cores were reduced by erosion and topographic relief became low throughout the area.

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

MINERAL DEPOSITS

The only commercially important mineral deposits in the Pine Mountain quadrangle are these that contain uranium, vanadium, and radium. Although deposits containing these metals were discovered in 1899 near Roc Creek, about 13 miles south-southwest of the Pine Mountain 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 in the Pine Mountain quadrangle are restricted to the upper layer of sandstone lenses in the Salt Wash sandstone member, but within this layer the deposits have a spotty distribution. Ore bodies range from small irregular masses containing only a few tons of ore to tabular masses containing several thousands of tons. The ore consists mainly of sandstone impregnated with uranium- and vanadium-bearing minerals.

Mineralogy

The most common ore minerals are carnotite and a fine-grained, vanadium-bearing micaceous mineral. Carnotite $(K_2(UO_2)_2 (VO_4)_2 \cdot 3H_2O)$ is a yellow, fine-grained, earthly or powdery material. Tyuyamunite $(Ca(UO_2)_2(VO_4)_2\ nH_2O)$, the calcium analogue of carnotite, is also present and is nearly indistinguishable from carnotite. The micaceous vanadium mineral, which formerly was thought to be rescoelite, is now considered to be related to the nontronite or montmorillonite group of clay minerals.

It forms aggregates of minute flakes coating or partly replacing sand grains and filling pore spaces in the sandstone. It colors the rock gray. Other vanadium ore minerals present are montroseite ($nFeO \cdot nV_2O_4 \cdot nV_2O_3 \cdot nH_2O$), corvusite ($V_2O_4 \cdot 6V_2O_5 \cdot nH_2O$), and hewettite ($CaO \cdot 3V_2O_5 \cdot 9H_2O$). Corvusite and montroseite occur together, forming compact masses of bluish-black ore, whereas hewettite commonly forms stringers and veinlets along joints and fractures. Recent deeper drilling and mining in the Plateau have indicated that below the zone of oxidation black oxides of uranium and vanadium, accompanied by pyrite and perhaps other sulfides, are more abundant, and uranyl vanadates are scarce or absent.

Ore bodies

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

Vaguely defined margins may have mineralized sandstone extending well beyond the limits of commercial ore; on the other hand, sharply defined margins, such as occur along the surfaces of rolls, ordinarily mark the limits of both the mineralized sandstone and the commercial ore.

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

Origin of ore

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

Most of the deposits are closely associated with certain sedimentary features. Layers of ore lie essentially parallel to the bedding; most of the deposits occur in the thicker parts and commonly near the base of the sandstone lenses; the trend of the long direction of the deposits and the trend of the ore rolls in the sandstone are roughly parallel to the trend of the fossil logs in the sandstone and to the average or resultant dip of the 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 it occurs, all the ores are of roughly the same age, and this age is no older than late Cretaceous (Stieff and Stern, 1952). Some geologists believe field relations in pre-Morrison formations at White Canyon (Benson, et al., 1952) and Temple Mountain in Utah, indicate that the deposits may be genetically related to faults and fractures. At the Rajah mine near Roc Creek, in Colorado, ore occurs along a fault and horsetails out into the wall rock.

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

Suggestions for prospecting

Regardless of the actual origin of the deposits, certain habits of the deposits--habits that have been recognized through geologic mapping and exploration experience--are useful as guides for finding ore (Weir, 1952). In southwestern Colorado most of the deposits are in the uppermost sandstone stratum in the Salt Wash member of the Morrison formation. Generally the central of 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 in more favorable than red or reddish-brown sandstone. Sandstone that contains considerable amounts of gray, altered mudstone or is underlain by a considerable thickness of this rock is more favorable than sandstone containing and underlain by red, unaltered mudstone--this guide is perhaps the most useful in diamond-drill exploration.

In the Pine Mountain quadrangle probably the most likely area for finding ore, because of the presence of favorable host rocks, is the southwestern corner. Many deposits occur in localities remote from areas of intensive structural deformation, and additional deposits will undoubtedly be found in such undeformed localities. If the deposits had a hypogene origin, as the author believes, then the more intensively deformed rocks, probably are favorable places to look for new deposits, provided that the favored formations and rock types known to be hosts for ore are present. In the Pine Mountain quadrangle, however, the rocks in the vicinity of the faults are, for the most part, unfavorable hosts for ore.

The mines

The only mines in the Pine Mountain quadrangle are those on the Sunflower claim in the extreme southwestern corner of the quadrangle. The mines are in the top layer of sandstone lenses of the Salt Wash sandstone member of the Morrison formation. The deposits occur as irregular tabular masses as much as 300 feet long and 100 feet wide that range from a few inches to 13 feet in thickness. Rolls are common. The only ore minerals of any importance are carnotite and the micaceous vanadium clay mineral.

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