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GEOLOGICAL SURVEY

GEOLOGY AND ORE DEPOSITS OF THE KLONDIKE RIDGE AREA, COLORADO

by

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This report is preliminary and has not been edited or reviewed for conformity with Geological Survey standards or nomenclature.

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Abstract

The region described in this report is in the northeastern part of the Colorado Plateau and is transitional between two major structural elements. The western part is typical of the salt anticline region of the Plateau, but the eastern part has features which reflect movements in the nearby San Juan Mountains.

There are five major structural elements in the report area: the Gypsum Valley anticline, Dry Creek Basin, the Horse Park fault block, Disappointment Valley, and the Dolores anticline. Three periods of major uplift are recognized in the southeastern end of the Gypsum Valley anticline. Each was followed by collapse of the overlying strata. Erosion after the first two periods removed nearly all topographic relief over the anticline; erosion after the last uplift has not yet had a profound effect on the topography except where evaporite beds are exposed at the surface.

The first and greatest period of salt flow and anticlinal uplift began in the late Pennsylvanian and continued intermittently and on an ever decreasing scale into the Early Cretaceous. Most movement was in the Permian and Triassic periods.

The second period of uplift and collapse was essentially contemporaneous with widespread tectonic activity on the northwestern side of the San Juan Mountains and may have occurred in the Oligocene and Miocene epochs. Granogabbro sills and dikes were intruded during the middle or upper Tertiary in Disappointment Valley and adjoining parts of the Gypsum Valley and Dolores anticlines.

The third and mildest period of uplift occurred in the Pleistocene and was essentially contemporaneous with the post-Hinsdale uplift of the San Juan Mountains. This uplift began near the end of the earliest, or Cerro, stage of glaciation.

Uranium-vanadium, manganese, and copper ore as well as gravel have been mined in the Klondike district. All deposits are small, and few have yielded more than 100 tons of ore. Most of the latter are carnotite deposits.

Carnotite occurs in the lower part of the basal sandstone unit of the Salt Wash member of the Morrison formation. Most deposits are in a narrow, elongate "mineral belt" that cuts obliquely across Klondike Ridge. The remaining deposits probably form a second "mineral belt" lying about 1/2 mile to the north.

Manganese and copper deposits show both stratigraphic and structural controls of mineralization. Most manganese deposits are in red beds near Tertiary faults; most copper deposits, on the other hand, are in brown sandstone, limestone, or gray-green shale and, like manganese, are in or near Tertiary faults.

The manganese and copper deposits are hydrothermal in origin and were formed in the roots of an ancient hot springs system, now deeply eroded. The ore-bearing solutions probably consisted of dilute, carbonate-sulfate ground water heated by the near-surface intrusion of sm bodies of igneous rock. These solutions obtained their metals by leac ing the wallrock; little, if any, material was added by the intrusives

The deposits were formed near the surface under conditions of hydrostatic pressure, and temperatures and pressures in the ore-bearir solutions were probably low. The early solutions were weakly alkaline and reducing in character. A convection cell was established as miner ization progressed, and surface water mingled at depth with the therma solutions. As a result of mixing and oxidation, the pH of the solutio decreased in later stages of mineralization and the Eh rose.

Introduction

Location and Extent of area

The region described in this report is in San Miguel and Dolores Counties in southwestern Colorado. It is an irregularly shaped area covering about 100 square miles and including all of the Cedar 1 NW 7 1/2 minute quadrangle and parts of the adjoining Cedar 2 NE, Gypsum Gap, and Paradox Valley 4 SE quadrangles. The location of this area a[n]d its relation to nearby parts of Colorado and adjoining states are show[n] in figure 1.

Purpose and Scope

This report describes the geology of the area with emphasis on the mineral deposits of the Klondike (or Klondyke) mining district. Small deposits of uranium- and vanadium-, manganese-, and copper-beari[ng] minerals have been mined intermittently in the district since at least 1914 (Jones, 1920, p. 68). Production has been negligible, but the unusual metal associations and the possibility of finding larger deposits at depth have helped maintain interest in the district.

The present investigation has yielded data pertaining to the origin and localization of the copper and manganese deposits, to the potential mineral reserves of the district, to the structural history of the southeastern end of the Gypsum Valley salt anticline, and to the geologic history of the area as a whole.

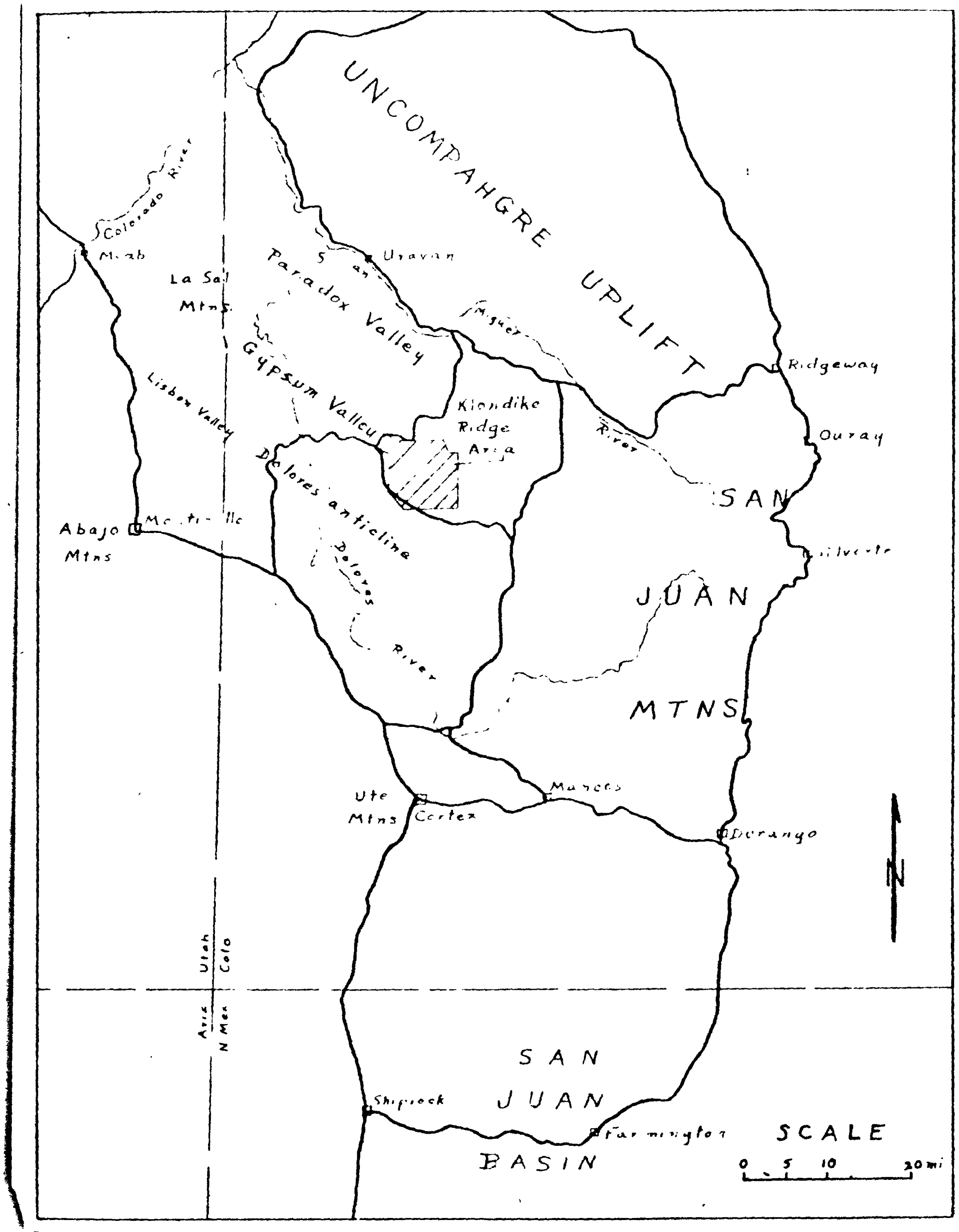


Figure 1. Index map showing location of areas referred to in the text.

Previous work

Many geologist and mining engineers have visited the Klondike district, and references to it are found in several publications. The geology and mineral resources were discussed briefly by Coffin in 1921 (p. 210-211). The manganese deposits were described by Muilenberg (1919, p. 50-52), Jones (1920), and Coffin (1921, p. 211). Part of the Klondike district is shown on Oil and Gas Investigations Preliminary Map 93 (Stokes and Phoenix, 1948). Cater (1955a) shows the northwestern part of the district in the geologic map of the Gypsum Gap quadrangle. The geology of the rest of the area has not been described in any published report.

Field and cartographic work

Field work covered the periods April-September 1956, and June-September 1957. C. A. Westcott was geologic assistant in 1957. Geology was plotted in the field on vertical aerial photographs, scale approximately 1:12,000 and 1:31,680 and later transferred to the base map with a Kail radial planimetric plotter. A transit-surveyed triangulation net for ground control was established by R. N. Brown and J. McKnight in the summer of 1956. One photograph of the Klondike district had too much tilt to be used with the Kail plotter. The geology of this area was plotted on photographic mosaics prepared by the United States Soil Conservation Service (scale 1:31,680) and transferred to the base map with a Saltzman projector. Elevations used in drawing the structure contours and geologic sections were taken from a preliminary copy of the "Cortez" two degree topographic map prepared by the Army Map Service.

Acknowledgments

The writer is indebted to C. A. Westcott for his able and conscientious cooperation and to R. N. Brown and J. McKnight for the survey control used in preparing the maps. To the many members of the U. S. Geological Survey who performed the chemical and spectrographic analyses the writer wishes to express his sincere appreciation. The writer is also grateful to the miners of the area whose cordial cooperation and generous assistance facilitated the progress of the field work.

Professor K. B. Krauskopf of Stanford University made many helpful suggestions during the course of the investigation. The writer is also indebted to A. L. Brokaw, D. R. Shawe, and D. G. Wyant for helpful discussions in the field and to Professors B. M. Page and C. F. Park of Stanford University who kindly read the manuscript and offered many valuable suggestions. The investigation was performed by the U. S. Geological Survey on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission.

Geography

General features

The Klondike Ridge area is in the Canyon Lands section of the Colorado Plateau physiographic province (Fenneman, 1931); it is in the northeastern part of this province in the region characterized by salt anticlines. The physiography reflects the transition between two major structural elements which occurs here. The western part is typical of the salt anticline region of the Plateau; long, en echelon, northwest-trending, collapsed anticlines are largely enclosed by high ridges with steep inner walls and gently sloping outer flanks that dip into broad, shallow synclines. The physiography of the eastern part, however, reflects movements in the San Juan Mountains to the east, making this the highest part of the area. Total relief is about 3,000 feet with elevations ranging from 5,850 feet at Disappointment Creek near the western edge of the map to 8,800 feet on the highlands along the eastern border.

For ease of description the map area has been divided into five subregions on the basis of structural and physiographic characteristics. These are: Dry Creek Basin in the north, Gypsum Valley, the Horse Park fault block, Disappointment Valley, and the Dolores anticline in the south (figure 2).

Dry Creek Basin for the most part is a broad, nearly level erosion surface carved out of the soft Mancos shale. A gently sloping alluvial fan on the southern side of the basin abuts against the Horse Park fault block (picture 12). Total relief is about 600 feet with elevations ranging from 6,400 feet in the western part to 7,000 feet in the east.

Gypsum Valley is a collapsed salt anticline. The flanks of the anticline rise above the valley floor in long, parallel hogback ridges that are steep-walled on the inside but dip gently outward into the adjacent synclines (picture 1). The floor of the valley in the map area is largely an irregular, hilly surface composed for the most part of highly contorted gypsum beds (picture 2); widespread alluvial deposits, however, cover the valley floor near Gypsum Gap in the northwestern part of the area. Elevations range from 6,180 feet in the floor of the valley to more than 7,300 feet on Klondike Ridge. Gypsum Gap is a low pass, or windgap, on the southern flank of the anticline near the northwestern edge of the map. Klondike Ridge is the southeastern part of the hogback extending in an easterly direction from Gypsum Gap toward Horse Park. The Klondike amphitheater is the name used in this report for a small area of irregular topography near the southeastern end of Gypsum Valley. The amphitheater is bounded on the northern and eastern sides by steep cliffs and owes its physiographic character both to the collapse of beds that once rose over the anticline and to extensive erosion (picture 5). The Klondike mining district extends southeast along Klondike Ridge from Gypsum Gap to the Klondike amphitheater and then swings north around the end of Gypsum Valley to the Horse Park fault (pl. 3).

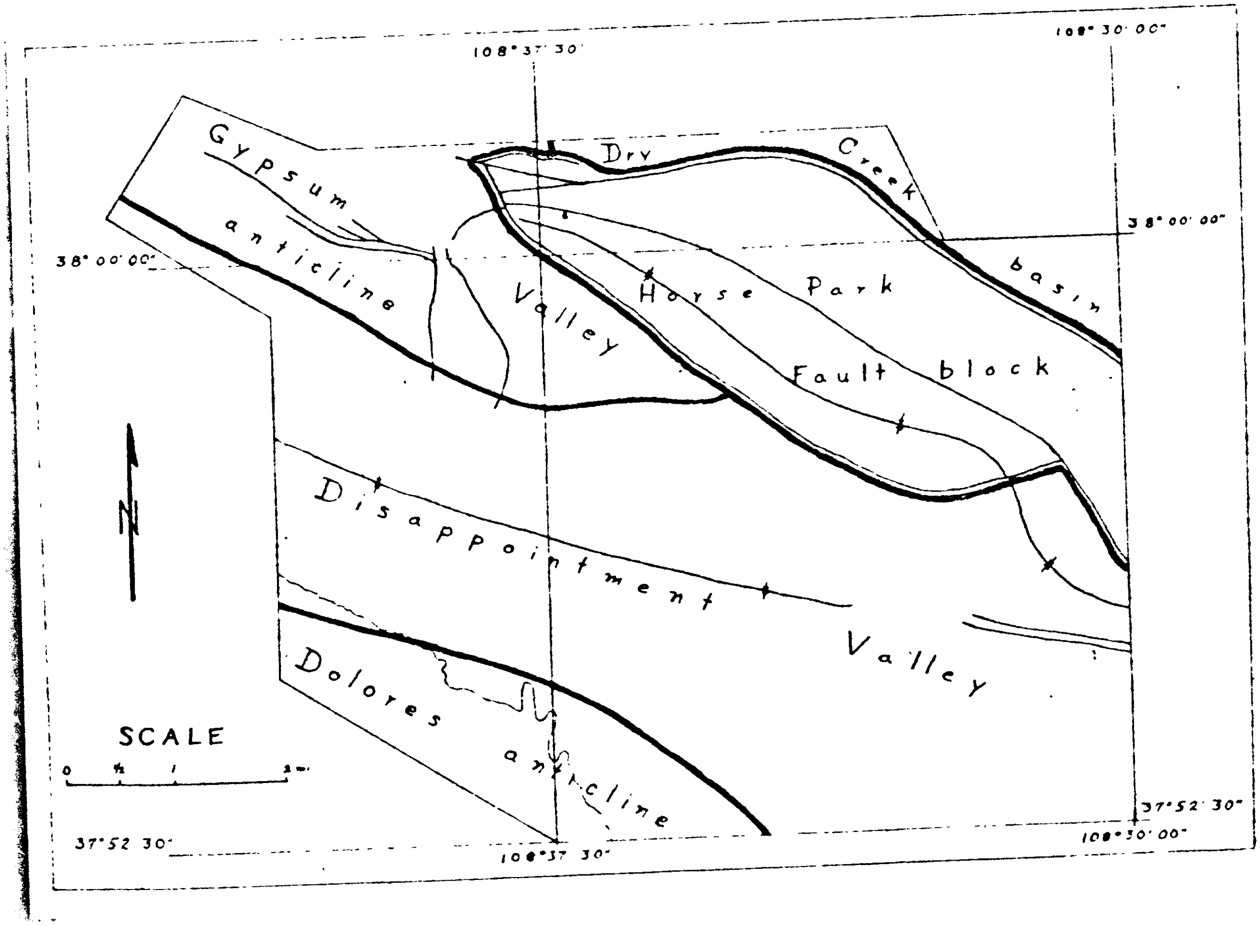
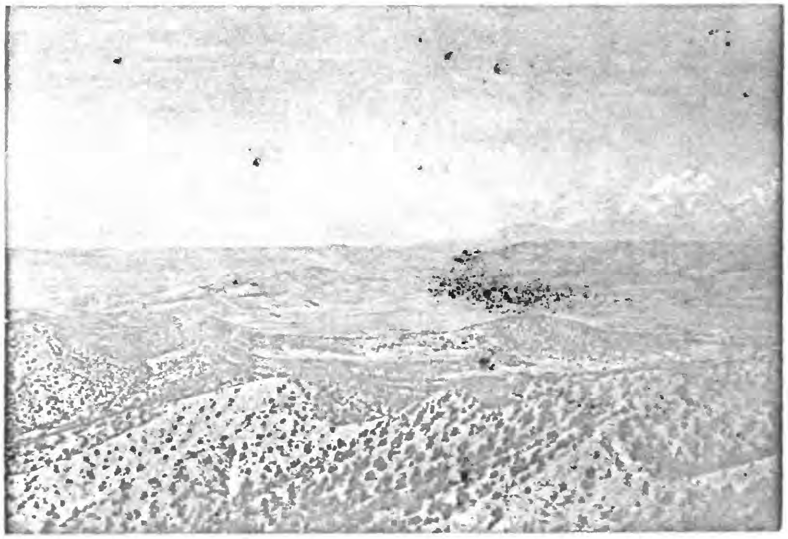


Figure 2. Klondike Ridge area showing major structural and geomorphic units.



Picture 1. Gypsum Valley and Klondike Ridge.

Looking northwest from the Klondike amphitheater.

Picture 2. Paradox member of the Hermosa formation

in the floor of Gypsum Valley.

The Horse Park fault block is a trough-shaped upland area. It is bounded on the north by the concealed Horse Park fault and Dry Creek Basin and on the south by an unnamed fault of major proportions and Disappointment Valley. A number of small faults, marked at the surface by low scarps, cut the fault block and interrupt the predominantly gentle inward slope of the beds. The fault block rises more than 1,000 feet above Dry Creek Basin (picture 12) and about 500 feet above Disappointment Valley. Elevations range from 6,700 feet in Spring Creek graben to 8,400 feet along the northeastern edge of the fault block.

Disappointment Valley is a broad valley carved in the Mancos shale. Its physiographic character changes progressively eastward from a nearly level valley in the western part of the report area (picture 14) to an increasingly hilly, irregular surface with many small buttes and steep-sided hills, some of which rise more than 400 feet above the valley floor. These pass eastward into badlands which in turn abut against high cliffs capped with Mesa Verde sandstone (picture 13). Locally these cliffs rise more than 1,800 feet above the floor of the valley. Beyond the cliffs is a basin-shaped upland area that extends eastward out of the map area. The surface of this upland is cut by several deep valleys and by a few low fault scarps. A low, west-facing cliff capped by intrusive igneous sills crosses Disappointment Valley in a north-south direction near the western edge of the report area. Elevations in Disappointment Valley range from 5,850 feet in the west near Disappointment Creek to 8,800 feet in the east and include both the lowest and the highest parts of the report area.

The Dolores anticline is another salt anticline, but one which has not collapsed. Only a small part of its northeastern flank is present in the map area. This consists of a nearly dip slope of Dakota sandstone which is cut by the steep, narrow canyon of Dissappointment Creek.

Drainage and water supply

Most of the area is drained by the intermittent Disappointment and Big Gypsum Creeks which are tributaries of the Dolores River. Dry Creek Basin is drained by Dry Creek, an intermittent stream that flows north into the San Miguel River. There are two springs near Gypsum Gap; both are in the Burro Canyon formation and ordinarily flow at rates of less than a gallon a minute. Most of the water used in the area is either pumped from water-bearing strata at depth or is collected during rainstorms in cisterns and large earthen stock reservoirs.

Climate and Vegetation

The climate is semiarid. No accurate information on rainfall is available, but the average annual precipitation is probably between 10 and 15 inches (U. S. Dept. Agriculture, 1941, p. 807).

Pinyon and juniper grow on the sandstone slopes around Gypsum Valley and the Dolores anticline; scrub oak, pine, and aspen as well grow in the upland regions. Where soil is abundant, sagebrush, grass, and cacti grow in Disappointment and Gypsum Valleys and in Dry Creek Basin. Vegetation, however, is absent on steep shale slopes in Disappointment Valley and Klondike Ridge and also on the floor of Gypsum Valley in areas where gypsum is exposed at the surface.

Population

The permanent population consists of less than a dozen people who live on ranches near the tiny community of Cedar in the southwestern part of the district. Farming, grazing, and mining are the principal industries. Farming is confined to bottom land near Disappointment Creek; cattle and sheep are grazed during the summer in the uplands to the east; mines in the Klondike district are worked sporadically for uranium and vanadium, manganese, or copper, and gravel on Klondike Ridge has been quarried for road ballast.

Accessibility

Colorado Highway 80, an improved gravel road, crosses the northern part of the map area, and side roads provide access to the ranches and mines. Unimproved roads suitable for four-wheel drive vehicles lead into more remote areas.

Geology

Stratigraphy

The Klondike Ridge area is in the northeastern part of the Paradox basin. This basin was an irregularly elliptical marine embayment about 360 miles long and 180 miles wide which received a thick series of limestone, shale, and evaporite deposits in the Middle and Late Pennsylvanian period (Wengerd, 1958). These sediments have been squeezed into a series of long, en echelon salt anticlines in the northeastern part of the basin as a result of salt flowage. Salt flowage may have begun in the late Pennsylvanian (Shoemaker, Case, and Elston, 1958, p. 48), and it has greatly affected the later depositional and structural history of the region.

Sedimentary rocks exposed in the report area range in age from Pennsylvanian to Late Cretaceous and include the Hermosa formation of Pennsylvanian age, the Rico formation of Pennsylvanian and Permian age, the Cutler formation of Permian age, the Chinle formation and Wingate sandstone of Triassic age, the Kayenta formation of probable Jurassic age, the Entrada sandstone, and the Summerville and Morrison formations of Jurassic age, the Burro Canyon formation of Early Cretaceous age, and the Dakota sandstone, Mancos shale, and Mesa Verde group of Late Cretaceous age. Tertiary rocks consist of igneous sills and dikes while Quaternary deposits consist of glacial boulders, outwash gravels, talus and landslide debris, and alluvial and eolian deposits. The Mancos shale and Mesa Verde group crop out over most of the area, but older rocks are exposed on the Gypsum Valley and Dolores anticlines. The igneous sills crop out in Disappointment Valley near the western edge of the area and on adjacent portions of the salt anticlines.

Paleozoic

Hermosa formation: This is the oldest formation exposed in the area. It was deposited in the Paradox basin and is marine in origin. Following standard terminology, the Hermosa formation is separated into three members in this report: the Lower Hermosa, Paradox, and Upper Hermosa members. A conflicting terminology, however, has been used by some stratigraphers in recent articles (Wengerd and Strickland, 1954; Wengerd and Matheny, 1958). These geologists raise the Hermosa to group status and call the Lower, Paradox, and Upper Hermosa members the Pinkerton Trail, Paradox, and Hanoker Trail formations, respectively.

The Lower and Upper members are similar in composition and consist of limestone and dolomite with interbedded shale, siltstone, and fine-grained sandstone. The Paradox member comprises a thick sequence of evaporite deposits with minor interbedded black shale, siltstone, and limestone beds. The Lower member is not exposed in the area and is not described in this report.

Paradox member: The Paradox member is of Middle Pennsylvanian age and contains fossils correlative with those from the Des Moines series in the Great Plains region (Herman and Sharps, 1956, p. 79). The Paradox is exposed in the floor of Gypsum Valley where it consists of earthy and porous gypsum with minor beds of black shale, sandstone, and limestone. These beds are highly contorted as a result of flowage into the anticline and settling caused by near surface leaching of soluble constituents. The Paradox is typically a dirty gray rock whose outcrops are nearly devoid of vegetation. It commonly weathers to low, rounded hills and mounds, but it forms high hills with steep, irregular slopes near the southeastern end of Gypsum Valley (picture 2).

The Paradox is divided into three units (Wengerd and Strickland, 1954, p. 2166). Both the upper and lower units are penesaline complexes of black shale, dolomitic limestone, gypsum, and fine-grained clastic material. The middle unit in Gypsum Valley consists of gypsum and minor black shale, siltstone, and dolomitic limestone. Drill-hole data, however, reveal that in addition to these deposits there are also great thicknesses of evaporite salts and anhydrite at depth, sediments not likely to survive long the effects of weathering near the surface. These data indicate that at depth the middle unit consists of about 80 percent evaporite deposits and about 20 percent clastic material (Shoemaker, Case, and Elston, 1948, p. 47).

The Paradox contains many thin beds of euxinic black shale. These are dense, dark-gray or black, organically rich rocks, which Wengerd and Strickland report (1954, p. 2186), can be correlated over great distances. In the middle unit these black shale beds are thin and are interbedded with evaporite deposits, but both the upper and lower units contain thick deposits of black shale. Locally, for example, black shale and associated rocks in the upper unit are as much as 500 feet thick (ibid, p. 2186-2187). These shales are thought to be the source beds of Pennsylvanian oil and gas in the Paradox basin (Herman and Sharps, 1956, p. 77-81); present studies also point to the black shales as a possible source of some metals found in the Klondike district (p. 148).

The thickness of undisturbed Paradox beds is probably greater than 4,000 feet in the report area (Wengerd and Matheny, 1958). The thickness of deformed salt in Gypsum Valley, however, is probably about 9,800 feet because a nearby test well drilled on the flank of the anticline passed out of salt at that depth.

There is a small carnotite deposit in the Paradox member in Gypsum Valley. This deposit is believed to be epigenetic and is described more completely on page 197.

Upper Hermosa member: The Upper Hermosa member consists of fossiliferous gray limestone, cherty limestone, dolomite, and minor gray-green and maroon calcareous shale, siltstone, and sandstone (table 4). Limestone and dolomite are more abundant in the upper part (Baker, Dane, and Reeside, 1933, p. 969). Limestone and dolomite beds are persistent over wide areas, but the other strata are lenticular. Only the upper part of the member is exposed in the report area, but nearby drill-hole data show that the member is 2,000 to 2,300 feet thick (Cater, 1955a).

The transition from evaporite deposits of the Paradox member to normal marine limestones and shales of the Upper Hermosa member marks the end of deposition in restricted seas of the Paradox basin and a change to deposition in freely circulating water of an open shelf environment. The Upper Hermosa member ranges in age from Middle to Late Pennsylvanian and contains fossils correlative with those from the upper Des Moines, Missouri, and Virgil series of the Great Plains region (Herman and Sharps, 1956, p. 81).

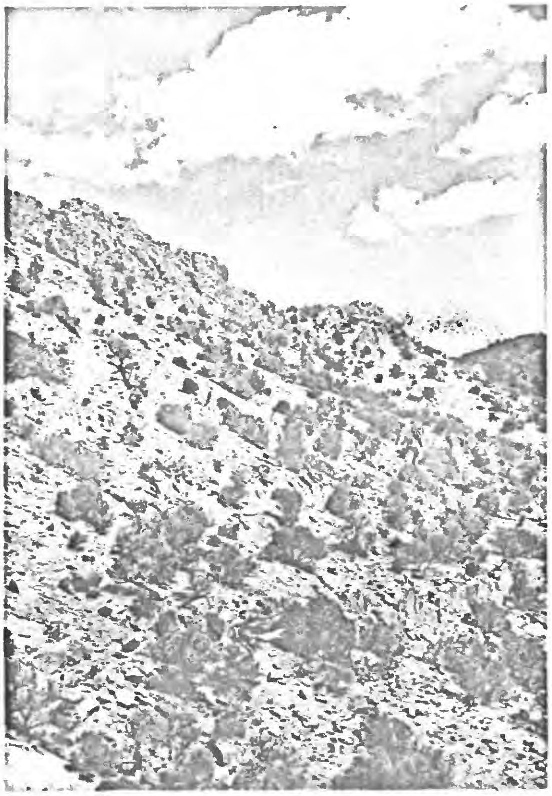
There are several small deposits of copper-bearing minerals in the Upper Hermosa member on Klondike Ridge. These deposits also contain secondary calcite and hydrocarbons and are closely associated with faults. They are thought to be epigenetic and are discussed more fully on pages 106 to 122.

Rico formation: The Rico formation is a transitional unit containing both marine and continental deposits. It conformably overlies the Hermosa and is exposed in the Klondike district at the southeastern end of Gypsum Valley. It is composed of fossiliferous marine limestone and shale with interbedded nonmarine red bed deposits (table 4). The marine deposits are similar to those of the Upper Hermosa member, but the nonmarine units comprise a heterogeneous assemblage of conglomerate, micaceous and arkosic sandstone, siltstone, and shale. These clastic sediments are predominantly red with minor gray-green banding and mottling, but locally they are light-brown or gray-green. The Hermosa-Rico contact is drawn at the base of the lowest nonmarine unit.

The clastic material comprises detritus shed from the rising Uncompahgre highland to the north and east and deposited near the shore of the Paradox sea. Fluvial cross-bedding is common, and locally plant debris is abundant. Marine limestone is more abundant than continental deposits in the lower part of the formation, but continental deposits predominate in the upper part. The limestone is more resistant to erosion than the clastic beds, and where the strata are nearly vertical, as in the western part of Klondike Ridge, the limestone beds form a series of steep, rib-like walls that locally rise more than 20 feet above the clastic deposits (picture 3).

A small sandstone dike in the Rico formation crops out on the eastern side of the Klondike amphitheater. The dike is about 2 inches wide, and only the lowermost 10 feet or so are exposed, the rest having been removed by erosion. The dike is in the upper part of the formation and cuts micaceous red mudstone. It is composed of a mixture of fine- to very fine grained sandstone and mudstone similar to clastic material in both the Rico and Cutler formations. The red mudstone wallrock is altered to green in a contact zone about half an inch wide The dike is cemented with calcite, and veinlets of calcite extend along the fracture for several feet below the clastic material. The dike apparently was formed by unconsolidated sediments from overlying beds falling into and filling an open fracture in the mudstone; the fracture presumably was formed by movement in the Gypsum Valley salt anticline.

The Rico formation ranges in age from Middle Pennsylvanian, Des Moines, to Permian (Henbest, 1948, p. 1330). It is about 640 feet thick on Klondike Ridge, but the thickness is quite variable. Several small manganese deposits and a deposit of iron and copper sulfides are found in the Rico formation on Klondike Ridge. All of these deposits are closely associated with faults and are thought to be epigenetic. They are described more fully on pages 102 to 122.



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Picutre 3. Differential weathering in the Rico formation. Some limestone beds rise more than 20 feet above the clastic deposits.

Cutler formation: The Cutler formation is exposed in the Klondike district where it conformably overlies the Rico. It is wholly nonmarine in origin and is composed of red, gray-green, and mottled and banded red and gray-green sandy mudstone and siltstone (table 5). These beds are similar to nonmarine beds in the underlying Rico formation and represent continued deposition of coarse clastic material shed from the Uncompahgre highland to the northeast. The Rico-Cutler contact is drawn on top of the highest marine unit in the section.

In general the Cutler formation is well cemented, but it is poorly cemented in the northeastern part of the Klondike amphitheater. The Cutler there is readily eroded into picturesque "hoodoo" structures (picture 4) which are tall sandstone pillars that have been protected from erosion by overlying talus blocks of Salt Wash sandstone. Elsewhere in the same area joints in conglomerate are filled with a mixture of calcite and sand, forming a tightly cemented sandstone network that locally stands up as much as a quarter of an inch above the conglomerate.

The Cutler formation is of Pennsylvanian and Permian age in the San Juan Mountains (Henbest, 1948, p. 1330). It is Early Permian in age in Utah, however, where it contains fossils correlative with those from the Wolfcamp and the lower part of the Leonard series of Texas and New Mexico (Wengerd and Strickland, 1954, p. 2190). It is probably Permian in age in the report area (Cater, 1955a).

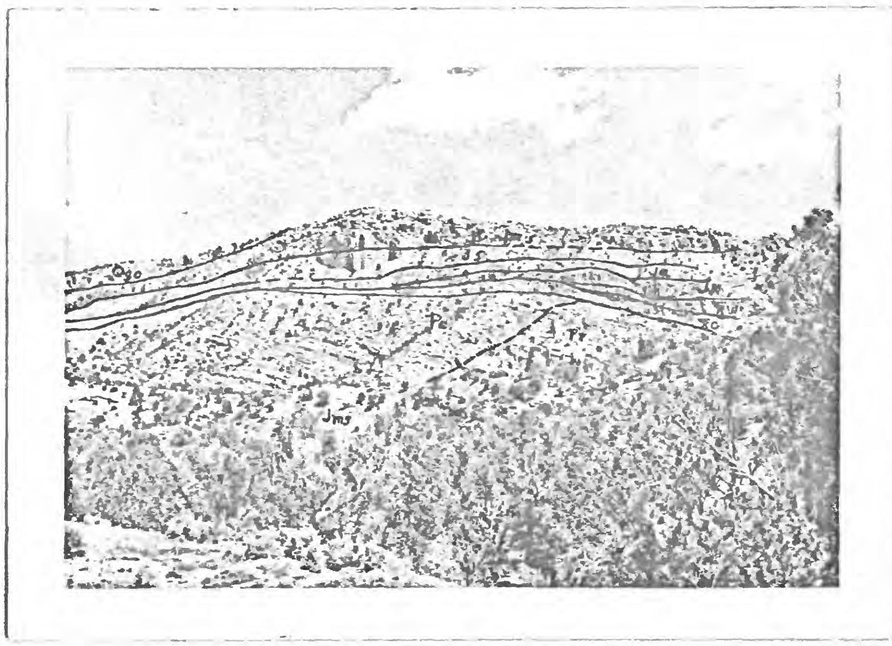
Paleozoic strata in the Klondike district are truncated by an angular unconformity (picture 5). As a result, only the lower 380 feet or so of the Cutler formation are exposed, but nearby well data show that the Cutler is more than 1,900 feet thick elsewhere in this region (Shawe, Simmons, and Archbold, 1957, p. 49). A somewhat thinner section was probably deposited over the salt anticlines because of uplift during Cutler time (page 62).

The Cutler formation contains several small deposits of copper- and manganese-bearing minerals on Klondike Ridge. Most deposits are closely associated with faults, and all are believed to be epigenetic. They are discussed more fully on pages 102 to 122.

Mesozoic

Chinle formation: Lower and Middle Triassic formations are not exposed in the report area, but the Upper Triassic is represented by the Chinle formation and the Wingate sandstone. The Chinle is present in the Klondike amphitheater and in a small exposure about 1/2 mile to the northeast. In the Klondike amphitheater the Chinle rests unconformably upon the maturely-developed Permian and Triassic erosion surface (picture 5). It pinches out to the north against the Gypsum Valley anticline and is truncated on the south by a fault.

Picture 4. "Hoodoo" pillars in the Cutler formation.



Picture 5. East wall of the Klondike amphitheater.

Chinle strata on Klondike Ridge consist mostly of coarse, gray-green limestone conglomerate (table 6), but some micaceous red and gray-green shale and sandstone units are also present. The conglomerate contains pebbles and cobbles of grayish-pink limestone, red and gray-green shale, and pale red sandstone. Most pebbles are well-rounded, indicating a relatively distant source, but a few intermixed angular shale and limestone fragments in the conglomerate show that some of this material is detritus washed off the Gypsum Valley anticline. Most sediments are cross-bedded and are of fluvial origin, but a few beds near the top of the section are red and gray-green shale and gray-green limestone of probable lacustrine origin. The Chinle varies in thickness from a knife-edge to about 48 feet where it is truncated by a fault. It probably increases to a normal thickness of about 475 to 550 feet (Cater, 1955a) beneath Disappointment Valley and Dry Creek Basin.

Only the upper part of the Chinle is present in southwestern Colorado (Stewart, 1956, p. 88). Chinle strata on Klondike Ridge probably belong to the lower part of this upper unit. Shawe, Simmons, and Archbold (1957, p. 48) report that Chinle strata in the nearby Slick Rock district consist predominantly of red siltstone with minor red and gray-green shale and sandstone units; conglomerate is minor except in the lowermost 50 feet or so which is mostly sandstone and conglomerate. The Chinle conglomerate on Klondike Ridge, therefore, probably belongs to this lowermost conglomerate unit.

The pinchout of Chinle strata on Klondike Ridge is due to both an intraformational wedgeout against the flank of the anticline and to post-Chinle erosion. Therefore, the pinchout indicates uplift on the anticline both during and after deposition of the Chinle conglomerate.

The Chinle is thought to have been deposited on a large alluvial plain containing numerous lakes (Stewart, 1956, p. 91). Streams carrying these sediments probably originated in the Uncompahgre highland to the northeast and flowed in a southwesterly direction across the report area into south-central Utah (ibid).

A small sandstone dike is exposed in the Chinle near the southeastern end of the Klondike amphitheater. This dike is about 2 inches wide and extends downward about 5 feet from the top of the formation. It fills a fracture in the conglomerate and was probably formed by unconsolidated sediments falling into and filling the fracture in the same way the clastic dike in the Rico formation was formed. This fracturing must have occurred after the Chinle was partially consolidated and was probably caused by movement in the Gypsum Valley anticline in late Chinle or early Wingate time.

Glen Canyon group: The Chinle is overlain by the Glen Canyon group which includes the Wingate sandstone of Triassic age, the Jurassic(?) Kayenta formation, and the Jurassic Navajo sandstone. The Navajo sandstone, however, is not exposed in the report area. Its eastern boundary in Gypsum Valley is a few miles west of Klondike Ridge (Stokes and Phoenix, 1948), so Navajo deposits may not be present in the report area.

The Glen Canyon group, for the most part, was deposited during a period of aridity. The strata are dominantly eolian in origin and consist of great, sweeping, tangentially cross-bedded sandstone units with minor interbedded aqueous deposits. The arid cycle was interrupted during Kayenta time by deposition of widespread fluvial sediments. The Chinle-Glen Canyon contact is conformable throughout most of the area (Cater, 1955a), but it is marked by an angular unconformity in the Klondike amphitheater (picture 5) caused by movement in the anticline during the Late Triassic.

Wingate sandstone: The Wingate is a pale-orange, cliff-forming sandstone that is ordinarily about 250 to 300 feet thick in this area (Cater, 1955a). It is primarily an eolian deposit and consists of thick, tangentially crossbedded sandstone units separated by a few horizontal bedding planes of probable fluvial origin (ibid). It is generally fine grained and is composed of clean, well-sorted quartz sand. The Wingate sandstone on Klondike Ridge, however, has an entirely different character. Here it is entirely fluvial in origin and contains numerous interbedded conglomerate lenses. The conglomerate consists mostly of rounded cobbles that were probably derived from the underlying Chinle conglomerate, but there are also a few angular fragments of shale that must have come from older formations exposed on the anticline.

The Wingate sandstone unconformably overlies the Chinle on Klondike Ridge and ranges in thickness from zero to about 23 feet (table 6). The unusual character of the sandstone undoubtedly results from contemporaneous uplift in the anticline during deposition of the sandstone.

The Wingate contains several small deposits of manganese-bearing minerals on Klondike Ridge. These deposits are epigenetic and are described in more detail on pages 102 to 105.

Kayenta formation: The Kayenta formation crops out on a narrow bench in the Klondike amphitheater. It is a poorly sorted sandstone and contains minor shale and calcareous siltstone lenses (table 6). The Kayenta is characteristically red in color, but it has a few gray-green calcareous siltstone units. The sandstones display both ripple marks and fluvial cross-bedding; plant debris is abundant on certain horizons.

The Kayenta conformably overlies the Wingate sandstone in most areas (Cater, 1955a), and the contact is gradational, but on Klondike Ridge the contact is unconformable. The Kayenta ranges in thickness from a knife-edge in the north, where it pinches out against the flank of the Gypsum Valley anticline, to about 200 feet near the southern edge of its exposure, where it is truncated by a fault. This probably represents the complete normal thickness of the Kayenta, which is thought to be about 190 to 230 feet thick (Cater, 1955a) beneath Disappointment Valley and Dry Creek Basin.

The Kayenta is primarily a fluvial deposit, but some sediments are lacustrine. The streams are thought to have originated in the ancestral Uncompahgre highland and to have flowed in a southwesterly direction across the report area (Craig and others, 1955, p. 95).

The Kayenta contains several small deposits of manganese-, copper-, and vanadium-bearing minerals on Klondike Ridge. These deposits are epigenetic and are discussed more fully on pages 102 to 122.

San Rafael group: The San Rafael group is of Late Jurassic age and consists of the Carmel formation, the Entrada sandstone, and the Summerville formation. Only the Entrada sandstone and Summerville formation are exposed in the report area. The base of the San Rafael group everywhere is marked by an unconformity (Craig and Dickey, 1956, p. 97) which is an angular unconformity in the Klondike amphitheater (picture 5).

Entrada sandstone: The Entrada sandstone crops out on Klondike Ridge where it unconformably overlies the Kayenta. It is a very fine grained, buff-tan sandstone and is distinctly bimodal. The Entrada in nearby areas is composed entirely of very fine grained, subrounded to angular grains of quartz sand with some admixed coarse, well-rounded quartz grains. The Entrada generally consists of thick, massively cross-bedded eolian units truncated by a few thin, horizontally bedded units of probable fluvial origin. On Klondike Ridge, however, an abnormally large proportion of the sandstone is fluvial, and these units show the effects of movement in the anticline during deposition (tables 7 and 8). Cross-bedded fluvial units increase in number and thickness toward the anticline; zones of chert pebble conglomerate and mudstone flakes are abundant locally in these units and also increase in number and thickness toward the anticline. Both pebbles and mudstone flakes evidently were derived from underlying formations eroded off the top of the anticline while the Entrada was being deposited around its flanks.

The Entrada ranges in thickness from a knife-edge to about 95 feet where it is truncated by a fault, but it probably increases to a normal thickness of about 110 to 130 feet (Cater, 1955a) beneath Disappointment Valley and Dry Creek Basin.

In general, the sandstone is firmly cemented and weathers to form a steep, smooth cliff overlain by shale slopes of the Summerville formation. It is very poorly cemented in the western part of Klondike Ridge, however, where its presence in many places is marked only by a narrow band of light-tan, sandy soil with little, if any, indurated sandstone in evidence.

The Entrada contains two small manganese deposits and several small deposits of copper-bearing minerals on Klondike Ridge. These deposits are epigenetic and are discussed more fully on pages 102 to 122.

Summerville formation: The Summerville formation is exposed on Klondike Ridge where it consists of thin, even-bedded shale units with minor siltstone and sandstone lenses and rare limestone beds (table 6). The shale is predominantly red of various shades, but some beds are gray-green, tan, or nearly white. Many beds are calcareous. The formation weathers to form a gentle slope which is commonly littered with sandstone talus from the overlying Morrison formation.

The Summerville is thought to be predominantly a flood plain deposit in southwestern Colorado (J. C Wright, oral communication), but thin limestone beds on Klondike Ridge attest to the presence of some lacustrine deposits also. In addition slump structures and thin alluvial fan deposits on Klondike Ridge record minor uplift in the anticline during Summerville time (picture 10). The Summerville ranges in thickness from a knife-edge to about 88 feet on Klondike Ridge but probably increases to a normal thickness of about 105 feet (Cater, 1955a) beneath Disappointment Valley and Dry Creek Basin.

The Summerville contains several small deposits of copper- and manganese-bearing minerals on Klondike Ridge. These are epigenetic and are described more fully on pages 102 to 122.

Morrison formation: The Morrison formation, of Late Jurassic age, is exposed on both the Gypsum Valley and Dolores anticlines. Two members are recognized in the report area, the Salt Wash and the overlying Brushy Basin. Both are predominantly fluvial in origin and are composed of thick stream and flood-plain deposits with minor interbedded lacustrine sediments. The Salt Wash member consists of thick sandstone units separated by relatively thin shale partings, while the Brushy Basin is predominantly shale but with minor sandstone and conglomerate lenses.

The Morrison formation is thought to be a large alluvial fan formed by aggrading streams that flowed in a northeasterly direction across the report area. The source of these streams is thought to have been western Arizona or southern California (Craig and others, 1955, p. 150, 157). The Morrison is also thought to be the first formation since the Cutler to have covered the salt anticlines completely (Cater, 1955a). In the report area, for instance, the Gypsum Valley anticline was completely eroded by early Morrison time and not only received stream deposits but was the site of a short-lived lake (see below). Other formations undoubtedly crossed the anticlines in places, but salt plugs and cupolas on the anticlines are thought to have prevented complete overlap.

The Morrison formation conformably overlies the Summerville, but the contact is gently undulating due to channeling by Morrison streams in the Summerville surface. A local angular unconformity is exposed in the Klondike amphitheater where the Summerville pinches out against the Gypsum Valley anticline. The Summerville-Morrison contact is drawn at the base of the lowest lenticular unit above the thin, even-bedded Summerville shales (Craig and Dickey, 1956, p. 101). This unit is commonly a crossbedded fluvial sandstone, but locally the basal Morrison consists of gray-green shale, a few inches to a few feet thick, which is distinguished from the underlying Summerville shales by its thick to massive bedding and its lenticularity.

Salt Wash member: The Salt Wash is exposed on Klondike Ridge where it crops out both as resistant sandstone ledges separated by soft shale partings and as broad dip slopes. Most of the Salt Wash on Klondike Ridge consists of flood-plain deposits. These are thin- to thick-, even-bedded sandstone units, Individual beds are lenticular over a distance of several dozens of feet and are commonly separated by thin shale partings (table 9). Many small stream channels filled with crossbedded sandstone and some organic debris are incised a foot or two into these deposits. Less common are large, thick units of superimposed and interfingering, crossbedded, lenticular sandstone units that were evidently deposited in channels of larger rivers. A thin bed of lacustrine limestone crops out near the base of the lowest Salt Wash sandstone unit in the western part of Klondike Ridge and in collapsed blocks of Salt Wash sandstone in Gypsum Valley.

The sandstone is a well sorted, fine-grained rock composed largely of subangular to subrounded quartz grains. Feldspar commonly forms about 5 percent of the rock; chert and heavy minerals are accessory. Calcite is the principal cementing material. Large quantities of interstitial mudstone and mudstone pebbles and flakes are concentrated in some lenses. Wood and plant debris are abundant locally. On Klondike Ridge this woody debris consists mostly of small twigs and branches; fossils trees are rare. The sandstone on Klondike Ridge is stained light-brown by limonite, but diamond drill exploration below the water table in nearby areas has shown that the unoxidized sandstone is light gray and contains many small grains of pyrite and marcasite.

The sandstone units are separated by partings of red and gray-green shale with interbedded sandstone lenses. These partings are mostly gray-green in color on Klondike Ridge, but they are probably reddish-brown beneath Disappointment Valley and Dry Creek Basin as this is their dominant color in southwestern Colorado (McKay, 1955, p. 268-269). The shale is composed of argillaceous material with small amounts of intermixed sand and silt.

The Salt Wash is of considerable economic importance in southwestern Colorado because of the widespread deposits of uranium- and vanadium-bearing minerals found in it. Most of these deposits are in the top sandstone unit of the Salt Wash and are in areas where the sandstone is thick, crossbedded, and has abundant scour and fill bedding, characteristic of stream channel sediments (ibid). The Salt Wash on Klondike Ridge, too, contains several deposits of uranium- and vanadium-bearing minerals as well as deposits of copper-bearing minerals. All of these deposits are small, however, and are in the bottom sandstone unit of the Salt Wash. They are probably epigenetic and are discussed at more length on pages 92 to 94 and 195 to 197.

Brushy Basin member: The Brushy Basin member of the Morrison formation crops out on the flanks of both the Gypsum Valley and Dolores anticlines. It consists of varicolored shales with minor interbedded conglomerate, sandstone, and limestone lenses (table 10). The shale ranges in color from green of various shades to blue, red, orange, or nearly white. Several horizons are bentonitic. Beds and lenses of light-brown chert pebble conglomerate and sandstone occur throughout the Brushy Basin but are most abundant in the lower part of the member.

The Brushy Basin shale weathers to form smooth slopes which are commonly littered with loose gravel and boulders of more resistant material; sandstone and conglomerate units form resistant ledges similar to those in the Salt Wash. The Brushy Basin is about 480 to 515 feet thick in the report area (tables 10 and 11). This is somewhat thicker than normal, about 350 to 420 feet in this part of southwestern Colorado (Cater, 1955a), and may indicate an eastward extension of the Disappointment basin into the report area (see page 80).

The Salt Wash-Brushy Basin contact is gradational and is arbitrarily drawn at the base of the lowest conglomeratic sandstone in the formation (Craig and others, 1955, p. 156). The Brushy Basin is predominantly fluvial in origin. Sandstone and conglomerate beds mark ancient stream channels, while the shales are largely flood-plain deposits. The limestone beds were probably deposited in small, ephemeral lakes; the bentonitic material is thought to be volcanic ash.

Burro Canyon formation: The Burro Canyon formation conformably overlies the Morrison and is exposed on the flanks of both the Dolores and Gypsum Valley anticlines. It characteristically crops out as a low cliff of series of thick ledges, but locally it forms dip slopes on the flanks of the anticlines. It is of Early Cretaceous age (Stokes, 1952, p. 1766) and consists of gray to light-brown, cross-bedded conglomerate and sandstone with some interbedded light-green shale (tables 11 and 12). Most of the conglomerate pebbles are chert, but some are composed of quartz, quartzite, limestone, sandstone, or shale.

The Morrison-Burro Canyon contact is drawn at the base of the first thick conglomeratic sandstone overlying the thick sequence of Brushy Basin shales (Stokes and Phoenix, 1948). This contact is irregular in most places because small conglomerate-filled stream channels have scoured into the underlying shale. In some areas, however, the contact is gradational and the two formations interfinger.

The Burro Canyon is about 160 feet thick near Gypsum Gap, but it increases to a thickness of about 194 feet in Disappointment Valley, where it also contains a larger proportion of channel deposits. This increased thickness was caused by the deposition of abnormally thick sandstone and conglomerate units in Disappointment Valley and probably indicates a deflection of some streams around the anticline in Burro Canyon time. The Burro Canyon on Klondike Ridge thins abruptly to a thickness of about 50 feet 1 1/2 miles east of Gypsum Gap (pl. 5). The normal thickness of Burro Canyon strata in southwestern Colorado is quite variable (L. C. Craig, oral communication), but on Klondike Ridge this abrupt thinning is due to an intraformational pinchout of strata east of Gypsum Gap. This pinchout was caused by uplift in the southeastern part of the salt anticline in Burro Canyon time (page 66).

Dakota sandstone: The Dakota sandstone is exposed on the flanks of both the Dolores and Gypsum Valley anticlines where it forms steep cliffs and long dip slopes. It is a gray to buff, medium- to fine-grained sandstone with minor carbonaceous gray shale, impure coal, and conglomerate beds (table 13). Some sandstone strata are thin to flaggy, but most are thick- and crossbedded. Locally, the basal sandstone contains chert and quartz pebbles which were probably derived from the underlying Burro Canyon formation. Interbedded with the sandstones are thin-bedded, gray and black, carbonaceous shales and thin, impure coal seams. Plant debris is abundant in both sandstones and shales.

The Dakota is probably of Late Cretaceous age in southwestern Colorado (Brown, 1950, p. 45). It is thought to have been deposited in front of an advancing Late Cretaceous sea and was laid down, for the most part, in flood-plain, swamp, and lagoonal environments. The upper part of the Dakota, however, grades into the overlying marine Mancos shale and was deposited in a littoral environment.

The Dakota is about 150 to 175 feet thick in the report area. Its lower contact with the Burro Canyon formation is marked by a widespread disconformity in southwestern Colorado (Lee, 1916, p. 34-36). The Dakota rests upon a gently undulating erosion surface, but Burro Canyon and Dakota beds are concordant.

Mancos shale

The Mancos shale is of Late Cretaceous age and conformably overlies the Dakota sandstone. It crops out in Disappointment Valley and Dry Creek Basin as a soft, drab-gray, fissile marine shale. Erosion produces broad, level valleys and smooth, rounded hills where a temporary base level has been reached (picture 14) and badlands where downcutting is rapid (picture 13).

The lithologies of the lower and upper parts of the Mancos are slightly different. The lower part contains many thin beds of limestone and brown, calcareous siltstone and sandstone. In addition large, irregularly shaped, limestone concretions are distributed erratically along certain horizons, and thin seams and veinlets of fibrous calcite are plentiful in some areas. Remains of the gastropod, Gryphea newberrii, are abundant in the lower hundred feet or so of shale, and some sandstone beds contain very abundant casts of Scaphites sp. The lower part of the Mancos also contains several bentonitic and pyritic zones which probably represent volcanic ash falls (Shawe, Simmons, and Archbold, 1957, p. 56). The Mancos shale is transitional into the underlying Dakota sandstone, and the two interfinger over a vertical distance of about 40 feet. The Dakota-Mancos contact is drawn on top of the highest sandstone lens below the thick section of Mancos shale.

The upper part of the Mancos is a homogeneous gray shale. Sandstone and limestone beds are thin and rare except near the top. The upper part of the Mancos is lighter gray in color than the lower, but the difference is slight and is rarely noticeable except where the two have been brought into juxtaposition by faulting. The top of the Mancos is transitional into the overlying Mesa Verde group over a vertical distance of about 310 feet (table 15). This transition zone consists of alternating sandstone and shale beds; sandstone beds become thicker and more numerous towards the top of the zone. The Mancos shale is about 2,615 feet thick in the report area (tables 14 and 15).

Traces of malachite are found in the Mancos shale on Klondike Ridge. These are epigenetic and are discussed more completely on page 108.

Mesa Verde group

The Mesa Verde group crops out in the northern and eastern parts of the area where it forms a sandstone cap over the Mancos shale (picture 13). The complete thickness of the Mesa Verde is probably about 1,000 feet (Pike, 1947, p. 11), but only the bottom 100 feet or so are present in the report area, the rest having been removed by erosion. For the most part, the Mesa Verde is a soft, friable, light-brown sandstone. It is well-sorted, fine- to very fine-grained, thick- and irregularly-bedded and cross-bedded, and has some plant debris on the bedding planes. This sandstone probably corresponds to the Point Lookout sandstone described by Collier (1919, p. 296) in the San Juan basin to the south. A gray, Mancos-type shale more than 75 feet thick overlies the sandstone in Spring Creek graben and on a hill in the southeastern part of the area. These exposures are small and are capped by glacial boulders and outwash gravels. They are undoubtedly remnants of a much more widespread shale unit that has been eroded from the rest of the area.

The Mesa Verde contains both marine and marginal marine deposits. The sandstone is thought to have been laid down along fluctuating strand lines of the Late Cretaceous sea, but the shales are marine and are similar to those in the Mancos (Pike, 1947, p. 13-16). The Mancos-Mesa Verde contact is drawn at the base of the lowest cliff-forming sandstone (Holmes, 1877, p. 252).

Cenozoic

Tertiary

Several thousand feet of Late Cretaceous and Eocene sediments were probably deposited over the Mesa Verde group (Hunt, 1956, p. 73-77). Erosion, however, has removed all traces of these beds, and the only Tertiary rocks remaining in the report area are several igneous sills and dikes.

Intrusives

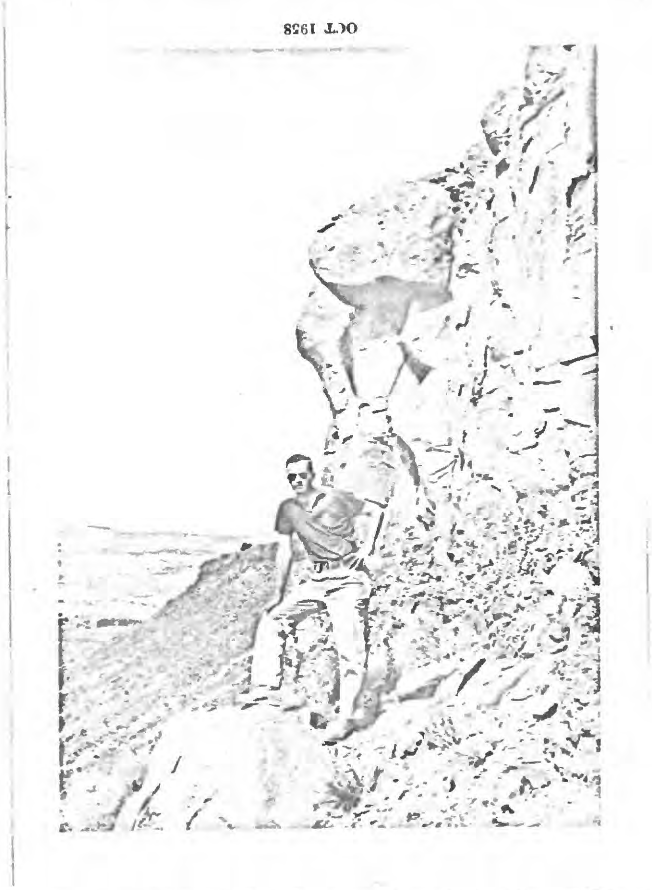
The sills are exposed in Disappointment Valley and adjacent parts of the Dolores and Gypsum Valley anticlines. These sills all have the same composition, and adjacent sills occupy almost the same stratigraphic horizon.

The sills cap a westward-facing bluff in Disappointment Valley and crop out on the adjacent anticlines as long dip slopes and low cliffs. The bluff in Disappointment Valley rises more than 100 feet above the valley floor, and the sills on top dip eastward at low angles into the Mancos shale. The sills are about 15 to 20 feet thick at the bluff but thicken rapidly downdip, in some places attaining thicknesses in excess of 100 feet. In general the sills are less than 15 feet thick on the Dolores anticline, but locally they are more than 100 feet thick on the Gypsum Valley anticline.

Taken as a whole their distribution shows a district-wide pattern. The sills are highest in the stratigraphic section near the center of Disappointment Valley where they are more than 900 feet above the base of the Mancos shale. They drop down progressively in the section towards the edges of the valley and on the Dolores and Gypsum Valley anticlines are in Dakota sandstone. Nevertheless, they have a shallow synclinal structure across Disappointment Valley.

The sills are heavily weathered; weathering is so advanced in some specimens that identification of primary minerals is impossible. The chief products of weathering are clays, chlorite, limonite, hematite, and calcite. In some areas considerable amounts of calcite and gypsum have been introduced from the wallrock. Gypsum tends to be more abundant in sills intruding the Mancos shale, but calcite shows little evidence of wallrock control.

Two processes predominate in the weathering of the sills, and each is dominant in certain places. In some areas mechanical weathering predominates and is marked by a slabbing off of joint blocks. This is the characteristic method of weathering where the sills are thick and joints well developed (picture 6). In other areas the dominant weathering process is chemical and is marked by exfoliation. Here the sills weather to rounded masses a few inches to a few feet in diameter with surface layers that spall off like the skin of an onion (picture 7). Blackwelder (1925, p. 793-806), Griggs (1936, p. 783-796), and more recently Howard (1950, p. 155-156) have suggested that this type of exfoliation is caused primarily by the hydration and oxidation of silicate minerals. Exfoliation is the characteristic method of weathering in areas where the sills are thin and joints poorly developed.



Picture 6. Mechanical weathering of sills in

Disappointment Valley.

Picture 7. Chemical weathering of sills in

Disappointment Valley.

Petrology

The sills are uniform in composition and consist of a very fine-grained, dark- to medium light-gray rock which turns brown upon weathering. It is seriate porphyritic; phenocrysts comprise about 15 percent of the rock and consist, for the most part, of creamy-white labradorite feldspar and greenish-black augite crystals. Biotite flakes are abundant in the central part of the sills but are lacking in the contact zones. The groundmass is very fine grained and has a hypidiomorphic granular texture. The chilled contact zones are microcrystalline and locally contain small amounts of interstitial glass.

Classified according to the system of Johannsen (1932), this rock is a microgranogabbro. It is of special interest in this report not only because of its occurrence, isolated as it is from any obvious nearby parent body, but also because it is a possible source of some of the Klondike ore deposits. Consequently, it will be described in more detail in the following pages than is strictly warranted by the small amount of rock exposed in the report area.

The primary rock-forming minerals are labradorite and andesine feldspar, augite, pigeonite, biotite, orthoclase, and quartz. Accessory minerals are titaniferous magnetite, pyrite, apatite, and zircon. Two modal analyses of the sills are given in table 1. These samples were collected from widely separated parts of the area and suggest that the gross composition of the sills is uniform throughout the district. Most of the differences in composition evident in the table are caused by differences in the amount of weathering of the samples.

The sills have an unusually large amount of orthoclase and biotite in their mode which is suggestive of a high potash content. Rocks from both the nearby San Juan volcanic province (Larsen and Cross, 1956) and the laccolithic mountains of the eastern part of the Colorado Plateau (Hunt, 1956) are characteristically high in potash, but potash in the sills seems to be high even for rocks from those areas.

The sills are probably related to rocks of the San Juan Mountains rather than to the laccolithic intrusives because gabbroic dikes, similar in hand specimens to the granogabbro sills of Disappointment Valley, are widespread on the northwestern side of the San Juan Mountains, and a dike near Dry Creek Basin can be traced in nearly continuous outcrop more than 12 miles up to the mountains. Moreover, the laccoliths are composed dominantly of diorite and more silicic rocks while gabbro is rare. (See Cross, 1894, p. 227; Emery, 1916, p. 354-361; Hunt, 1953, p. 157-159.)

Plagioclase

About a third of the total plagioclase occurs as euhedral phenocrysts, up to 1 1/2 mm long, of intermediate labradorite. The phenocrysts are twinned, albite and combined carlsbad-albite twins predominating. Large, irregular inclusions of groundmass material are common. Many crystals are fractured or broken; fractures extend up to the edges of the crystals, and broken fragments have only very narrow plagioclase overgrowths. This protoclastic fracturing evidently occurred after the phenocrysts had grown to their present size, probably during intrusion of the sills.

Table 1. Modal analyses of igneous rock in Disappointment Valley

	1	2	3	4
Plagioclase	49.0	45.1	58	9.4
phenocrysts	14.9	16.7		
groundmass	34.1	28.4		
Orthoclase	15.4	16.0	12	67.2
Quartz	3.6	2.4	12	7.0
Biotite	9.2	6.5	Tr	3.1
Magnetite	5.0	2.4	4	Tr
Pyroxene	6.2	7.6	11	Tr
Hornblende			1	
Weathering products	11.3	18.3	5	13.3

1. Granogabbro sill in Disappointment Valley. Potash feldspar stained with cobalti-nitrite. Mode based upon 530 points.
2. Syenogabbro sill on Klondike Ridge. Potash feldspar stained with cobalti-nitrite. Mode based upon 538 points.
3. Granogabbro from Little Cone laccolith. Mode based upon 500 points. R. B. Taylor, analyst.
4. Aplite dike in granogabbro sill, Disappointment Valley. Potash feldspar stained with cobalti-nitrite. Mode based upon 451 points.

The rest of the plagioclase occurs in the groundmass where it forms narrow, subhedral laths up to 1/3 mm long. It is dominantly sodic labradorite, but some crystals are andesine. Plagioclase crystals in the groundmass are commonly twinned according to the albite or carlsbad laws; combined carlsbad-albite twins are rare.

Zoning is pronounced in phenocrysts but lacking in the groundmass crystals. This zoning is commonly of the normal type as defined by Phemister (1934, p. 542), the centers being more calcic than the rims, but wavy and oscillatory zoning is also seen in some crystals.

Most crystals are partially weathered to clay and, to a lesser extent, calcite. In some specimens alteration is nearly complete and is accompanied by the addition of calcite or gypsum from the wallrocks. In general weathering is more advanced in the calcic inner portions of phenocrysts than in their more sodic rims and in the coarser-grained inner portions of sills than in the fine-grained contact zones.

Orthoclase

Orthoclase forms about 16 percent of the rock by volume and occurs as irregularly-shaped growths around plagioclase crystals and as anhedral grains in the groundmass. It is not found in the chilled contact zones and evidently did not start to crystallize until the sills were emplaced. Orthoclase is partially weathered to clay minerals, but in general alteration is not as advanced as in plagioclase.

Pyroxene

Both augite and pigeonite occur in the sills, and together they make up about 7 percent of the rock by volume. Pigeonite occurs as small grains in the groundmass, but it does not form phenocrysts. Augite, on the other hand, occurs both in the groundmass and in large, euhedral phenocrysts, and it ranges in size from minute crystals in the groundmass no more than a few hundredths of a millimeter long up to crystals over 2 millimeters in length.

Most augite crystals were fractured or shattered during intrusion of the sills. Some crystals are twinned with (100) as twin plane. The composition of the augite was determined with the Federov stage using the method of Nemoto (1938) and charts compiled by Deer and Wager (1938, p. 22). The 2V was found to be 47° and the extinction angle ($Z_{\wedge}C$) is 41°. The composition of the augite is En 53 Wo 31 Fs 16.

Augite was one of the first minerals to crystallize in the magma. It started to form at about the same time as plagioclase and titaniferous magnetite and probably continued crystallizing until the sills were emplaced. Some pyroxene crystals show evidence of incipient late magmatic alteration. This ordinarily affects only the smallest crystals and narrow, broken fragments of larger ones and consists of biotitization and more rarely uralitization, as shown by the formation of green and brown hornblende and epidote. Pyroxene crystals in the contact zones, however, have not been affected by late magmatic alteration, so alteration probably occurred after the sills were emplaced. Pyroxene weathers to clay minerals, chlorite, and hydrated iron oxides. In some specimens alteration is complete and only casts of the crystals remain.

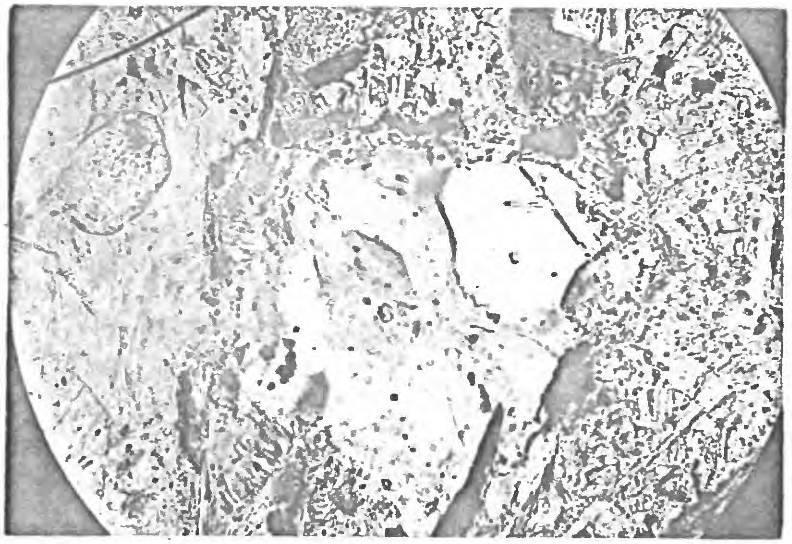
Biotite

Biotite forms about 9 percent of the rock by volume. It is the most abundant mafic mineral in the inner portions of the sills but is not found in the chilled contact zones. It commonly forms small grains, rarely more than 1/2 mm long, in the groundmass, but it also forms alteration rims around titaniferous magnetite and is a rare alteration product of pyroxene.

The biotite is strongly pleochroic, with α = light tan, β = yellow-brown, and γ = deep red-brown. The absence of biotite in the chilled contact zones shows that it formed after intrusion of the sills. Biotite weathers to clay minerals and iron oxides. Nontronite, a common weathering product of the mafic minerals, is very similar to biotite in appearance and is easily mistaken for it in these rocks.

Quartz

Quartz forms about 4 percent of the rock by volume. It occurs as anhedral grains in the groundmass where it is commonly associated with orthoclase. It is not found in the contact zones, so it probably crystallized after the sills were emplaced. Some specimens contain a few corroded, rounded, and partially resorbed quartz phenocrysts that are as much as 1/2 mm in diameter (picture 8). Many phenocrysts are fractured, and nearly all show strain shadows. Larsen, Irving, Gonyer, and Larsen (1936, p. 682-687) found similar phenocrysts in lavas of the San Juan Mountains and concluded that those are remnants of more silicic wallrocks that were partially assimilated by the magma. The granogabbro sills in the report area seem to be closely related to rocks of the San Juan Mountains (page 43), so quartz phenocrysts in the sills probably came from more silicic wallrocks, too.



Picture 8. Quartz phenocryst showing strain shadows and rounded, partially resorbed outline. Crossed nicols. X645

Accessory minerals

Accessory minerals include titaniferous magnetite, apatite, pyrite, and rarely zircon. Magnetite is by far the most abundant and locally exceeds 5 percent by volume of the rock. Magnetite was one of the first minerals to crystallize. It was stable in the magma until the sills were intruded, when it reacted with the melt to form halos of biotite. It weathers readily to limonite; this alteration is nearly complete in the contact zones where the sites of former crystals are marked in many places by euhedral cavities surrounded by halos of limonite. Leucoxene "dust" is abundant in unaltered specimens.

Small amounts of apatite were found in every section studied. It forms tiny needles in the groundmass that are commonly about 1/20 mm long but locally are as long as 1/2 mm. Pyrite, too, occurs throughout the area but is very unevenly distributed. It forms as much as 2 percent by volume of some specimens but more commonly is entirely lacking in the rock. It weathers to hematite and, more rarely, limonite. In general it does not alter as readily as magnetite, and in some specimens magnetite is almost completely altered to limonite while nearby grains of pyrite are still fresh.

Aplite dikes

Two small aplite dikes cut the sills in the central and northern parts of the area. These dikes are light gray in color, less than 3 inches wide, and have an allotriomorphic granular texture. Their grain size is smaller than that of the sills; crystals average less than 0.2 mm in length. The minerals are dominantly orthoclase and quartz; but small, angular remnants of calcic feldspar, biotite, apatite, titaniferous magnetite, and pyroxene together with its alteration products, hornblende and epidote, are present in minor amounts (table 1).

The dike-wallrock contact appears smooth and sharp to the naked eye, but under the microscope the contact is seen to be irregular, and the dike grades into the wallrock over a distance of a few tenths of a millimeter. A few long biotite laths are found in the dikes near the wallrock contacts. These laths are anomalous in the very fine grained dikes and are thought to represent minor wallrock contamination. Johannsen (1932, p. 94-96) has suggested that aplite dikes such as these represent residual fluids that were squeezed up into joints from the interstices of the crystallizing magma along with tiny fragments of crystalline material.

Contact effects

The intrusion of the sills had very little effect on the wallrock. The Dakota sandstone is stained to a medium-gray color by the formation of dark iron oxides and small amounts of clay minerals, primarily nontronite. The Mancos shale, on the other hand, has been bleached light gray near the contact by the expulsion of some dark coloring matter and the recrystallization of calcite into relatively large grains. These changes rarely extend more than a few feet into the wallrock.

It is well known that the effects of metamorphism are controlled by temperature, pressure, and water content of the rocks as well as by their composition. Laboratory investigations have shown that the formation of metamorphic minerals is promoted by high temperature and large water content and is retarded by high rock and water pressures (Yoder, 1955). Under near-surface conditions this means that the amount of wallrock alteration is largely controlled by the water content of the rocks. Since the sills were probably emplaced near the surface (see below), very mild wallrock alteration in Disappointment Valley suggests that the rocks were nearly dry and that little volatile matter escaped into the sediments from the magma.

Age

The rocks seem to correlate with dikes and sills of similar composition in the San Juan Mountains where they are thought to be of middle Miocene age (R. B. Taylor, oral communication, 1959). The sills in the report area, therefore, are probably also middle Miocene in age.

In terms of the structural development of the report area, mapping on Klondike Ridge clearly shows that the sills are younger than the middle Tertiary faults. The sills have not been displaced across the faults, and locally they seem to have used fault planes as conduits during intrusion.

The mineralogy of the sills suggests that a middle Miocene age also is consistent with the inferred erosional history of Disappointment Valley. Hess (1941, p. 532-535) pointed out that pigeonite is not uncommon in rapidly cooled basaltic lavas and hypabyssal rocks but is unstable in plutonic rocks. Moreover, data presented by Larsen, Irving, Gonyer, and Larsen (1936, p. 694-700) suggest that pigeonite inverts readily to hypersthene in volcanic rocks of the San Juan Mountains. The presence of pigeonite in the sills of Disappointment Valley, therefore, suggests that the rocks crystallized rather rapidly and, consequently, were probably emplaced near the surface. This region was subjected to prolonged erosion during the middle and late Tertiary (p. 89), and the inference is that the sills are no older than this period of erosion.

Summary of intrusive rocks

There does not seem to have been anything particularly unusual about the magma prior to its intrusion. The earliest minerals to form were labradorite of intermediate composition, pyroxene, titaniferous magnetite, apatite, and some pyrite. All of these started to crystallize at about the same time and were stable in the melt until the sills were emplaced.

The principal minerals formed after intrusion of the sills, those not found in the chilled contact zones, are sodium-rich labradorite and andesine, orthoclase, quartz, and biotite. In addition the early minerals, magnetite, augite, and pigeonite, became unstable and were partially altered to biotite and more rarely hornblende and epidote. The formation of amphiboles may have been inhibited by relatively large amounts of potash which favored the formation of biotite instead. This late suite of minerals suggests that the concentration of both sodium and potassium in the melt increased slightly after the sills were intruded, possibly the result of contamination by the thick section of evaporite deposits in the Hermosa formation. The mildness of contact effects on the wallrock and the absence of contact metamorphic minerals suggest that the wallrocks were nearly dry and that the sills had little excess volatile matter.

Clastic dikes

There are three breccia dikes on the Dolores anticline which seem to have been formed in an unusual manner. All three are in the upper part of the Dakota sandstone and consists of unsorted, angular to subrounded fragments of sandstone in a matrix of comminuted sand grains. This breccia is tightly cemented by red and yellow iron oxides. Iron oxides also stain breccia fragments and the walls of the dikes while locally gypsum, calcite, and red mud coat rock fragments and sand grains in the matrix.

Most sandstone fragments are less than an inch in diameter, but some are more than a foot long. The largest fragments are angular; but the degree of rounding increases as their size decreases, and many of the smallest pebbles are well-rounded. Clastic material in the dikes is similar to that of the enclosing rocks, and no material was found that was clearly derived from other formations. The small, well-rounded pebbles were evidently formed by abrasion against each other in a manner that did not involve much transport; comminuted sand grains in the matrix also were probably formed by abrasion of sandstone pebbles.

Two of the dikes are about half a mile long, but the third is only a few hundred feet long. All are discontinuous along the strike of their outcrops. Their widths are variable both along strike and vertically between different sandstone beds. In general the dikes are less than 5 feet wide, but locally their widths may exceed 15 feet. The dike-wallrock contact is irregular and gradational, and iron stain extends a few inches to a few feet into the wallrock. The dikes trend in a direction parallel to that of the drainage and to one set of joints in the sandstone. There has been no perceptible wallrock displacement across the dikes.

Clastic dikes can be formed in a number of ways. Newsom (1902), for instance, showed that they can be produced by sedimentary, tectonic, and volcanic processes including injection of unconsolidated material from below, injection from overlying beds, by submarine deposition in open fissures, and in limestone areas by solution of the carbonate rock and collapse of the overlying beds. Injection of clastic material from underlying beds is the most common origin. Dikes of this type can be formed by hydrostatic pressure during folding or faulting, pressure from overlying beds, and by gas pressure (ibid).

Theories involving marine deposition or solution of limestone are clearly not applicable to breccia dikes on the Dolores anticline. Moreover, the lack of either faults, tight folds, close association with the syncline in Disappointment Valley, or of included material from the overlying Mancos shale makes it seem unlikely that the dikes were formed either by overlying sediments filling open joints or by underlying material being squeezed up into joints during folding or faulting. Volcanic proccesses, therefore, are most likely to have produced the breccia dikes. Structure contours on the Dolores anticline show an anomalous bulge in the vicinity of the dikes which may result from concealed intrusives. If so, the dikes possibly could have been formed by volcanic processes, but such a source is considered unlikely.

Before offering a different explanation, it is well to review field evidence bearing on the formation of these breccia dikes. All known dikes are on the Dolores anticline, although most sills are in Disappointment Valley. Iron oxides, mud, and a little gypsum and calcite are the only accessory minerals; no sulfides or other minerals commonly associated with volcanic emanations, such as quartz, epidote, opal, chalcedony, have been found. The short and discontinuous nature of the dikes and the fact that iron stains in the wallrock are confined to the contact zone, even though the Dakota sandstone is very permeable, suggest that only a small volume of solutions passed through the dikes and probably for only a short period of time. Since only small fragments are rounded, the degree of rounding decreasing with increasing size of the fragments, and since there has been little, if any, transport of clastic material, it is probable that the dikes were formed by relatively weak explosive forces.

A number of clastic dikes have been found in the nearby San Juan Mountains, and these are closely related to volcanic activity. They bear little resemblance to breccia dikes on the Dolores anticline, however. Many contain a hydrothermal suite of minerals, and some are ore-bearing. A clastic dike in the Bachelor mine, for instance, has been mined for silver (Burbank, 1930, p. 195-200). Many show features suggestive of violent explosions. Burbank (1941, p. 143) describes clastic dikes in the Red Mountain district near Ouray which contain material he thinks has been injected more than 3,000 feet into the overlying rocks.

Thus, even though the breccia dikes in the report area could have been formed by volcanic explosions, such an origin does not explain satisfactorily many of their features. Clastic dikes in the San Juan Mountains contrast with those on the Dolores anticline in the apparent violence of their origin, the degree of wallrock alteration, and the nature and extent of hydrothermal mineralization. Furthermore, a postulated origin by volcanic explosions leaves unexplained the location of the dikes, why they are on the Dolores anticline near the edge of the group of sills instead of being in Disappointment Valley where most intrusives are located. Such an origin is not compatible, either, with the apparent lack of excess volatile material in the magma as deduced from the mildness of wallrock alteration. A different explanation seems desirable.

Since the breccia dikes apparently were formed by mild explosions, it is suggested that the explosions were caused by vaporization of ground-water when the sill-forming magma was intruded. Most groundwater was probably driven out of the sandstone gradually by the heat of the advancing magma, but some water is presumed to have been trapped under the Mancos shale and to have been vaporized while confined. Breccia dikes were produced wherever the resulting pressures were great enough to burst through the overlying rock. These explosions were localized by lines of weakness in the sandstone and followed pre-existing joints.

The reason for the dikes being near the edge of the intrusives rather than in Disappointment Valley where the sills are thicker now becomes clear. The sills in Disappointment Valley intrude permeable Dakota sandstone which was probably saturated with ground water (see page 140). Furthermore, the proposed hypothesis does not require large quantities of igneous emanations, a feature compatible with observed relationships which suggest that the intrusives did not have an excess of volatile material.

Quaternary

These deposits consist of glacial boulders, outwash gravel, talus, landslide debris, and alluvial and eolian deposits.

Glacial deposits

Glacial deposits are found on the highest parts of the upland region along the eastern border of the area. These deposits contain large, angular boulders of volcanic rock, up to 7 feet in diameter, that apparently came from the San Juan Mountains.

Glacial outwash

This material is found in many places throughout the area. A channel deposit more than 200 feet thick is exposed on a cliff along the northern side of the Klondike amphitheater. Smaller deposits, the smallest only a foot or two thick, are found in Gypsum Gap, Spring Creek graben, along an abandoned river channel in the northeastern part of the Horse Park fault block, on river terraces overlooking Disappointment Creek, and capping some buttes in Disappointment Valley.

These gravels consist of rounded, water-worn pebbles, cobbles, and boulders with minor thin sand and silt lenses. The boulders are as much as 4 1/2 feet in diameter, but pebble- and cobble-size material predominates. The interstices of the gravel are filled with a heterogeneous assortment of clastic material ranging in size from pebbles to clay. Channel scours abound. The gravels consist mostly of volcanic rocks; but Salt Wash sandstone pebbles occur throughout the section, and minor amounts of angular to rounded sandstone from nearby exposures of the Mesa Verde and shell fragments from the Mancos shale are found locally in the upper part of the section (table 16). In general the gravels are unconsolidated or only loosely cemented, but locally they are tightly cemented by earthy white caliche.

Similar gravels have been found at many other localities near the San Juan Mountains (Coffin, 1921, p. 123), and they seem to be widespread throughout this whole area. Atwood and Mather (1932, p. 82) report that there were widespread piedmont glaciers during the earliest or Cerro, stage of glaciation in the San Juan Mountains, and it is possible that outwash gravels in the Klondike Ridge Area came from one of these.

Landslide debris

This material consists for the most part of large, angular Mesa Verde sandstone blocks and is located near Cenozoic folds and faults in the northern and eastern parts of the report area. An unusual deposit of landslide debris is found on top of a large butte in Disappointment Valley (pl. 1). This debris is more than six miles from the nearest outcrop of Mesa Verde sandstone and is more than 1,300 feet below the top of the Mancos shale. The lower part consists of large blocks, some more than 30 feet long, of slightly crumpled, thin-bedded sandstone and shale from the upper Mancos transition zone (picture 9). This material clearly has not rolled to its present position but must have slid over a slick, smooth surface of Mancos shale. The top of the butte is covered with large boulders of Mesa Verde sandstone, some as much as 20 feet in diameter. This deposit is discussed in more detail on page 81 .

Talus

Talus deposits are found near steep cliffs and on top of small buttes in Disappointment Valley and Dry Creek Basin. Most deposits consist of angular blocks of Mesa Verde sandstone, but some contain rubble from other formations. Several talus deposits consist primarily of redistributed outwash gravels. These occur on top of low hills in Gypsum Valley and blanketing slopes below outwash deposits on Klondike Ridge.

Alluvial and eolian deposits

These consist of decomposed rock, windblown material, mudflows, sheet wash, slump blocks, and fan and stream deposits. A large alluvial fan is forming in Dry Creek Basin along the northern side of the Horse Park fault scarp. Streams near the scarp have carved gullies in the fan that in some places are more than 25 feet deep, but this action has not exposed the underlying Mancos shale.

Structure

The Klondike Ridge Area is in the Canyon Lands section of the Colorado Plateau physiographic province (Fenneman, 1931). It is in the northeastern part of the province in the region characterized by salt anticlines, but it is also near the edge of the Plateau in an area that is transitional between two major structural elements. The western part is representative of the salt anticline region of the Colorado Plateau; long, en echelon, northwest-trending collapsed anticlines are separated by broad, shallow synclines. The eastern part, however, in addition to structures typical of the Colorado Plateau also contains structures produced by movements in the San Juan Mountains to the east. These mountains are part of the Southern Rocky Mountain physiographic province (ibid) and are an entirely different structural element.

The report area has been divided into five subregions for ease of description. These are separated on the basis of structural and geomorphic characteristics and are: the Gypsum Valley anticline, the Dolores anticline, the Horse Park fault block, Disappointment Valley, and Dry Creek Basin (fig. 2). The location and physiography of these units have been described on pages 8 to 12.

Gypsum Valley anticline

The Gypsum Valley anticline is a large, collapsed salt anticline. It trends about N. 55° W. and is more than 23 miles long (Stokes and Phoenix, 1948), but only the southeastern 4 miles or so extend into the map area. Physiographically, the anticline is characterized by a broad, nearly level valley floor flanked by steep, hogback cliffs of outward-dipping strata (picture 1). Leached evaporite material from the Paradox member of the Hermosa formation underlies the valley, but this is covered in most places by alluvium. Many large blocks of overlying formations are exposed, partially submerged, in the floor of the valley. These are collapsed remnants of younger formations that once extended across the anticline.

Paradox strata crop out in the valley floor east of Gypsum Gap. The valley here, instead of being a smooth, nearly level surface as it is in most of Gypsum Valley, consists of low, irregularly shaped mounds and hills of evaporite material. These become steeper and more irregular in shape toward the southeast (picture 2). Total relief increases in that direction, also, and locally exceeds 200 feet near the southeastern end of the valley. A small wedge of evaporite material at the end of the valley projects eastward into the Horse Park fault block along the concealed Horse Park fault (pl. 4).

The structural evolution of the Gypsum V·lley anticline and of the salt anticlines as a whole has been described by many writers (for example, see Cater, 1955a; ibid, 1955b; Hunt, 1956; Kelley, 1955; Shoemaker, 1954; Shoemaker, Case, and Elston, 1958; Stokes, 1948; ibid, 1956; Stokes and Phoenix, 1948). Although their interpretations differ somewhat in detail, these writers show that there are striking similarities both in the structural development of the anticlines and in the synchronism of events affecting them. The evolution of the Gypsum Valley anticline in the Klondike Ridge area, therefore, in all likelihood is not just an isolated event of only local importance, but probably is representative of a great chain of events that affected a much larger part of the Colorado Plateau.

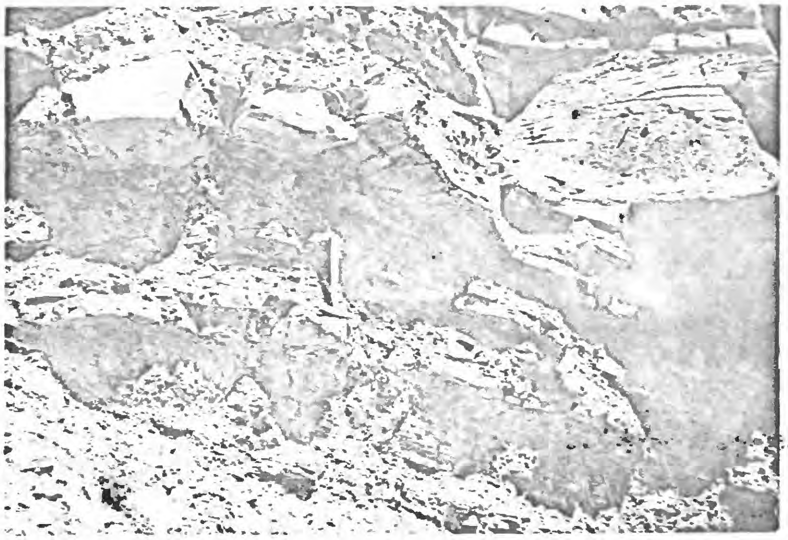
Three periods of major uplift can be recognized in the southeastern end of the Gypsum Valley anticline. Each was followed by collapse of the overlying strata. Erosion after the first two periods removed nearly all topographic expression of the anticline; erosion after the last uplift, which began in the Pleistocene, has not yet had a profound effect on its physiographic expression, except where the evaporite core is exposed at the surface.

The principles involved in the formation of the salt anticlines are not understood completely. Uplift apparently was caused by the flow of Paradox evaporite material into the anticlines, but the factors initiating this flow and localizing the salt in long, en echelon anticlines are imperfectly understood. The fact that the anticlines parallel the Uncompahgre Plateau has suggested to many writers that the anticlines may have been localized by small flexures in the basement created by the same compressive forces that formed the Uncompahgre highland. This is speculative, however, because aeromagnetic surveys have not detected any such flexures (Joesting and Byerly, 1958, p. 11-12).

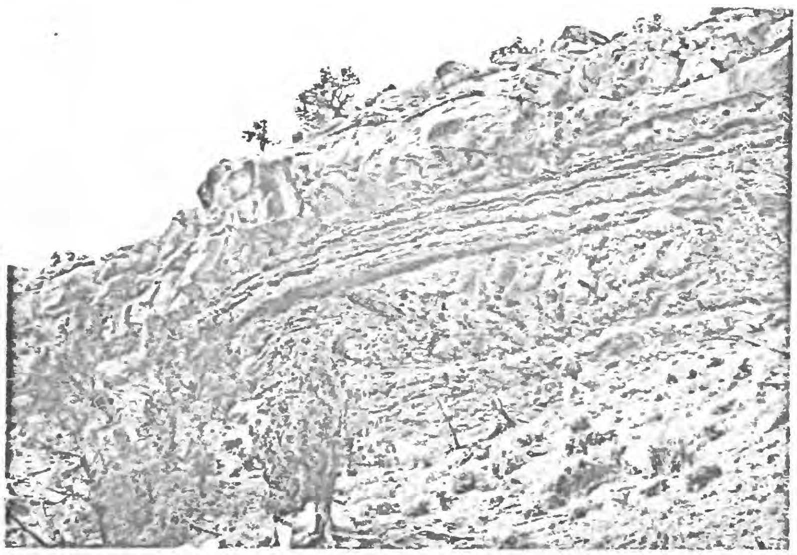
Uplift in the salt anticlines may have begun in the late Pennsylvanian (Shoemaker, Case, and Elston, 1958, p. 48), but there is no clear evidence in the report area of uplift at that time. Nevertheless, a period of major uplift occurred at the end of the Paleozoic era and probably continued well into the Triassic. The magnitude of this uplift in the report area is indicated by the angle of the unconformity between upper Paleozoic deposits and the Triassic and Jurassic erosion surface locally exceeds 55 degrees on Klondike Ridge, which is considerably greater than the present 26 degree dip of that erosion surface itself. Regional studies show that the evaporite cores of the anticlines were exposed at the surface by late Cutler time (Cater, 1955a). The normal thickness of Paleozoic sediments overlying the evaporites is about 4,500 to 5,000 feet, which, therefore, must be the amount the salt core rose in the late Paleozoic.

Exposure of evaporite material at the surface resulted in its rapid removal by both erosion and solution. This, combined with the probable flow of evaporite material from the flanks to the exposed center of the anticline, caused widespread collapse in which younger strata were downfaulted over the crest of the anticline. Measurable displacement on one fault formed at this time in the Klondike amphitheater exceeds 200 feet, and total displacement may have been much greater.

Prolonged erosion in the Triassic produced a smooth surface upon which Upper Triassic and younger formations progressively overlapped. Nevertheless, continued upwelling of salt prevented complete bevelling, and the anticline remained a topographic high against whose sides Triassic and most Jurassic sediments wedged out (picture 5). Many thin horizons of conglomerate, fan deposits, and intraformational slump structures, as well as a thinning of most strata across the anticline, show that upwelling of salt continued intermittently into the Lower Cretaceous. Pebbles are coarser, however, and conglomerate horizons more numerous in the lower part of the sequence (table 6). These relationships as well as the progressive overlap of Mesozoic sediments onto the anticline indicate a gradual decrease in the rate of salt flow during this period. In addition, conglomerate units are thin and, for the most part, are sharply differentiated from the normal sedimentary strata above and below which suggests that uplift was characterized by many short, spasmodic surges with only a small amount of movement during each surge. The rapidity of movement during one of these surges is shown by slump structures in the Summerville formation which were formed when unconsolidated sediments slid down a slope created by rapid uplift (picture 10).



Picture 9. Large blocks, some more than 30 feet long, of landslide debris. Material covers top of a butte in Disappointment Valley and came from the upper Mancos transition zone.



Picture 10. Contemporaneous slump structures in the Summerville formation, southeast end of the Gypsum Valley anticline. Slump structures terminate at left behind tree.

In all probability the rate of salt flow gradually decreased after the initial Permian and Triassic surge. As a result, many Triassic and Jurassic formations undoubtedly were deposited across the anticlines in some places, but the Upper Jurassic Morrison formation is believed to have been the first since the Cutler to cross the anticlines everywhere on the Colorado Plateau (Cater, 1955a). Deposition of Morrison sediments over the anticline shows that salt flowage had slowed down enough by the Upper Jurassic for erosion to exceed uplift and that by Morrison time erosion had removed all topographic expression of the anticline. Indeed, a widespread limestone unit in the basal Salt Wash on Klondike Ridge and in Gypsum Valley (p. 32) shows that erosion and solution of the evaporite deposits so greatly exceeded uplift that a shallow basin filled by a short-lived lake was formed on the anticline at that time. The normal stratigraphic interval between the earliest Triassic sediments deposited on the anticline, the upper part of the Chinle, and the Morrison formation is about 1,100 to 1,300 feet which, therefore, must have been the amount of Upper Triassic and Jurassic uplift. Uplift continued for a while after this, but total movement seems to have been small. The Burro Canyon formation, for instance, is thicker in Disappointment Valley than on the anticline (tables 11 and 12) which suggests that minor adjustments may have continued into the Lower Cretaceous.

The presence of a persistent cupola or dome on the salt anticline east of Gypsum Gap is indicated by unusual depositional, erosional, and structural relationships in sediments along the southern flank of the anticline. The distribution of these features suggests that the cupola occupied about the same area as the present hills and mounds of evaporite material in Gypsum Valley.

This cupola, for example, may have been responsible for the irregular pattern of sedimentary pinchouts along the southern flank of the anticline (plate 4). Both the Entrada sandstone and Summerville formation pinch out much lower on the anticline near the southeastern end of Gypsum Valley than they do near Gypsum Gap. Similarly, the Burro Canyon formation thins from a thickness of about 135 feet at Gypsum Gap to less than 45 feet near the southeastern end of the valley (plate 5). Moreover, the proportion of conglomerate in the Burro Canyon decreases near the cupola while shale and siltstone become relatively more abundant.

It is also possible that a large river was deflected around the cupola during Burro Canyon time because the ratio of conglomeratic sandstone to shale is abnormally large near the edge of the cupola on both the northern and southern flanks of the valley (pl. 5). In addition, the distribution of Burro Canyon strata affected by this uplift suggest that the anticline was both wider and longer in the Lower Cretaceous than in the Upper Jurassic (see below). This increase in size may have resulted from the fact that sediments completely covered the anticline in the uppermost Jurassic for the first time since the Permian. Therefore, upwelling salt may have had less tendency to flow in towards the crest of the anticline and instead formed a broader anticlinal arch than before.

The second period of uplift probably occurred in the middle Tertiary (p. 76). A broad anticlinal fold, guided and localized by the pre-existing structure, was formed in the southeastern end of Gypsum Valley. The anticline may have risen more than 4,600 feet at that time, as this is the amount of measurable pre-Quaternary uplift in Salt Wash sandstone near the cupola. Although considerably less than the 5,600 to 6,300 feet of uplift estimated for the first period (pages 62 and 65), this was nevertheless a period of major uplift in the anticline.

As in the Early Cretaceous, the anticline was probably longer and wider in the Tertiary than in the Triassic. This is suggested by the following relationships: the area affected by Tertiary subsidence is larger than the area of Triassic subsidence; Tertiary collapse structures extend south from the Klondike amphitheater nearly 1 3/4 miles beyond the pinchout of Chinle sediments, which are believed to be among the oldest Triassic sediments in the report area (p. 25); and fan deposits in the Entrada sandstone, as well as slump structures and fan deposits in the Summerville formation, pinch out nearly 1 1/2 miles north of the southern edge of the area affected by Tertiary subsidence.

Collapse of the anticline probably began soon after uplift, possibly in the Miocene (p. 76), when erosion of overlying sediments had again exposed the salt core at the surface. Parenthetically, it is interesting to note that this collapse probably occurred at different times in different parts of Gypsum Valley. The youngest beds preserved by collapse near the Dolores river northwest of the map area are basal Mesa Verde and upper Mancos transition zone (Stokes and Phoenix, 1948). The salt core clearly could not have been exposed to erosion by the time these beds collapsed, so collapse must have been caused by salt flowage; The most likely direction for this salt to flow was toward the nearby Dolores River. This could only have happened, of course, if the Dolores River were antecedent to the Tertiary anticline (Stokes, 1956, p. 44) and if the river had cut through to the evaporite core before erosion stripped the Mesa Verde from the crest of the anticline.

The youngest beds exposed in the floor of Gypsum Valley become older with increasing distance from the river, and in the report area only the basal Salt Wash is preserved. Tertiary collapse, therefore, must have occurred somewhat later in the report area than near the Dolores River. Furthermore, since Salt Wash beds were the first sediments to be deposited over the cupola since the Cutler, collapse probably did not occur in the report area until the cupola had been breached and the salt core exposed at the surface. In contrast to deposits near the Dolores River, therefore, erosion was probably a more important cause of Tertiary collapse in the Klondike area than was salt flow.

Collapse was followed by a period of prolonged erosion which lasted through the rest of the Tertiary. A widespread surface of low relief was formed, and nearly all topographic expression of the anticline was removed. Epeirogenic uplift in the late Miocene or early Pliocene (Longwell, 1946, p. 834) raised the Plateau to its present elevation of about a mile above sea level.

Outwash gravel from an early Pleistocene piedmont glacier was deposited on the Tertiary erosion surface as far west as Gypsum Gap. This gravel consists mostly of volcanic rocks from the San Juan Mountains, and one deposit on the northern side of the Klondike amphitheater is more than 200 feet thick. This deposit fills a large river channel that cuts down into basal Salt Wash sandstone; the bottom of the channel is more than 200 feet below the top of Salt Wash strata exposed nearby on the eastern side of the amphitheater (picture 5). The almost complete lack of outwash gravel on adjacent parts of Klondike Ridge and the Horse Park fault block suggests that there may have been enough topographic relief over those structures in the early Pleistocene to confine the river to this relatively narrow channel.

Two small deposits of outwash gravel in Gypsum Gap are important because they show that a river flowed across part of the anticline in the early Pleistocene, and thereby indicate little topographic relief over the anticline at that time. Cobbles in Gypsum Gap are smaller, for the most part, than those in the main channel above the Klondike amphitheater, and they not only are composed of volcanic rocks from the San Juan Mountains but also contain pebbles and cobbles of Salt Wash and Mesa Verde dandstone. Table 16 shows that detritus from the Mesa Verde is only found in the upper part of gravel deposits on Klondike Ridge, so the deposits in Gypsum Gap are probably among the youngest in the area.

The third and final period of uplift began in the early Pleistocene, and, except for subsequent collapse features, the anticline attained essentially its present shape at that time. This was the mildest of the three periods of uplift, and outwash gravel in Gypsum Gap was only raised about 175 feet above the old erosion surface.

The third period of collapse must have begun soon after uplift because the evaporite core was already exposed to erosion at the surface in many places. Most faults formed during the Tertiary collapse were probably reactivated at this time, and some new folds and faults were also formed.

Small faults in Quaternary talus deposits show that minor subsidence and local readjustments are still continuing in Gypsum Valley. The small shear shown in picture 11, for instance, was caused by recent settling in the valley floor. Cater (1955a) reports that minor settling is still going on in other salt valleys on the Colorado Plateau, too. In addition, minor upwelling of salt in the former cupola may be still continuing because the steep mounds and hills of evaporite material in the valley east of Gypsum Gap (p. 9) are in the area formerly occupied by the cupola.

Finally, and in the realm of speculation, it is interesting to wonder if there may have been a slight northward shift in the axis of the anticline, possibly in the Tertiary. It will be recalled that a wedge of evaporite material extends eastward beyond Gypsum Valley along the Horse Park fault (pl. 4). This is surprising because the Horse Park fault block truncates structures formed by this wedge and seems to be younger than all structures on the anticline except those produced by the latest period of uplift. The western segment of the Horse Park fault in Gypsum Valley, therefore, may be older than the rest of the fault farther east and, accordingly, may have formed during an earlier period of collapse on the anticline.

Pursuing this further, geologic maps of the southeastern end of Gypsum Valley (Cater, 1955a; Stokes and Phoenix, 1948) show that Triassic formations crop out on the northern flank of the valley, but not the southern, and thus must have been deposited higher on the present flank of the anticline on that side. Furthermore, data presented in table 2 suggest that the angular unconformity between Upper Jurassic and Paleozoic formations is greater on the southern flank of the anticline than the northern. These relationships are anomalous and suggest that the locus of uplift in the Tertiary had moved northward, possibly along the western segment of the Horse Park fault. This change would produce a slight northward shift in the axis of the anticline and may account for the evaporite wedge southeast of Gypsum Valley, the presence of Triassic and Jurassic sediments on the northern wall of the valley, but not the southern, and the apparent discrepancy in the angle of the unconformity between Paleozoic and Upper Jurassic sediments on the two flanks of the anticline.

Table 2. Representative angular unconformities on the northern and southern flanks of the Gypsum Valley anticline.

Southern flank of Gypsum Valley:

North side of Klondike Ridge facing Gypsum Valley. Sequence of measurements is in a southeasterly direction. First is near Gypsum Gap and last is near the Tertiary cross faults at southeastern end of Gypsum Valley.

1. Pr-Jms 42°
2. Prc-Jms 40°
3. Phl-Jms 72°
4. Phl-Jms 74°
5. Phl-Jms 68°

South side of Klondike Ridge. All measurements are southeast of no. 4 above.

Phl-Je	40°	Pc-Je	32°
Pr-Je	32°	Pc Je	12°
Pc-Jms	53°		

Northern flank of Gypsum Valley:

Measurements taken across the valley from no. 4 above and correspond to no. 4 with respect to position on the flank of the anticline.

Pr-Jk 41°

Jk-Jms 6°

Dolores anticline

The Dolores anticline is another salt anticline, but one that has not yet collapsed. It trends about N. 55° W. and is characterized in the map area by a nearly dip slope of Dakota sandstone. Only about 1 1/2 square miles of the anticline's northeastern flank are present in the area, so very little of its history can be determined. Perched meander scours, however, and deposits of coarse outwash gravel similar to those on Klondike Ridge show that Disappointment Creek meandered across an advanced erosion surface of low relief before final uplift of the anticline. They also show that final uplift occurred after the early Pleistocene piedmont glaciation, so uplift probably was essentially contemporaneous with that of the Gypsum Valley anticline. This tends to confirm the findings of other writers (page 61) that salt anticlines on the Plateau show many similarities in their structural histories and in the synchronism of events affecting them.

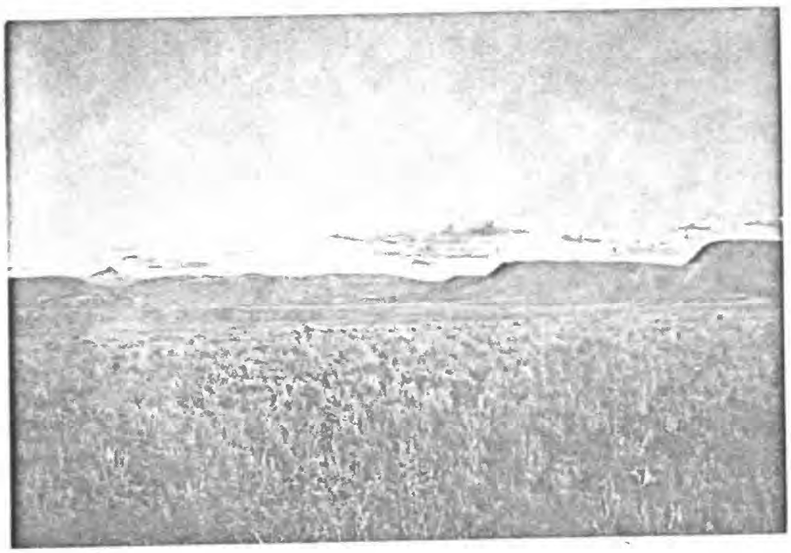
Horse Park fault block

The Horse Park fault block is a scoop-shaped upland area that trends about N. 55° W. and slopes to the northwest. It is bounded on the north by the Horse Park fault and on the south by an unnamed fault with a stratigraphic throw near Gypsum Valley of about 3,300 feet. A number of smaller structures in the fault block, such as Spring Creek graben, a syncline, and several minor faults, are clearly subsidiary to these boundary faults.

The Horse Park fault separates the Horse Park fault block and Disappointment Valley to the south, both of which were affected by Cenozoic movement in the San Juan Mountains, from Dry Creek Basin to the north, which was not affected by this movement. The fault is entirely covered by alluvium in Dry Creek Basin but can be seen in the uplands to the east where Mesa Verde sandstone has been faulted into contact with the lower part of the Mancos shale. Its extension into the map area is inferred to explain the north-facing scarp which truncates the Dry Creek erosion surface (picture 12), the perched outwash gravels and steep canyon near Horse Park, and collapse structures within the fault block itself. Initial subsidence on this fault may have exceeded 3,000 feet near Gypsum Valley.

The Horse Park fault block is a large graben located on the northern edge of a much larger area of downfaulting. The region affected by subsidence extends far beyond the eastern border of the map and south beyond the fault block, across Disappointment Valley, and possibly farther. This movement was probably an integral part of regional subsidence on the northwestern side of the San Juan Mountains which, Larsen and Cross (1956, p. 259) report, occurred in the early Miocene.

Picture 11. Shear in Quaternary gravel talus, southeastern end of Gypsum Valley.



Picture 12. Dry Creek Basin. Looking southeast toward the Horse Park fault block (right) and the San Juan uplift (background).

Several bits of evidence connect movements in the Horse Park fault block with those in the Gypsum Valley anticline. These suggest that subsidence in the fault block occurred soon after Tertiary uplift of the salt anticline and before the anticline collapsed. The fault block, for example, truncates structures in Gypsum Valley that were formed in part during Tertiary uplift of the anticline (plate 4), so the fault block must be younger than this uplift. Moreover, erosion of Mesa Verde sediments on the fault block is no more advanced near the salt anticline than on the eastern side of the report area, suggesting that collapse took place before the anticline was deeply eroded. Furthermore, Upper Cretaceous strata on the fault block have been faulted into contact with Jurassic and upper Paleozoic strata on the anticline, showing that the sedimentary cover was still several thousand feet thick when faulting occurred. This in turn means that the fault block was probably formed before the anticline collapsed because anticlinal collapse in the report area is thought to have been caused by rapid erosion of the evaporite core after overlying beds had been stripped away (page 68). Uplift of the Gypsum Valley salt anticline, therefore, probably occurred shortly before subsidence in the Horse Park fault block, possibly in the late Oligocene or early Miocene.

Subsidence of the fault block was followed by an interval of prolonged erosion, during which a nearly level erosion surface was formed. Early Pleistocene rivers carried glacial outwash across this surface, forming a gravel deposit on Klondike Ridge that is more than 200 feet thick.

A second period of movement took place in the early Pleistocene towards the end of the Cerro stage of glaciation (p. 57). It probably occurred in conjunction with post-Hinsdale uplift in the San Juan Mountains, and it caused renewed movement on the Horse Park fault, but in a reverse sense. The H rse Park fault block was raised more than 1,000 feet, the height of the fault line scarp truncating Dry Creek Basin, and was tilted toward the west.

The fault block did not behave as a separate structural unit this time as it did during the earlier period of subsidence. Instead, it rose as an integral part of regional uplift to the south and contemporaneously with Quaternary uplift of the Gypsum Valley salt anticline. This is shown by the small amount of recent movement on the unnamed boundary fault along the southern side of the fault block. The scarp at the eastern end of the fault, where most movement took place, is about 200 feet high. There is no scarp at all along the western part of this fault, and displacement here is probably less than 50 feet. Instead, both sides of the fault seem to have risen together.

The fault block contains many secondary structures of which Spring Creek graben is the largest. An unusually thick section of Mesa Verde is preserved in the graben near the axis of the syncline showing that the syncline was formed during the middle Tertiary collapse before extensive upper Tertiary erosion had stripped these deposits from the area. Spring Creek itself, however, is clearly antecedent to the present structure, and this fact together with low fault scarps in the eastern part of the area shows that there was renewed folding and faultigg in the Spring Creek graben during the Quaternary uplift.

A large V-shaped canyon near Horse Park marks the abandoned channel of a large river, possibly ancestral Dry Creek. Outwash gravel at the head of this canyon shows that it was carved during the early Pleistocene by a river flowing across the Horse Park fault block into Dry Creek Basin. Apparently after uplift, the river first carved this short, steep canyon and then was forced to abandon its channel when more rapid downcutting in soft Mancos shale to the north diverted it from the fault block.

Disappointment Valley

Disappointment Valley is the erosional expression of a broad, shallow syncline more than 20 miles long. Throughout most of this length it is a smooth, nearly level valley (picture 13) that was probably formed during the period of prolonged erosion in the upper Tertiary. This smooth surface is replaced in the western part of the map area by an irregular topography of hills and buttes. These become higher and more numerous to the east and finally pass into badland topography near the Mesa Verde cliffs (picture 14). These cliffs rise more than 1,500 feet above the valley floor and mark the beginning of the upland area around the western side of the San Juan Mountains.

Disappointment Valley trends about N. 60° W. in the report area. This represents a shift of 5° from its dominant trend farther west of about N. 55°W. (Stokes and Phoenix, 1948). In addition, the axis of the syncline cuts obliquely across the valley; this obliqueness increases eastward.

Picture 13. Disappointment Valley. Looking northeast from the Dolores anticline. Intrusive sills cap first low cliffs.

Picture 14. Southeastern end of Disappointment Valley. Mesa Verde-capped cliffs in background on right.

Very little of the pre-Tertiary history of Disappointment Valley can be determined from rocks exposed in the report area. Simmons (1957, p. 2521) reports unusually thick sections of Jurassic and Lower Cretaceous sediments in the northwestern part of Disappointment Valley, and he postulates a basin, the Disappointment basin, to receive them. Drill hole data (table 11) show an unusually thick section of Burro Canyon conglomerate in the report area, too, which suggests that this basin may have extended eastward into the Klondike Ridge area.

Stokes (1956, p. 46) has suggested that synclines, such as Disappointment Valley, separating salt anticlines on the Colorado Plateau were formed by salt flowage into the anticlines and correspond to rim synclines surrounding salt domes in the Gulf Coast region. Following Stoke's suggestion, it is possible that sediments in Disappointment Valley were deposited in an actively sinking syncline which developed contemporaneously with the salt anticlines and, therefore, probably first appeared as a structural unit in the late Pennsylvanian.

Most structural and topographic features of Disappointment Valley exposed in the report area were formed by movements originating in the San Juan Mountains rather than the salt anticlines, so the Cenozoic history of the valley is very similar to that of the Horse Park fault block. The peculiar shift in the trend of Disappointment Valley, for instance, probably represents a slight northeasterly tilt in the valley floor caused by middle Tertiary subsidence along the Horse Park fault.

Prolonged erosion in the upper Tertiary produced a widespread surface of low relief over much of the Colorado Plateau (Gregory, 1947, p. 700-701). Later, during the Quaternary post-Hinsdale uplift of the San Juan Mountains, the eastern end of Disappointment Valley was raised more than 1,500 feet, and this Tertiary erosion surface was tilted about 3° to the west. The obliquity of the synclinal axis with respect to Disappointment Valley probably originated in this uplift and represents a northward deflection of the axis caused by the rising mountain area to the east.

Shortly after uplift, large blocks of upper Mancos and Mesa Verde sandstone and shale broke loose and slid down into Disappointment Valley over the smooth erosion surface. Friction between this material and the Mancos shale must have been very slight because debris from one such landslide traveled more than six miles, but blocks more than 30 feet long suffered only very gentle crumpling (pl. 1 and picture 9).

The Tertiary erosion surface has been deeply dissected since this uplift. Streams crossing it in the Pleistocene deposited a thin veneer of outwash gravel which now caps many of the buttes in Disappointment Valley. In addition, the topography presents differing degrees of erosional maturity which are undoubtedly a function of the amount of downcutting needed to reach a new base level. The drainage is still cutting headwards and entrenching itself near the eastern end of the valley where uplift was greatest. Here are many isolated buttes, narrow, steep-walled valleys, and much talus along the base of the cliff (picture 14). Badland topography prevails.

Uplift was not as great in the western part of the area. The streams are nearly at grade and are primarily engaged in widening their valleys. This process is most advanced near the western edge of the map where Quaternary uplift was least. Here the gently sloping surface is broken by only a few low hills (picture 13).

Dry Creek basin

Dry Creek Basin is a broad, nearly level plain carved in the Mancos shale. Structurally, it is a shallow syncline lying between the Gypsum Valley and Paradox Valley salt anticlines, but it is truncated on the southeast by the Horse Park fault block and on the east by the Quaternary uplift of the San Juan Mountains. Only a narrow strip comprising about five square miles is present in the report area, so very little of the syncline's pre-Tertiary history can be determined. This history, however, is probably similar to that of the Disappointment Valley syncline to the south.

The feature of chief interest in this report is the contrast the nearly level erosion surface in Dry Creek Basin affords with both the Horse Park fault block and the southeastern end of Disappointment Valley (pictures 12 and 14). The Dry Creek Basin erosion surface is clearly an old surface that was not greatly affected by Quaternary uplift in the San Juan Mountains and the Horse Park fault block. This means that the uplift extends nearly 7 miles farther west on the southern side of the Horse Park fault than on the northern.

Geologic history

Paleozoic strata exposed in the report area are dominantly marine and were deposited in the Paradox basin. This was an irregularly elliptical depression about 360 miles long and 180 miles wide which first appeared in the Pennsylvanian. At that time it was a nearly isolated basin with only restricted access to the open sea. The Hermosa is the oldest formation exposed in the Klondike Ridge area; the oldest beds exposed, those of the Paradox member, consist of a thick series of evaporite deposits with some interbedded fine-grained clastic material and black shale. Barriers to the sea were lowered during upper Hermosa time, and, as a result, the upper part of the formation comprises a thick sequence of normal marine limestone, dolomitic limestone, shale, and sandstone.

The uppermost marine deposits are interbedded with coarse clastic debris shed from the Uncompahgre Plateau to the north. This transition zone is the Rico formation. The Paradox sea withdrew from the map area by the lower Permian, and a highly variable sequence of coarse conglomeratic sandstone, siltstone, and silty shale was deposited. This material is similar to the non-marine portion of the Rico formation and is the Cutler formation.

Salt flow and uplift of the Gypsum Valley anticline may have begun in the late Pennsylvanian; by late Cutler time erosion had stripped away the overlying sediments exposing the salt core at the surface. The thickness of Paleozoic sediments overlying the evaporite deposits is about 4,500 to 5,000 feet which, therfore, must be the amount the salt core rose by late Cutler time. Major uplift probably continued into the Triassic, and movements of lesser extent are recorded in most formations through the Lower Cretaceous.

Collapse of the anticline probably began soon after uplift when overlying sediments had been stripped away and the evaporite core was exposed to erosion. Collapse was caused by removal of salt and resulted from both erosion and solution of soluble constituents and from salt flowage towards the axis of the anticline where the core was exposed at the surface. One fault formed during this subsidence has a measurable displacement in excess of 200 feet.

Erosion in the Triassic produced a smooth surface upon which Chinle and younger formations overlapped. Continued upwelling of salt, although gradually decreasing in intensity, maintained some topographic expression of the anticline throughout most of the Jurassic, and the Upper Jurassic Morrison formation is thought to have been the first to cross the anticline everywhere on the Plateau (Cater, 1955a). The normal stratigraphic interval between the base of the upper part of the Chinle and the Morrison formation is about 1,100 to 1,300 feet which, therefore, must be the amount of Upper Triassic and Jurassic uplift on the anticline.

The anticline may have been shorter and narrower in that period than it is now. The southern flank of the anticline, for instance, was probably about 1 3/4 miles north of its present position as that is where the oldest known Triassic sediments in the district pinch out and where slump structures and fan deposits formed in Upper Jurassic sediments. The anticline was larger in the Lower Cretaceous, however, and was probably about as wide and long then as it is now.

A persistent cupola or dome on the anticline southeast of Gypsum Gap appeared during an early phase of anticlinal growth and has affected much of the subsequent structural and depositional history of this area. The effects of the cupola are seen in the fault pattern around Gypsum Valley and in the distribution of sediments along its flanks.

Nearly all Triassic and Jurassic formations on Klondike Ridge show the effects of contemporaneous uplift in the anticline. Only part of the Chinle formation is present, and that contains many angular pebbles and chips from older formations eroded off the anticline. The overlying Glen Canyon group, consisting of the Wingate and Kayenta sandstones in the report area, is entirely fluvial on Klondike Ridge although in most places the group is dominantly eolian. In addition, the sandstones contain many thin conglomerate horizons. These are abundant in the lower part of the group, but gradually disappear upwards. Sandstone units in between are free of conglomerate pebbles, suggesting that uplift was spasmodic and that movement during individual surges was small.

The Upper Jurassic San Rafael group overlies the Glen Canyon group and includes the Entrada sandstone and Summerville formation in the report area. These formations also show the effects of contemporaneous uplift in the salt anticline, but to a lesser extent than the Glen Canyon group. Abnormal depositional features include thin conglomerate horizons, fan deposits, and contemporaneous slump structures. The Entrada sandstone is dominantly eolian in most places, but on Klondike Ridge it is predominantly fluvial and has several conglomeratic sandstone lenses. The Summerville formation is a flood-plain deposit and is of fluvial origin, but it also contains lacustrine deposits on Klondike Ridge. These deposits show that small ephemeral lakes formed on part of the anticline during Summerville time and, therefore, that most topographic expression of the anticline must have been removed by then. Slump structures and fan deposits in Summerville sediments on Klondike Ridge, however, show that uplift was still continuing, but evidently on a greatly reduced scale.

The Morrison formation overlies the Summerville and apparently was the first Mesozoic formation to be deposited on the cupola. The basal Morrison contains a thin limestone bed which extends far out into Gypsum Valley and evidently was deposited on top of the salt cupola itself. This shows that the cupola had been eroded by early Morrison time and was even the site of a short-lived lake.

The Morrison formation is a large alluvial fan formed by a system of aggrading streams (Craig and others, 1955, p. 151, 157). The lower part, the Salt Wash member, consists of sandstone with interbedded shale and minor limestone while the upper part, the Brushy Basin member, consists mostly of variegated shale with minor conglomeratic sandstone and limestone. Impure bentonitic clay is abundant in the Brushy Basin and is partly volcanic in origin.

The Brushy Basin is conformably overlain by conglomeratic sandstone and shale of the Lower Cretaceous Burro Canyon formation. The Burro Canyon is abnormally thin near the cupola on the Gypsum Valley anticline, and it contains an unusually large proportion of shale; the proportion of conglomeratic sandstone is correspondingly greater around the margins of the cupola. These relationships were caused by a deflection of rivers around the cupola and probably indicate minor uplift in Burro Canyon time.

Outcrop and drill hole information in the nearby Slick Rock district show that many Mesozoic formations are unusually thick in Disappointment Valley. Simmons (1957, p. 2521) postulates a basin, the Disappointment basin, to receive these deposits. Drill hole data in the Klondike Ridge area show that here, too, the Burro Canyon formation is abnormally thick in the syncline and that the Disappointment basin probably extended into the report area. Stokes (1956, p. 46) has suggested that synclines such as this may have been formed by salt flowage from the syncline into adjacent salt anticlines and, therefore, correspond to rim synclines found around salt domes in the Gulf Coast region.

The region was flooded by a Late Cretaceous sea in which the marginal marine Dakota sandstone, marine Mancos shale, and marine and marginal marine Mesa Verde group were deposited. These rocks blanket most of the report area, and older formations are exposed only on the flanks of the salt anticlines. In addition, several thousand feet of Late Cretaceous and early Tertiary fluvial and lacustrine sediments were probably deposited in the report area after the sea withdrew, but all traces of these rocks have been removed by erosion.

The second period of uplift on the Gypsum Valley anticline probably began in the middle Tertiary. Uplift was not as great as during the first period, but, nevertheless, it may have exceeded 4,600 feet on the cupola. The second period of collapse occurred after the overlying sediments were stripped off the anticline and the salt core was again exposed to erosion at the surface. Displacement on some faults formed at this time exceeds 300 feet.

Regional subsidence on the northwestern side of the San Juan Mountains in the early Miocene extended into the report area. The Horse Park fault marks the northern limit of subsidence here, and displacement on the fault may have exceeded 3,000 feet near the Gypsum Valley anticline. The Horse Park fault block also was formed at that time, and the eastern end of Disappointment Valley was tilted a few degrees to the northeast, producing a westward shift in the trend of the valley.

Subsidence was followed by a period of prolonged erosion which produced a widespread surface of low relief. All Tertiary and Upper Cretaceous deposits down to the Mancos shale were removed from the area, except where protected by earlier faulting, and overlying formations down to the basal sandstone of the Morrison formation were stripped off the cupola on the Gypsum Valley anticline. Epeirogenic uplift in the late Miocene or early Pliocene raised the area about a mile.

Igneous sills of microgranogabbro, similar to dikes and sills in the San Juan Mountains, were intruded during the middle or upper Tertiary. Three small breccia dikes were also formed at this time on the Dolores anticline when groundwater, vaporized by the intruding sills, burst through to the surface along joints in the Dakota sandstone. Glaciation in the early Pleistocene saw the advance of a piedmont glacier into the eastern part of the area. Outwash from this glacier is found as far west as Gypsum Gap; one gravel deposit formed at that time on Klondike Ridge is more than 200 feet thick.

A second period of movement in the Horse Park fault block began while outwash gravel was still being deposited in the area. It probably coincided with the post-Hinsdale uplift in the San Juan Mountains, and it produced movement in a reverse sense on the Horse Park fault. The fault block was raised about 1,000 feet, but there was no corresponding movement in Dry Creek Basin. A river near Horse Park carrying outwash gravel into Dry Creek Basin carved a deep canyon in the fault block before its channel was deflected into the soft Mancos shale in Dry Creek Basin.

The eastern end of Disappointment Valley was raised about 1,500 feet at that time, too, and its surface was tilted nearly 3° to the west. As a result, the axis of the syncline was deflected to the north and now cuts obliquely across the valley. Landslide debris slid down over this surface, in one case traveling more than 6 miles from its source. Subsequent erosion has produced a deeply dissected, irregular surface with many hills and buttes at the eastern end of the valley. These become smaller to the west and finally pass into a surface of low relief beyond the area affected by uplift of the San Juan Mountains.

The third period of major uplift in the Gypsum Valley salt anticline occurred almost simultaneously with uplift of the Horse Park fault block. Movement in the anticline was probably less than in either of the two earlier periods, however, because outwash gravel in Gypsum Gap was only raised about 175 feet. Collapse of the anticline must have begun soon after uplift because the evaporite core was already exposed to erosion at the surface in many places.

Uplift of both the anticline and the fault block may have begun before glaciation because no outwash gravel was deposited on the cupola in Gypsum Valley or very far east of the river channel on the fault block. Irregular, hilly topography near the eastern end of Gypsum Valley and small shears in recent talus deposits in the floor of the valley suggest that both upwelling of salt in the cupola and subsidence around the edge of the valley are still continuing.

Ore deposits

Introduction

The Klondike mining district is located on Klondike Ridge. It extends in a southeasterly direction from Gypsum Gap to the Klondike amphitheater and then swings north around Gypsum Valley to the Horse Park fault (pl. 4). Uranium-vanadium, copper, and manganese ore as well as gravel have been mined in the district, but all deposits are small, and it is estimated that fewer than a dozen have yielded as much as 100 tons of ore. Most of the latter have been carnotite deposits.

Carnotite deposits

Carnotite deposits have been known in the district for many years (Coffin, 1921, p. 210-211), but little ore has been mined. It is estimated that only about 1,000 tons of ore have been shipped from the district and that most of this production has occurred since 1950.

The Klondike district is a few miles east of the so-called Uravan mineral belt. This mineral belt was described by Fischer and Hilpert (1952, p. 3) as "a narrow, elongate area in which carnotite deposits generally have closer spacing, larger size, and higher grade than those in the adjoining areas". In addition, deposits within the mineral belt have "ratios of uranium to vanadium ranging from 1 part U_3O_8 to 5 to 10 parts V_2O_5 whereas deposits outside the belt have ratios ranging from 1 part U_3O_8 to 10 to 20 parts V_2O_5" (ibid, p. 4-5). By way of comparison, the U_3O_8-V_2O_5 ratio in ore from the Klondike district ranges from 1:3 to 1:26. These writers further point out that most of the uranium and vanadium mined in southwestern Colorado have come from deposits within the mineral belt.

It is not surprising, therefore, that uranium production in the Klondike district has been so small. Nevertheless, interest in the district has continued because the edges of the Uravan mineral belt are poorly defined in Gypsum Valley (ibid, p. 4), so there may be large uranium deposits in nearby areas such as this. The district is also of interest because the association of manganese and copper deposits with carnotite is unusual on the Colorado Plateau.

The present study, however, has found no evidence of concealed uranium deposits that might be comparable in either size or grade to those in the Uravan mineral belt. Furthermore, the association of carnotite deposits with those of manganese and copper is accidental, for the latter are much younger.

Mineralogy

All uranium deposits in the district are of the carnotite-type. The mineralogy of these deposits is similar to that of carnotite deposits in the nearby Uravan mineral belt which have been described by Weeks and Thompson (1954, p. 19-20).

The principal minerals are: carnotite, $K_2(UO_2)_2(VO_4)_2 \cdot 1\text{-}3H_2O$; tyuyamunite, $Ca(UO_2)_2(VO_4)_2 \cdot 7\text{-}10 1/2 H_2O$; roscoelite and vanadium hydromica, $(Al, V)_2(Al,Si_3)(K,Na)O_{10}(OH,F)_2$; limonite; calcite; mariposite(?), a chromium-bearing mica; marcasite; and pyrite. These minerals fill pore spaces in the sandstone and also partially replace sand grains and associated argillaceous and carbonaceous material. In addition, small amounts of carnotite, tyuyamunite, limonite, and caliche coat fracture surfaces near the deposits. The latter minerals rarely extend more than a few feet into the sandstone and probably have been leached from the main part of the deposits. Carnotite and tyuyamunite are closely associated in these deposits (Weeks and Thompson, 1954) and are difficult to tell apart because both are fine-grained and have a canary-yellow color. For simplicity, therefore, these uranium-bearing minerals will be referred to as "carnotite" in this report although in all probability some of the material is tyuyamunite.

The carnotite suite of minerals is thought to be secondary and to have formed from primary oxides and hydroxides by oxidation through a complex suite of intermediate minerals (Weeks, 1956, p. 189-190). The principal primary minerals are uraninite, coffinite, montroseite, roscoelite, vanadium hydromica, marcasite, and pyrite (ibid, p. 188). With the exception of the vanadium silicates, which are not altered during weathering (Evans and Garrels, 1958, p. 145), the only primary minerals remaining in the Klondike deposits are some heavily weathered marcasite nodules. Uranium and vanadium showed little tendency to migrate during oxidation, however, and neither leaching nor supergene enrichment of the deposits has been extensive.

Zoning

Most deposits are zoned. Some carnotite is disseminated through the deposits, but most carnotite is closely associated with organic debris or mudstone flakes and lenses. Limonite, roscoelite, and vanadium hydromica occur with carnotite in these high-grade zones and also in the adjacent sandstone. Locally, these minerals also extend beyond the deposits along slightly argillaceous bedding planes from which they are disseminated short distances into the adjacent sandstone. Thus the uranium-vanadium ratio decreases towards the edges of many deposits, and sandstones near the edges locally have a grayish cast caused by vanadium clay minerals. Limonite also increases towards the edges of many deposits where it colors the rocks brown. Where zoning involves both vanadium and iron minerals, iron minerals increase relative to those of vanadium near the edge of a deposit.

Character and Distribution of the Deposits

The habits of ore are similar in all deposits of the district and are similar also to ore habits in the larger and richer deposits of the Uravan mineral belt. The geology of carnotite deposits in the Uravan mineral belt has been described by many writers (see Fischer, 1942; Fischer and Hilpert, 1952; Fischer, 1950; Weir, 1952; McKay, 1955; and Fischer, 1956) and, accordingly, will be considered only briefly in this report.

The ore bodies are tabular deposits, essentially parallel to the bedding but in detail undulant and crossing the bedding. Deposits range in length from a few feet to more than a hundred feet and in thickness from about an inch to three or four feet. The deposits tend to occur in clusters, a relationship clearly evident in the Klondike district where there are about 11 of these clusters. The clusters vary tremendously in size and are separated from each other by several hundred feet of seemingly barren rock.

Most deposits are in the bottom sandstone unit of the Salt Wash. Locally, however, carbonaceous material in overlying sandstones is weakly mineralized, and, in addition, there is a small carnotite deposit in black shale of the Hermosa formation in the northwestern part of the district. These occurrences are of no commercial value, but carnotite is unusual in the Hermosa formation, so this deposit is described in more detail in Appendix B. By way of contrast, most carnotite deposits in the nearby Uravan mineral belt are in the top sandstone unit of the Salt Wash, and the bottom sandstone has no economic importance.

A persistent limestone bed occurs in the lower part of the basal Salt Wash sandstone throughout much of the Klondike district (page 32). All known carnotite deposits are below this limestone where present, and miners use it as a marker horizon for prospecting (E. J. Reed, oral communication, 1956).

By analogy with deposits in the Uravan mineral belt, the basal Salt Wash sandstone in the Klondike district must be considered unfavorable for large, high-grade carnotite deposits. Here the sandstone consists of thin, non-lenticular, horizontally bedded floodplain deposits which are cut by a few, shallow stream scours. Thick cross-bedded, channel-type sandstones, considered by McKay (1955, p. 265) to be most favorable for uranium deposits, are rare. Furthermore, deposits in the Uravan mineral belt commonly occur in sandstone units containing numerous mudstone seams, clay galls, and detrital organic matter, the so-called "trash zones" associated with channel sediments in the Salt Wash; such zones are rare in the Klondike district. Instead, many deposits here are on bedding planes and near the base of shallow stream scours where fragments of plant debris and thin films of silt and shale are especially abundant.

Most carnotite deposits on Klondike Ridge are in a narrow belt about 1/2 mile wide and more than 5 miles long that trends about N. 45° W. and cuts obliquely across the ridge without regard for either the Gypsum Valley salt anticline or changes in elevation. The northwestern end of this belt is truncated by evaporite deposits in Gypsum Valley, and the southeastern end is buried under younger sediments; there is no consistent change in either size or grade of deposits along the belt. The only known deposits outside this zone are about a half mile north of it in a small cluster above the Klondike amphitheater. Exploratory drilling performed outside the main belt had not discovered any minable ore up to 1957. Similar concentrations of uranium deposits in narrow belts that trend nearly normal to the Uravan mineral belt have been noted in several other districts nearby (Fischer and Hilpert, 1952; Shawe, Simmons, and Archbold, 1957).

Detailed descriptions of the deposits are not warranted because of their small size and lack of productivity. A brief description of three deposits is presented in Appendix B, however, to illustrate the habits of ore in carnotite deposits of the district and to point out features of general significance. Most deposits described in Appendix B and, in other parts of this report are identified by both name and number. The numbers refer to sample numbers in table 17 through 21 and identify the deposits on plates 4 and 6 through 13.

Origin

The origin of the Colorado Plateau uranium deposits has been a subject of much discussion in recent years, and a large body of literature has arisen. An excellent review of this subject can be found in McKelvey, Everhart, and Garrels (1955). In brief, theories on the origin of these deposits range through just about the entire spectrum of possibilities. The theories can be separated into two groups, syngenetic and epigenetic; epigenetic theories in turn fall into two categories depending upon whether the ore-bearing solutions are thought to have been supergene or hypogene.

According to the syngenetic theory, the "primary ore minerals were introduced into their present position contemporaneously with or not long after the sands were deposited" (Fischer, 1942, p. 389). The metals are thought to have been transported by surface water or near-surface ground water. Age determinations on uranium minerals, however, suggest that the deposits are all about 60 to 70 million years old (Stieff, Stern, and Milkey, 1953, p. 15), which is much younger than the Late Jurassic age of the Salt Wash. Consequently, the syngenetic theory has been somewhat eclipsed in recent years by epigenetic theories.

Epigenetic theories involving supergene solutions hold that the deposits were formed by precipitation from normal, circulating ground water (Gruner, 1956, p. 515-516), from migrating petroleum or solutions that obtained their uranium either by leaching volcanic ash (Koeberlin, 1938, p. 458-461) or uranium-bearing minerals within the immediate stratigraphic column (Hillebrand and Ransome, 1905, p. 17). The Brushy Basin is often cited as the most likely source of uraniferous volcanic ash, but there may also be enough uranium in nearby detrital minerals of the Salt Wash to furnish all uranium in the deposits (Shawe, Simmons, and Archbold, 1957, p. 64).

Theories involving hypogene solutions envisage uranium deposits being formed either from warm solutions of remote magmatic origin (Rasor, 1952, p. 90) or from ground water heated by nearby intrusives. In the latter case the ground water is thought to have acquired its uranium either by contamination with magmatic emanations (Waters and Granger, 1953, p. 21) or by leaching uranium-bearing detrital minerals in the sediments (Shawe, 1956, p. 241).

The present study contributes little that bears on the origin of these deposits. It seems reasonable, however, to assume that deposits in the Klondike district were formed at the same time and by the same processes as deposits in the nearby Uravan mineral belt. Therefore, any theory that applies to deposits in the Uravan mineral belt probably applies also to deposits in the Klondike district, and conversely, theories which seem incompatible with features observed in the Klondike district may also have little applicability to deposits in the mineral belt. For example, the location of the Klondike deposits, high on the flank of the anticline and also in the bottom sandstone unit of the Salt Wash, does not seem compatible with the concept of descending ground water depositing metals leached from an uniquely uraniferous source in the Brushy Basin.

Similarly, district-wide localization of deposits in a single sandstone unit, the bottom sandstone of the Salt Wash in the Klondike district and the top sandstone in the nearby Uravan mineral belt, seems incompatible with theories involving supergene leaching of uraniferous material scattered throughout the Morrison formation. Instead, these relationships are suggestive of ore-bearing solutions of unique composition and limited volume that did not saturate the entire stratigraphic column. Furthermore the apparent localization of deposits high on the flank of the anticline seems to bear out Shawe's suggestion (1956, p. 24) that the ore-bearing solutions had lower densities than the surrounding ground water.

Stratigraphic and structural relationships in and near the Klondike district, therefore, cast doubt on the effectiveness of large scale supergene leaching and transport of uranium from nearby parts of the stratigraphic column. Instead, field relationships suggest that deposition took place from ore-bearing solutions of unique composition, limited volume, and with lower densities than the ground water.

Suggestions for prospecting

The present study has shown that nearly all known carnotite deposits are in the bottom sandstone of the Salt Wash and that nearly all deposits are in a single mineral belt that cuts obliquely across Klondike Ridge. Using this as a guide and reasoning by analogy with deposits in the nearby Uravan mineral belt (p. 97), it probably can be assumed that the rest of the known deposits are in a second mineral belt parallel to the first and about 1/2 mile north of it. Future prospecting, therefore, should be designed to explore the bottom sandstone unit of the Salt Wash for extensions of these belts into areas of deeper cover. Using the analogy with the Uravan mineral belt again, it also might be advantageous to search for additional belts, one northeast of the Klondike amphitheater near the Horse Park fault block and another south of Gypsum Gap.

However, 66 carnotite deposits are now known in the district, and these are probably representative of all such deposits. In other words, it does not seem likely that future exploration will locate new deposits that are significantly larger or of higher grade than those now known.

Manganese and copper deposits

Manganese deposits

The manganese deposits are located in the central part of the district. All deposits are small, and records show that only 395 tons of manganese ore have been shipped from the district. Approximately 370 tons were shipped in 1915-16 (Muilenburg, 1919, p. 52; and Jones, 1920, p. 68-72) and about 25 tons during 1929-31 (C. N. Harrer, written communication). Shipments totaling about 50 tons were made during the period 1942-53 but were rejected because of low grade and high copper content (ibid). Several deposits have been described by other geologists[1].

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[1] See Muilenburg, 1919; Jones, 1920; and Coffin, 1921.

Controls of mineralization

Both stratigraphic and structural controls were effective in localizing the deposits. The importance of red beds as host rocks is striking because all but four deposits are in red sandstone, siltstone, or silty mudstone of the Hermosa, Rico, Cutler, Wingate, Kayenta, and Summerville formations. Structural control is evident in the fact that nearly all deposits are in or near faults and associated fractures or are near fissures projecting beyond the faults.

Mineralogy

The mineral suite consists of pyrolusite, manganite(?), limonite, hematite, goethite, barite, calcite, and locally malachite.

Manganese oxides

Manganese oxide minerals are difficult to study. Fleischer and Richmond (1943) showed that X-ray analysis provides the only positive identification of these minerals and, therefore, that information from other sources concerning the identification of these minerals, the conditions of their formation, or their paragenesis is unreliable. Identification of representative specimens from the Klondike district was made by the writer using powder diffraction techniques and X-ray equipment at Stanford University.

This study showed that pyrolusite is by far the most common manganese mineral in the Klondike deposits. It occurs as oolites; as platy crystals; as irregular, sooty grains impregnating sandstone; and as radiating needles, locally as much as an inch long, that commonly are intergrown with calcite and barite. The latter type in particular is common in fissure-filling deposits. Polished surfaces of this material show whorls and feather-shaped clusters of crystals which become finer-grained towards the wallrock and finally grade into sooty impregnations in the sandstone. In some specimens pyrolusite has clearly formed by alteration of an earlier mineral, possibly manganite (picture 15).

Iron oxides

The iron oxide minerals are limonite, hematite, and locally goethite. Limonite and hematite are intergrown with manganese oxide minerals, but goethite commonly forms colloform masses which replace other gangue minerals.

Barite and calcite

These minerals occur as fissure fillings, flat-lying veins, and irregularly-shaped pods in the wallrock. They form small grains and large anhedral crystals and locally are intergrown with manganese minerals.

Malachite

Malachite is rare in manganese deposits but occurs in some that are in rocks containing considerable calcite or gray-green shale. A deposit north of #405 in the Kayenta sandstone, for example, contains sooty pyrolusite and traces of malachite. A lens of light-brown, conglomeratic sandstone a few feet below the manganiferous horizon has abundant calcite cement and also a little malachite. Some malachite is also found below this in a gray-green mudstone lens.

Deposits

There are three types of manganese deposits in the district: 1) fissure-filling and disseminated deposits without much gangue, 2) fissure-filling and bedded deposits with abundant gangue, and 3) a vein of black calcite in the Hidden Treasure deposit. Among deposits in the Klondike amphitheater, the first type is more common near the major Tertiary fault in the south while the second type predominates in deposits farther north.

The first type, deposits without much gangue, is the most common, but these deposits have not been productive. Manganese occurs as fissure fillings in faults and fractures and as irregularly distributed, nodular impregnations and partial replacements of the adjacent wallrock. The Monarch mine, near sample #448, is an example of this type of deposit. Manganese minerals here impregnate and partially replace Kayenta sandstone along a major fault that brings Kayenta sandstone into contact with the Salt Wash. Manganese minerals occur only in the Kayenta, but small amounts of malachite are found in Salt Wash sandstone adjacent to the fault. Fischer (written communication, 1940) reports that "a face (of Kayenta sandstone) about 5 feet wide and 8 feet high is exposed in the prospect cut along the fault plane. An estimated 20% of this face is high-grade ore and about 40% is intermediate- to low-grade ore. The rest of the rock is essentially barren sandstone. These types of ore are 'spotty' and grade back and forth from one to the other." Manganese oxide minerals also stain joint and fracture surfaces in the Kayenta for more than 100 feet north of the deposit. There is a little manganese in sandstone along the fault northwest of the prospect, but none is found to the southeast although the fault is well exposed there.

The second type, deposits with abundant gangue, is the only one that has been productive. The White mine (samples #3 and #450), formerly the Black Diamond mine described by Muilenburg (1919, p. 50-52), is of this type and has produced all the manganese mined in the district up to 1956, about 395 tons. Most of the workings are caved, but the deposit is exposed for several hundred feet along the face of a cliff and in an adit driven about 40 feet into the cliff. The adit follows a small shear which displaces the rock about 8 inches. The deposit consists of a discontinuous, flat-lying calcite vein containing a small amount of pyrolusite. The vein is in red silty shale of the Summerville formation but is at the contact with a lens of light-gray sandstone below; the shale is bleached light brown along the contact. The vein is in the bleached zone in most places, but this is probably fortuitous because there is no sign of bleaching where the vein cuts red shale. The vein ranges in thickness from 0 to about 16 inches.

Only one example is known of the third type, manganese in a black calcite vein. This is in the Hidden Treasure deposit and is described on page 116.

Copper deposits

There are many small copper deposits in the Klondike district, but the only recorded production has come from the Hidden Treasure mine (sample #247, et seq.). Henderson (1922, p. 546) reports that "two small lots of copper-silver ore" were shipped in 1921, and Henderson and Martin (1938, p. 260) report that a shipment of copper-silver ore totaling 1,700 pounds Cu and 71 fine ounces Ag was made in 1937.

Controls of mineralization

Copper deposits, like those of manganese, show the effects of both structural and stratigraphic controls of mineralization. Structural control is shown by the localization of most deposits in or near major faults. Stratigraphic control, on the other hand, is shown by the fact that most deposits are in the Morrison or Summerville formations and that nearly all are in light-brown sandstone and conglomeratic sandstone or gray limestone.

Only three deposits have been found in red beds. Two are in Kayenta sandstone near a major fault while the third is a copper-bearing jasper deposit in red shale of the Summerville formation. These unusual deposits are described on pages 122 and 123.

Mineralogy

There are three types of copper deposits in the district: 1) malachite deposits, 2) copper sulfide deposits, and 3) jasper deposits. The first type, in addition to malachite, may contain small amounts of calcite, hydrocarbons, chalcocite, and azurite.

The second type, copper sulfide deposits, in addition to the minerals found in malachite deposits, may contain any or all of the following: native copper, bornite, covellite, galena(?), pyrite, pyrolusite, chalcedony, aragonite, celestite, barite, and their alteration products: limonite, hematite, and volborthite, a copper vanadate. Wallrock in these deposits may also contain small amounts of epidote, chlorite, clay, and sericite. All sulfide deposits are in or near major Tertiary faults, but many malachite deposits are disseminated in sediments a short distance from the faults.

Jasper deposits consist of quartz and chalcedony with minor amounts of calcite, limonite, hematite, malachite, and manganese oxides. With one exception, jasper deposits are located in the highest parts of the district.

Malachite deposits

Malachite deposits are found in light-brown sandstone, gray-green mudstone, and limestone. Most are small and low-grade; none have produced ore although a small concentrating mill was built at one time near deposit #386 to treat this material.

Most deposits are in sandstone, are flat-lying, and are near faults. Some are actually in faults or fissures, and few are more than two or three hundred yards from a fault. Sulfide minerals are lacking in most malachite deposits and where present are so closely associated with carbonaceous matter that it is reasonable to believe they were precipitated by organic or pyritic sulfur associated with the plant remains (c.f. Miller, 1958, p. 544). The principal mineral is malachite; calcite is minor while azurite and chalcocite are rare. Hydrocarbon specks are abundant in many deposits but lacking in others. Malachite deposits have been localized by carbonaceous matter, mudstone, limestone, and in some instances by calcareous cement in the sandstone.

One small deposit northeast of the Klondike amphitheater is in Mancos shale. This deposit is unusual because it is the only known occurrence of copper in Cretaceous rocks. The deposit is near a major Tertiary fault and is probably related to other malachite deposits nearby.

Sulfide deposits

Hidden Treasure deposit (sample #247, et seq.)

This deposit, named after the Hidden Treasure mine, is the only one with recorded copper production (p. 106). It is also the largest deposit in the district and therefore will be described in more detail than the others.

The deposit is on a major Tertiary fault that brings Upper Jurassic rocks into contact with the Rico-Cutler conglomerate. Most mineralized material is in light-brown sandstone and conglomerate of the Brushy Basin, Summerville, and Entrada, but some Rico-Cutler conglomerate has also been mineralized. Small patches of mineralized material, such as malachite, calcite stringers, or iron and manganese oxides, are found locally along the entire northern part of the fault, but the most extensively mineralized area is in the vicinity of the Hidden Treasure mine. Most of the Brushy Basin sandstone there is mineralized, and mineralized material in the Entrada sandstone and Summerville formation extends nearly a quarter mile west of the fault.

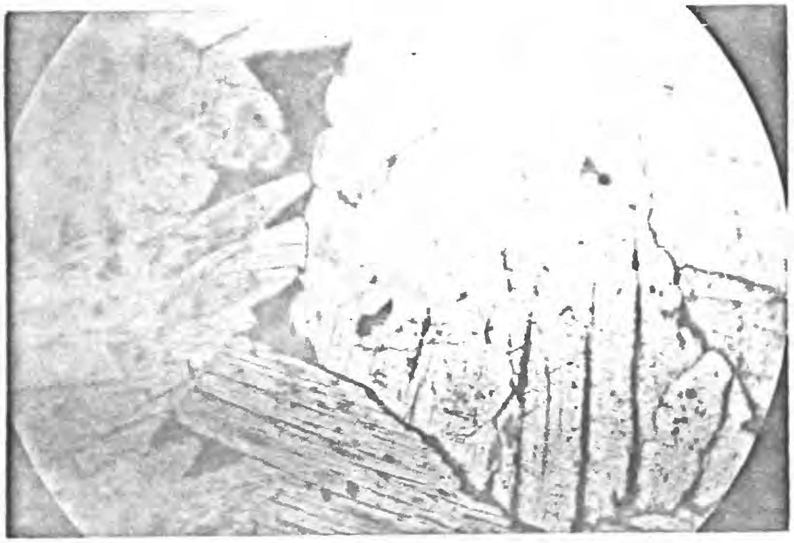
Wallrock alteration

Three zones of wallrock alteration, termed the central, intermediate, and outer zones (fig. 3), can be distinguished. The central zone lies along the Tertiary fault. The sandstone here is bleached grayish-white and is mineralized with large amounts of gangue. The intermediate zone is characterized by an unusually dark-brown sandstone produced by the addition of considerable limonite. The outer zone is distinguished primarily by the abundance of calcite; bleaching and limonite enrichment are lacking.

Sandstone in the two outer zones weathers to form peculiar, rounded pellets (picture 16) which range in size from about a quarter inch in diameter in the intermediate zone to more than an inch in diameter near the edge of the deposit. The pellets are more tightly cemented than the rest of the sandstone, and in general they are also more tightly cemented near the center of the deposit. The cement in most pellets is calcite, with small amounts of barite in some; barite, however, is the dominant cement in a few. The calcite cement of some pellets forms large, anhedral crystals that envelope several sand grains. Evidently, the sandstone pellets were formed before the malachite phase of mineralization (see below), because malachite and hydrocarbon specks mineralize sandstone between pellets, but not the pellets themselves.

Mineral distribution

The distribution of many minerals is related to these zones of wall-rock alteration. The central zone, for example, is distinctive because copper sulfide minerals occur only in it; celestite, too, is confined almost entirely to the central zone. The distribution of manganese minerals, on the other hand, is not as closely related to the zones of wall-rock alteration. Manganese minerals are concentrated along the Tertiary fault and also in sandstone and conglomerate near the margines of the deposit, but are lacking in most of the central zone.



Picture 15. Manganite(?), light-gray, altering to pyrolusite, white. Alteration proceeds inwards from crystal edges and fractures. X 645

Picture 16. Sandstone pellets in the Hidden Treasure deposit.

The Hidden Treasure mine (fig. 4) is in the central zone. It consists of a shaft about 90 feet deep and a cross cut extending up to the fault. The shaft is collared in Brushy Basin sandstone but passes through the fault into Rico-Cutler conglomerate at a depth of about 25 feet. The conglomerate contains a small amount of malachite, hydrocarbon specks, and pods and veinlets of calcite surrounded by limonite halos. These become more abundant near the fault. A vein of calcite, barite, and celestite with traces of native copper, chalcocite, bornite, malachite, volborthite, and limonite crops out immediately south of the mine. The wallrock there is badly shattered, and sandstone fragments form subangular inclusions in the vein.

According to the mine owner, Edgar J. Reed, early workings started from an incline, now caved, near the collar of the present shaft. He reports that the principal ore mineral was chalcopyrite and that there was "abundant" native copper in the wallrock. According to Mr. Reed, the incline was abandoned at a depth of about 50 feet when it entered a "syenite porphyry". No sign of this rock was found in the present workings, but, if the report is accurate, the rock is probably similar in composition to the intrusive dike and sills found along the southern margin of the Klondike district.

The intermediate zone of alteration contains a few deposits of chalcocite, malachite, and volborthite as well as manganese oxide minerals near the fault. The outer zone contains several small malachite deposits in light-brown sandstone and conglomerate and manganese deposits in red sandstone and conglomerate. Tiny hydrocarbon specks are closely associated with malachite and in many places are so abundant that they color the normally light-brown sandstone gray. Hydrocarbon specks are so abundant in some prospect pits that it seems probable the prospects were mistakenly explored for vanadium which also colors sandstone gray. This association of hydrocarbons with malachite is characteristic of many deposits in the Klondike district but is especially pronounced in the Hidden Treasure deposit.

Mineralogy and paragenesis

The mineral suite varies through the deposit. In the Hidden Treasure mine it consists of calcite, barite, and celestite with small amounts of chalcocite, bornite, native copper and their alteration products: malachite, limonite, and volborthite. Two phases of mineralization are recognized in the mine: small, anhedral grains of calcite, commonly stained now with limonite, were deposited during an early phase while large crystals and anhedral grains of calcite, barite, and celestite were deposited during a later phase. Many rounded remnants of quartz grains, evidently obtained from the sandstone wallrock, are associated with early calcite, but quartz remnants and limonite stains are rare in the younger material. No direct evidence links metallization with either phase; probably copper and iron minerals were deposited during both phases (see below). It is not likely, however, that malachite was formed at the same time as the copper sulfides because of the great difference in the solubilities of these minerals and because the only malachite closely associated with copper sulfides is clearly secondary. More probably, copper sulfides were deposited during an early phase of mineralization while malachite was formed later.

The character of mineralization changed laterally along the fault. Two small prospect pits (sample #422) about 60 feet north of the Hidden Treasure mine are in manganese ore. Arkosic and argillaceous Brushy Basin sandstone here is stained black by manganese minerals and is cut by veinlets of late, white calcite. Quartz and feldspar grains from the wallrock are badly fractured and corroded (picture 17). Some fractures are filled with chlorite and epidote, and many feldspar grains are weakly argillized and sericitized. These relationships are indicative of low-temperature hydrothermal alteration and are only found in sulfide deposits.

The mineral suite, consisting of chalcedony, barite, calcite, aragonite, and oxides of manganese and iron, was formed during three phases of mineralization. Chalcedony, calcite, and aragonite were deposited during the first phase. These minerals and the wallrock are partially replaced by black, colloform pyrolusite, hematite, barite, and calcite from the second phase. Finally, the deposit is cut by stringers of white calcite marking the third and last phase.

Calcite, therefore, was deposited during the entire period of mineralization. It is intergrown with chalcedony from the first phase, with manganese and barite from the second phase, and late calcite stringers from the third phase cut the entire mineral assemblage. Aragonite, on the other hand, is rare not only in this deposit but in all deposits of the Klondike district. It has only been found in a few specimens from sulfide deposits and only in association with chalcedony or copper sulfides.

Superficially there appears to be little similarity between the mineral suite in the manganese prospect pits and that of the Hidden Treasure mine, but the two probably were formed at the same time and by the same ore-bearing solutions. The third phase of manganese mineralization, therefore, probably corresponds to the second phase of mineralization in the Hidden Treasure mine, and the second phase of manganese mineralization probably corresponds to the first phase of mineralization in the mine. Nothing comparable to the first phase of manganese mineralization was found in the Hidden Treasure mine, but additional mining along the fault would probably encounter this material.

A minor variation in the occurrence of manganese is found in some flat-lying black calcite veins. These veins are in the top sandstone of the Summerville formation and are near the southwestern margin of the deposit (sample 422). There are two generations of calcite here; the first, a black phase, is cut by small veinlets of clear calcite from the second phase. Pyrolusite occurs in both generations, but by far the greatest amount is in the early one. This pyrolusite forms a thick dispersion of tiny, rounded specks in calcite gangue; in contrast, second generation pyrolusite forms jagged anhedral masses in clear calcite which are many times larger than the tiny specks of early pyrolusite.

Black calcite-bearing debris extends southeast to the fault along the same horizon, but no other outcrops of this material were found. Sandstone in the lower part of the Summerville and in the underlying Entrada, however, are mineralized with malachite and tiny hydrocarbon specks (sample 441). Mineral relationships in the black calcite suggest that it was formed by rapid and essentially contemporaneous precipitation, or dumping, of both manganese and calcite from the ore-bearing solutions, possibly a result of rapid cooling near the outer edge of the deposit.

Summary

The features described above suggest that the Hidden Treasure deposit was formed by hydrothermal solutions which spread far out into the wallrock from a major Tertiary fault and that the character of mineralization changed with time. The focus of mineralization was a narrow zone near the Hidden Treasure mine. The earliest solutions leached and altered the wallrock minerals; they corroded quartz and feldspar grains, deposited chlorite and epidote in fractures, and produced minor argillization and sericitization of feldspar grains near the fault. In all probability, iron-bearing minerals were leached from sandstone near the fault at this time, too, and the iron redeposited a short distance away, creating the central and intermediate zones of wallrock alteration.

Chalcedony, calcite, and aragonite were the first vein minerals to be deposited. Somewhat later fine-grained calcite together with chalcocite, bornite, and probably pyrite were deposited in the Hidden Treasure mine, and barite and calcite together with oxides of manganese and iron were deposited a short distance away. Mineralizing solutions at this time partially replaced earlier minerals, cement, and wallrock near the fault and spread far out into the surrounding sandstones where they deposited small amounts of calcite and barite to form the characteristic sandstone pellets of the outer zones.

Malachite, hydrocarbon specks, calcite, barite, and oxides of manganese and iron, as well as black calcite were deposited during a later phase of mineralization. The last minerals to form were calcite, barite, and celestite; these were deposited in open fissures in the Hidden Treasure mine, but calcite alone was deposited at a distance.

Hidden Treasure #3 deposit (samples #346 and #245)

This deposit, named after the Hidden Treasure #3 mine, is very similar to the last. It, too, lies on a major Tertiary fault and is in lower Brushy Basin sandstone. The mineral suite consists of calcite, barite, and celestite with minor amounts of chalcedony, aragonite, and sulfides of copper, iron, and lead(?). Their alteration products, malachite, volborthite, and limonite, stain sandstone nearby. Paragenetic relationships here are about the same as in the preceding Hidden Treasure deposit.

There are several minor variations between the deposits, however. Neither sandstone pellets nor the zones of wallrock alteration are found in this deposit. Barite and celestite are much less abundant while sulfide minerals are more plentiful and less altered. Manganese minerals are lacking.

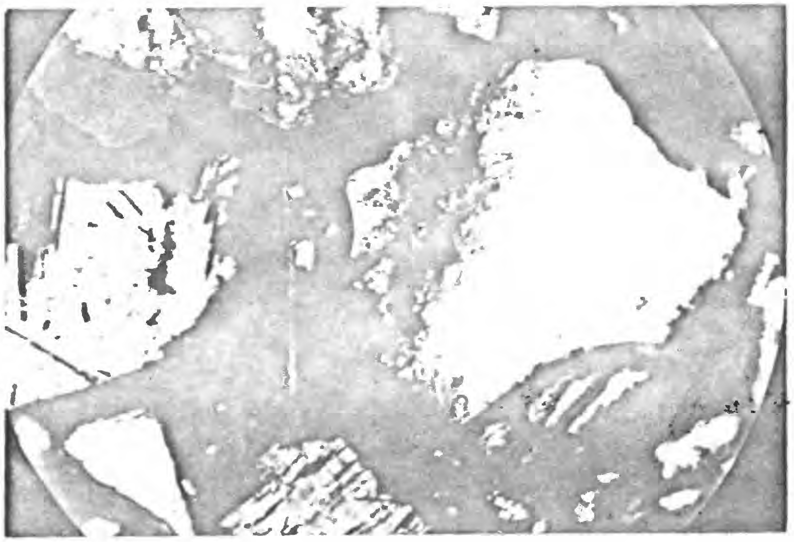
Sulfide minerals

The most interesting feature of the deposit is its suite of sulfide minerals. These will be described briefly to give a clearer picture of the sulfide phase of mineralization. The sulfide minerals consist of bornite, covellite, chalcocite, pyrite, and galena(?). They fill fissures and have disseminated from the fissures a few millimeters into the sandstone wallrock. Alteration products, consisting of malachite, limonite, and volborthite, stain the adjacent wallrock. Calcite commonly occurs with the alteration products but is not closely associated with the sulfide minerals.

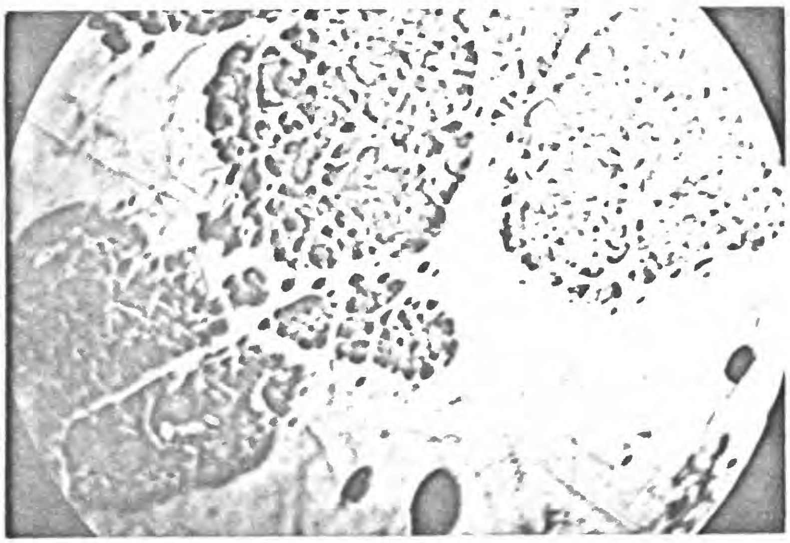
The sulfide minerals were probably formed during a single phase of mineralization but by solutions whose composition changed somewhat with time. The earliest minerals were bornite and pyrite, possibly accompanied by chalcocite and galena(?); the latest were probably chalcocite and galena(?) alone.

Most bornite forms small, irregularly shaped remnants in the centers of veinlets where it is almost entirely replaced by supergene chalcocite. This type of bornite is one of the oldese sulfide minerals in the deposit. The remaining bornite is intergrown with chalcocite and covellite in sandstone wallrock near the veinlets. There is no indication that the latter type of bornite is older than the chalcocite associated with it or that it is being replaced by chalcocite. This bornite may have formed by contamination with iron-bearing minerals in the wallrock, and, if so, may not be as old as bornite in the veinlets.

Pyrite is a minor constituent of the veinlets. It forms anhedral, rounded, and intensely shattered grains that are partially replaced by chalcocite and other late minerals (picture 18). Paragenetic relationships between pyrite and bornite are obscured by the thorough-going alteration of bornite, but pyrite is one of the earliest sulfide minerals in the deposit.



Picture 17. Corroded quartz and feldspar grains in in a matrix of manganese oxides, barite, and calcite. Hidden Treasure deposit.



Picture 18. Rounded, shattered, and partially replaced pyrite grains in a matrix of chalcocite and bornite. Hidden Treasure #3 deposit. X 495

Chalcocite is by far the most abundant sulfide mineral. Both gray and blue chalcocite are present, but gray chalcocite predominates. It is the orthorhombic, low temperature variety, and some of it has clearly formed by supergene alteration of bornite. Hypogene chalcocite, if present, can not be recognized because the extensive supergene alteration of bornite obscures other paragenetic relationships. Blue chalcocite forms narrow rims around bornite which it replaces. The blue color is probably caused by cupric sulfide, but whether cupric sulfide is present in the mineral digenite or as a solid solution in chalcocite is not known.

Covellite is rare. For the most part it forms tiny specks and laths associated with chalcocite and bornite in the sandstone wallrock. It also forms rims around quartz grains in the wallrock separating them from chalcocite and bornite, and a little covellite is found in heavily weathered portions of sulfide veins.

Galena(?) also is minor. It forms tiny, anhedral grains in gray chalcocite where it has been identified tentatively by its color and the presence of lead in samples from the deposit (table 22).

Paragenesis

These relationships suggest that the earliest sulfide minerals were bornite, pyrite, and possibly chalcocite and galena(?). Deposition of chalcocite must have continued after that of pyrite ceased because pyrite grains are shattered, partially replaced, and the fractures filled with gray chalcocite. Most bornite is now altered to chalcocite.

Where mineral-bearing solutions permeated the sandstone, they deposited chalcocite and, through reactions with the wallrock, covellite and bornite. Calcite was probably deposited throughout the entire sulfide phase of mineralization. The sulfide minerals are partially weathered to malachite, volborthite, and limonite.

Deposits #447 and #438

These deposits are in the Kayenta sandstone and Rico conglomerate respectively. They both contain sulfide minerals, and their wallrocks show signs of incipient low-temperature hydrothermal alteration. The chief differences between these and the Hidden Treasure deposits are their size and a gangue consisting almost exclusively of calcite. The deposits are only a little larger than the prospect pits dug to explore them and, therefore, are many times smaller than the Hidden Treasure deposits.

Jasper deposits

Only three jasper deposits have been found in the district, and these have no commercial value. The largest deposit is on the eastern side of the Klondike amphitheater, near the top of the cliff, in red shale of the Summerville formation. The deposit has been prospected for manganese, and two small test pits have been sunk in it. The shale wallrock is shattered, contorted, silicified, and mineralized with small amounts of malachite, calcite, and oxides of iron and manganese. The groundmass is silicified by quartz and minor chalcedony; these are deeply stained by hematite and a little limonite, forming jasper. Fractures are filled with chalcedony, calcite, and minor malachite. Traces of malachite also accompany quartz in the groundmass, but malachite is more abundant in the fractures. The entire deposit is cut by stringers of late, clear calcite which contain neither limonite nor malachite.

The two other jasper deposits contain fewer ore minerals. One is in the northern part of the district, in a fault block that has been dropped into the floor of Gypsum Valley by recent faulting. This deposit is in Brushy Basin shale and contains a little malachite but no manganese minerals. The other deposit crops out near the top of Klondike Ridge, near sample #444. It is in limestone near the base of the Rico formation and is barren of both copper and manganese minerals.

Origin

Several theories for the origin of the manganese deposits have been proposed by earlier visitors to the area, but the origin of the copper deposits has not been discussed. Muilenburg (1919, p. 52) thought that the bedded manganese deposits were essentially syngenetic but suggested that the fissure-filling deposits had been formed by supergene leaching of manganiferous material higher in the section. Jones (1920, p. 71) thought that manganese was originally disseminated through the red beds but was later leached by supergene solutions and concentrated into deposits by replacing pre-existing calcite in the rocks. Coffin (1921, p. 234) suggested that some manganese deposits are associated with an unconformity at the base of the Summerville formation (basal McElmo formation in his report); he also recognized the importance of faults in localizing the copper deposits.

None of these theories explain all of the manganese deposits, nor do they imply a genetic relationship between the manganese and copper minerals. The present study, however, shows that manganese minerals are found in some copper deposits and copper in some manganese deposits, that manganese and copper deposits in a given area have both been localized by the same structure, and that manganese deposits form in different types of rock than copper deposits. This suggests that the manganese and copper deposits have a common origin and that the metals are in separate deposits primarily because of differing requirements for a host rock.

Hydrothermal origin

Many features of the deposits, such as zoning of certain metals around "conduits" (page 136), incipient low-temperature hydrothermal alteration of wallrock in copper sulfide deposits, and the close association of most deposits with faults and related fissures, point to a hydrothermal origin. Proven hydrothermal deposits are rare on the Colorado Plateau, but the lack of manganese and copper deposits in nearby areas shows that deposits in the Klondike district must have had an unique origin.

Igneous rocks, which could have provided the thermal solutions, are not exposed at the surface, but some may be concealed at shallow depths. Early mining operations in the Hidden Treasure deposit reportedly encountered igneous rocks a short distance below the surface (p. 112), and preliminary results of an airborne magnetometer survey suggest that small bodies of intrusive rock may underlie other parts of the Klondike district as well (H. R. Joesting, oral communication, 1956). It is possible that the thermal solutions were related to these intrusives.

The hypothesis of hydrothermal origin, however, is difficult to maintain because it seems likely that the igneous source would have been altogether inadequate to supply either the metals or the solutions in which they were carried. A relatively large volume of ore-bearing solution must have been involved in mineralization because manganese and copper deposits occur throughout the Klondike district and in almost every sedimentary formation. This means that the ore-bearing solutions must have permeated the entire stratigraphic column throughout almost the entire district. But this seemingly large volume of solution contrasts sharply with the small amount of intrusive rock, in the form of narrow dikes or small plugs, likely to underlie the Klondike district. Furthermore, concealed igneous rocks in this area are probably similar in composition to intrusive rocks exposed along the southern margin of the district and in Disappointment Valley, but those intrusives did not add much volatile matter to their wallrocks (page 50).

The intrusives also are an unlikely source of metals in the deposits. Manganese and copper deposits similar to those in the Klondike district are not found anywhere else on the western side of the San Juan Mountains, although dikes and sills similar to those in the report area are widespread throughout that region (Bush, Taylor, Marsh, and Bromfield, 1956, Shawe, oral communication, 1956). It is not likely, of course, that the ore metals would be concentrated in the magma only in the Klondike district.

A possible hypothesis to account for both the apparent hydrothermal origin of the deposits and the seeming inability of the intrusives to furnish either the solutions or the metals is the activity of ground water. Normal ground water in this area carries small amounts of the ore metals in solution (table 3). The near surface intrusion of igneous rocks would have heated this ground water considerably, thereby increasing the solubility of metals in it and making it a more concentrated ore-bearing solution.

The following hypothesis, therefore, is proposed to explain the origin of these deposits. It is suggested that the deposits were formed when small bodies of basic igneous rock were emplaced at shallow depths in parts of the Klondike district. These intrusives added little, if any, volatile matter to the ground water, but they heated the water which then rose to the surface along faults, joints, and fissures. This hot water leached small amounts of copper and manganese from the wall-rocks at depth. As it rose, the ground water cooled, and some of the metals were precipitated in the enclosing sediments, precipitation being controlled by physical and chemical changes in both the solutions and the wallrocks.

The chemical composition of the ore-bearing solutions, and consequently the nature of the deposits formed from them, was controlled by the original composition of the ground water modified only by reactions with the wallrock. These reactions in turn were caused by physical and chemical changes in the solutions resulting from the near-surface intrusion of igneous rock.

Summary

Copper and manganese deposits in the Klondike district show relationships that are not normally found in supergene deposits, so some other mechanism must be found to concentrate the metals. Igneous emanations are inadequate because the apparent volume of ore-bearing solutions seems to have been disproportionately large for the small amount of igneous rock likely to underlie the Klondike district. Such emanations seem inadequate also because nearby igneous rocks in Disappointment Valley did not add much volatile matter to the wallrocks and because similar deposits are not associated with similar igneous rocks elsewhere in the region, although such rocks are widespread on the western side of the San Juan Mountains.

Ground water, however, carries these metals under normal conditions. It is possible, therefore, that the near surface intrusion of igneous rocks heated this water, thereby increasing the solubility of metals in it and causing the solutions to rise along faults and fissures to the surface.

In other words, manganese and copper deposits in the Klondike district probably were formed in what is now the deeply eroded roots of an ancient hot springs system. Judging from the distribution of copper and manganese deposits, these hot springs must have covered an area of about one square mile, and thermal solutions must have spread out along faults for more than three miles beyond this.

Description of the hydrothermal system

Composition of the ore-bearing solutions

The small size of the Klondike district together with the excellent exposure of most deposits and the apparent simplicity of processes involved in mineralization suggest that some physical and chemical characteristics of the ore-bearing solutions can be determined.

Pressure

Available information suggests that most deposits were formed near the surface and, therefore, that pressures were low. The intrusive rocks, for example, were probably emplaced near the surface. The sills in Disappointment Valley have several petrographic features indicative of rapid crystallization: the groundmass is very fine grained, there is glass in the contact zones, and pigeonite has not inverted to hypersthene. Moreover, breccia dikes on the Dolores anticline were evidently formed by explosions so mild that they could hardly have occurred under a thick cover of Mancos shale. On the other hand, some sills did not approach the surface more closely than 200 feet, as shown by the thickness of sediments overlying igneous rock in a butte in Disappointment Valley; the top of the butte is covered by Quaternary landslide debris showing that it must have been part of the valley floor shortly after the Pleistocene uplift. In short, it seems reasonable to assume that the sills in Disappointment Valley were emplaced within a few hundred feet of the surface.

Evidence points towards shallow emplacement of intrusive rocks in the Klondike district also. A shallow, concealed dike has been reported beneath the Hidden Treasure deposit (p. 112), and evidence that erosion in the lower Tertiary had exposed basal Salt Wash near the crest of the anticline (page 68) suggests that the overlying Mancos and Brushy Basin shales were stripped off the anticline in the Klondike district, too, before intrusion occurred.

This means that the deposits must have been formed at depths ranging from less than 100 feet near the top of Klondike Ridge to possibly as much as 500 feet in the deepest deposits exposed. The deposits were probably formed under conditions of hydrostatic pressure because many are in or near open fissures; hydrostatic pressure at these depths ranges from less than 3 to nearly 15 atmospheres.

Temperature

The mildness of wallrock alteration suggest low temperatures during mineralization. If pressures were as low as indicated, solutions in the deepest deposits exposed could not have been appreciably hotter than 199°C., the boiling point of water at 15 atmospheres pressure (Handbook of Chemistry and Physics, 1956).

The thermal gradient must have been steep because the intrusives were small and could not have heated the wallrocks greatly, except at the immediate contacts. Moreover, channelways along faults and fissures were so narrow that the volume of solution at any given point must have been small, and, accordingly, the wallrock should have had a pronounced cooling effect on the solutions. Furthermore, the thermal solutions were continually mixing with cooler surface water (page 140) which also must have helped lower the temperature and thus steepen the thermal gradient. In all likelihood, therefore, the ore-bearing solutions were cooler than 199°C., maybe as cool as 100°C., and possibly even cooler in deposits formed near the surface.

pH

The early ore-bearing solutions were probably mildly alkaline at depth. Present ground water in the Morrison formation is weakly alkaline (Phoenix, 1959, p. 64), and a sample from Gypsum Gap spring in the Burro Canyon formation had a pH in excess of 8.4 (Judson and Osmond, 1955, p. 108). Furthermore, the weak argillic, chloritic, and sericitic wallrock alteration formed during the sulfide phase of mineralization was probably produced by alkaline solutions (Stringham, 1952, p. 661-662). Moreover, it would seem reasonable to assume on theoretical grounds that the solutions would be alkaline at depth because of the hydrolysis of calcite and silicate minerals below the water table and out of contact with air.

The scarcity of aragonite suggests that the solutions never became strongly alkaline. Aragonite is rare and has only been found in deposits formed in conduits during the early phases of mineralization. Experimental data of Wray and Daniels (1957) suggest that the formation of aragonite instead of calcite is favored by small amounts of barium, strontium, or lead ions in solution; on this basis it seems odd that aragonite is not more common in the deposits. Zeller and Wray (1956) however, found that aragonite is minor in precipitates, even those formed in warm solutions containing strontium and barium ions, if the pH of the solutions is less than 8.0. Therefore, it seems likely that even the earliest ore-bearing solutions were only mildly alkaline.

The ore-bearing solutions may even have become slightly acid near the surface. White (1955, p. 121) points out that two processes, exsolution of CO_2 and oxidation of H_2S, predominate in controlling the pH of water in hot springs as it approaches the surface. Exsolution of CO_2 tends to raise the pH, but this probably was not important in the Klondike district because of the low pressures. It seems more likely that oxidation of H_2S, caused by mixing with fresh surface water, was the dominant process and that, accordingly, the pH of the solutions may have dropped as they approached the surface, possibly even becoming slightly acid. This process probably became increasingly important at depth, too, as mineralization progressed and convective overturn (page 140) carried oxygenated surface water into deeper parts of the system.

Eh

Some tentative conclusions can also be drawn about the Eh of the ore-bearing solutions. Copper and iron sulfides were only deposited during the early phases of mineralization. Data compiled by Krauskopf (1957, p. 67) show that a negative redox potential is required to maintain much iron in solution with sulfide ions at low temperatures and at a pH near 7. These copper and iron sulfide minerals, therefore, probably indicate reducing conditions in the early ore-bearing solutions.

The redox potential of the solutions may have risen as they approached the surface because of dilution with surface water. As with pH, the influx of surface water into deeper parts of the system may also have raised the Eh of the solutions at depth as mineralization progressed.

Composition

Since the deposits are thought to have been formed by heated ground water, the composition of the present ground water in this area should provide some clues to the composition of the ore-bearing solutions. Phoenix (table 3) shows that the principal dissolved salts in ground water of the Morrison formation consist of bicarbonate and sulfate anions and calcium, magnesium, and sodium cations. He also shows that uranium, vanadium, copper, lead, iron, manganese, and selenium ions are commonly present but in concentrations below 1 ppm. These concentrations fall within the broad range shown by Clarke (1924, p. 194) to be normal for the slightly alkaline, mixed carbonate-sulfate type of ground water.

Extrapolating these data back to assumed conditions in the ore-bearing solutions is risky. However, if assumptions about the chemical and physical character of those solutions outlined in the preceding pages are correct, then chemical equilibria in the ore-bearing solutions probably were not greatly different from chemical equilibria in present ground water, and the composition of the ore-bearing solutions probably was not greatly different from that of the present ground water.

Summary

The ore-bearing solutions probably had low temperatures and pressures, a pH near 7 and an Eh near 0. The character of these solutions may have changed somewhat as mineralization progressed, the pH dropping slightly and the Eh increasing. The composition of all but the deepest and hottest solutions probably was not greatly different from that of normal ground water.

Table 3. Chemical analyses (in parts per million) of ground water from wells and springs in the Morrison formation.

	Brushy Basin member				Salt Wash member			
	Ave.	Max.	Min.	No. of samples	Ave.	Max.	Min.	No. of samples
Silica (SiO_2)	14.2	20.	9.6	6	15.	23.	11.	9
Iron (Fe), (in solution)	.04	.07	.01	6	0.05	.1	.02	9
Iron (Fe), (total)	.12	.18	.07	2	0.12	.19	.04	6
Calcium (Ca)	61.8	98.	5.8	6	63.	86.	30.	9
Magnesium (Mg)	50.3	104.	12.	6	56.	88.	37.	9
Sodium (Na)	328.	847.	118.	6	64.	129.	10.	9
Potassium (K)	9.3	16.0	4.4	6	7.0	13.0	4.2	9
Manganese (Mn)*	.05	.29	.00	6	0	0	0	9
Bicarbonate (HCO_3) and Carbonate (CO_3)	725.	1900.	354.	6	431.	620.	351.	9
Sulfate (SO_4)	327.	798.	63.	6	111.	353.	28.	9
Chloride (Cl)	104.	198.	24.	6	38.	69.	18.	9
Fluoride (F)	.9	2.6	.3	6	.4	.7	.2	9
Nitrate (NO_3)	3.6	14.0	.1	6	3.1	6.1	.2	9
Boron (B)	.11	.40	.03	6	.03	.08	.00	9
Uranium (U)	.04	.06	.02	3	0.18	.6	.0	9
Vanadium (V)	.17	.30	.09	3	<0.1	.16	<.1	9
Copper (Cu)	.01	.05	.00	3	.02	.07	.00	9
Lead (Pb)	.00	.00	.00	3	.08	.50	.00	9
Selenium (Se)	<.05	.05	<.05	3	.00	< .05	.00	9

3. Chemical analyses (in parts per million) of ground water from wells and springs in the Morrison formation--continued

	Brushy Basin member				Salt Wash member			
	Ave.	Max.	Min.	No. of samples	Ave.	Max.	Min.	No. of samples
[in] parts per [mi]llion (residue [on] evaporation [at] 180°C.	1256	2180	566	6	570	844	361	9
[Hard]ness as $CaCO_3$								
[Ca]lcium-Magnesium	361	670	64	6	387	572	227	9
[No]n-carbonate	99	380	0	6	50	100	0	9
[Perc]ent Sodium	60	96	27	6	24	44	6	9
[Lab]oratory pH	8.2	9.4	7.7	6	7.8	8.3	7.5	9

[Ma]nganese detected in only one sample.

Changes in the ore-bearing solutions

The following discussion is based upon analyses of channel samples collected from entire mineral deposits, not just ore. Most deposits are small, and zoning within deposits is simple. Accordingly, one or at most a composite of three channel samples probably provides a representative sample of that deposit. Most deposits were sampled in this manner, but the larger Hidden Treasure deposits were sampled more extensively. Several deposits were sampled during both field seasons to check the reproducibility of sampling techniques. The results agree quite well, and, in most cases, assays from nearby deposits are very similar. Therefore, the samples are believed to be representative of their deposits and satisfactory for the uses made of them. The samples were analyzed by the U. S. Geological Survey, and all assays are thought to be accurate to at least one order of magnitude; most assays are more accurate than this. Sample locations are shown on plates 4 and 6-13.

For convenience in making comparisons, most metal concentrations (pl. 6-13) are expressed as ratios of two or more elements rather than as absolute values. These ratios apply only to mineralized ground and are not necessarily representative of barren rock between deposits.

The normal background concentrations of many metals are markedly different in red beds and light-brown sandstones. Accordingly, the assays must be adjusted for different background levels before comparing the effects of mineralization throughout the district. Background values estimated for the Klondike district are shown in table 23, together with "average" background values in the Brushy Basin and Kayenta sandstones of southwestern Colorado. The latter were calculated from data compiled by Newman (written communication, 1956).

Background values estimated for the Klondike district have no significance outside the district. The depositional history alone of sediments around salt anticlines precludes the likelihood of widespread uniformity in minor element content. Furthermore, pervasive hydrothermal activity has undoubtedly modified the minor element content of rocks in the Klondike district, and these changes are necessarily incorporated in the estimated background values.

Zoning

The adjusted ratios reveal a zonal distribution of many elements. Plate 7, for example, shows that calcium is enriched relative to sodium and potassium in the two Hidden Treasure deposits, along faults nearby, and near the southeastern corner of the Klondike amphitheater. Similarly, plate 9 shows that strontium is enriched relative to barium in the Hidden Treasure deposits and near the southeastern corner of the Klondike amphitheater.

Rigorous interpretation of this zoning is impossible because, although most metals that are zoned are zoned around the two Hidden Treasure deposits, different metals show different relationships around smaller deposits and along faults. In view of the complexity of the zoning, it is suggested that the two Hidden Treasure deposits occupy "conduits" representing major channels used by the ore-bearing solutions. The more ambiguous zonal relationships around smaller deposits and along the faults are thought to represent the overlapping effects of additional, shifting conduits used temporarily by the ore-bearing solutions.

Reversed zoning and the convection cell

One of the most interesting features of the district is the unusual zoning of manganese and iron in deposits along the eastern side of the Klondike amphitheater (pl. 6).

Iron oxides are normally precipitated before those of manganese (Clarke, 1924, p. 541) under surface conditions. This relationship, however, cannot be applied directly to zoning in the Klondike district because the latter was produced by hydrothermal solutions. Zoning indicates changing metal ratios in the ore-bearing solutions which in turn are caused both by physical and chemical changes in those solutions and by reactions withthe wallrock. Of these, changes in temperature, pressure, Eh, and pH are most likely to have effected the solubility of manganese and iron in the ore-bearing solutions. In addition, the possible effects of catalysts and chemical reactions with the wallrocks must be considered.

Chemical reactions under hydrothermal conditions, of course, cannot be predicted with much certainty; some effects of these changes can probably be estimated, however, if it is assumed that most deposits were formed between 25° C. and 100° C. and between 1 and 15 atmosphere pressure (page 129), and if it is further assumed that under those conditions chemical reactions in the hydrothermal solutions were similar to those taking place at the surface. The Eh of the orebearing solutions may have risen during mineralization, and the pH probably fell (page 131). Thermodynamic calculations suggest that these changes would favor precipitation of iron oxides before those of manganese (Krauskopf, 1957). Similarly, calculations show that chemical equilibria with possible iron compounds are more susceptible to temperature changes between 100° C. and 25° C. than are those of manganese so that falling temperatures also would favor precipitation of iron before manganese.

The effect of pressure probably can be ignored because Owen and Brinkley (1941) showed that pressures as low as 15 atmospheres should have no significant effect on the equilibrium constants of reactions like these. The effect of catalysts can not be evaluated per se. However, in contrast to deposits in the amphitheater, manganese-iron ratios in deposits north of the Hidden Treasure mine increase away from the fault. This is the normal type of zoning for near-surface conditions and suggests that catalysts, if effective at all, did not significantly modify predictable zonal relations. Similarly, there is no evidence to suggest that chemical reactions with the wallrock were effective in localizing individual manganese deposits even though these deposits, as a whole are virtually confined to red beds. In summary, therefore, predictable changes in three variables, Eh, pH, and temperature, would favor deposition of iron oxides before those of manganese. Pressure changes, catalysts, and reactions with the wallrocks probably had no significant effect on zoning.

If, as seems likely, the ore-bearing solutions traveled up through the faults and spread out from them into the wallrock, then iron should have been deposited nearer the faults than manganese, and zonal relationships in the Klondike amphitheater are anomalous. Reversed zoning in the amphitheater is also suggested by several other metal ratios (pl. 7, 10, and 11). This reversed zoning must have been produced either by ore-bearing solutions converging upon the fault and selectively precipitating first iron and then manganese or by solutions converging upon the fault and selectively leaching manganese, redepositing it later in the fault. The latter process is thought to have been dominant (page 141).

It seems reasonable to believe that the normal direction of ground water flow at depth in a hydrothermal system such as this would be towards the fault to replenish water that had risen to the surface. The following hypothesis, therefore, is offered as a possible explanation of the reversed zoning. Ground water entering the hydrothermal system at depth converged upon the fault and leached manganese from earlier deposits. In effect, this means that early thermal solutions traveled far out into the sandstone depositing manganese and iron in the normal sequence as they went, and then later, as the intrusive rocks cooled and the hydrothermal system became sluggish, ground water entering the system at depth encroached upon and leached the earlier deposits.

The supply of ground water for maintaining this system must have been limited. The district is high on the flank of the Gypsum Valley anticline so ground water could only have come from nearby sandstones on the anticline. Little water would have been available from this source, however, because most of these sediments pinch out against the anticline. Furthermore, since the sandstones are overlain by several thousand feet of impermeable Brushy Basin and Mancos shales, the only catchment area for replenishing water was a small strip of sandstone exposed along the crest of the anticline in and adjacent to the Klondike district (page 68). This means that groundwater entering the system at depth probably consisted in part of surface runoff from the hot springs and, therefore, that a convection cell was probably established in the hydrothermal system.

One result of a convection cell is that ground water entering the system at depth must have had a lower pH than the original ore-bearing solutions because of the near-surface oxidation of H_2S. This may explain the reversed zoning inasmuch as ground water of lower pH should be able to leach manganese from the earlier deposits. The pH rose, however, when this water entered the alkaline vein system, and manganese was reprecipitated on the fissure walls. Iron oxide minerals, which are less soluble than their manganese counterparts, were not as readily leached and mostly remained behind in the wallrock.

Another corollary of a convection cell is that the redox potential of the ore-bearing solutions should rise during mineralization as a result of dilution with oxygenated surface water. Possible evidence of such a rise is found in the paragenesis of minerals in the "conduits". It will be recalled that copper and iron sulfides were only formed during an early phase of mineralization and that malachite and hematite were formed later (page 117). This suggests that the sulfide-sulfate ratio in the solutions decreased and, consequently, that the redox potential rose.

If the postulate of a convection cell is correct, it follows that reversed zoning of manganese and iron in the amphitheater was caused primarily by the leaching of manganese from earlier deposits rather than from the wallrock (page 139). Manganese deposits in the amphitheater are near the top of the red bed sequence, but these red beds are also the most likely source of manganese (page 148). Consequently, descending water could not have obtained much manganese from the wallrocks until it reached the red beds, where the largest source of manganese was the deposits.

Distribution of minor elements, gangue, and hydrocarbons

The only elements beside copper and manganese that are significantly enriched in these deposits are Ca, Ba, Sr, U, V, Zn, Cr, Pb, Fe, Co, Ni, Mo, Ag, Se, As, and the hydrocarbons. Tables 20, 21, and 22 show the distribution of these elements in various types of deposits.

Calcium, as the mineral calcite, is the most abundant gangue mineral in nearly every deposit. Plate 7 compares the distribution of calcium with that of sodium and potassium, which were probably among the most mobile components of the system. This map, therefore, shows some approximate boundaries of the hydrothermal system and in a general way marks conduits used by the ore-bearing solutions. Plate 8 shows the conduits more clearly. Here the least mobile components of the gangue, barium and strontium are compared with the more mobile calcium. As is to be expected, barium and strontium are concentrated for the most part along faults near the two Hidden Treasure deposits and in the southeastern part of the Klondike amphitheater.

Plates 9 and 10 compare the distributions of copper and manganese with that of calcium. A possible interpretation of relationships in plate 9 is that copper was less mobile relative to calcium in the early, sulfide solutions than it was in later solutions. The former are represented by deposits north and west of the Hidden Treasure mine, along the fault southwest of the Hidden Treasure mine, and along the fault southwest of the Hidden Treasure #3 deposit; the latter are represented by malachite deposits and by both of the Hidden Treasure conduits. Manganese-calcium relationships are ambigueous, and no satisfactory interpretation of these data can be made.

Barium, as barite, is common in the gangue of manganese deposits. It is found in every manganese deposit in the district and also in some copper deposits near faults.

Strontium, as the mineral celestite, is most concentrated in conduits. The estimated background value of strontium in red beds of the district, however, is abnormally high (table 23) which may indicate widespread, weak strontium mineralization of these strata.

Plate 11 compares the distribution of barium and strontium. Two different zonal relationships are evident; the most common consists of a very rapid increase in barium-strontium ratios away from conduits, a feature displayed well in zoning around the Hidden Treasure mine. In the second type of relationship, however, barium-strontium ratios increase very slowly away from the conduits. This relationship is seen northwest of the Hidden Treasure mine and may also be responsible for the high background concentration of strontium in red beds of the district. These seemingly contradictory relationships are thought to indicate a marked change in the conditions favoring deposition of strontium during mineralization; its mobility presumably decreased with time because celestite is common only as a late mineral in conduits.

Uranium is confined to the vicinity of faults, and even in the Hidden Treasure deposit, the largest in the district, the halo of uranium mineralization extends only a few feet into the wallrock. Some malachite deposits south of the Hidden Treasure mine, however, are slightly enriched in uranium. These are on the same stratigraphic horizon as carnotite deposits and are only a short distance down dip from them. It is suggested, therefore, that uranium in these deposits has been leached from the nearby carnotite deposits and is supergene.

There are unusually large concentrations of uranium and vanadium in the Hidden Treasure and Hidden Treasure #3 deposits. Both deposits are in Brushy Basin sandstones and are in possible uranium mineral belts (pl. 4). Accordingly, uranium deposits can be expected at depth in the Salt Wash of these areas. Without belaboring the matter at this point, it is suggested that uranium and vanadium in the Hidden Treasure deposits were leached from concealed uranium deposits in the Salt Wash.

Vanadium is found in two different associations. It occurs with uranium in the Hidden Treasure deposits, and it occurs in some uranium-free copper sulfide deposits. Vanadium in the Brushy Basin sandstone of the Hidden Treasure conduits could have been leached from concealed uranium deposits in the Salt Wash. Most vanadiferous sulfide deposits, however, lie below the Salt Wash, so this vanadium could not have been leached from uranium deposits.

Plate 12 compares the distribution of uranium and vanadium. Vanadium was clearly more mobile than uranium in the thermal solutions, but neither element is enriched above "background" in deposits far from faults. This "background" itself, however, is unusually high for vanadium in red beds of the district (table 23) which may indicate widespread, weak vanadium enrichment of those strata.

Zinc is not enriched in most copper or manganese deposits but is concentrated slightly in the Hidden Treasure deposits. Zinc also is enriched in carnotite deposits (Miesch, 1955), so zinc in the Hidden Treasure conduits may also have been leached from concealed uranium deposits.

Chromium is not greatly enriched in most copper or manganese deposits. It is a common accessory in uranium deposits (ibid), however, so the unusually large concentration of chromium in deposits #443 and #452 may have occurred during the period of uranium mineralization rather than that of copper and manganese.

Lead shows no clear pattern of enrichment but is most concentrated in some manganese and copper sulfide deposits.

Iron is concentrated in and near manganese deposits. Iron-bearing minerals are also common in copper sulfide deposits, but spectrographic analyses do not show any significant iron enrichment of those deposits (table 22).

Cobalt is most consistently enriched in manganese deposits. It is also enriched in some copper sulfide deposits and in malachite deposits near carnotite.

Nickel occurs in small amounts with both copper and manganese but is most consistently enriched in manganese deposits. It is virtually absent from the Hidden Treasure deposit, but small amounts were detected in the Hidden Treasure #3 mine.

Molybdenum is not greatly concentrated in any deposit. It is slightly enriched in manganese deposits, however, and possibly, in some copper sulfide deposits.

Silver, occurs only with copper but is found in nearly every copper sulfide and malachite deposit. It has been found in only one manganese deposit; all other argentiferous red bed occurrences are copper sulfide deposits.

Selenium is concentrated in some early sulfide deposits (pl. 13) where it presumably substitutes for sulfur (Goldschmidt, 1954, p. 532). It is not concentrated in other types of deposits, nor is it concentrated in a late calcite vein cutting Mancos shale (sample #451), although this shale is very seleniferous (Trelease and Beath, 1949, p. 73).

Arsenic has a very erratic distribution. No conclusions can be drawn from the pattern of arsenic enrichment.

Hydrocarbons only occur near malachite deposits (see page 108).

Source Beds

Since igneous emanations were probably minor or lacking altogether from the ore-bearing solutions, it follows that metals concentrated in the deposits must have been leached from underlying sedimentary rocks. Several possible sources of these metals are suggested by the distribution of minor elements in the deposits.

The principal elements added to the deposits were Mn, Fe, Cu, Ag, U, V, Cr, Zn, Pb, Ni, Co, Mo, Se, As, Ba, Sr, Ca, and hydrocarbons. Miesch, Shoemaker, and Newman (written communication) report that the principal elements concentrated in the Salt Wash uranium deposits are Fe, Cu, U, V, Cr, Zn, Pb, Ni, Co, Mo, Se, As, Mg, Ti, Zr, Ba, Sr, and Y. With the exception of Mn, Ag, Ca, and hydrocarbons, all elements enriched in the hydrothermal deposits are also concentrated in uranium deposits. Evidently, thermal solutions leaching uranium deposits in the Salt Wash at depth could have obtained at least a part of the added elements from those deposits. This source is especially probable in the Two Hidden Treasure deposits where uranium-vanadium enrichment is marked (p. 144). Examination of tables 20, 21, and 22 indicates that the elements whose concentrations vary most consistently with that of uranium, and, accordingly, the ones most likely to have been leached from concealed uranium deposits are U, V, Zn, Cr, Pb, and As.

Not all of the mineralized material, however, could have been leached from concealed uranium deposits. Such a source is unlikely for metals in copper and manganese deposits lying below the Salt Wash. Similarly, uranium deposits are unlikely sources of elements like manganese and silver that are not concentrated in uranium deposits, and also of elements like copper that are relatively concentrated in manganese or copper deposits but are only present in very minor amounts in uranium deposits.

Copper and silver are closely associated with hydrocarbons. The most obvious source of hydrocarbons is the black shale in the Paradox member of the Hermosa formation, because this shale yields oil and gas elsewhere in the Paradox basin (p. 17). Copper and silver are known to be concentrated in petroleum ash (Krauskopf, 1955, p. 419), and their close association with hydrocarbons in the Klondike district suggests that they had a common source.

Other elements enriched in petroleum ash or black shale (ibid) and also in the Klondike deposits are Co, Ni, Mo, As, V, Cr, and Pb. Circumstantially, therefore, the black shale is also a possible source of these elements. Selenium, too, may have been leached from the Paradox member which is very seleniferous (Trelease and Beath, 1949, p. 86).

The red beds themselves are the most likely source of iron and manganese because both of these metals are concentrated in oxidate sediments (Rankama and Sahama, 1950, p. 198-199). It may be significant in this respect that the only manganese deposits that are not near the top of the red-bed sequence are near the tops of ridges or in steeply dipping strata where ore-bearing solutions first had to pass through a thick section of red beds.

The jasper deposits are located in the highest parts of the district except for one that has been dropped into Gypsum Valley by recent faulting. Evidently jasper deposits were formed much nearer the surface than most of the other deposits, so it is possible that proximity to the surface was an important factor in their formation. White, Brannock, and Murata (1956, p. 52) suggest that the solubility of silica in thermal solutions depends in part on the amount of CO_2 in solution. They suggest that thermal waters with a high CO_2 content leach silica from susceptible silicate minerals at depth and that this silica is later precipitated near the surface when CO_2 exsolves. The necessary conditions for this reaction seem to have existed in the Klondike district, and picture 17 shows that some silica has indeed been leached from wallrock minerals in the conduits. Part of this silica may have been precipitated near the surface as chalcedony and quartz to form the jasper deposits.

Suggestions for prospecting

The present study shows that the copper and manganese deposits are hydrothermal in origin. The ore-bearing solutions rose through conduits and spread out from them along faults and fissures into the adjacent wallrock. Nearly all of the resulting copper deposits are in light-brown sandstone, gray-green shale, or limestone, whereas most manganese deposits are in red sandstone and shale. These relationships can be used as guides in prospecting for concealed deposits in the district.

More than 30 copper deposits are now known, but the Hidden Treasure mine is the only one that has been productive. This mine contains copper sulfide minerals and is in a conduit on a major Tertiary fault. Therefore, it seems reasonable to assume that other productive deposits are likely to be sulfide deposits and that future prospecting should concentrate on subsurface exploration of favorable strata near conduits.

Similarly, about 15 manganese deposits are now known in the district. Since almost all are in red beds near Tertiary faults and fissures, the most promising areas for future manganese exploration also are favorable strata near Tertiary faults. Just as with carnotite deposits, however, it is unlikely that future exploration will find new manganese or copper deposits that differ much in either size or grade from those now known in the district.

Conclusions

Uranium-vanadium, manganese, and copper ore as well as gravel have been mined in the Klondike district. All deposits are small, however, and only a few have yielded more than 100 tons of ore. Most of the latter have been carnotite deposits.

Carnotite occurs in the lower part of the basal sandstone unit of the Salt Wash. Most deposits are in a single, narrow belt that cuts obliquely across Klondike Ridge; the remaining deposits are thought to be in a second belt parallel to the first and about ½ mile north of it. Exploration for concealed deposits would probably prove extensions of these "mineral belts" into areas of deeper cover, but it is unlikely that the new deposits would be either larger or higher grade than those now known.

Both copper and manganese deposits show stratigraphic and structural controls of mineralization. Manganese deposits occur in red sandstone and shale without regard for the age of the enclosing beds but are in or near Tertiary faults. Copper deposits occur in light-brown sandstone, gray-green shale, or gray limestone of all ages and, like manganese deposits, are in or near Tertiary faults.

There are three types of manganese deposits in the Klondike district: 1) fissure-filling and disseminated deposits without much gangue, 2) fissure filling and bedded deposits with abundant gangue, and 3) a black calcite vein in the Hidden Treasure deposit. The principal minerals in all of these deposits are pyrolusite, hematite, limonite, calcite, and barite.

There are also three types of copper deposits in the district. These are: 1) sulfide deposits, 2) malachite deposits, and 3) jasper deposits. Sulfide deposits may contain any or all of the following minerals: native copper, bornite, covellite, chalcocite, galena (?), pyrite, pyrolusite, chalcedony, aragonite, calcite, celestite, barite and their alteration products: malachite, volborthite, limonite, and hematite. In addition, small amounts of clay, epidote, chlorite, and sericite may occur as alteration products in the wallrock.

Malachite deposits consist predominantly of malachite but locally contain small amounts of calcite, hydrocarbons, chalcocite, and azurite. Jasper deposits contain quartz, chalcedony, calcite, limonite, hematite, malachite, and manganese oxides. Most sulfide deposits are in or near faults and associated fissures, but many malachite deposits are disseminated in sediments a short distance from the faults. Jasper deposits are located near the tops of Klondike Ridge, the Klondike amphitheater, and in a fault block in Gypsum Valley.

The manganese and copper deposits are of hydrothermal origin and were formed in the roots of an ancient hot springs system, now deeply eroded. The ore-bearing solutions consisted of groundwater heated by the near-surface intrusion of small bodies of igneous rock.. These solutions obtained their metals by leaching the wallrock; little, if any, material was added by volatile emanations from the intrusives. The intrusives are correlated with dikes and sills of similar composition and petrographic characteristics in the San Juan Mountains and are thought to be of middle Miocene age.

The deposits were formed near the surface, so the ore-bearing solutions probably had low temperatures and pressures. The pH was controlled at depth by the hydrolysis of calcite and silicate minerals and, as mineralization progressed, by the influx of surface water. Near the surface, it was also controlled by oxidation of H_2S. The early ore-bearing solutions were probably slightly alkaline; but the pH fell during mineralization, and the solutions may even have become acid toward the end, especially above the water table where most oxidation of H_2S took place. The Eh was controlled primarily by the influx of oxygenated surface water. The early ore-bearing solutions were mildly reducing in character, but the Eh probably rose as mineralization progressed.

Under these conditions it is not likely that high-temperature or high-pressure chemical reactions could have produced as yet unknown, but very soluble, complex ions in the ore-bearing solutions. Instead, the composition of these solutions was probably that of normal groundwater below the water table modified somewhat by reactions with the wallrock caused by heating. Consequently, the mineralizing solutions must have been very dilute.

Analyses of present day groundwater in the area suggest that the ore-bearing solutions were formed from the mixed carbonate-sulfate type of groundwater. The dominant constituents, in addition to HCO_3^- and $SO_4^{=}$, were Ca^{++}, Mg^{++}, Na^+, Cl^-, K^+, NO_3^-, H_4SiO_4, and possibly colloidal silica. The early solutions deposited copper and iron sulfides in the faults and manganese and iron oxides in the red beds. As mineralization progressed, a convection cell was established, and oxygenated surface water mingled at depth with the thermal solutions.

Gradually, the solutions became cooler and the system less vigorous. Descending ground water entering the hydrothermal system at depth began to encroach upon earlier deposits. This water, having a lower pH than the ore-bearing solutions by virtue of chemical reactions at the surface, leached manganese from early deposits in the Klondike amphitheater and carried it back to the fault, creating the reversed zoning of that area. The principal metal products of this phase are malachite and manganese oxide deposits.

Deposits formed during the final phase of mineralization are restricted to conduits and adjacent segments of the faults. Calcite, barite, and celestite were deposited in conduits at this time and calcite alone at a distance.

Exploration for concealed deposits should concentrate on favorable strata near Tertiary faults and especially near conduits on the faults. As with carnotite, however, it is not likely that new deposits will be either larger or higher grade than those now known.

(p. 154a-j follow)

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Appendix A

Stratigraphic sections measured in the Klondike Ridge area, San Miguel and Dolores Counties, Colorado

Table 4.--Section of the Rico formation and part of the Upper Hermosa member of the Hermosa formation. Section measured on Klondike Ridge about 3 miles southeast of Gypsum Gap.

(Section measured by J. D. Vogel, 1956)

	Feet
Cutler formation (upper part of formation missing through erosion):	
Sandstone, light-brown, conglomeratic. Some gray-green interstitial shale pebbles and flakes	28.0
Shale, red and maroon	26.2
Sandstone, gray, fine- to medium fine-grained, poorly cemented	9.7
Soil, red. Contains abundant red siltstone fragments . . .	213.0
Total Cutler formation .	276.9
Rico formation:	
Limestone, gray and maroon	7.3
Shale, lavender with some green	6.4
Quartzite, gray, very fine grained; becomes maroon towards the base. Lower part is very calcareous.	56.8
Conglomerate, red, coarse-grained, arkosic. Fluvial crossbedding. Contains some casts of branches. Poorly consolidated	58.7
Siltstone, red and green, very calcareous, thin-bedded . .	6.0
Conglomerate, maroon and green, coarse-grained, arkosic, crossbedded, micaceous, poorly consolidated	27.8
Siltstone, red with very sparse green mottling. Very calcareous and argillaceous. Shaly irregular bedding . .	9.0

Table 4.--Section of the Rico formation and part of the Upper Hermosa member of the Hermosa formation. Section measured on Klondike Ridge about 3 miles southeast of Gypsum Gap. (continued)

	Feet
Rico formation: (continued)	
Limestone, gray	4.0
Siltstone, gray, calcareous. Interbedded with gray, calcareous shale	34.2
Limestone, gray, thin-bedded	6.6
Conglomerate, red, arkosic. Fluvial crossbedding	20.7
Siltstone, gray, calcareous. Some red units. Irregularly bedded. Much biotite	14.1
Sandstone, red and gray, coarse-grained. Irregular bedding; a few conglomerate lenses	109.1
Shale, red; abundant green, micaceous sandstone lenses	19.9
Limestone, gray. Alternates with gray argillaceous limestone	18.3
Shale, green; maroon at top	33.4
Arkose, red and green, medium-grained; irregular bedding, locally conglomeratic. Becomes calcareous near base	106.7
Limestone, gray	3.6
Sandstone, gray and green, arkosic, medium-grained; irregular bedding. Grades downward into shaly and calcareous red siltstone which in turn grades into the underlying unit	59.8

Table 4.--Section of the Rico formation and part of the Upper Hermosa member of the Hermosa formation. Section measured on Klondike Ridge about 3 miles southeast of Gypsum Gap (continued).

	Feet
Rico formation: (continued)	
Limestone, gray, coarsely crystalline	6.9
Shale, gray-green and maroon, calcareous. Alternates with argillaceous limestone	6.9
Limestone, gray-green argillaceous	2.3
Siltstone, red, gray, and gray-green. Alternates with very fine grained sandstone. Indistinct bedding. Abundant mica.	23.5
Total Rico formation	642.0
Hermosa formation:	
Upper Hermosa member:	
Limestone, gray	17.2
Shale, gray and some maroon. Some siltstone. Very calcareous	58.2
Limestone, dark-gray	87.2
Shale, buff to maroon, calcareous, dominantly thin-bedded . . .	33.6
Siltstone, maroon, thin-bedded. Some very fine grained sandstone	2.4
Siltstone, light-gray, calcareous, Some limestone. Weathers buff-tan	28.8
Limestone, light-gray. Weathers buff-tan. Contains many nodules of chert	21.7
Chert, gray. Badly fractured. Slightly calcareous	1.6
Siltstone, gray, slightly calcareous and cherty	47.7

Table 4.--Section of the Rico formation and part of the Upper Hermosa member of the Hermosa formation. Section measured on Klondike Ridge about 3 miles southeast of Gypsum Gap (continued).

	Feet
Hermosa formation: (continued)	
Upper Hermosa member: (continued)	
Limestone, gray. Some chert nodules and interbedded siltstone. Weathers to buff tan.	12.1
Limestone, dark-gray, thin-bedded	66.7
(Section truncated by a fault)	
Total incomplete Upper Hermosa member	377.2
Morrison formation:	
Salt Wash member:	
Sandstone, brown	

Table 5.--Section of the Summerville formation, Entrada sandstone, Kayenta formation, Chinle formation, Cutler formation, and part of the Rico formation; east side of the Klondike amphitheater about 4½ miles southeast of Gypsum Gap in San Miguel County, Colo.

(Measured by C. A. Westcott, 1957)

	Feet
Morrison formation:	
Salt Wash member (Section starts in the basal salt wash):	
Sandstone, yellowish-gray, fine- to medium fine-grained; thickbedded; moderate crossbedding . Shale, gray-green	7.3
Summerville formation:	
Shale and siltstone, dark reddish-brown and gray-green. Alternates with a thin-bedded, yellowish-gray, fine- to very fine grained sandstone. Shale predominates. Shale beds are 1 to 1½ feet thick; irregular, subparallel bedding with some channeling. Sandstone beds 2 to 3 feet thick. Sandstone beds are lenticular and pinch and swell over distances of 25 to 50 feet. Sandstone and shale units grade into each other. Some thin limestone and calcareous siltstone beds. Some malachite stain in the sandstone	61.8
Shale, dark reddish-brown, silty	26.0
Total Summerville formation	87.8

Table 5.--Section of the Summerville formation, Entrada sandstone, Kayenta formation, Chinle formation, Cutler formation, and part of the Rico formation; east side of the Klondike amphitheater about 4½ miles southeast of Gypsum Gap in San Miguel County, Colo. (continued).

	Feet
Entrada Sandstone:	
Sandstone, pinkish-gray, fine- to medium-grained. Becomes finer-grained and thinner-bedded towards the top. Bimodal	1.2
Sandstone, light-brown, fine- to medium-grained, bimodal	24.4
Sandstone, pale yellowish-orange, fine- to very fine-grained. Weathers dark yellowish-orange. Bimodal. Some sandstone pellets like those in the Hidden Treasure deposit	14.7
Sandstone, light-brown, fine- and medium-grained. Bimodal. Eolian crossbeds	10.4
Sandstone, yellowish-gray, fine- and medium-grained.	
Sandstone, yellowish-gray, fine- and medium-grained. Bimodal. Weathers grayish-orange. Angular unconformity with the Kayenta formation and some malachite in a gray-green shale seam separating the formations	2.5
Total Entrada sandstone	53.2

Table 5.--Section of the Summerville formation, Entrada sandstone, Kayenta formation, Chinle formation, Cutler formation, and part of the Rico formation; east side of the Klondike amphitheater about 4½ miles southeast of Gypsum Gap in San Miguel County, Colo. (continued)

	Feet
Kayenta formation:	
Shale, greenish-gray and dark reddish-brown. Two colors about equal. Individual beds one foot or more thick. Shale is silty, sandy, and micaceous. Gray limestone 6 inches thick at 14.5 feet above base.	23.1
Shale, dark reddish-brown	2.4
Total Kayenta formation	25.5
Chinle formation:	
Shale, greenish-gray. Weathers pale yellowish-green. Some conglomeratic sandstone units at base. Some interbedded dark reddish-brown shale	19.0
Total Chinle formation.	19.0
Cutler formation (top of formation missing):	
Shale, dark reddish-brown, micaceous. Some thin bands of light greenish-gray, fine grained sandstone.	23.1
Sandstone, grayish red-purple and grayish orange-pink, medium fine- to medium coarse-grained. Some arkose. Some conglomerate layers	37.8
Sandstone, grayish-red, conglomeratic. Contains some malachite stain	3.1
Sandstone, grayish-red and grayish orange-pink, medium- to very coarse-grained, arkosic. Conglomeratic in places	10.4

Table 5.--Section of the Summerville formation. Entrada sandstone, Kayenta formation, Chinle formation, Cutler formation, and parts of the Rico formation; east side of the Klondike amphitheater about 4½ miles southeast of Gypsum Gap in San Miguel County, Colo. (continued).

	Feet
Cutler formation (continued)	
Shale, dark reddish-brown	1.7
Sandstone, grayish orange-pink, medium- to very coarse-grained, arkosic, conglomeratic. Some manganese stain near center of unit	21.5
Shale, gray-green	0.1
Shale, moderate-brown, micaceous	7.2
Shale, grayish red-purple, micaceous	9.7
Siltstone, dark reddish-brown. Trace of malachite in gray-green shale seam at base	3.1
Sandstone, moderate reddish-brown, medium fine-grained, micaceous	3.1
Siltstone, dark reddish-purple	11.2
Shale, dark-red, micaceous	6.7
Sandstone, grayish red-purple, fine-grained. Some pinkish-gray conglomeratic sandstone	40.6
Sandstone, yellowish-gray, conglomeratic	74.6
Shale, dark-red and gray-green, micaceous	7.8
Siltstone, dark reddish-brown	9.9

Table 5.--Section of the Summerville formation, Entrada sandstone, Kayenta formation, Chinle formation, Cutler formation, and parts of the Rico formation; east side of the Klondike amphitheater about 4½ miles southeast of Gypsum Gap in San Miguel County, Colo. (continued).

	Feet
Cutler formation (continued)	
Shale, dark-red and gray-green, micaceous	12.4
Sandstone, grayish-red and gray, conglomeratic	20.4
Sandstone, yellowish-gray, medium fine- to coarse-grained, conglomeratic. Some grayish-red sandstone. . .	45.5
Sandstone, pinkish-gray, conglomeratic.	1.4
Shale, dark-red and red sandstone, micaceous.	14.2
Sandstone, dark-red and gray-green. Some interbedded red shale	4.7
Shale, dusky red and dark greenish-gray, micaceous.	8.8
Total incomplete Cutler formation . .	379.0
Rico formation:	
Limestone, light olive-gray, sandy, fossiliferous. Some red shale	4.9
Sandstone, grayish-red and grayish-yellow, fine-grained, thin-bedded, micaceous.	10.9
Shale, dark-gray and red, micaceous	8.3
Sandstone, pale-olive, medium fine- to medium-grained. Thin-bedded with some red shale along the bedding	2.1
Shale, greenish-gray	3.2
Limestone, dark greenish-gray, fossiliferous, and red shale	26.8

Table 5.--Section of the Summerville formation. Entrada sandstone, Kayenta formation, Chinle formation, Cutler formation, and parts of the Rico formation; east side of the Klondike amphitheater about 4½ miles southeast of Gypsum Gap in San Miguel County, Colo. (continued).

	Feet
Rico formation (continued):	
Limestone, medium-gray. Some red shale	0.4
Shale, red and greenish-gray	1.1
Shale, dark-red	2.8
Total Rico formation. . . .	60.5

Table 6.--Section of the Kayenta formation, Wingate sandstone, and Chinle formation; southeast side of the Klondike amphitheater about 5 miles southeast of Gypsum Gap in San Miguel County, Colo.

(Measured by C. A. Westcott, 1957)

	Feet
Kayenta formation: (Section starts at contact with the Entrada sandstone).	
Siltstone, grayish-red.	2.5
Sandstone, pale-red, fine- to very fine grained; massive bedding	1.0
Siltstone, moderate reddish-brown; thin-bedded	49.8
Sandstone, pale-red, very fine to fine-grained; thin-bedded with moderate crossbedding	32.0
Sandstone, grayish-red and light brownish-gray, medium fine- to very fine grained. Fluvial crossbeds and some conglomerate seams.	37.7
Shale, dark reddish-brown, conglomeratic.	55.0
Sandstone, pale-red, fine- to very fine grained; thin, parallel beds	19.1
Shale, dark reddish-brown	3.3
Total Kayenta formation. .	200.4

Table 6.--Section of the Kayenta formation, Wingate sandstone, and Chinle formation; southeast side of the Klondike amphitheater about 5 miles southeast of Gypsum Gap in San Miguel County, Colo. (continued).

	Feet
Wingate sandstone:	
Sandstone, light-gray, medium fine- to very fine-grained, thin-bedded	4.9
Conglomerate, grayish-pink to grayish-red; abundant limestone pebbles	0.8
Sandstone, pale-red, fine-grained to silty; thin parallel beds	17.3
Total Wingate sandstone	23.0
Chinle formation:	
Conglomerate, grayish-pink and gray-green. Abundant limestone pebbles, red shale, and sandstone	39.2
Total Chinle formation	39.2

Rico formation: Undescribed

Table 7.--Section of the Entrada sandstone; southeast side of the Klondike amphitheater about 5 miles southeast of Gypsum Gap in San Miguel County, Colo.

(Measured by C. A. Westcott, 1957)

	Feet
Entrada sandstone (section starts at top of Entrada sandstone):	
Sandstone, very light gray, medium fine-grained	2.3
Shale, dark reddish-brown. Contains some spherical, frosted Entrada sand grains	7.0
Sandstone, grayish-orange, fine- to medium fine-grained. Some contorted bedding. Sandstone is bimodal in upper part	30.2
Sandstone, medium reddish-brown, bimodal. Eolian cross-bedding	48.4
Sandstone, light-brown and very pale-orange. Eolian crossbeds	2.2
Sandstone, very pale-orange, bimodal. Fluvial crossbeds, Irregular contact with underlying unit	2.4
Sandstone, light-brown, bimodal. Fluvial crossbeds	0.6
Siltstone, medium reddish-brown. Very sparse medium fine- to fine-grained sand grains	2.3
Total Entrada sandstone	95.4
Kayenta formation:	
Shale, medium brown, silty, micaceous; thin, parallel beds	60.6

Table 8.--Section of the Entrada sandstone; north side of the Klondike amphitheater about 4½ miles southeast of Gypsum Gap in San Miguel County, Colo.

(Measured by J. D. Vogel, 1957)

	Feet
Entrada sandstone (Section starts at the top of the Entrada sandstone):	
Sandstone, pale-brown, conglomeratic. Many fluvial beds interspersed with eolian beds. Top of section is entirely fluvial. Lower part contains eolian units about 1 foot thick truncated by thin, parallel-bedded water-lain units. Fluvial units are less than 1 foot thick near bottom of the section and more than 1 foot thick at the top. Conglomerate is more abundant near the top. Section is gradational from dominantly fluvial deposits at the top to dominantly eolian deposits at the base.	15.0
Sandstone, light brown, thin-bedded; eolian crossbedding. Some sandstone pellets similar to those in the Hidden Treasure deposit.	8.0
Total Entrada sandstone	23.0
Regolith:	
Shale, green, brown, and red. Sandy. Contains some frosted Entrada sand grains and fragments of Rico and Cutler formations.	

Table 9.--Section of the Salt Wash member of the Morrison formation, Klondike Ridge about 2½ miles southeast of Gypsum Gap in San Miguel County, Colo.

(Measured by C. A. Westcott, 1957)

	Feet
Morrison formation:	
Brushy Basin member:	
Sandstone, pale-brown, medium fine-grained. Some strata are conglomeratic	30.6
Total Brushy Basin member	30.6
Salt Wash member:	
Shale, dark reddish-brown and gray-green	5.4
Sandstone, pale-brown, medium fine-grained; thin-bedded with some shallow crossbedding. Some shallow channel scours	57.7
Shale, red	7.9
Sandstone, pale-brown, medium fine-grained; thin-bedded; some shallow crossbedding	37.8
Shale, red	39.5
Sandstone, pinkish-gray, fine-grained; thinbedded; some shallow crossbedding	3.5
Shale, red	9.8
Sandstone, pinkish-gray, fine-grained, massive	6.8
Shale, red and gray-green	6.2

Table 9.--Section of the Salt Wash member of the Morrison formation, Klondike Ridge about 2½ miles southeast of Gypsum Gap in San Miguel County, Colo. (continued)

	Feet
Morrison formation: (continued)	
Salt Wash member: (continued)	
Shale, gray-green. Some red shale and thin, brown sandstone seams	16.4
Limestone, gray	0.6
Shale, gray-green	5.9
Sandstone, light-brown; some thin gray-green shale seams	15.3
Shale, gray-green	1.8
Sandstone, pale-brown; some thin, gray-green shale seams	14.0
Shale, gray-green	1.0
Sandstone, pale-brown	27.3
Total Salt Wash member	256.9
Total Morrison formation	287.5
Summerville formation:	
Shale, gray-green	1.3
Shale, red. Some gray-green shale	4.5
Sandstone, gray-green	0.3
Shale, red. Some gray-green shale	1.4
Sandstone, pale-brown	4.6
Shale, gray-green and red	2.4
Shale, red	1.2
Sandstone, pale-brown	1.3
Shale, red with thin, pale-red sandstone ribs	2.1

Table 9.--Section of the Salt Wash member of the Morrison formation, Klondike Ridge about 2½ miles southeast of Gypsum Gap in San Miguel County, Colo. (continued)

	Feet
Summerville formation: (continued)	
Siltstone, gray and red	0.7
Shale, red and gray-green with some thin, pale-red sandstone ribs	2.8
Shale, gray-green	.5
Shale, red	1.8
Sandstone, pale-brown	.6
Shale, gray	.5
Shale, red	.7
Shale, gray and thin, pale-brown sandstone ribs	.5
Shale, red	.7
Sandstone, pale-brown	.8
Total Summerville formation	28.7

Table 10.--Section of the Brushy Basin member of the Morrison formation Klondike Ridge about 3 miles southeast of Gypsum Gap in San Miguel County, Colo.

(Measured by C. A. Westcott, 1957)

	Feet
Burro Canyon formation:	
Sandstone, very light-gray, fine-grained with some medium fine chert grains	2.4
Total Burro Canyon formation	2.4
Morrison formation:	
Brushy Basin member:	
Shale, gray and red	7.1
Sandstone, medium light-gray	1.6
Shale, gray	31.8
Sandstone, pinkish-gray, fine-grained. Contains a few medium-coarse chert and quartz grains	0.6
Shale, red	4.5
Sandstone, yellowish-gray, very fine to fine-grained. Contains some red chert pebbles	20.4
Sandstone, very light-gray. Tightly cemented, massive. Contains some red chert pebbles	7.2
Shale, red	26.1
Sandstone, pale-red, fine-grained to silty. Massive bedding	2.2
Shale, red	27.8
Sandstone, pale yellowish-brown, conglomeratic. Poorly sorted. Thin- to thick-bedded, crossbedded. Fossil bones. Quartz pebbles from ½ to 1 inch in diameter	55.1

Table 10.--Section of the Brushy Basin Member of the Morrison formation Klondike Ridge about 3 miles southeast of Gypsum Gap in San Miguel County, Colo. (continued).

	Feet
Morrison formation: (continued)	
Brushy Basin member: (continued)	
Shale, reddish-brown	7.6
Sandstone, gray, tightly cemented	2.5
Shale, bright-red	3.6
Sandstone, green, tightly cemented	7.5
Shale, bright-red	8.2
Chert, pale yellowish-gray	3.0
Shale, red	10.4
Limestone, pale-red with some gray mottling	1.2
Shale, bright-red	14.0
Sandstone, medium greenish-gray, firmly cemented	3.3
Shale, medium to pale reddish-brown. Weathers very bright red	1.5
Shale, red and gray with interbedded siltstone and limestone	9.8
Shale, reddish-brown	9.3
Limestone, pale-red	1.1
Shale, reddish-brown	48.0
Shale, gray and reddish-brown	37.5

Table 10.--Section of the Brushy Basin Member of the Morrison formation Klondike Ridge about 3 miles southeast of Gypsum Gap in San Miguel County, Colo. (continued)

	Feet
Morrison formation: (continued)	
Brushy Basin member: (continued)	
Sandstone, grayish-yellow to grayish orange pink, medium-grained. Thin-bedded; Crossbedded.	55.3
Shale, red and gray	16.7
Sandstone, grayish yellow-green medium fine-grained	3.6
Shale, green	4.0
Sandstone, grayish yellow-green, medium fine-grained . . .	3.6
Shale, red with some gray-green	18.0
Sandstone, grayish yellow-green, fine-grained	0.6
Shale, red and some gray-green.	12.9
Sandstone, pinkish-gray, fine-grained. Abundant red chert grains	6.0
Shale, red.	9.3
Sandstone, very pale orange. Fine- to coarse-grained. Conglomeratic; pebbles range from ¼ to 1 inch in diameter. Fluvial crossbedding. Less coarsely conglomeratic in upper part	31.3
Total Brushy Basin member	514.2
Salt Wash member: Undescribed	

Table 11.--Log of diamond drill core, DV-1, through lower part of the Mancos shale, Dakota sandstone, Burro Canyon formation, Brushy Basin member of the Morrison formation, and the upper part of the Salt Wash member of the Morrison formation. Hole drilled in Disappointment Valley about 5 miles southeast of Gypsum Gap in San Miguel County, Colo.

(Modified from geologic log by D. R. Shawe, 1955)

	Feet
Mancos shale (upper part of formation missing through erosion):	
Mudstone, dark-gray, calcareous	56.2
Sandstone, light-gray, fine-grained	0.2
Mudstone, dark-gray and some light green-gray claystone. Some thin, fibrous calcite laminae	174.9
Siltstone, light-gray	0.3
Mudstone, dark-gray	15.6
Siltstone, light-gray	0.3
Mudstone, dark-gray and some thin, light-gray claystone lenses. Some pyrite disseminated through the shale. Some fossil fragments	244.4
Limestone, medium-gray	0.1
Mudstone, dark-gray and some thin, light-gray claystone lenses. Some limestone and silty laminae.	24.1
Limestone, light-gray	0.9
Mudstone, dark-gray	22.7
Coquina, dark-gray	0.3
Mudstone, dark-gray and some thin, light-gray claystone lenses. Some silty laminae.	318.9
Total Mancos shale.	858.9

Table 11.--Log of diamond drill core, DV-1, through lower part of the Mancos shale, Dakota sandstone, Burro Canyon formation, Brushy Basin member of the Morrison formation, and the upper part of the Salt Wash member of the Morrison formation. Hole drilled in Disappointment Valley about 5 miles southeast of Gypsum Gap in San Miguel County, Colo. (continued)

	Feet
Dakota sandstone:	
Sandstone, dark- to light-gray, medium fine-grained. Abundant worm borings and carbonaceous laminae. Grades into unit below	18.8
Mudstone, dark-gray. Some sand grains and thin claystone units. Some carbonaceous matter.	19.0
Limestone, light-gray	0.3
Mudstone, dark-gray; abundant thin sandstone laminae.	5.6
Sandstone, light-gray, very fine grained. Abundant carbonaceous laminae.	20.1
Mudstone, dark-gray; abundant carbonaceous matter	1.6
Sandstone, light-gray, very fine grained. Very abundant carbonaceous matter. Grades into unit below.	5.7
Mudstone, dark-gray. Contains some coal.	11.5
Siltstone, light-gray; abundant carbonaceous matter	1.0
Claystone, medium-gray	1.0
Mudstone, dark-gray and light-gray sandstone. Abundant carbonaceous matter	1.2
Coal, black and dark-gray mudstone.	38.2
Sandstone, light-gray, very fine grained. Abundant carbonaceous matter	2.6

Table 11.--Log of diamond drill core, DV-1, through lower part of the Mancos shale, Dakota sandstone, Burro Canyon formation, Brushy Basin member of the Morrison formation, and the upper part of the Salt Wash member of the Morrison formation. Hole drilled in Disappointment Valley about 5 miles southeast of Gypsum Gap in San Miguel County, Colo. (continued)

	Feet
Dakota sandstone: (continued)	
Mudstone, black. Very abundant carbonaceous matter	2.6
Siltstone, light-gray. Some carbonaceous matter and some shale laminae	3.2
Mudstone, medium-gray	2.0
Sandstone, light-gray, very fine grained	1.9
Mudstone, black. Very abundant carbonaceous matter	7.8
Sandstone, light-gray, fine-grained. Abundant carbonaceous matter. Some conglomerate laminae	6.6
Total Dakota sandstone	150.7
Burro Canyon formation:	
Mudstone, light green-gray	26.7
Sandstone, light-gray, medium-grained. Some dark-gray and red chert pebbles and granules	13.0
Sandstone, light-gray, fine-grained. Some chert granules . .	12.0
Sandstone, light-gray, coarse-grained, conglomeratic	2.3
Sandstone, light-gray, medium-grained	10.2
Sandstone, white, fine-grained	19.6
Mudstone, green-gray, sandy in places	11.4
Sandstone, light green-gray, fine-grained	34.0
Mudstone, green-gray, sandy	0.5

Table 11.--Log of diamond drill core, DV-1, through lower part of the Mancos shale, Dakota sandstone, Burro Canyon formation, Brushy Basin member of the Morrison formation, and the upper part of the Salt Wash member of the Morrison formation. Hole drilled in Disappointment Valley about 5 miles southeast of Gypsum Gap in San Miguel County, Colo. (continued).

	Feet
Burro Canyon formation: (continued)	
Sandstone, light green-gray, medium fine-grained. Conglomeratic on some horizons	34.8
Conglomerate, light green-gray. Abundant red-brown, white, and buff chert pebbles	8.8
Sandstone, light green-gray, medium-grained. Some conglomeratic sandstone	16.9
Conglomerate, light green-gray	4.0
Total Burro Canyon formation	194.2
Morrison formation:	
Brushy Basin member:	
Mudstone, green-gray	2.5
Mudstone, red-brown	10.7
Sandstone, light green-gray, medium-grained. Some conglomeratic sandstone	8.0
Mudstone, red-brown. Green at base	7.2
Sandstone, light green-gray, medium fine-grained; Conglomeratic in places	28.0

Table 11.--Log of diamond drill core, DV-1, through lower part of the Mancos shale, Dakota sandstone, Burro Canyon formation, Brushy Basin member of the Morrison formation, and the upper part of the Salt Wash member of the Morrison formation. Hole drilled in Disappointment Valley about 5 miles southeast of Gypsum Gap in San Miguel County, Colo. (continued).

	Feet
Morrison formation: (continued)	
Brushy Basin member: (continued)	
Mudstone, light green-gray.	23.2
Sandstone, light green-gray, medium-grained, poorly sorted. Contains some chert pebbles.	43.1
Mudstone, red-brown; Green-gray at top and mottled red-brown and green-gray at base.	3.1
Mudstone, green-gray.	3.4
Mudstone, red-brown alternating with light green-gray and light-brown siltstone. Color layers 0.1 to 10 feet thick. Red-brown predominates.	220.2
Sandstone, light green-gray, coarse-grained	4.6
Mudstone, green-gray, alternating with red-brown siltstone. Bentonitic in places	48.0
Sandstone, light red-brown and very light brown, very fine to medium-grained. Abundant red, green, dark-gray, and buff chert pebbles in places	22.5
Mudstone, red-brown alternating with light green-gray. Red-brown predominates. Some silty units	55.6
Total Brushy Basin member	480.1

Table 11.--Log of diamond drill core, DV-1, through lower part of the Mancos shale, Dakota sandstone, Burro Canyon formation, Brushy Basin member of the Morrison formation, and the upper part of the Salt Wash member of the Morrison formation. Hole drilled in Disappointment Valley about 5 miles southeast of Gypsum Gap in San Miguel County, Colo. (continued).

	Feet
Morrison formation: (continued).	
Salt Wash member:	
Sandstone, light-gray, fine-grained. Some carbonaceous flakes and seams.	36.1
Mudstone, green-gray.	1.1
Mudstone, red-brown. Sparse green-gray mottling.	7.7
Sandstone, light-gray, fine- to very fine-grained. Some carbonaceous flakes, pebbles, and seams. Very abundant green-gray mudstone pebbles on some horizons.	16.8
Mudstone, red-brown. Green-gray at top 0.1 foot.	3.6
Sandstone, light-gray, fine- to very fine-grained. Some carbonaceous films and interstitial material.	11.1
Mudstone, red-brown and green-gray. Green-gray at top 0.1 foot. Silty in places	20.3
Sandstone, light-gray, very fine- to fine-grained. Some green-gray mudstone pebbles, seams, and interstitial in the sandstone.	30.7
Mudstone, green-gray, silty	1.3
Mudstone, red-brown	6.2
Total incomplete Salt Wash member.	134.9

Bottom of the hole.

Table 12.--Section of the Burro Canyon formation on Klondike Ridge, about ¼ mile southeast of Gypsum Gap, San Miguel County, Colo.

(Measured by C. A. Westcott, 1957)

	Feet
Dakota sandstone:	
Sandstone, light-brown, fine-grained. Overlain by a coal seam. Angular chert pebbles at base.	17.8
Total Dakota sandstone . .	17.8
Burro Canyon formation:	
Shale, gray-green	31.2
Limestone, medium-gray, cherty.	1.8
Shale, gray	19.4
Sandstone, fine-grained	12.8
Shale, gray	8.4
Sandstone, pale-brown, conglomeratic; abundant chert pebbles	21.9
Shale, gray	5.3
Sandstone, light-brown, medium- to fine-grained, conglomeratic; fluvial crossbeds	24.2
Total Burro Canyon formation . .	125.0
Morrison formation:	
Brushy Basin member:	
Shale, gray-green	11.3

Table 13.--Section of the Dakota sandstone on Klondike Ridge about 3 miles southeast of Gypsum Gap, San Miguel County, Colo.

(Measured by C. A. Westcott, 1957)

	Feet
Dakota sandstone (Section starts in the Dakota-Mancos transition zone):	
Shale, dark-gray. Contains <u>Gryphaea newberrii</u> shells	
Sandstone, pale-brown, medium- to medium coarse-grained.	10.0
Soil	38.8
Sandstone, pale- to light-brown, fine- to medium fine-grained; thin, irregular bedding	4.2
Soil	3.3
Shale, gray-black, carbonaceous	6.6
Sandstone, pale- to light-brown, fine-grained	19.8
Limestone, light-gray with some chert	2.2
Shale, gray and black, abundant carbonaceous material	9.7
Soil, light-brown with sandstone fragments	18.0
Sandstone, light-gray, fine-grained. Some gray shale seams . .	3.6
Shale, black, abundant carbonaceous material	9.2
Sandstone, light-brown, fine-grained.	0.9
Soil	16.7
Siltstone, light gray-brown. Thin, fissile bedding	1.8
Shale, black, abundant carbonaceous material	6.1
Siltstone, gray, weathers light medium-brown.	5.1
Shale, black, abundant carbonaceous material	2.1
Sandstone, dusky-yellow, fine-grained	2.0
Shale, black, abundant carbonaceous material.	1.9
Sandstone, dusky-yellow, fine-grained	3.3

Table 13.--Section of the Dakota sandstone on Klondike Ridge about 3 miles southeast of Gypsum Gap, San Miguel County, Colo. (continued)

	Feet
Dakota sandstone: (continued)	
Shale, black, abundant, carbonaceous material	4.0
Sandstone, moderate olive-brown, medium fine-grained. Some chert and gray-green shale pebbles	3.6
Total Dakota sandstone.	172.9
Burro Canyon formation:	
Shale, gray-green	15.9
Sandstone, yellowish-gray, medium-grained with very coarse chert pebbles	0.6

Table 14.--Section of Mancos shale in Disappointment Valley about 10.3 miles southeast of Gypsum Gap, San Miguel and Dolores Counties, Colo.

(Measured by O. T. Marsh, 1955)

	Feet
Mancos shale (section starts at base of the upper transition zone in the Mancos shale):	
Shale, dark-gray, fossiliferous	2.0
Shale, dark-gray	476.0
Shale, dark-gray, fossiliferous	2.0
Shale, dark-gray	123.0
Shale, dark-gray, fossiliferous	2.0
Shale, dark-gray	113.0
Shale, dark-gray, fossiliferous	2.0
Shale, dark-gray	133.0
Shale, dark-gray, fossiliferous	2.0
Shale, dark-gray	14.0
Shale, dark-gray, fossiliferous	1.0
Shale, dark gray; 1-foot thick bed of yellowish-brown, highly calcareous siltstone at base	10.0
Shale, dark-gray	113.0
Shale, dark-gray, fossiliferous, with a persistent, 1-foot thick bed of platy, light-brown, highly calcareous siltstone in layers 1/8 to ¼ inch thick	2.0
Shale, dark-gray; a prominently outcropping, continuous ledge of shale 20 feet thick occurs 860 feet above the base of the Mancos	505.0

Table 14.--Section of Mancos shale in Disappointment Valley about 10.3 miles southeast of Gypsum Gap, San Miguel and Dolores Counties, Colo. (continued)

	Feet
Mancos shale (continued):	
Shale, dark-gray. Contains moderately abundant fragments of pelecypods and, at top of the unit, rare fragments of large, thick-ribbed ammonites	185.0
Shale, dark-gray.	94.0
Sandstone, dark-gray, weathering yellowish-brown, fine-grained, highly calcareous, in beds up to 1 inch thick	3.0
Shale, dark-gray.	13.0
Sandstone and some dark-gray shale; sandstone is yellowish-brown, platy, very thin bedded, fine-grained, and fossiliferous	15.0
Shale, dark-gray, interbedded with sandstone, light-brown, very thin bedded (beds 1/8 to 1/4 inch thick), platy, fine- to very fine grained; shale contains discoidal nodules up to 1 foot in diameter and 5 inches thick; also gypsum and thin layers of yellowish-brown, cone- in-cone calcite; some limonitic layers as well. Two layers of nodular limestone or dolomite occur at 372 and 427 feet above base of the Mancos; 2 to 3 feet thick, dark-gray, weathering yellowish-brown, consisting of irregular to well-rounded calcareous bodies, locally veined with dark-purple calcite; some have cores of coarsely crystalline white calcite.	380.0

Table 14.--Section of Mancos shale in Disappointment Valley about 10.3 miles southeast of Gypsum Gap, San Miguel and Dolores Counties, Colo. (continued)

	Feet
Mancos shale (continued):	
Shale, dark-gray. Contains very abundant Gryphaea newberrii and rare sharks' teeth; at top of unit is a 6-inch ledge of very light gray weathering, dark-gray, fine-grained, glauconitic sandstone with flaky fracture	25.0
Shale, dark-gray.	90.0
Total Mancos shale	2305.0

Dakota sandstone: Undescribed

Table 15.--Section through lower part of the Mesa Verde group and upper Mancos transition zone, About 3 miles east of Horse Park on Horse Park scarp, San Miguel County, Colo.

(Measured by C. A. Westcott, 1957)

	Feet
Mesa Verde group (upper part missing through erosion):	
Sandstone, dark yellowish-orange, very fine grained	8.1
Sandstone, grayish-orange, very fine grained. Alternates with thin olive-gray shale beds. Individual sandstone and shale beds are up to 4 feet thick. Sandstone units very lenticular	51.2
Sandstone, light olive-gray, very fine grained, thin bedded . .	3.3
Total incomplete Mesa Verde group	62.6
Mancos shale:	
Shale, olive-gray, silty, some sandstone lenses	23.9
Sandstone, yellowish-gray, very fine-grained, thin beds	9.3
Shale, olive-gray, alternates with dark yellowish-orange sandstone. Sandstone units are thin, crossbedded, very fine grained. Both shale and sandstone units are thin. . . .	36.7
Shale, gray, interbedded with moderate yellow-brown sandstone	13.8
Sandstone, light olive-gray, very fine grained; thin-bedded and some crossbedding. Some gray shale seams	63.9
Shale, olive-gray, silty. Some thin sandstone partings	9.2
Sandstone, dusky yellow, very fine grained; thin-bedded and some crossbedding	4.1
Shale, olive-gray	3.5

Table 15.--Section through lower part of the Mesa Verde group and upper Mancos transition zone. About 3 miles east of Horse Park on Horse Park scarp, San Miguel County, Colo. (continued)

	Feet
Mancos shale: (continued)	
Sandstone, dark yellowish-brown, very fine grained; thin bedded and some cross-bedding; individual sandstone beds up to 2 feet thick. Some thin shale beds	35.4
Sandstone, dark yellowish-brown. Alternates with olive-gray, silty shale. Individual units up to ½ foot thick	30.7
Sandstone, moderate yellowish-brown, very fine grained; thin bedded, some cross-bedding	3.5

Table 15.--Section through lower part of the Mesa Verde group and upper Mancos transition zone. About 3 miles east of Horse Park on Horse Park scarp, San Miguel County, Colo. (continued)

	Feet
Mancos shale (continued):	
Shale, olive-gray. Alternates with thin-bedded, yellowish-brown sandstone	7.7
Sandstone, moderate yellowish-brown, very fine-grained; thin bedded and some crossbedding	2.5
Shale, olive-gray, silty	2.3
Sandstone, light olive-gray, very fine grained. Some carbon flakes on bedding planes. Thin-bedded and some crossbedding	28.1
Shale, dark gray, silty; interbedded with pale yellowish-brown sandstone. Individual shale beds up to 4 feet thick in lower part but decrease to about 1.5 feet thick in upper part. Sandstone beds up to ½ foot thick in lower part of unit but increase to about 1 foot thick in upper part. Shale predominates in lower part and sandstone in upper part	49.1
Sandstone, moderate yellowish-brown, very fine grained; thin bedded and some crossbedding. Weathers dusky yellow. Some interbedded gray shale	8.0
Total Mancos shale	311.7
Shale, olive-gray, silty, thin bedded. Below transition zone. Weathers light gray to light olive-gray. Contains some carbon particles.	

able 16.--Section through glacial outwash gravel, north side of the Klondike amphitheater about 4 miles southeast of Gypsum Gap, San Miguel County, Colo.

(Measured by J. D. Vogel, 1957)

	Feet
utwash gravel (upper part missing through erosion):	
Gravel, poorly consolidated. Pebbles average about one inch in diameter but range up to about 3 inches. About 1 percent of gravel consists of Salt Wash sandstone fragments	7.0
Gravel, Cobbles up to 9 inches in diameter. Salt Wash sandstone forms about 3 percent of the gravel; pebbles and cobbles average about 2 inches in diameter but range up to about 7 inches.	35.4
Gravel. Pebbles up to 3 inches in diameter. Pebbles of Salt Wash sandstone are as much as 2 inches in diameter and form about 2 percent of the gravel . . .	7.5
Soil, sandy	10.4
Gravel. Very few Salt Wash sandstone pebbles	11.7
Soil. Pebbles of outwash gravel up to 2 inches in diameter form about 20 percent of this unit. Flat, angular fragments of Salt Wash sandstone form about 2 percent of the unit	2.1
Gravel, Cobbles up to 6 inches in diameter form about 90 percent of the unit. Very few Salt Wash sandstone chips. Interstices filled with sand- and silt-sized material	6.8

Table 16.--Section through glacial outwash gravel, north side of the Klondike amphitheater about 4 miles southeast of Gypsum Gap, San Miguel County, Colo. (continued)

	Feet
Outwash gravel (continued):	
Gravel. Very few Salt Wash sandstone pebbles. These a average about ½ inch in diameter but range up to 6 inches	9.7
Gravel. Some pebbles of Mesa Verde and Salt Wash sandstone up to ½ inch in diameter	8.1
Gravel, forms about 85 percent of unit. Pebbles up to 4 inches in diameter. About 1 percent of gravel is Mesa Verde sandstone. Pebbles up to 2½ inches in diameter. Rest is sand and silt	14.6
Gravel. Gravel forms about 80 percent of the unit. Pebbles range up to 4 inches in diameter. About 1 percent is Salt Wash sandstone pebbles up to 2 inches in diameter. Some fragments of Dakota sandstone and flakes of Mancos shale with fragments of _Gryphia Newberrii_. Rest is sand and silt.	31.7
Gravel. Gravel forms about 90 percent of the unit. Cobbles up to 12 inches in diameter. Some Salt Wash sandstone pebbles and chips in lower part, but these disappear upwards. Rest is sand and silt	34.9
Gravel. Gravel forms about 90 percent of the unit. Salt Wash sandstone chips and pebbles form about 2 percent of the unit in the lower part but disappear upwards. Rest is sand and silt	21.7

Table 16.--Section through glacial outwash gravel, north side of the Klondike amphitheater about 4 miles southeast of Gypsum Gap, San Miguel County, Colo. (continued)

	Feet
Outwash gravel (continued):	
Gravel. About 20 percent of the unit consists of flat, angular fragments up to 6 inches in diameter of Rico (?) limestone and sandstone. Very few chips of Salt Wash sandstone	1.6
Sand, coarse-grained, Some chips of Salt Wash sandstone	2.2
Gravel, cobbles up to 6 inches in diameter form about 80 percent of the unit. Many chips of Salt Wash sandstone and siltstone	5.6
Gravel, pebbles up to 2 inches in diameter form about 30 percent of the unit. Salt Wash sandstone and red shale form flat, angular fragments up to 10 inches in diameter and comprise about 5 percent of the unit. About 1 percent of the unit is angular, micaceous sandstone and shale of the Rico and Cutler formations. Rest is sand and silt	3.9
Total outwash gravel	214.9
Regolith:	
Soil, reddish-brown, sandy. Contains some Entrada sand grains and angular chips of Salt Wash sandstone up to ½ inch in diameter	4.8
Total regolith.	4.8

Table 16.--Section through glacial outwash gravel, north side of the Klondike amphitheater about 4 miles southeast of Gypsum Gap, San Miguel County, Colo. (continued)

	Feet
Rico formation:	
Arkose, gray and reddish-brown. Weathered. Almost a sand. . .	2.9
Shale, reddish-brown, micaceous, silty	3.7

APPENDIX B

Descriptions of

Selected carnotite deposits

Penju mine, Deposit #241

This mine consists of several small pits from which, it is estimated, about 400 tons of ore was shipped during the summer of 1956. The deposit is in moderately dipping sandstone near the base of the Salt Wash and is overlain by a limestone bed 12 to 18 inches thick. The deposit is tabular but is not quite parallel to the bedding; it dips less steeply into Disappointment Valley than the enclosing sandstone and consequently rises a few feet in the section down dip. Its down-dip end abuts against the limestone.

The deposit is irregular in shape, but, for the most part, its edges are sharply defined. Metal concentrations vary erratically through the deposit; there is some high-grade carnotite ore near fragments of wood, but detrital wood is not abundant. Elsewhere, carnotite is concentrated in sandstone lenses containing abundant comminuted plant fragments or clay pellets and seams. In addition, irregular fingers of carnotite and vanadium clay project a few inches along bedding planes into otherwise barren sandstone, and carnotite stains joint surfaces in and near the deposit. This material has probably been leached from the main body of the deposit.

Two sandstone units are mineralized. The lower consists of thin, parallel beds of fine-grained sandstone; films of silt- and clay-size material together with fine-grained opaque minerals and small pieces of plant debris cover the bedding planes and help to delineate the beds. This unit is overlain by a massive, somewhat coarser sandstone 2½ to 3½ feet thick from which most of the production has come.

Limonite is associated with carnotite and vanadium silicates and also stains otherwise barren sandstone nearby. Several weathered remnants of marcasite nodules, about an inch in diameter and surrounded by limonite, occur in weakly mineralized sandstone near the southern edge of the deposit.

Deposit #440

This deposit also is in the bottom sandstone unit of the Salt Wash and is similar to the Penju deposit. The most important feature of this deposit is the fact that it is truncated by a middle Tertiary fault showing that the deposit is older than the fault. This is in accord with the calculated Late Cretaceous or early Tertiary age of uranium deposits on the Colorado Plateau (Stieff, Stern, and Milkey, 1953, p. 15) and contrasts with the nearby copper and manganese deposits which are clearly younger than the faults.

The ore is in thin-bedded, carbonaceous sandstone near the base of the Salt Wash in a place where the sandstone is wedged between two faults and is badly shattered. Bedding planes in nearby sandstones are stained with limonite and minor carnotite, but, in general, neither limonite nor carnotite has disseminated more than half an inch or so into the sandstone from these surfaces. There are carnotite stains on carbonaceous mudstone seams, however, as much as 7 feet above the ore.

Several small veinlets of calcite and pink barite cut the deposit and are clearly later than the carnotite. These veinlets also carry traces of limonite and carnotite, which were evidently leached from the deposit. There is a little malachite in the Salt Wash and Brushy Basin sandstones nearby, but none is found in the deposit itself. In all probability, this malachite is genetically related to the nearby copper deposits, and therefore, is much younger than the carnotite.

Deposit in the Hermosa formation

This small deposit is in black shale of the Hermosa formation. The shale has been strongly contorted and shattered by repeated folding and faulting on the salt anticline, and fracture surfaces are coated with limonite, gypsum, and traces of carnotite. The deposit is of no commercial value but is of interest because uranium-bearing minerals are unusual in the Hermosa formation.

The deposit is near the base of an angular unconformity separating Paradox shale from Salt Wash sandstone. In view of this relationship, it is likely that carnotite in the black shale was leached from nearby uranium deposits in the overlying Salt Wash.

APPENDIX C

Chemical and semiquantitative spectrographic analyses

of carnotite deposits

in the

Klondike district

Table 17.--Chemical analyses of carnotite deposits in the Klondike district.

/Analysts: eU, C. G. Angelo; U, J. S. Wahlberg and H. H. Lipp; V_2O_5, J. S. Wahlberg; Zn, J. S. Wahlberg and W. D. Goss; Cu, D. L. Skinner/

Explanation of symbols:

<with number, concentration below number shown (Standard sensitivities do not apply at such low concentrations).

Deposit	eU	U	V_2O_5	Zn	Se	As	MnO	Pb	Cu
	percent				parts per million		percent		
231	0.081	0.099	0.95	0.056	0.5	16	0.050	<0.01	0.0020
232	.019	.030	.63	.012	4	12	.100	< .01	.0015
233	.088	.12	1.49	.037	8	48	.020	< .01	.0190
234	.015	.020	.53	.043	4	51	.003	< .01	.0025
235	.085	.14	.95	.030	0.5	24	.001	< .01	.0015
236	.024	.024	1.64	.010	6	56	.005	< .01	.0065
237	.062	.11	1.22	.004	0.5	< 5	.003	< .01	.0020
238	.22	.32	1.89	.065	2	78	.010	< .01	.0075
239	.005	.005	1.22	.71	3	22	.005	.02	<.0005
240	.025	.035	.63	.029	1	12	.020	< .01	<.0005
241	.17	.25	3.36	.038	12	90	.020	< .01	<.0005
242	.004	.006	.76	.039	2	34	.009	< .01	.0210
243	.001	.001	1.66	.064	< 0.5	8	.070	< .01	.0020
257	.034	.038	.97	.050	3	120	.060	.02	.0060
258	.024	.031	1.76	.072	12	114	.040	.07	.0155
259	.005	.005	.65	.064	25	374	.009	.03	.45
260	.024	.030	.67	.17	1	10	.010	< .01	.0230
262	.003	.005	1.85	.032	.5	27	.005	< .01	.0045
263	.16	.22	1.07	.006	5	180	.006	.01	.0015

APPENDIX D

Chemical and semiquantitative spectrographic analyses

of manganese and copper deposits

in the

Klondike district

Table 20.--Chemical analyses of copper deposits in the Klondike district. [Analyses in percent. Explanation of symbols: < with number, concentration below number shown (standard sensitivities do not apply at such low concentrations). Analysts: As, J. P. Schuch; Carbon, J. P. Schuch; Cu, D. L. Skinner; MnO, E. C. Mallory; Pb, W. D. Goss; Se, G. T. Burrow; eU, C. G. Angelo; U, J. S. Wahlberg and H. H. Lipp; V_2O_5, J. S. Wahlberg; Zn, J. S. Wahlberg and W. D. Goss.]

Deposit	As	Carbon Total	Carbon Mineral	Carbon Organic	Cu	MnO	Pb	Se	eU	U	V_2O_5	Zn
230	0.0026	2.0	0.4	1.6	0.0080	0.020	<0.01	0.0002	0.038	0.052	0.42	0.002
244	.0014	1.5	.8	.7	.15	.100	< .01	.0001	.020	.031	1.18	.004
245	.0025	4.9	1.6	3.3	1.06	.130	.01	<.00005	.012	.013	.36	.007
246	.0012	7.2	6.7	.5	1.90	.200	.01	.0003	.044	.063	1.01	.012
247	.0051	8.7	7.2	1.5	1.64	.[illegible]50	< .01	.00005	.002	.001	1.28	.012
248	.0108	2.9	2.7	<.5	.24	.130	< .01	<.00005	.007	.004	.90	.008
249	.0080	3.0	1.2	2.0	1.68	.230	< .01	<.00005	.002	.001	<0.1	.012
250	.0190	2.0	.3	1.7	.0660	.050	.02	.00005	.005	.005	2.71	.010
261	.0012	2.5	.6	1.9	.91	.030	< .01	.0025	.021	.023	.57	.13

APPENDIX E

Estimated background values of minor elements
in rocks of the
Klondike district

Table 22.--Estimated background values of trace elements in rocks of the Klondike district and "average" values for those elements in Brushy Basin and Kayenta sandstone of southwestern Colorado. [All values in percent]

Estimated background values in the Klondike district

[Values based on assays of "barren" and weakly mineralized rock]

Brown Sandstone		Red Sandstone		Brown Sandstone		Red Sandstone	
Ba	0.03	Ba	0.03	Mn	0.07	Mn	0.3
Ca	.7	Ca	.3	Na	.15	Na	.3
Cr	.0007	Cr	.003	Pb	.003	Pb	.007
Cu	.003	Cu	.007	Sr	.015	Sr	.15
Fe	.3	Fe	.7	U	.001	U	.001
K	.7	K	.7	V	.007	V	.03

"Average" Values for Brushy Basin and Kayenta sandstone in Southwestern Colorado

[Data from W. L. Newman and others, written communication, 1956]

Brushy Basin member (Ave. of 12 samples)		Kayenta formation (Ave. of 3 samples)	
Ba	0.07	Ba	0.04
Ca	4.0	Ca	1.0
Cr	.0003	Cr	.001
Cu	.0008	Cu	.0008
Fe	.3	Fe	.4
Mn	.05	Mn	.03
Pb	0	Pb	0
Sr	.007	Sr	.01
U	.001	U	.001
V	.0007	V	.0008

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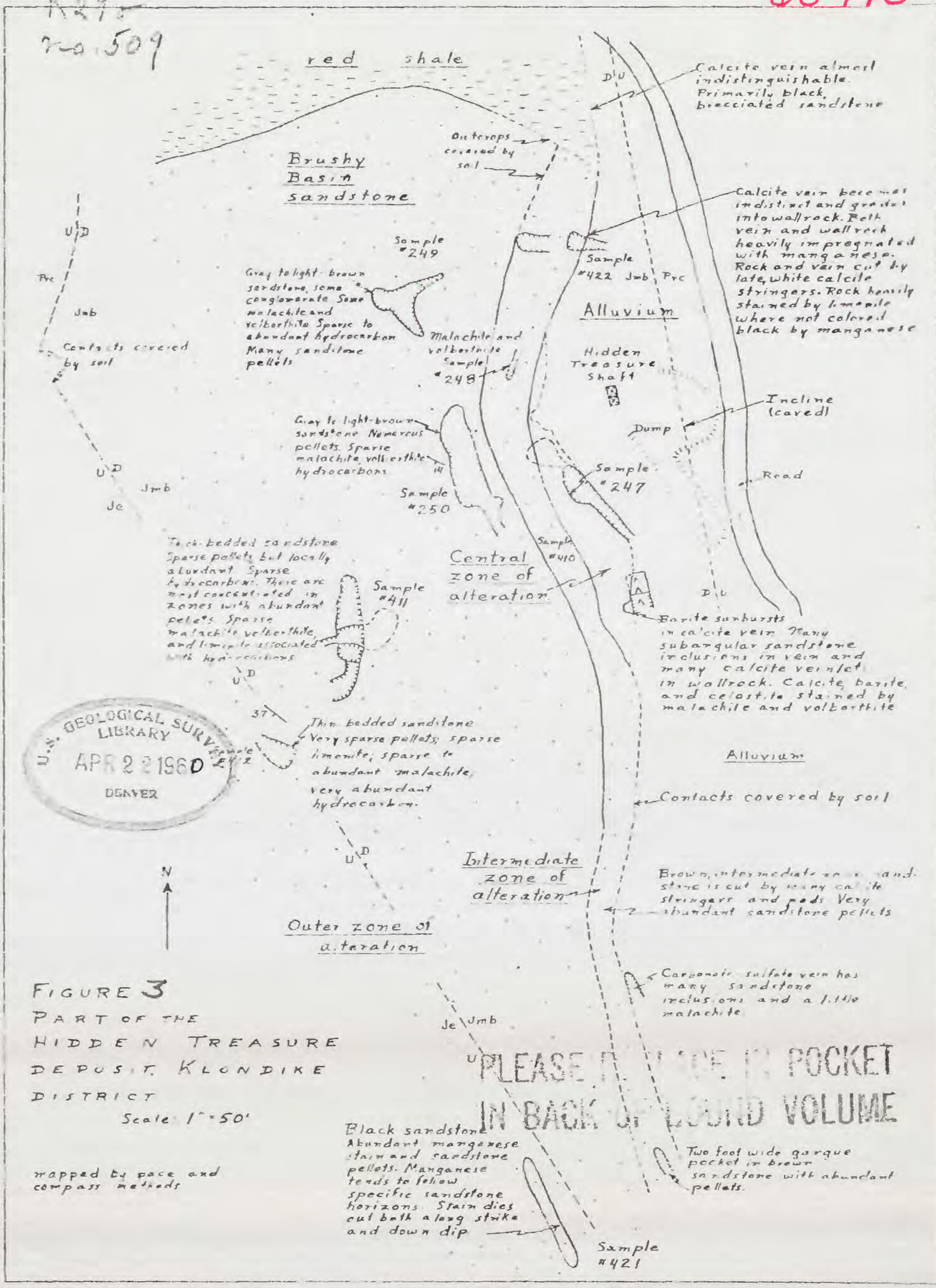
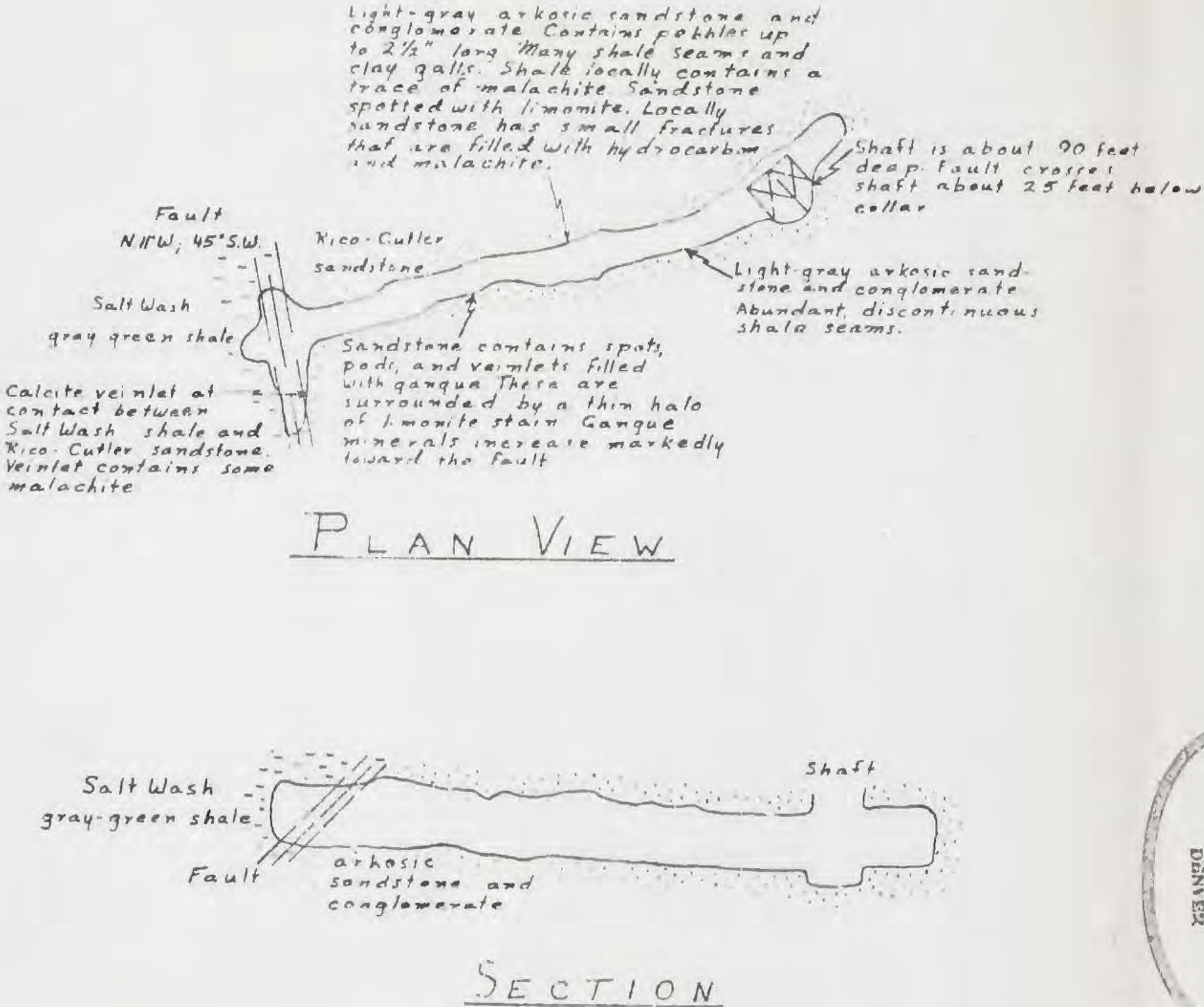


FIGURE 3
PART OF THE HIDDEN TREASURE DEPOSIT, KLONDIKE DISTRICT

Scale 1" = 50'

mapped by pace and compass methods



VIEW FACING NORTH

FIGURE 4 : HIDDEN TREASURE MINE

Scale: 1" = 20'

mapped with chain and compass

60-145

PLATE 2

U. S. Geological Survey
OPEN FILE MAP
This map is preliminary and has not been edited or reviewed for conformity with Geological Survey standards or nomenclature.

PREPARED IN COOPERATION WITH THE
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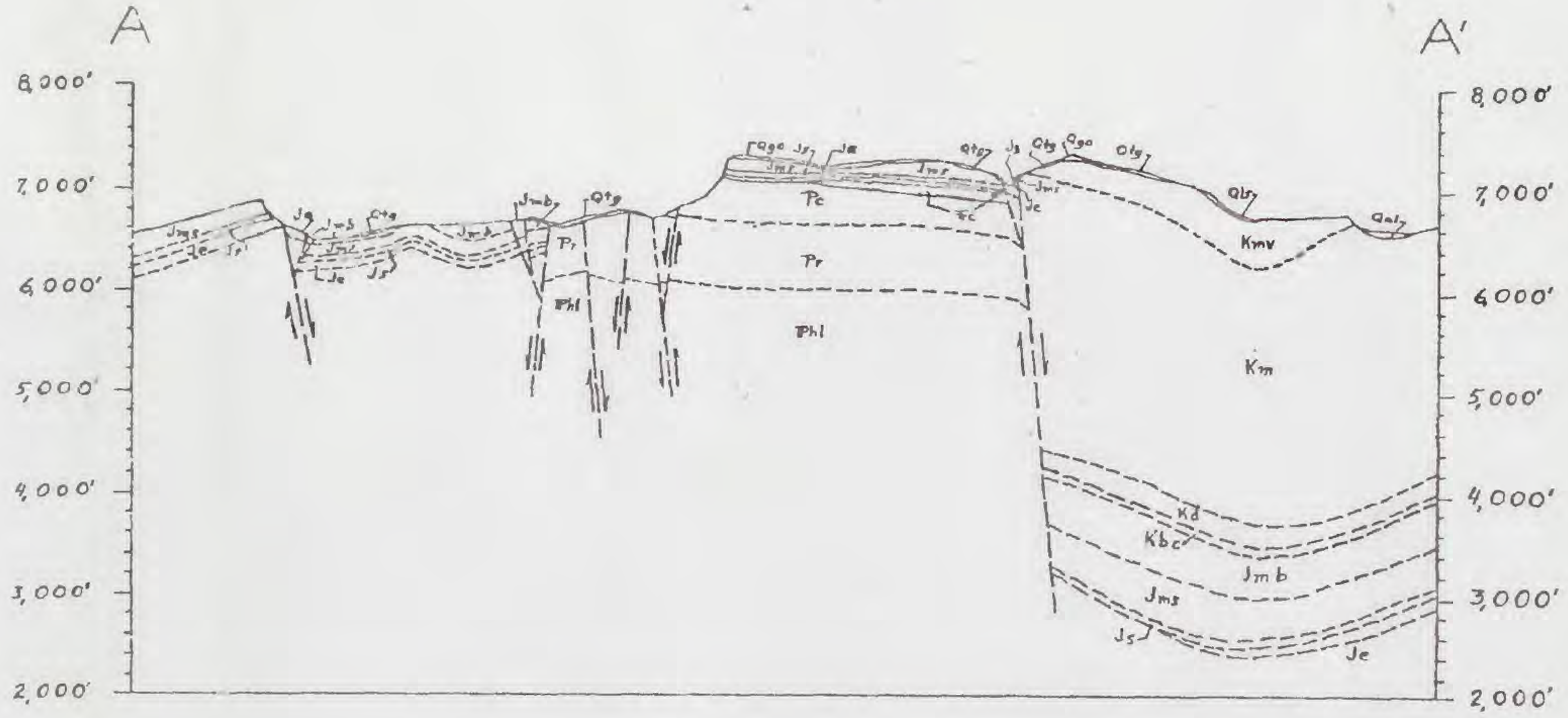

STRUCTURE SECTIONS
A - A' and B - B'
Scale 1:24,000

GEOLOGY AND ORE DEPOSITS
OF THE
KLONDIKE RIDGE AREA,
COLORADO

PLATE 3

GEOLOGY AND ORE DEPOSITS OF THE KLONDIKE RIDGE AREA COLORADO

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Reproduced from a preliminary copy of the "Cortez" map, NJ12-9, series V502, prepared by the Army Map Service, Corps of Engineers, U. S. Army, Washington, D. C.

TOPOGRAPHIC MAP OF THE KLONDIKE RIDGE AREA AND VICINITY

TRUE NORTH
MAGNETIC NORTH

Scale 1:62,500
Contour interval 200 feet with supplementary contours at 100 foot intervals.

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PLATE 5

HORIZONTAL SCALE: 1:24,000
VERTICAL SCALE: 1:500

GEOLOGIC SECTION
OF THE
BURRO CANYON FORMATION
ON
KLONDIKE RIDGE

U. S. Geological Survey
OPEN FILE MAP
This map is preliminary and has not been edited or reviewed for conformity with Geological Survey standards or nomenclature.

PREPARED IN COOPERATION WITH THE
U. S. ATOMIC ENERGY COMMISSION

GEOLOGY AND ORE DEPOSITS
OF THE
KLONDIKE RIDGE AREA,
COLORADO

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Table 16.--Chemical and semiquantitative spectrographic analyses of carnotite deposits in the Klondike district. [Only elements that show, or might be expected to show, significant variations are included. Analyses in percent. Explanation of symbols: 0, looked for but not detected; Tr, trace, near threshold of spectrographic method (below limit of detectability); M, major constituent, greater than 10%; -, not looked for.]

Deposit	Ag [1]	B	Ba	Ca	Co	Cr	Cu	Fe	In	K	Mg	Mn
258	0.0003	0.003	0.07	1.5	0.003	0.0003	0.03	0.3	0	0	1.5	0.07
260	Tr	.0015	.03	1.5	.0015	.0015	0.03	1.5	0	1.5	3.0	.03
300	.0007	.003	.03	1.5	.003	.0007	.003	.15	0	1.5	.3	.03
301	0	.003	.7	3.0	.003	.0007	.003	.3	0	0	.3	.07
304	0	.007	.015	.3	.0015	.0015	.0015	.3	0	.7	.7	.03
305	.0003	0	.015	.3	.0015	.0007	.015	.3	0	.7	.7	.015
310	0	.003	.03	7.0	.003	.0007	.003	.3	0	.7	.3	.07
440	0	0	.15	M	.0007	.0003	.015	.3	0	.7	.3	.15

Deposit	Mo	Na	Ni	Pb	Sr	V	W	Y	As [2]	Se [3]	eU [4]	U [5]	Zn [6]	Bi
258	0.007	0.15	0.0015	0.15	0.015	1.5	0	0.003	0	--	0.033	0.03	0.07	0
260	0	.15	.0007	.015	.003	.7	0	0.007	0	-	0.028	0.03	.3	0
300	.0015	.07	.0007	.03	.003	.07	0	0	0.0018	.0005	.0020	.0012	.028	0
301	0	0	.0015	.03	.07	.3	0	.0015	.0090	.0004	.001	.0017	.005	0
304	0	.15	.0015	.003	.007	.7	0	.0015	.0025	.0001	.004	.0033	.029	0
305	.003	.07	.0007	.03	.003	.3	0	.0015	.0009	.0012	.013	.012	.46	0
310	.0015	.15	.0007	.007	.015	.3	0	0	.0041	.0005	.007	.0057	.009	0
440	0	.3	.0007	.003	.015	.15	0	.0015	.0008	.0001	.040	.058	.0038	0

1. Spectrographic analyses by J. C. Hamilton and R. G. Havens.
2. Analyzed by colorimetric method. Analysts: Claude Huffman and D. L. Ferguson.
3. Analyzed by colorimetric method. Analyst: G. T. Burrow
4. Analysts: W. W. Niles, G. S. Erickson and C. G. Angelo
5. Analyzed by fluorimetric method. Analysts: E. J. Fennelly and D. L. Ferguson
6. Analyzed by colorimetric method. Analysts: H. H. Lipp, Claude Huffman, D. L. Ferguson, and G. T. Burrow.

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Table 19.--Chemical and semiquantitative spectrographic analyses of manganese deposit[illegible] the Klondike district. [Only elements that show, or might be expected to show, significant variations are included. Analyses in percent. Explanation of symbols: 0, looked for but not detected. M, major constituent, greater than 10 percent. < with number, concentration below number shown (standard sensitivities do not apply at such low concentrations).]

Deposit	Ag[3]	B	Ba	Ca	Co	Cr	Cu	Fe	In	Bi	K	Mg	Mn	Mo	Na	Ni	Fb	Sr	V	W	Y	As[4]	Se[5]	eU[6]	U[7]	Zn[8]
3[1]	0.0005	0	0.7	M	0.0007	0.03	0.05	3.0	0	0	0	0.5	5.0	0	0.07	0	0.07	3.	0.007	0	0.005	0	-	-	0.3	0
328[2]	0	0.007	.15	0.3	0	.0015	.007	.7	0	0	0.7	.15	.15	0	.7	.0007	.003	.15	.003	0	.0015	0.0012	0.00005	.001	.0001	.007
388	0	.03	.03	.15	0	.0015	.03	M	0	0	1.5	.07	.15	0.003	.3	.0007	.07	.07	.015	0	.0015	.0028	.0001	.002	.0005	.004
389	0	.003	.7	M	.0015	.003	.07	1.5	0	0	.7	.07	7.0	,003	.3	.0003	.15	7.0	.015	0	.003	.0025	.0001	.001	.0006	.004
405	0	0	.7	.7	.0015	.003	.15	.3	0	0	.7	.07	M	.015	,7	.0007	.07	3.0	.03	0	.0015	.0018	.0001	.003	.0024	.004
406	0	.003	.3	.3	.003	.0015	.15	.7	0	0	1.5	.07	M	.007	.3	.0015	.15	1.5	0.015	0	.0015	.0021	.00005	.002	.0008	.004
408	0	0	.7	7.0	.0015	.007	.15	.15	0	0	.7	.07	M	.003	.3	.0007	.03	.7	.007	0	.0015	.0027	.00005	.001	.0009	.003
421	0	.003	.15	M	0	.0007	.015	.3	0	0	1.5	.15	.7	0	.3	0	.015	.03	.0015	0	.0015	.0007	.00005	.001	.0001	.005
422	0	.015	1.5	M	.003	.0007	.3	1.5	0	0	1.5	.7	7.0	.003	.3	0	.03	3.0	.015	0	.0015	.0083	.0005	.001	.0004	.005
426	0	0	1.5	M	.0007	.003	.07	7.0	0	0	.7	.3	1.5	.003	.07	.0007	.03	M	.015	0	.003	.0107	.00005	<.001	.0005	.005
427	0	0	.03	M	.0007	.0015	.03	M	0	0	3.0	.3	.3	.03	.7	.0015	.007	.07	.07	0	.003	.0205	.0022	.004	.0040	.009
442	0	0	1.5	M	.003	.003	.3	.3	0	0	.7	.3	7.0	0	.15	0	.15	.3	.03	0	.0015	.0024	<.00005	.002	.0005	.018
445	0	0	7.	7.	.003	.0015	.3	.7	0	0	1.5	.3	M	.003	.3	.0015	.07	.15	.015	0	0	.0360	.00005	.002	.001	.0036
446	0	0	.3	M	.0015	.0015	.015	M	0	0	3.0	.3	.7	.015	.7	.0015	.007	.3	.15	0	.003	.0076	.0012	.002	.002	.012
450	0	0	.7	M	.0015	.015	.07	1.5	0	0	0	.15	7.0	<.002	.07	0	.15	1.5	.03	0	.0015	.0045	.0001	.001	.0007	.0063

1. Sampled by E. M. Shoemaker.
2. Barren Kayenta sandstone.
3. Spectrographic analyses by J. C. Hamilton and R. G. Ha[illegible].
4. Analyses (colorimetric method) by Claude Huffman and D. [illegible] Ferguson.
5. Analyses (colorimetric method) by G. T. Burrow.
6. Analyses by W. W. Niles and C. S. Erickson.
7. Analyses (fluorimetric method) by E. J. Fennelly and D. [illegible]uson.
8. Analyses (colorimetric method) by H. H. Lipp, Claude H[illegible], [illegible]. L. Ferguson and C. T. Burrow.

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Table 21.--Chemical and semiquantitative spectrographic analyses of copper deposits in the Klondike district. [Only elements that s[illegible] [illegible]ight be expected to show, significant variations are included. Analyses in percent. Explanation of symbols: 0, looked for but not detected; -, not looked for; M, major constituent, greater than 10 percent < [illegible] number, concentration below number shown (standard sensitivities do not apply at such low concentrations)]

Deposit	Ag	As	B	Ba	Bi	Ca	Co	Cr	Cu	Fe	In	K	Mg	Mn	[illegible]	Na	Ni	Pb	Se[3]	Sr	eU[4]	U[5]	V	W	Y	Zn[6]
													Sulfide deposits													
244	0.007	0.0013	0	0.007	0	3.	0	0.0003	0.15	0.15	0	0	0.15	0.15		0.15	0.0007	0	0.0001	0.003	0.019	0.021	0.3	0	0.0015	0.0038
245	0.003	-	0.0015	.07	0	M	0.0003	.003	1.5	.3	0	1.5	.7	.15	0	.7	.0007	Tr.	-	.015	.013	-	.3	0	0.0015	-
246	.0007	.0010	0	.03	0	M	0	.0015	1.5	.3	0	.7	.3	.15	0	.15	0	0.007	.0004	.3	.036	.040	.15	0	.0015	.015
247(1)	.003	-	0	.3	0	M	0	.03	1.5	.3	0	1.5	.7	1.5	< .003	.3	.0003	Tr.	-	M	.001	-	.7	0	.0015	-
247(2)	.0015	.0047	0	.15	0	M	0	.015	1.5	.15	0	.7	.3	.7	0	.15	.0003	0	.0001	7.0	< .001	.0009	.3	0	0	.010
438	.00015	.0340	0	.03	0	7.0	.003	.0015	7.0	1.5	0	3.0	.15	.07	.0015	.7	.0015	.015	.0225	.07	.002	.0009	.03	0	.0015	.0057
447	.007	.0007	.003	.15	0	1.5	.0007	.0015	7.0	.7	0	1.5	.3	.15	0	.7	.0015	.3	.0325	.7	.002	.001	.07	0	.0015	.0025
449	.003	.0003	.003	.03	0	3.0	.0007	.0015	3.0	.3	0	3.0	.7	.07		.7	.0015	.0015	.0200	.015	.006	.006	.3	0	.0015	.010
													Malachite deposits													
386	0.0015	0.0001	0.007	0.03	0	7.	0	0.0007	1.5	0.15	0	1.5	0.15	.15		0.3	0.0003	0.003	0.0001	0.015	0.001	0.0007	0.0015	0	0.0015	0.004
410	.0003	.0085	0	.03	0	M	0	.0007	0.7	.15	0	1.5	0.15	.3		.3	0	0	<.00005	.7	< .001	.0003	.015	0	0	.006
411	.003	.0029	0	.15	0	7.	0	.0007	.07	.15	0	3.0	.15	.15		.7	.0003	0	.00005	.03	.003	.0025	.3	0	.0015	.006
412	.003	.0019	0	.7	0	M	0	.0015	.07	.07	0	1.5	.15	.7	0	.7	.0003	.003	<.00005	.03	< .001	.0002	.015	0	.003	.006
428	.015	.0016	0	.015	0	.7	.0007	.00015	3.0	.3	0	.7	.15	.03	.0015	.15	0	.03	.0025	.003	.003	.0013	.07	0	0	.002
429	.015	.0004	0	.015	0	3	.0007	.0003	7.0	.15	0	.7	.15	.07	.007	.3	0	.003	.0028	.007	.002	.0015	.007	0	0	.001
439	0	.0076	0	.015	0	.7	0	.003	1.5	.3	0	1.5	.07	.007		.15	0	0	.0003	.0015	.002	.0002	.0015	0	0	.015
441	0	.0018	0	.015	0	M	0	.0007	.7	.07	0	.7	.07	.3	0	.3	0	0	.0001	.015	.001	.0005	.003	0	.0015	.0028
448	.003	.0002	0	.015	0	.7	0	.0003	1.5	.07	0	0	.15	.07	0	.15	0	.0015	.0012	.015	.001	.0007	.003	0	0	.0028
452	.0003	.0004	.003	.07	0	1.5	0	.15	1.5	.7	0	1.5	.3	.07		.07	0	0	.0001	.003	< .001	.0006	.003	0	0	.0010
												Calcite veins														
444	0	.0003	0	.007	0	M .003	0	.003	.003	.15	0	0	.3	.3	0	.3	0	.007	.0001	.03	< .001	.0004	.007	0	.0015	.0009
451	0	.0001	0	.007	0	M	0	.0003	.003	.3	0	0	.07	.07	0	0	0	0	.0001	.03	< .001	< .0001	.003	0	.0015	< .0005
												Type uncertain														
382	.0003	.0007	.007	.03	0	7.	0	.003	7.	.15	0	3	.3	.15	0	.7	.0007	.003	.0004	.015	.002	< .0001	.03	0	.0015	.011
443	0	.0006	.003	.03	0	1.5	0	.07	.003	.3	0	1.5	.3	.03	0	.3	0	0	.00005	.003	.002	.0002	.03	0	0	.0022

1. Semiquantitative spectrographic analyses by [illegible]
2. As analyzed by: D. L. Ferguson and Claude Huffman.
3. Se analyzed by G. T. Burrow.
4. eU analyzed by C. G. Angelo, W. W. Niles, and G. S. Erickson.
5. U analyzed by: E. J. Fennelly and D. L. Ferguson.
6. Zn analyzed by Claude Huffman, H. H. Lipp, D. L. Ferguson, and G. T. Burrow.