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Present and Past Ground-Water Conditions in the Morrison Formation in Southwestern Colorado and Southeastern Utah

By D. A. Phoenix 1916–

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PRESENT AND PAST GROUND-WATER CONDITIONS IN THE MORRISON FORMATION IN SOUTHWESTERN COLORADO AND SOUTHEASTERN UTAH*

By

D. A. Phoenix

October 1952

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

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By D. A. Phoenix

ABSTRACT

Field and laboratory studies of ground-water conditions in the carnotite-bearing Morrison formation in southwestern Colorado and southeastern Utah were undertaken to determine possible relations between ground waters and the carnotite deposits.

The ore-bearing sandstone consists of lenticular sandstone strata, interbedded with thin, discontinuous layers of mudstone; these strata were deposited in a stream environment. The porosity and permeability of the ore-bearing sandstone in one area are relatively low, porosity averaging about 15 percent and permeability ranging between 30 and 300 millidarcys. Permeability studies in this same area show that sandstone classed as favorable for ore is slightly more permeable than and has nearly twice the transmissibility of sandstone classed as semifavorable; outcrop studies also suggest a lower transmissibility for sandstone that is unfavorable.

Samples of water from the ore-bearing and associated strata show considerable variation in chemical character. These water samples are generally low in uranium, vanadium, copper, and lead, most samples containing less than 1 part per million (ppm) of each metal.

General geologic relations suggest that ground-water movement probably was active through the ore-bearing strata during their deposition and shortly afterward. Movement during this time probably occurred largely through the more permeable sand strata and in the general direction of initial dip and stream flow. During Cretaceous time, when several thousand feet of marine sediments accumulated over the Morrison, the water contained in the ore-bearing strata probably was immobile or nearly so and was protected from escape or contamination. Following Tertiary deformation and erosion, active ground-water circulation no doubt was restored, but because of the low permeability and the lenticular character and therefore low

transmissibility of the ore-bearing sandstone, ground-water movement probably was slow. Faulting probably also influenced the direction and rate of ground-water movement during Tertiary time.

Movement and localization of ground water would permit the concentration of metal-bearing solutions during Salt Wash and early Brushy Basin time in the beds that now contain ore deposits. It is more difficult to explain the formation of these deposits, which have a wide geographic distribution at a restricted stratigraphic position, from solutions circulating through the rocks at a later date.

Whatever mode of origin is used to explain the deposits, geologists almost without exception, agree that the metals were transported by solutions that have migrated through the sediments for considerable distances. For this reason, a study of the horizontal and vertical transmissibility characteristics of all exposed sedimentary formations on the Colorado Plateau is planned.

INTRODUCTION

Carnotite deposits are widespread on the Colorado Plateau and have been the principal domestic source of uranium and vanadium. Although the geologic environment of these deposits differs from place to place, nearly all the deposits have many features in common. In general, they are largely restricted to a few stratigraphic zones and show a closer relationship to sedimentary structural features than to structures resulting from regional deformation. These habits suggest that the deposits were formed from solutions introduced into the ore-bearing sandstone, perhaps before regional deformation, rather than along through-going vertical channels, such as fractures. Futhermore, the types and habits of most of the ore minerals are such as to suggest low-intensity type of mineralization at low temperatures and from dilute solutions. Thus the deposits may have an origin more nearly related to normal ground waters than to hydrothermal activity. For these reasons, field and laboratory studies were undertaken to determine the present and past ground-water conditions and their relations to the carnotite deposits. Because more information is available regarding the deposits in the Salt Wash member of the Morrison formation than in other formations, these studies were restricted wholly to the Morrison and younger formations. The work was done as part of the U. S. Geological Survey's Colorado Plateau project, a coordinated program of geologic studies and exploration. This program, which was begun in 1947, is being done on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission.

Field work was planned to obtain information on the present and past ground-water conditions. Detailed studies were restricted to three areas in southwestern Colorado--Calamity Mesa, Mesa County; Atkinson Mesa, Montrose County; and the Slick Rock area, San Miguel County (fig. 1)--but reconnaissance investigations were made in other parts of southwestern Colorado and southeastern Utah. The general information obtained from these studies and the interpretations based on them can be extended to apply, in general, to other carnotite-bearing areas on the Colorado Plateau.

This report reviews briefly the lithologic character and paleogeography of the Morrison and younger formations, the geologic history of the region, and the character and habits of the carnotite deposits in the

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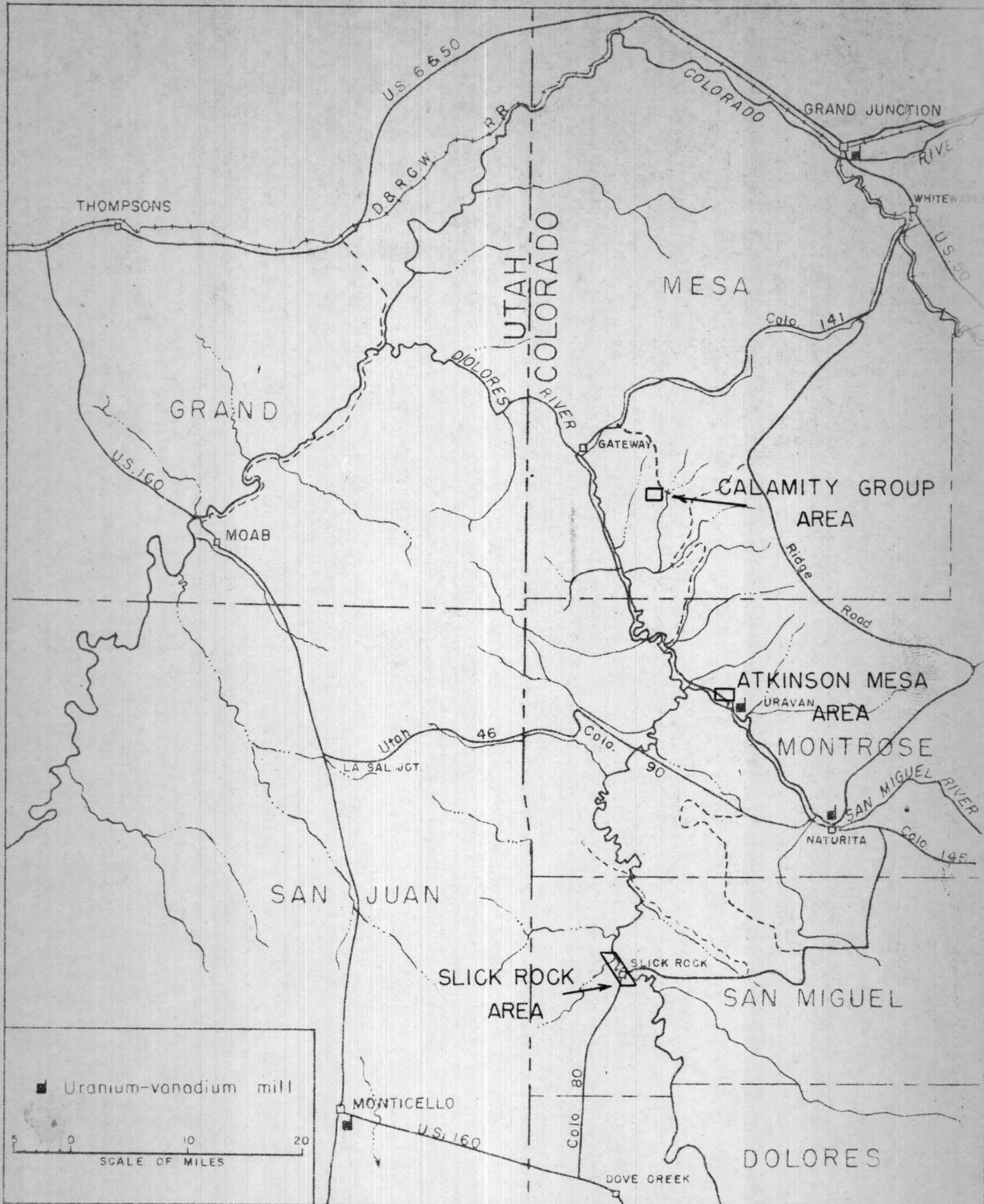

Figure 1.--INDEX MAP OF SOUTHWESTERN COLORADO AND SOUTHEASTERN UTAH SHOWING AREAS OF DETAILED STUDY.

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Morrison formation. The present ground-water conditions are discussed and the probable past ground-water conditions are reconstructed insofar as the meager evidence permits.

The field and laboratory work was conducted under the general supervision of R. P. Fischer. S. W. Lohman of the Ground Water Branch, and C. S. Howard of the Quality of Water Branch, U. S. Geological Survey, served as consultants and advisors during the work. Many of the laboratory techniques for determining permeability and porosity were adopted at the suggestion of G. E. Manger of the Geophysics Branch.

GEOGRAPHIC SETTING

The region containing most of the ore deposits in the Morrison formation is in the northeastern part of the Colorado Plateau province. This region is characterized by many steep-walled canyons and flat-topped mesas, and is commonly known as the "Canyon Lands". Isolated mountain ranges rise prominently above the general level of the region. Except for some of the higher mountain masses and bottoms of the deeper canyons, most of the region ranges in altitude from 5,000 to 7,500 feet.

The climate of the region is semi-arid except in the higher mountains. The average monthly and annual precipitation is summarized in table 1. Precipitation at the Norwood and Northdale stations is probably typical for the higher mesas, whereas precipitation at the Paradox and Gateway stations is probably typical for the lower altitudes.

GEOLOGY

The rocks exposed in the Colorado Plateau province are mainly sedimentary and range in age from Paleozoic to early Tertiary. Although most of the beds lie nearly flat, they have been disturbed in places by broad folds, salt intrusions, and high-angle faults. Moderate-sized igneous bodies of Tertiary age have intruded these sediments in the La Sal, Abajo, El Late (Ute), Carrizo, and Henry Mountains. A generalized description of the late Paleozoic to early Tertiary strata in southwestern Colorado and adjoining parts of Utah is given in table 2.

Table 1.--Average monthly and annual precipitation, in inches, at four climatological stations in southwestern Colorado

(Data from U. S. Department of Commerce, Weather Bureau. Recorded from establishment of station to 1950, inclusive.)

Station	Altitude	No. years	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Average Annual
Norwood	7,017	22	0.93	1.22	1.48	1.64	1.17	0.62	1.84	2.12	1.60	1.49	0.88	1.14	16.10
Northdale	6,842	20	0.99	1.17	1.30	1.16	0.83	0.31	1.05	1.54	1.99	1.55	0.94	1.24	14.41
Paradox a/ (2 mi. SE)	5,280	8	0.88	0.63	0.47	0.69	0.85	0.93	1.17	1.78	0.55	1.88	0.59	0.74	11.16
Gateway b/ (4 mi. NE)	4,903	3	1.38	0.88	1.13	1.19	0.67	0.87	1.64	0.79	0.75	1.02	0.47	0.62	11.41

a/Averages based on incomplete record, 1942-50, inclusive

b/Averages based on incomplete record, 1947-50, inclusive

Table 2.--Generalized section of Jurassic and Cretaceous strata in southwestern Colorado and adjoining parts of Utah

System	Group	Formation	Thickness (feet)	Character and distribution
Cretaceous		Mesa Verde formation	1,000 ±	Light-colored sandstone and gray shale; coal-bearing; cliff-forming widespread
		Mancos shale	2,000 - 5,000	Gray shale; forms valleys and steep slopes; widespread
		Dakota sandstone	0 - 200	Gray and brown sandstone and shale; mesa capping; widespread
		Burro Canyon formation	50 - 250	Light-colored conglomeratic sandstone and green and maroon mudstone; mesa-capping
Jurassic		Morrison formation	300 - 500	Brushy Basin shale member; varicolored shale (or mudstone), some sandstone lenses; forms slopes; widespread
			200 - 400	Salt Wash sandstone member; light-colored sandstone and red mudstone; forms cliffs and benches; widespread. Carnotite-bearing
	San Rafael group	Summerville formation	0 - 400	Red and gray shale, thin sandstone; forms slopes; thickens westward
		Curtis formation	0 - 250	Glauconitic sandstone, greenish shale, gypsum; present only in central Utah
		*Entrada sandstone	50 - 1,000	Light-colored, massive, cliff-forming sandstone in Colorado and eastern Utah; thickens westward and becomes red, earthy sandstone. Vanadium-bearing
		Carmel formation	0 - 600	Red, earthy sandstone in Colorado and eastern Utah; thickens westward and becomes gray and red shale, limestone and gypsum
Jurassic (?)	Glen Canyon group	Navajo sandstone	0 - 2,000	Light-colored, massive sandstone; cliff-forming; thins to extinction in western Colorado, thickens westward
		Kayenta formation	0 - 300	Red sandstone, irregularly bedded; bench-forming; absent in eastern part of region
		Wingate sandstone	0 - 400	Red, massive sandstone, cliff-forming; absent in eastern part of region

Stratigraphy

Pre-Morrison formations

The oldest sedimentary rocks exposed in the region consist of a thick series of marine limestones and shales of Pennsylvanian age. Intrusive masses of gypsum and salt, also of Pennsylvanian age, are present in southwestern Colorado and southeastern Utah. They are overlain by continental clastic rocks of upper Pennsylvanian, Permian, Triassic, and Jurassic age, consisting dominantly of sandstone and shale with lesser amounts of conglomerate and arkose.

Morrison formation

The Morrison formation of Upper Jurassic age consists dominantly of stream-laid deposits of sandstone and mudstone. The formation is divided into four members--Salt Wash sandstone, Recapture shale, Brushy Basin shale, and Westwater Canyon sandstone (Craig, et al., 1951).

Salt Wash sandstone member. --The Salt Wash sandstone member comprises a broad fan-shaped lobe of stream-laid sediments. This lobe extends northeastward from a blunt apex on the midpoint of the Utah-Arizona state line into eastern Utah, western Colorado, northeastern Arizona, and northwestern New Mexico.

Near the apex of the lobe which is near the source of the sediments, the Salt Wash is about 600 feet thick and consists dominantly of conglomeratic sandstone. The Salt Wash gradually thins radially outward to the north, northeast, and east. In the main carnotite-producing areas of southeastern Utah and southwestern Colorado, it is about 300 feet thick and consists of widespread but lenticular strata of moderately permeable, medium- to fine-grained sandstone, interbedded with less permeable siltstone and mudstone. Eastward, toward central Colorado, the Salt Wash continues to thin gradually to about 150 feet, and consists of finer grained and more evenly bedded layers of sandstone and mudstone as well as appreciable amounts of limestone. In central Colorado these beds lose their identity and are not separable from the overlying

Brushy Basin shale member. In northeastern Arizona and northwestern New Mexico, the alternating strata of Salt Wash sandstone and mudstone interfinger with similar strata of the Recapture shale member, which is thought to be equivalent in age to the Salt Wash.

Recapture shale member. --The Recapture shale member comprises a fan-shaped lobe of clastic sediments in northwestern New Mexico and northeastern Arizona. The source of the Recapture is evidently south of Gallup, N. Mex., for it has a maximum thickness of several hundred feet and is partly conglomeratic in the area immediately north and northwest of Gallup. Northward, the member thins and becomes fine-grained, interfingering with the Salt Wash sediments along the northern boundaries of Arizona and New Mexico.

Brushy Basin shale member. --The Brushy Basin shale member is composed mainly of vari-colored mudstone, but sandstone and conglomerate are present locally. The member is between 350 and 450 feet thick in the main carnotite producing area of southeastern Utah and southwestern Colorado. It thins gradually in all directions, though thickening locally to 600 feet in northeastern Utah.

In parts of southwestern Colorado and southeastern Utah the basal part of the member contains lenticular strata of conglomeratic sandstone that in places reach a maximum thickness of 70 feet. Locally this conglomeratic sandstone rests directly upon sandstone of the Salt Wash, but in most places it is separated from the Salt Wash sandstone by about 30 feet of mudstone. Above the basal conglomeratic sandstone strata, the member consists dominantly of argillaceous sediments, in part bentonitic, with a few discontinuous beds of sandstone and conglomerate.

Westwater Canyon sandstone member. --The Westwater Canyon sandstone member is composed of coarse sandstone and conglomerate in the vicinity of Gallup, N. Mex., where it attains a maximum thickness of about 300 feet. Northward the sediments become finer grained and are interbedded with shale. Near the northern boundaries of Arizona and New Mexico, this member loses its identity and merges into the lower part of the Brushy Basin shale member.

Paleogeography of the Morrison formation. --The Salt Wash sandstone was probably deposited from aggrading streams flowing over a surface of low relief. These streams entered the area of deposition in south-central Utah, and flowed in a radiating pattern outward to the north, northeast, and east. The lenticular strata of sandstone in southeastern Utah and southwestern Colorado probably were deposited along stream channels that shifted frequently. The mudstones interbedded with the sand lenses presumably accumulated on the floodplains bordering the stream channels. The gradient of the Salt Wash streams in south-central Utah was perhaps no greater than 3 feet per mile. In southwestern Colorado and southeastern Utah the gradient was probably less. No regional deformation is known to have modified the stream gradients during Salt Wash time, though, locally, basins of subsidence and movement of salt in southwestern Colorado and southeastern Utah probably modified the local conditions of stream flow. Shallow water-table conditions are believed to have prevailed along the streams in the central part of the Salt Wash area of deposition.

Although plants obviously grew along Salt Wash streams, as indicated by the fossil plant remains in the rocks, geologists in general believe that the climate during Salt Wash time was semiarid. Thin lacustrine sediments are found locally in the Salt Wash member but no large lakes appear to have existed during Salt Wash time.

The Recapture shale and the Westwater Canyon sandstone were probably deposited under conditions similar to those accompanying deposition of the Salt Wash sandstone. The Recapture and Westwater streams probably flowed northward and co-mingled with the Salt Wash and Brushy Basin streams, respectively, in the area where these members interfinger.

Although the source of the Brushy Basin sediments is not clearly established, sedimentary structures within the Brushy Basin conglomeratic-sandstone strata suggest that these sediments were deposited by streams flowing in an easterly or northeasterly direction. The abundance of fossils in the Brushy Basin, plus the abundance of mudstone, suggest that this member was deposited by streams and in lakes under humid conditions.

Post-Morrison formations

The Morrison formation is overlain by the Burro Canyon formation, which consists of about 200 feet of lenticular conglomeratic sandstones interbedded with green shale. The Burro Canyon is of Lower Cretaceous age and was deposited under continental conditions. It is overlain by the Upper Cretaceous Dakota sandstone, which comprises about 100 to 150 feet of interbedded sandstone and shale, and in places contains thin discontinuous seams of coal. The Dakota in turn is overlain by the Upper Cretaceous Mancos shale, comprising about 5,000 feet of dark-gray marine shale. The Mesa Verde group, also of Upper Cretaceous age, overlies the Mancos and consists of a few thousand feet of sandstone and shale and some beds of coal. The Wasatch and Green-river formations of Tertiary age, which overlie the Cretaceous, consist of sandstone and shale deposited in a continental environment.

Geologic history

The geologic history of the Colorado Plateau is divided into two major chapters. The first chapter is a long and complex depositional history that, in southwestern Colorado and southeastern Utah, started with deposition of the oldest exposed rocks--salt and gypsum of Pennsylvanian age--and continued to the deposition of the late Cretaceous Mesa Verde formation. It represents a time interval of about 120 million years ending with the late Cretaceous. The second chapter, although containing long intervals of deposition, is a time during which the older strata were broadly folded and uplifted, intruded by igneous rocks, and finally deeply dissected to produce the present plateau landscape. The period occupied by these later events, probably about 70 million years, extends from late Cretaceous time to the Recent. The chronology of events during this time must be inferred from scattered geologic evidence for the post-Cretaceous stratigraphic record has been removed in the region of southwestern Colorado and southeastern Utah.

A resumé of our uncertain knowledge of these complex events in southwestern Colorado and southeastern Utah is as follows:

1. Deposition of Pennsylvanian marine limestone, shale, and salt.

2. Uplift of the ancestral Rockies during Pennsylvanian time to form a northwestward-trending highland in the region of central and western Colorado--the Uncompahgre Highland.

3. Erosion of this highland contributed continental sediments to southwestern Colorado and southeastern Utah throughout Permian and until late Triassic time.

4. Intrusion of salt masses into the continental sediments, the masses paralleling the southwestern front of the Uncompahgre Highland, was probably initiated by regional compression during the Permian but with the upward movement of salt intermittently breaching the land surface until late Jurassic time.

5. Reduction of the Uncompahgre Highland to a peneplain by late Triassic time eliminated most of the eastward source of sediments. The source areas for the sediments then shifted to the west and southwest of central Utah and the contribution of continental sediments from distant source areas in these directions continued until middle Cretaceous time.

6. The gradual encroachment of a marine environment with attendant beveling of the earlier sediments coupled with subsidence of the area had by late Cretaceous time resulted in the deposition of marine and marginal marine deposits to a thickness of several thousand feet. These deposits culminated the long succession of depositional events that produced the sedimentary strata of southwestern Colorado and southeastern Utah.

7. Crustal movements at the close of the Cretaceous opened the second long chapter in the geologic history of the Colorado Plateau. These movements resulted in retreat of the Cretaceous seas by general uplift and folding of the earlier strata.

8. Subareal erosion probably prior and attendant to deposition in broad interior basins continued throughout the Eocene. Sediments, like the lacustrine and fluviatile rocks of the Wasatch group preserved in the Wasatch mountains of Utah and the Uinta basin of Utah and Colorado, were probably deposited in these basins.

9. Renewed uplift and faulting accompanied by intrusion of the laccoliths, and salt flowage, probably followed Eocene deposition. This succession of Eocene events may have set the stage for the present drainage.

10. By Quaternary time the major streams had probably reached a profile of equilibrium, but general uplift again accelerated erosion that in turn enlarged and deepened the canyons of the Colorado Plateau. Erosion and solution by ground and surface waters at this time is believed to be largely responsible for the physiographic development of the salt valleys.

Carnotite deposits

Habits

The carnotite ore consists mainly of sandstone impregnated with uranium and vanadium minerals, but within the ore some of the fossil plant and shaly material is rich in vanadium. Carnotite--$K_2(UO_2)_2(VO_4)_2 \cdot 3H_2O$--is the principal uranium mineral. It is bright yellow and occurs finely disseminated in the sandstone and partly replaces fossil plant material. The principal vanadium mineral is a fine-grained and micaceous clay-like mineral. It occurs disseminated in the sandstone and colors the rock a greenish-gray, the color darkening as the vanadium content increases. Dark-colored vanadium oxides and bright-colored calcium vanadates are present in places.

The ore bodies are irregular tabular layers that range from 2 to 4 feet thick. They generally lie parallel to sandstone bedding, but they do not follow the bedding in detail. They range in size from bodies only a few feet wide, containing only a few tons of ore, to bodies several hundred feet wide, which may contain many thousand tons of ore.

In southwestern Colorado and southeastern Utah, most of the deposits, and nearly all of the productive ones, occur in the uppermost sandstone strata of the Salt Wash sandstone member of the Morrison formation. Within these strata the deposits have a spotty distribution but tend to be clustered in relatively small, poorly defined areas, where they show a close relationship to sedimentary structures within the host rock. Most of the deposits are localized in and near the central, thicker parts of the sandstone strata.

Most ore bodies, as well as the clusters of deposits, trend to be elongate parallel to the long axes of the enclosing sandstone strata as well as being parallel to the trend of the sedimentary structures composing these strata. Within the ore itself, peculiar elongate concretionary structures, called "rolls", have a common orientation in any local area. The deposits in general do not show a close genetic relationship with vertical through-going fractures that might have influenced the direction and movement of ground waters or hydrothermal solutions.

The habits of the ore bodies in southwestern Colorado and southeastern Utah suggest that the early ore minerals were emplaced from metal-bearing solutions that migrated freely through the Salt Wash sediments, at a time when the regional structures of Tertiary age did not control the direction and rate of migration of the solutions. Hence the deposits appear to be older than Tertiary deformation, although lead-uranium isotope studies suggest an early Tertiary age.

GROUND-WATER STUDIES

Detailed studies of the character and distribution of the lithologic varieties of the ore-bearing sandstone and associated sedimentary units were undertaken to learn the hydrologic properties and their possible influence on the localization of carnotite deposits. Attention was focused on the habits and composition of the present ground waters to determine their possible relation to the deposits. These and other geologic features must be appraised collectively to interpret ground-water conditions during the past.

Character of the ore-bearing sandstone

Lithology

The Salt Wash sandstone member in southwestern Colorado is about 300 feet thick and is composed of alternating units of sandstone and mudstone in about equal proportions. These units of sandstone and mudstone are here termed strata. A stratum is separated from other strata by contrasting lithology or by local unconformity. The sandstone strata contain sedimentary structures with orientations that indicate a dominant direction of current flow and are believed to have been deposited within the channel margins of an aggrading stream.

The strata of mudstone--mudstone being used in a collective sense--are composed of sediments ranging from clay to silt. These sediments are commonly thin bedded and red brown. The clay found at the top of a mudstone stratum in the vicinity of carnotite deposits is altered to gray or green. These sediments are difficult to observe for they commonly do not crop out.

The sandstone strata are composed of fine- to medium-grained quartz with minor amounts of white chert and feldspar; clay as pellets, films and seams is also common. The sandstone is predominantly gray or light brown, but in places it is reddish brown. Calcite, quartz, and clay are the principal cementing materials. In general, the sandstone strata are broadly lenticular but near the top and base of the Salt Wash they are numerous enough to give the gross appearance of persistent sandstone layers. Carnotite deposits are localized almost wholly within the group of strata that form the uppermost sandstone layer--a layer commonly called the "ore-bearing sandstone".

The ore-bearing sandstone was mapped and studied in detail in the area of the Calamity group of claims on the east side of Calamity Mesa, Mesa County, Colo., where exposures are good, and where a number of carnotite deposits were found by Geological Survey drilling. At this locality the ore-bearing sandstone ranges from 35 to 75 feet in thickness. It contains as many as four separate sandstone strata that are broadly lenticular and individually range in thickness from about 26 feet, near their central portions, to a featheredge. Near the ore deposits the thick portions of at least two or three sandstone strata are superimposed or are separated only by thin layers of mudstone, whereas away from the deposits these sandstone units generally thin and are separated by thicker units of mudstone (pl. 1).

An individual stratum of sandstone is composed of one or more beds. These beds range from a featheredge to 11 feet in thickness. They may have a lateral extent of several hundred feet or more, or they may be narrow lenses of limited extent due either to restricted deposition in a scour or truncation by another bed. Carbonized plant remains are locally abundant in the beds and films or thin beds of mudstone or siltstone and thin layers of mudstone pebble conglomerate separate one bed from another in many places. The detailed character of the beds and strata composing the ore-bearing sandstone are shown by the geologic logs of core from diamond-drill holes (pl. 2).

The sandstone in the Salt Wash is thought to have been deposited by streams (Craig, et al., 1951). The orientation of the streams depositing these sediments can be shown by various geologic structures. Current lineation is useful in determining the orientation of the current movement of streams for the lineation is believed to trend nearly parallel to the direction of stream flow. The trend of current lineation marks on the individual sandstone strata in the Calamity Mesa area are shown on plate 1. The trend of current lineation within a single sandstone stratum is generally consistent in direction and indicates that a single stratum represents an interval during which the depositing stream generally was fixed in flow direction and probably position as well. Observations in the Calamity Mesa area show that most of the sandstone strata were deposited from northeastward-flowing streams, but that the uppermost stratum was deposited from a stream that trended in a southeasterly direction. This uppermost stratum was not observed to extend beyond the restricted area of ore deposits on the east side of Calamity Mesa. Less detailed observations on Outlaw Mesa, immediately east of Calamity Mesa, suggest that the carnotite deposits in the northeastern part of the mesa are in sandstone strata that were deposited by northeastward-trending streams and that these strata are in turn overlapped by a stratum having a southeasterly depositional trend, as on Calamity Mesa. The coincidence of the overlapping southeastward-trending sandstone to the relatively narrow southeastward-trending mineral belt, described by Fischer and Hilpert (1951), suggests a possible influence in the localization and restriction of the deposits in Calamity and Outlaw Mesas.

Hydrologic properties

The hydrologic character of rocks can be described by three properties: porosity, permeability, and coefficient of storage. The combined effect of the permeability and the hydraulic gradient control the direction of movement and amount of water that will pass through a given unit of rock in a given unit of time. Although the past hydrologic properties of a rock may differ from those existing today, owing to differences in compaction, cementation, and jointing, it is desirable to appraise the porosity and permeability in order to understand more fully past ground-water conditions.

The porosity of a rock is its property of containing interstices or pore spaces, and therefore a rock having a high porosity can contain more water per unit volume than a rock having a low porosity. Porosity commonly is expressed as the percentage of a unit volume of rock occupied by interstices. The porosity of rock specimens was determined with a Washburn-Bunting type porosimeter using methods outlined by Fancher, Lewis, and Barnes (1933, pp. 112-117).

The permeability of a rock is its capacity to transmit a gas or liquid under pressure, and is expressed in various units by workers in different fields. The unit of permeability used by the petroleum industry is called the darcy. As defined by Wyckoff, et al., (1933, pp. 394-405) 1 darcy equals 1 cubic centimeter per second per square centimeter under a pressure of 1 atmosphere per centimeter and a viscosity of 1 centipoise. A millidarcy is 0.001 darcy. The permeability of selected rock samples was determined by using nitrogen in a permeameter with suitable manometers for measuring inflow pressures. A calibrated glass capillary-tube flowmeter was used for determining the outflow pressure and rate of gas discharge. The permeability to nitrogen was calculated in millidarcy units by procedures adopted by the American Petroleum Institute (1942, pp. 4-14).

Theis (1935) defined the coefficient of transmissibility as Meinzer's coefficient of permeability (per unit thickness) times the total thickness (in the same units). The original definition was given in units used by the Ground Water Branch of the Geological Survey, but the term may conveniently be adapted to other units of permeability, such as the darcy or the millidarcy. Thus the coefficient of permeability denotes a characteristic of a unit thickness of the water-bearing material, whereas the coefficient of transmissibility denotes the analagous characteristic of the aquifer as a whole.

In connection with the detailed mapping that was done in the Calamity group area, Calamity Mesa, Mesa County, Colo. (pl. 1), the porosity and permeability of samples of core from three selected drill holes were determined. Samples were cut, parallel to the bedding, from the core samples of the ore-bearing sandstone at intervals of 0.3 foot. The porosity and permeability of these samples were determined, and the values obtained are shown on plate 2 alongside a graphic geologic log of these drill holes.

The porosity of the sandstone ranges from about 10 to 20 percent and averages about 15 percent. The permeability of the sandstone generally ranges from 30 to 300 millidarcys.

The sandstone in the drill core may be divided visually into lithologic units corresponding to related groups of permeability values. The sandstone units in the lowest part of the ore-bearing sandstone have a permeability of less than 15 millidarcys owing to their well-cemented character. The permeability of most of the sandstone units is lowest near the bottom and the top, and rises to a maximum near the middle.

This change in permeability helps to distinguish one sandstone unit from another. Cencentration of relatively impermeable silty mudstone as seams, films, and pellets, also separates many of the units and helps further to distinguish one unit from another. Projection of these units to the surface outcrop suggests that they correspond to bedded or laminated sedimentary structures that make up the strata of the ore-bearing sandstone.

Mudstone and associated siltstone are relatively impermeable--their permeability rarely exceeds 25 millidarcys.

Generally, the sandstone strata composing the ore-bearing sandstone are separated by strata of mudstone. In the vicinity of the ore deposits in the Calamity group area, however, the most permeable sandstone strata are commonly in contact with each other and compose almost the full thickness of the ore-bearing sandstone.

In addition to the detailed study of the porosity and permeability relations in the three drill holes, 344 samples were selected from the cores of 79 holes to determine the average permeability and transmissibility of the ore-bearing sandstone (pl. 3). Seventy-one of the holes studied are in ground classed as geologically favorable for ore deposits on the basis of criteria being used to guide exploration. The other eight holes are in ground classed as semifavorable. In the favorable ground, the transmissibility (the product of average permeability times thickness of the sandstone) averages 1,631 millidarcy-feet and the permeability averages 37 millidarcys; in the semifavorable ground the transmissibility averages 880 millidarcy-feet and the permeability 31 millidarcys. These results suggest that the ore-bearing sandstone in ground favorable for ore, and near known ore deposits, has a transmissibility of about twice that of the ore-bearing sandstone in semifavorable ground.

In addition to the gross analysis of the water-bearing properties of the ore-bearing sandstone, the permeability of 20 oriented sandstone specimens was determined. The results suggest that the sediments are more permeable in the plane of bedding and parallel to the trend of current lineation than in any other direction. Because ore deposits are elongate parallel to the general trend of current lineation the above results suggest that the deposits are elongate parallel to the direction of greater permeability in the ore-bearing sandstone.

Relation of ore deposits to the basal conglomerate of the Brushy Basin shale member

The relations of the ore deposits on Calamity and Outlaw Mesas to the distribution and trend of the sandstone strata composing the ore-bearing sandstone were described briefly on pages 19 and 20. In these areas the ore deposits are in the thicker parts of two or three sandstone strata that are superimposed and have a northeasterly trend, and which are overlain by a relatively thin sandstone stratum that trends southeastward. Detailed mapping in the southern part of Atkinson Mesa, Montrose County, and near Slick Rock, San Miguel County, Colo., shows a similar correlation of carnotite deposits in the upper part of the Salt Wash member to conglomeratic strata in the basal part of the Brushy Basin shale member. On Atkinson Mesa the thicker parts of the ore-bearing sandstone contain carnotite deposits beneath or near strata of Brushy Basin conglomerate. In the vicinity of Slick Rock the thicker parts of the ore-bearing sandstone also contain carnotite deposits where conglomeratic strata are present in the Brushy Basin. These relations, although ill-defined, suggest the possibility that the more favorable places for carnotite deposits in the ore-bearing sandstone are where this sandstone is covered by a younger sandstone or conglomerate stratum. Perhaps ground waters moving as underflow beneath the streams that deposited the younger sandstone or conglomerate strata introduced and localized the ore-bearing metals in the thicker and more favorable parts of the ore-bearing sandstone.

Atkinson Mesa

The ore-bearing sandstone on Atkinson Mesa comprises one to three strata (pl. 4). Near the carnotite deposits these strata are superincumbent and crop out as a conspicuous ledge from 40 to 75 feet thick. Away from ore deposits these strata generally thin, are separated by mudstone, and in places one or two of them pinch out altogether. The uppermost of these strata trends northwest and current lineation on the bedding planes also trends northwest suggesting that the thicker part of this stratum was deposited by a stream that was flowing either northwest or southeast across the southwestern part of Atkinson Mesa. (It must be noted that the relations mentioned above are based on field observations and are not fully substantiated by information being obtained from the drilling in progress on Atkinson Mesa since this report was written.

The information from drilling may require a change in the interpretations presented. It must also be noted that studies of the sedimentary structures in the vicinity of the Dolores group of mines--studies made independently by another member of the Colorado Plateau project--suggest that the sandstone strata in the ore-bearing sandstone trend northeastward instead of northwestward and were probably deposited by a stream flowing in a northeasterly direction. Field checks must be made to resolve this apparent difference in observation and, for this reason, it may also be necessary to modify the interpretations presented here.)

Within the thicker parts of the ore-bearing sandstone the carnotite deposits are grouped in about three major clusters. One cluster comprises the Black Rock and Cliff Dweller mines and adjoining deposits; the second cluster comprises the Dolores group of mines; and the third cluster comprises a few small deposits on the Atkinson Creek side of the mesa, but which are not shown on plate 4. These clusters of deposits are all beneath or near lenticular conglomeratic strata in the basal part of the Brushy Basin shale member. These strata range from 1,000 to 2,000 feet in width, and from a featheredge to a maximum thickness of about 40 feet. Sedimentary structures show that these strata were deposited by streams flowing in a general easterly or northeasterly direction.

Slick Rock area

Along the Dolores River in the vicinity of Slick Rock (pl. 5) the carnotite deposits are in relatively thick parts of the ore-bearing sandstone. These thick parts, judging from observations at the outcrop, are alined along a southeasterly trend through Slick Rock and form a belt approximately a mile wide. Current lineation on the bedding planes in the ore-bearing sandstone within this belt also shows a southeasterly trend. To the northeast and to the southwest of this belt, the ore-bearing sandstone thins.

Most of the carnotite deposits are grouped in several clusters, and each of these clusters is beneath or near lenticular strata of conglomeratic sandstone in the basal part of the underlying Brushy Basin shale. These conglomeratic strata have a general easterly trend, are 1,000 to 2,000 feet wide, and are half a mile to 1 mile apart.

If the apparent correlation of carnotite deposits to conglomeratic strata in the Brushy Basin is real, as suggested by the observations in the Slick Rock area and on Atkinson Mesa, ground favorable for carnotite deposits should occur where Brushy Basin conglomeratic strata and thick parts of the ore-bearing sandstone are in juxtaposition. These relationships might prove a useful guide in exploration for carnotite deposits, regardless of what may be the factors controlling the localization of the deposits.

Present ground-water conditions

Water table and movement of ground water

Detailed studies were made in part of the area of the Calamity group of claims, Mesa County, Colo., to determine the occurrence of ground water in the ore-bearing sandstone. Several hundred diamond-drill holes had been put down in this area by the Geological Survey. In November 1949, several months after drilling had stopped, 246 of these holes were tested for the presence of ground water, of which 202 contained water.

Plate 6 shows the drill holes that were tested for ground water and water-table contours that were drawn from the water-level measurements. This water table has a general slope of about 3 degrees SW, approximately the same slope as the dip of the rocks. The water is in the lower part of the ore-bearing sandstone and is perched on the underlying mudstone, through which little or none of it can escape by downward percolation. Discharge of this ground water occurs along the outcrop at the southern edge of the area shown in plate 6. Probably most of the water is lost by evaporation through imperceptible seeps and by transpiration through plants, but a small amount of it is concentrated in a spring (pl. 6) that flows about half a gallon a minute. Recharge probably is mainly by water that seeps into the ore-bearing sandstone from the ground surface in the Calamity group area.

A year later, in November 1950, the water levels were again measured in most of these drill holes. In about a third of the holes the water level was about 1 to 2 feet below the previous year's measurements, and in the rest of the holes the water levels were at about the same position. Although possible differences in the amount of precipitation in 1949 and 1950 would have some influence on these two sets of measurements, it seems fairly evident that the artificial recharge by the addition of drilling water during drilling operations did not materially affect local ground-water conditions and the interpretations that can be made from the observations.

The water levels in 22 diamond-drill holes (pl. 6) were measured at monthly intervals from late 1949 or early 1950 through July 1951. The monthly measurements of 10 of these holes are plotted on plate 7 to show the fluctuations of the water table. Although the water table in some of these holes, notably CA-125, CA-501, CA-505, and CA-678, shows fluctuations through the period of observation, other holes show little or no fluctuations. These data suggest that the water table near the holes showing fluctuations is being locally recharged by precipitation, probably introduced into the sandstone from fractures that are open to the surface. The lack of response in the other holes to seasonal variations in precipitation suggests that the sandstone in the immediate vicinity of these holes has a relatively low permeability.

The rate of ground-water movement through the ore-bearing sandstone can be computed by substituting the field measurements of water-table gradient; permeability, and porosity in the formula $Pm = \frac{7.48\ pv\ Ct}{I}$ where Pm is the coefficient of permeability in Meinzer's units (gallons a day per square foot); p is the porosity, expressed as a decimal fraction; v, the average velocity, is in feet per day; Ct is the temperature correction to 60° F.; I, the gradient, is in foot per foot, (Wenzel and Fischel, 1942, p. 71). Substituting the value 0.015 (darcys) times a factor of 20.5 to convert to Meinzer's units, Pm, 0.15 for p, 1.16 for Ct, and 0.0524 for I, the rate of movement is 0.01 foot per day. It is suggested that because of the joints in the cemented sandstone, the actual rate of ground-water movement through the sediments is probably greater than indicated by the permeability of the unfractured rock and the slope of the water table.

Chemical character of ground water

Twenty-four samples of ground water from the Colorado Plateau were analyzed in the laboratory of the Quality of Water Branch of the Geological Survey at Salt Lake City (table 3). These samples were collected from mines, springs, and wells (fig. 2) in the Salt Wash and Brushy Basin members of the Morrison

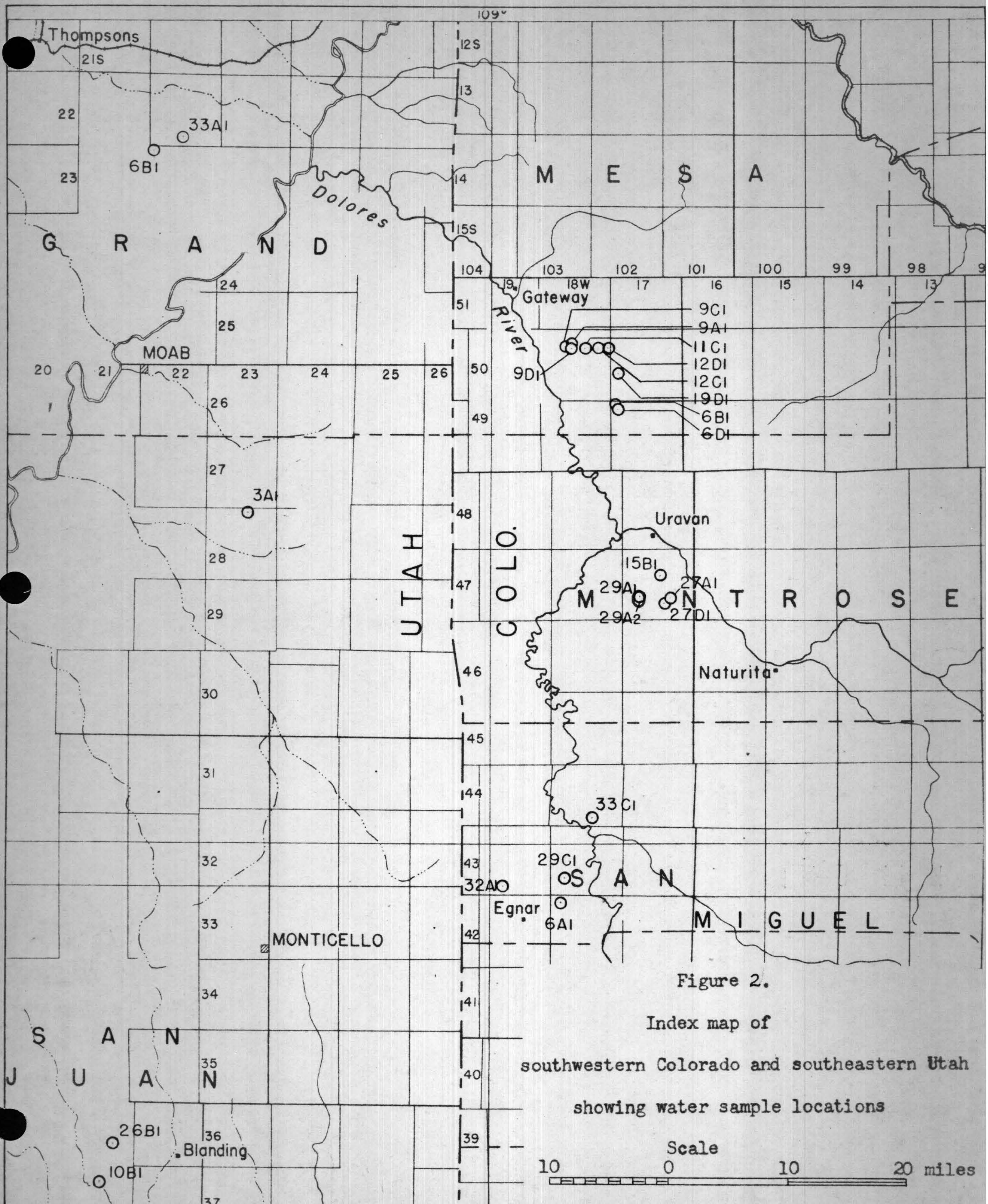

Figure 2.

Index map of

southwestern Colorado and southeastern Utah

showing water sample locations

formation. All samples from the Salt Wash were collected near ground known to be mineralized with uranium- and vanadium-bearing minerals. Samples from the overlying Brushy Basin member presumably had not percolated through or near rocks containing these ore minerals. Although the character of these waters has been described in a previous report (Phoenix, 1951), much of the data are repeated here because of the significant relationship they bear to a study of the deposits.

The uranium, vanadium, copper, lead, and selenium content of 21 of the 24 water samples were determined in the Trace Elements Section Denver Laboratory and are given in table 3. The concentration of uranium, vanadium, copper, and lead at the threshold of detection is about 0.01 ppm, whereas the concentration of selenium at the threshold of detection is 0.05 ppm. Where 0.00 parts per million is reported for selenium, it indicates less than 0.05 ppm; for the other metals it indicates a concentration of less than 0.01 ppm. As a general rule, these metals were found in amounts of less than 1 ppm, while some are present in such small amounts that they are just above the threshold of detection. Although the concentrations of these metals differed within these limits, the amounts present do not seem to correspond to other chemical variations of the ground waters.

Uranium and vanadium in small amounts were detected in all the water samples that were analyzed for these metals. The greatest amount of uranium and vanadium was detected in ground water from sumps in the Matchless mine on Maverick Mesa, Colo., and East Bank mine near Blanding, Utah. In the water from the Matchless mine sump ($50/18W\text{-}9A_1$, collected November 16, 1949), 18 ppm of uranium and 95 ppm of vanadium were detected, while water from the East Bank mine sump ($37/21E\text{-}10B_1$, collected June 24, 1950) contains 8.7 ppm uranium and 22.8 ppm vanadium. It seems likely that these waters are not representative of normal ground water, for when they were collected they were turbid with suspended minerals due to mining activity. A clean sample was later collected from the Matchless mine, and this sample ($50/18W\text{-}9A_1$, collected July 29, 1950) contains only 0.82 ppm uranium and 11.8 ppm vanadium. In the remaining 18 samples, neither metal is present in amounts greater than 1.2 ppm, while the median amount of either metal ion in the normal ground-water solution is only about 0.1 ppm.

It was expected that there might be a major difference in the uranium and vanadium content between the waters collected from the Salt Wash member and those collected from the overlying Brushy Basin member, for the Salt Wash contains practically all the ore deposits found in the Morrison formation. Differences, however, are not too striking. Three water samples from the Brushy Basin (50/18W-9D_1, 49/17W-6D_1, and 43/19W-32C_1) average 0.04 ppm uranium and 0.17 ppm vanadium. Samples of ground water from the Salt Wash, excluding samples reported from ore or from mine sumps, and exclusive of those for which a "less than" value is given, have the following average content: 0.24 ppm uranium in five samples (50/18W-9C_1, 50/18W-11C_1, 50/18W-12C_1, 49/17W-6B_1, and 47/17W-15B_1) and 0.13 ppm vanadium in two samples (49/17W-6B_1 and 36/21E-26B_1).

If Jurassic Morrison ground water originally introduced the metals to the Salt Wash, or the recent or near-recent water caused their secondary migration, and these waters were chemically comparable to the present Morrison ground water, then it seems unlikely that the metals were transported in amounts exceeding 1 ppm.

Observed secondary migration of the uranium and vanadium minerals suggested that the concentration of the uranium and vanadium ions in the ground water might bear some diagnostic spatial relationship to the ore deposits. To test this suggestion, sample 49/17W-6B_1 was collected at a spring issuing from the ore-bearing sandstone of the Salt Wash, at a point approximately 2,000 feet down dip from the nearest known ore body, and sample 47/17W-29A_1 was collected from an underground spring in the immediate vicinity of sandstone observed to be mineralized. The first sample contained 0.02 ppm uranium and 0.16 ppm vanadium while the second contained 0.2 ppm uranium and 0.1 ppm vanadium. The higher concentration of the uranium ions in the sample of ground water collected from near an ore body suggests a difference that may be directly related to the position of the deposits. However, the significance of the difference in concentration of uranium ions in the two water samples cannot be determined from the few samples available.

Visual observations of the efflorescent coating of various bicarbonate and sulfate salts around the rims of spring or seep outlets show no indication that carnotite, or some similar mineral, is being precipitated from the normal ground water. On the other hand, the carnotite observed coating many fracture surfaces in the ore-bearing sandstone, near the ore deposits, and above the present water table, shows that uranium and vanadium are migratory. It is suggested that this carnotite formed either from earlier ground water or that possible capillary water in the zone of aeration dissolves previously deposited minerals and carries uranium and vanadium a short distance before precipitation.

Copper and lead were detected in trace amounts in some of the samples collected from the ore-bearing Salt Wash sandstone. At the localities from which these waters were collected these metals are known or believed to occur in minor amounts in the uranium-vanadium ore.

Selenium is not a constituent of all samples of Salt Wash ground water. It was, however, detected in sump water collected from the Matchless mine (50/18W-9A_1), the Telluride 18 mines (23/22E-6B_1), and the Cactus Rat mine (22/22E-33A_1), as well as in water from a spring on Blue Mesa (49/17W-6B_1). One sample (50/18W-9D_1) from the Brushy Basin shale was reported to contain 0.05 ppm of selenium, an amount which is about at the threshold of detection.

The milligram equivalents, or reacting values (Palmer, 1911, p. 5), of the soluble ions, have been computed for 22 of the analyzed samples. The equivalents per million for each sample are shown graphically on plate 8 and indicate the chemical character of the water from each locality at the time the water was sampled for analysis. Of the 22 samples, 13 are classed as calcium bicarbonate water, 2 as calcium or magnesium sulfate water, 3 as sodium sulfate water, and 4 as sodium bicarbonate water. The water, therefore, differs in its reaction capacity. These differences in character are probably determined in part by the distance that the ground water has percolated through the rocks, by the composition and physical properties of the rocks, by the presence or absence of soluble salts in the paths of ground-water movement, and by the degree to which the solution has been concentrated by evaporation and plant transpiration.

Past ground-water conditions

Salt Wash time

The Salt Wash sandstone member of the Morrison formation was deposited by streams that meandered over a broad area of low relief. These streams entered the area of deposition in south-central Utah, where the Salt Wash is composed of conglomeratic sandstone. From here the streams spread northward, northeastward, and eastward, depositing lenticular sandstone strata interbedded with mudstone.

Ground-water recharge.--Ground-water recharge to the Salt Wash beds during Salt Wash time was probably largely accomplished by the downward percolation of stream water and surface precipitation. Because the conglomeratic sandstone facies in south-central Utah are probably permeable throughout and were deposited on the upper reaches of the stream profile, it is likely that the area encompassed by these sediments constituted a major area of surface-water infiltration. Water-table conditions were probably prevalent in this area, for the sediments do not contain widespread beds of shale that might have confined bodies of ground water.

The movement of ground water from the area containing the conglomeratic sandstone probably followed closely the general northerly, northeasterly, and easterly trends of the streams that deposited the Salt Wash sediments and was largely confined to the pathways of the more permeable sandstone strata. In part these strata were enclosed by mudstone, and the ground water in them was probably under some hydrostatic pressure. Immediately below the streams, however, the ground water in the sands was probably under water-table conditions, and free to fluctuate with the periodic resurgence of stream flow and variations of surface precipitation, and to move down gradient with the streams as underflow.

A break in continuity of the Salt Wash sandstone strata between Thompsons, Utah, and the southeast corner of Utah that is suggested by the lithofacies study of Mullens and Freeman (1951), and Craig, et al. (1951, pp. 28-32 and fig. 7), marks a line along which upward leakage to the surface might have occurred as the result of artesian pressure in the restricted aquifers. The upturned edges of formations along the southwest flanks of the salt domes likewise may have afforded pathways for upward leakage of ground water from sediments even older than the Salt Wash. Ground water upwelling along these belts may have added to the flow of the Salt Wash streams and to the ground water in the uppermost layers of sand. These phenomena may have been factors contributing to the localization of most carnotite deposits in the uppermost sandstone strata of the Salt Wash in southwestern Colorado.

Ground-water discharge.--The suggested environment for ground-water discharge during Salt Wash time is based upon a comparison of the geology of the Salt Wash with present-day ground-water environments. The Salt Wash environment is inferred from the following: (1) the sweeping pattern of sedimentary structures in the lenticular sandstone strata of the Salt Wash suggests a depositional environment of broad, meandering and shallow streams; (2) fine-grained mudstone and clayey sediments underlying the lenticular sandstone strata suggest that the streams, at least in southwestern Colorado and southeastern Utah, could not readily lose large quantities of water by deep percolation to underlying sandstone strata; (3) the abundance of preserved reed fragments in the Salt Wash suggests local marshy or swampy conditions in Salt Wash time throughout much of the ore producing area; and (4) sparsely preserved thorny vegetation suggests an arid to semi-arid climate. By analogy of these data and seemingly justifiable conclusions with present-day ground-water environments it seems logical to assume that throughout Salt Wash time and at least in the area of southwestern Colorado and southeastern Utah, shallow water-table conditions prevailed; moreover, evaporation and plant transpiration were major processes contributing to ground-water discharge.

Chemical character.--In the area of ground-water recharge it seems likely that Salt Wash streams initially carried some free carbon dioxide. Reaction of this slightly acid solution with the sediments of the Salt Wash aquifers probably increased the mineral content of the water. As this water progressed farther from the area of recharge and was in contact with the sediments for greater periods of time, the total dissolved solids probably gradually increased. Locally, the solution of the salt plugs probably added considerable salts to the ground water. Evaporation from the water table and plant transpiration undoubtedly played an important role in further concentrating the solution. The liberation of carbon dioxide in local areas of buried and decaying plant vegetation to the ground water probably changed the reaction capacity of the ground water locally.

The large amounts of calcite cement in the Salt Wash sandatone in southeastern Utah and southwestern Colorado suggest that in this area the Salt Wash ground water at some time probably carried both calcium and bicarbonate ions in large amounts. Moreover, the embayed and etched borders of the quartz grains suggest that these solutions at some time were alkaline. Gypsum, barite, quartz overgrowths, and various iron oxide minerals cementing the sediments indicate that Salt Wash ground water probably carried the ions of the elements composing these minerals. Ions of the more soluble salts such as sodium, chloride, and potassium were probably present in the water but are believed to have been carried from the rocks by renewed ground-water circulation in the late Tertiary. A more comprehensive thin-section analysis of the ore-bearing sandstone than has been undertaken by the present work should reveal many of the chemical changes that Salt Wash ground waters have undergone.

If uranium and vanadium were carried in solution by ground waters during Salt Wash time, evaporation and transpiration probably played an important role in increasing the concentration of these metals in solution and thus perhaps contributed to their ultimate precipitation.

Brushy Basin time

The regional and local direction of ground-water movement in the permeable Salt Wash sandstone strata is believed to have followed the trend and courses of the streams during the initial stages of Brushy Basin deposition. These streams are believed to have entered southeastern Utah and southwestern Colorado flowing in a general northeasterly and easterly direction from south-central Utah and north-central Arizona.

The local direction of ground-water movement below the Brushy Basin streams was dependent upon whether the streams were influent or effluent. If the streams were influent, they were contributing water to the zone of saturation, and ground water was moving down the stream channel with a component direction outward from the overlying stream. If the streams were effluent, they were receiving water from the zone of saturation, and ground water was moving toward and down the stream channels. Effluent ground water seepage is suggested to be the most likely, for the gradual encroachment of fine-grained sediments over the Salt Wash terrain in the basin of Brushy Basin deposition would probably prevent leakage from the extremities of the Salt Wash aquifers. Hydrostatic pressure, resulting from the slope of deposition of these confined aquifers may have been sufficient to force ground water upward into the Brushy Basin streams. Later in Brushy Basin times the gradual encroachment of fine-grained and impermeable sediments over the permeable Salt Wash sediments gradually inhibited the movement of ground water. At the close of Brushy Basin time ground water in the Salt Wash was presumably confined.

The grouping of ore deposits below the basal conglomerate of the Brushy Basin may be related to the movement of ground water below the early Brushy Basin streams. Under conditions of influent seepage, the metals may have been introduced to the Salt Wash sandstone by downward percolation of mineralized surface and ground waters accompanying the deposition of the Brushy Basin conglomerate. Under conditions of effluent seepage, mineralized ground-water solutions at the top of the Salt Wash could have been enriched locally in the process of underflow and migration toward the stream channels.

Cretaceous time

Cretaceous sedimentation began with the accumulation of a relatively thin but widespread aggregate of continental sandstone and shale followed by a thick sequence of marine shales, and ended with a thick assemblage of sandstone and shale and some coal. These sediments accumulated in a basin of deposition that extended far beyond the general area of carnotite-bearing Salt Wash, and this basin probably sank gradually and acted as a single tectonic unit with little or no local deformation during Cretaceous time.

During Cretaceous time water contained in the Salt Wash beds probably was immobile or nearly so and was protected from ready escape or contamination by the overlying relatively impervious beds as well as by hydrostatic pressure.

Tertiary and Quaternary time

Ground water in the Morrison formation was profoundly influenced by the complex events that took place in the Tertiary and no doubt its circulation, hydrostatic pressure, temperature, and composition were influenced by faulting, folding, and the intrusion of igneous rocks. However, it is difficult, if not impossible, to decipher the local or even regional complexities of the Tertiary ground-water conditions without a more complete knowledge of the Tertiary events that affected the Morrison formation. Only the broadest generalization and conjecture can be made until more data become available.

The regional uplift and broad folding in the early Tertiary decreased artesian heads on the crests of the broad anticlines and increased heads in the synclines. The temperature of the Salt Wash ground water was probably similarly affected. Faulting accompanying this folding may have allowed ground water to percolate upwards from deeply buried aquifers below the Salt Wash, but it seems unlikely that widespread lateral movement was possible because the Salt Wash sandstone aquifers are highly lenticular.

If the Salt Wash ground water moved, it did so very slowly--probably even slower than it is in the rocks that now yield water to wells and springs. Part of this movement may have been very slow seepage into or from overlying clay strata.

Intrusion of the laccoliths was probably both preceded and accompained by thermal and pressure effects on the ground water in the overlying and flanking sediments. Salt Wash ground water in the vicinity of the intruding bodies probably attained temperatures and pressures in excess of those realized at any earlier time. The temperature probably diminished away from the centers of igneous activity. Thermal currents may have sufficiently influenced the ground water to cause mixing and exchange over wide areas encircling the intrusive bodies, but this seems unlikely because of the lenticularity of the permeable sandstone strata of the Salt Wash. The introduction of large amounts of hydrothermal solutions to the Salt Wash ground water seems unlikely for the rocks in contact with the igneous bodies are nowhere greatly affected by hydrothermal alteration, (Gilbert, 1880, p. 60; Hunt, 1946, p. 17). Likewise, the widespread upward percolation of hydrothermal solutions probably would have been impeded by clay strata below the ore-bearing sandstone of the Salt Wash as well as by the plastic salt and gypsum of the Paradox formation.

Erosion of the sediments in the Colorado Plateau during the late Tertiary and Quaternary exposed the Salt Wash. Ground water was discharged, at first locally, and then as erosion progressed, along increasingly large areas of exposure. Recharge on the higher exposures was affected in a similar manner, with, at first, only local recharge followed by recharge over increasingly large catchment areas. Uniform ground-water movement over large areas was not possible for the lenticular character of the sandstone strata and the folds, faults and joints imposed upon these strata created numerous local ground-water barriers as well as pathways throughout the region of southwestern Colorado and southeastern Utah.

CONCLUSIONS

Principles of ground-water movement, enrichment, and localization can be applied to the interpretation of the origin of the uranium deposits of southwestern Colorado and southeastern Utah. These principles strongly suggest the influence of parts of the hydrologic cycle for formation of the deposits.

The environment of Salt Wash deposition favored the enrichment and localization of metal-bearing ground water in the ore-bearing beds. A vast supply of ground water continuously replenished by recharge from streams, and continuously enriched by evaporation and plant transpiration was present in the Salt Wash throughout the period of its deposition. Furthermore the majority of the Morrison uranium deposits are clustered in restricted bodies of permeable sandstone far out on the Salt Wash lobe of continental sediments where mineralized waters could accumulate but not readily escape.

Some aspects of Brushy Basin deposition also favor the enrichment and localization of metal-bearing ground water in the ore-bearing beds. Localization of the carnotite deposits below conglomerate strata at the base of the Brushy Basin member suggests the possibility that underflow either accompanying influent or effluent ground-water seepage may have been responsible for introduction and localization of the metals.

Widespread deposition of the clayey sediments of the Brushy Basin followed by a thick series of Cretaceous sediments, some of which are marine, inhibited ground-water movement in the Salt Wash and hence restricted the opportunity for concentration and localization of the metals in a ground-water environment. Events during the Tertiary offered little opportunity for the introduction of the metals to the ground water in the Salt Wash except possibly from contamination by hydrothermal solutions. Even with such possible contamination, it is difficult to conceive of sufficient migration of the ground water to account for the wide geographic distribution of the deposits and their restricted stratigraphic position.

The recent ground water on Calamity Mesa is perched on mudstone at the base of the ore-bearing sandstone. The water table, usually not more than 3 feet above the mudstone, slopes in the direction of the dip of the rocks; ground-water movement is largely along joints. Ground water is replenished by the infiltration of precipitation; discharge is by spring flow, evaporation, and transpiration. These ground-water conditions are believed to by typical for the isolated mesas in southwestern Colorado and southeastern Utah.

Analyses of the recent Morrison ground water indicate that, although these waters vary in chemical character, they normally contain only very small amounts of uranium or vanadium. If the Jurassic Morrison ground water that is believed to have originally introduced the metals to the Salt Wash was chemically comparable to the present Morrison ground water, then it seems unlikely that the metals were transported in amounts exceeding 1 ppm.

PLANS

Regardless of what may be the source of the ore-bearing solutions, their time of introduction into the beds, and the age of formation of the ore deposits, evidence shows that the permeability of the ore-bearing beds is an important factor in the migration of mineralized solutions and the localization of carnotite deposits.

In order to test the capacity of rocks on the Colorado Plateau to transmit ore-bearing solutions to the sites of the known deposits, in all ore-bearing formations, and at various times during the geologic history, a study of the horizontal and vertical transmissibility relations of all of the exposed sedimentary formations on the Colorado Plateau will be undertaken by the Survey. These formations will be sampled at selected points over a broad area to establish the porosity and permeability of these samples, and to determine the local transmissibility of the various stratigraphic units. By coordinating this information with general knowledge regarding the lithology and the sedimentary and structural characteristics of these beds, it is expected that the general transmissibility characteristics of each formation can be determined for relatively broad areas. This information will then be coordinated with available information regarding the structural history of the Colorado Plateau since Morrison time, to relate the abundance and location of regional structural features that may have served as through-going vertical channels for the introduction of ore-bearing solutions, either ascending or descending, into the various ore-bearing formations on the Colorado Plateau. It is hoped also that this study will show whether or not the ore-bearing formations offer the most permeable routes for the horizontal migrations of solutions, and what their capacity for horizontal migration might be over short distances and over distances of many miles. These findings may indicate whether or not it is possible for the ore-bearing solutions to have come up through vertical channels into the Salt Wash member and to have migrated laterally along the sandstone beds to the points of ore deposition. Detailed studies of pertinent related problems will have to be undertaken in the field and in the laboratory.

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Location and number 3/ 4/ 5/	Source and date of collection	PARTS PER MILLION: Silica (SiO_2)	Iron (Fe) (in solution)	Iron (Fe) (total)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K) and Manganese (Mn) 6/	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Uranium (U) 7/	Vanadium (V) 8/	Copper (Cu) 8/	Lead (Pb) 8/	Selenium (Se)	DISSOLVED SOLIDS: Sum-p. p. m.	Sum-tons/acre ft.	HARDNESS 2/ AS $CaCO_3$: Total	Noncarbonate	Specific conductance (Microhms at 25° C.)	Percent sodium 9/	Laboratory pH	Remarks
50/17W-19D1 3812 B-2	Outlaw Mesa, dug well. 11/15/49	23	0.10	.16	84	88	65	7.6	620	105	64	0.7	0.2	0.04	0.0	<.1	0.06	0.03	0.00	743	1.01	572	64	1,230	20	7.5	Ore-bearing sandstone, 30 ft. down dip from mined ore body. Sediment analyzed 10/.
50/18W-9A1 3811 B-4 11/ B-17 12/	Maverick Mesa, Matchless mine sump. 11/16/49 7/29/50	13/ 22	.07	14/ 99	524	389	58	15/ n.d.	479	2,310	165	.9	16/	17/	18.0 .82	95.0 11.8	.01 .00	.03 .00	12.50 3.13	3,700	5.03	2,910	2,510	4,410	4	6.8	Seep from mineralized sandstone. B-4 sediment analyzed 10/.
50/18W-9C1 3810 B-3	Maverick Mesa, spring. 11/16/49	15	.05	.12	56	50	129	13.0	483	119	69	.6	.9	.08	.1	<.1	.03	.17	.00	690	.94	345	0	1,100	44	8.0	Ore-bearing sandstone (?). Sediment analyzed 10/.
50/18W-9D1 6402 4/51	Maverick Mesa, spring. 4/12/51	15	.01	n.d.	41	36	123	9.6	509	63	24	.7	3.3	.03	.05	.09	.00	.00	.05	566	.77	250	0	908	50	8.1	Basal conglomerate of Brushy Basin. Temp. 54° F.
50/18W-11C1 4536 B-5	Calamity Mesa, spring. 4/18/50	16	.03	.04	62	57	33	4.8	408	65	40	.5	4.7	.06	.3	<.1	.00	.00	.00	484	.66	389	54	820	15	7.5	Base of ore-bearing sandstone. Temp. 50° F.
50/18W-12C1 3813 B-1	Outlaw Mesa, spring. 11/16/49	20	.05	.06	82	49	32	4.2	417	59	36	.5	5.6	.02	.2	<.1	.07	.06	.00	494	.67	406	64	807	14	7.7	Ore-bearing sandstone 100 feet down dip from mined ore body. Sediment analyzed 10/.
50/18W-12D1 4537 B-6	Outlaw Mesa, Ronnie No. 1 mine, underground spring. 4/19/50	13	.03	n.d.	62	35	11	3.0	344	23	14	.3	4.1	.04	0	<.1	.00	.00	.00	335	.46	298	16	584	7	7.9	Top of ore-bearing sandstone. Temp. 50° F.
49/17W-6B1 6321 2/51	Blue Mesa, spring. 3/31/51	11	.02	n.d.	30	37	68	8.0	18/ 391	32	18	.4	4.1	.03	.02	.16	.00	.00	<.05	401	.55	227	0	669	38	8.1	Ore-bearing sandstone, 2,000 ft. down dip from nearest known ore body. Field pH 6 19/.
49/17W-6D1 6322 3/51	Blue Mesa, spring. 3/31/51	9.6	.07	.18	5.8	12	847	11.0	20/ 1,900	296	55	2.6	3.8	.40	.06	.30	.05	.00	<.05	2,180	2.96	64	0	3,270	96	9.4	Brushy Basin sandstone. Field pH 9.
47/17W-15B1 4686 B-8	Long Park area, spring. 5/28/50	12.0	.07	.19	50	67	92	8.7	425	192	33	.2	1.2	.02	.6	<.1	.00	.00	.00	666	.91	400	52	1,030	33	7.9	Base of ore-bearing sandstone. Temp. 52° F.
47/17W-27A1 6317	Long Park area, dug well. 3/23/51	15	.03	.07	97	104	318	16.0	354	798	171	.7	.2	.06	n.d.	n.d.	n.d.	n.d.	n.d.	1,690	2.30	670	380	2,360	50	8.0	Brushy Basin sandstone. Temp. 38° F. Field pH 6-7.
47/17W-27D1 4685 B-7	Long Park, Long Park No. 10 mine, ore chute 5/28/50	13	.82	1.24	62	33	17	3.2	245	77	18	.4	15.0	.00	.3	1.2	.00	.00	.00	360	.49	290	89	576	11	7.7	Ore-bearing sandstone. Temp. 53½° F.
47/17W-29A1 4687 B-10	Long Park, Henry Clay mine, underground spring. 5/27/50	14	.09	.15	86	43	19	5.9	406	43	34	.3	6.1	.01	.2	<.1	.00	.00	.00	451	.61	392	59	740	9	7.7	Mineralized sandstone. Temp. 45½° F.
47/17W-29A2 4688 B-9	Long Park, Henry Clay mine sump. 5/27/50	10	.11	.26	59	43	20	6.1	317	48	37	.3	6.2	.02	.6	<.1	.00	.00	.00	386	.52	324	64	655	12	7.7	Mineralized sandstone.
44/18W-33C1 6318	Joe Davis Canyon, spring. 3/24/51	9.9	.04	n.d.	41	13	360	8.8	528	435	61	1.0	.3	.07	n.d.	n.d.	n.d.	n.d.	n.d.	1,190	1.62	156	0	1,730	82	8.1	Brushy Basin sandy shale. Field pH 7.
43/19W-32C1 6319 1/51	Bishop Canyon, Strawberry Spring. 3/24/51	16	.05	n.d.	88	34	203	4.4	506	212	113	.3	.1	.09	.02	.12	.00	.00	<.05	920	1.25	360	0	1,420	55	7.9	Basal conglomerate of Brushy Basin. Field pH 7.
43/18W-29C1 4733 B-11	Spud Patch, May Day mine sump. 6/26/50	17	.04	n.d.	64	16	27	4.8	226	42	30	.4	1.7	.04	<.1	<.1	.00	.33	.00	314	.43	226	40	523	20	7.7	Mineralized sandstone. Temp. 44° F. Field pH 6.
42/18W-6A1 6320	Spud Patch, dug well. 3/24/51	20	.07	n.d.	98	103	118	6.6	554	158	198	.3	14.0	.03	n.d.	n.d.	n.d.	n.d.	n.d.	989	1.35	668	214	1,610	27	7.7	Quaternary alluvium derived from Brushy Basin shale member (?). Field pH 7.
37/21E-10B1 4735 B-13	Blanding district, East Bank mine sump. 6/24/50	13	.11	.25	116	114	179	10.0	480	631	91	.4	1.9	n.d.	8.7	22.8	.00	.00	.00	1,400	1.90	758	364	1,990	34	7.4	Mineralized sandstone. Temp. 47° F. Field pH 7.
36/21E-26B1 4734 B-12	Blanding district, A.E.C. diamond-drill hole No. BA-6 6/24/50	13	.02	n.d.	77	53	128	6.4	378	353	27	.2	.2	.00	<.1	<.1	.00	.00	.00	844	1.15	410	100	1,250	40	7.7	Ore-bearing sandstone. Temp. 56° F. Field pH 6.5.
28/23E-3A1 4779 B-16	Yellow Circle district, Yellow Circle mine spring. 6/28/50	12	.03	n.d.	38	59	10	4.6	365	28	24	.4	5.4	.02	.2	<.1	.00	.50	.00	361	.49	338	38	647	6	8.3	Mineralized sandstone. Temp. 58° F.
23/22E-6B1 4777 B-15	Yellow Cat district, Telluride No. 18 mine sump. 6/29/50	11	.20	n.d.	89	20	129	6.1	202	388	13	.4	2.6	.04	.8	<.1	.00	.04	1.00	759	1.03	304	138	1,100	47	7.9	Mineralized sandstone. Temp. 50° F.
22/22E-33A1 4778 B-14	Cactus Rat mine, 20 foot adit. 6/29/50	10	.03	n.d.	101	15	343	3.4	205	806	47	.3	5.8	.02	.2	<.1	.00	.02	7.87	1,430	1.94	314	146	2,030	70	7.9	Ore-bearing sandstone, 50 ft. below mineralized sandstone. Temp. 56° F. Field pH 6.5-7.
Threshold of detection for the ions.		n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	.01	.01	.01	.01	.05								

1/ Analyses for U, V, Cu, Pb, Se, and of sediment by George J. Petretic or Lewis F. Rader, Jr., Geochemistry and Petrology Branch, Geologic Division, U. S. Geological Survey. Analyses for other constituents by E. L. Singleton, W. M. Webster, and E. F. Williams, Quality of Water Branch, Water Resources Division, U. S. Geological Survey.

2/ Total hardness is the sum of all the constituents causing hardness; noncarbonate hardness is the sum of all the constituents but carbonate causing hardness. The two hardnesses are, by common practice, expressed as "Hardness as $CaCO_3$."

3/ Field number (example: 50/17W-19D), Geologic Division, U. S. Geological Survey, indicating township (50), range (17 west), section (19), and quarter section (A, B, C, or D lettered counter-clockwise from the NE¼).

4/ Salt Lake City Laboratory number (example: 3812), Quality of Water Branch, U. S. Geological Survey.

5/ Denver Trace Elements Laboratory number (example: B-2 or 1/51), Geochemistry and Petrology Branch, U. S. Geological Survey.

6/ 0.29 p. p. m. manganese detected in sample, 42/18W-6A1. Other samples 0.00 p. p. m.

7/ Method of determination: Fluorimetric.

8/ Method of determination: Colorimetric.

9/ Percent sodium is obtained by dividing the total milligram equivalents into the sodium milligram equivalents.

10/

Lab. No.	Sediment (p. p. m.)	UO_3 %	V_2O_5 %	Fe_2O_3 %*	CaO %**	K_2O %**
B-1	5.4	0.5	1.7	4.9	1.0	1.4
B-2	2.2	0.11	1.4	9.4	5.6	2.5
B-3	7.7	0.1	1.8	1.7	0.2	0.5
B-4	39.5	6.4	14.4	3.9	0.2	1.3

* Method of determination: Colorimetric.
** Method of determination: Flame photometric.

11/ Sample collected from sludge pit in drift. Water contaminated by drill sludge. Source: Underground seep from face of ore.

12/ Sample collected from flooded winze. Water uncontaminated by drill sludge. Source: Underground seep from face of ore.

13/ On addition of HCl, yellow color developed, but faded after standing.

14/ Iron and aluminum oxide Fe_2O_3+Al_2O_3. Total includes 2.4 p. p. m. Fe_2O_3.

15/ n.d. - not determined.

16/ Deep blue color developed on addition of phenodisulphonic acid to evaporated sample. Color disappears with addition of H_2O. Deep yellow developed with NH_4OH.

17/ Unable to determine (B) green-yellow color.

18/ Includes 7.9 p. p. m. CO_3.

19/ Field pH as determined by "Hydrion" paper.

20/ Includes 311 p. p. m. CO_3.

< Less than

Compiled by David A. Phoenix

Table 3.--ANALYSES OF GROUND WATER FROM WELLS, SPRINGS, AND MINES IN THE MORRISON FORMATION 1/

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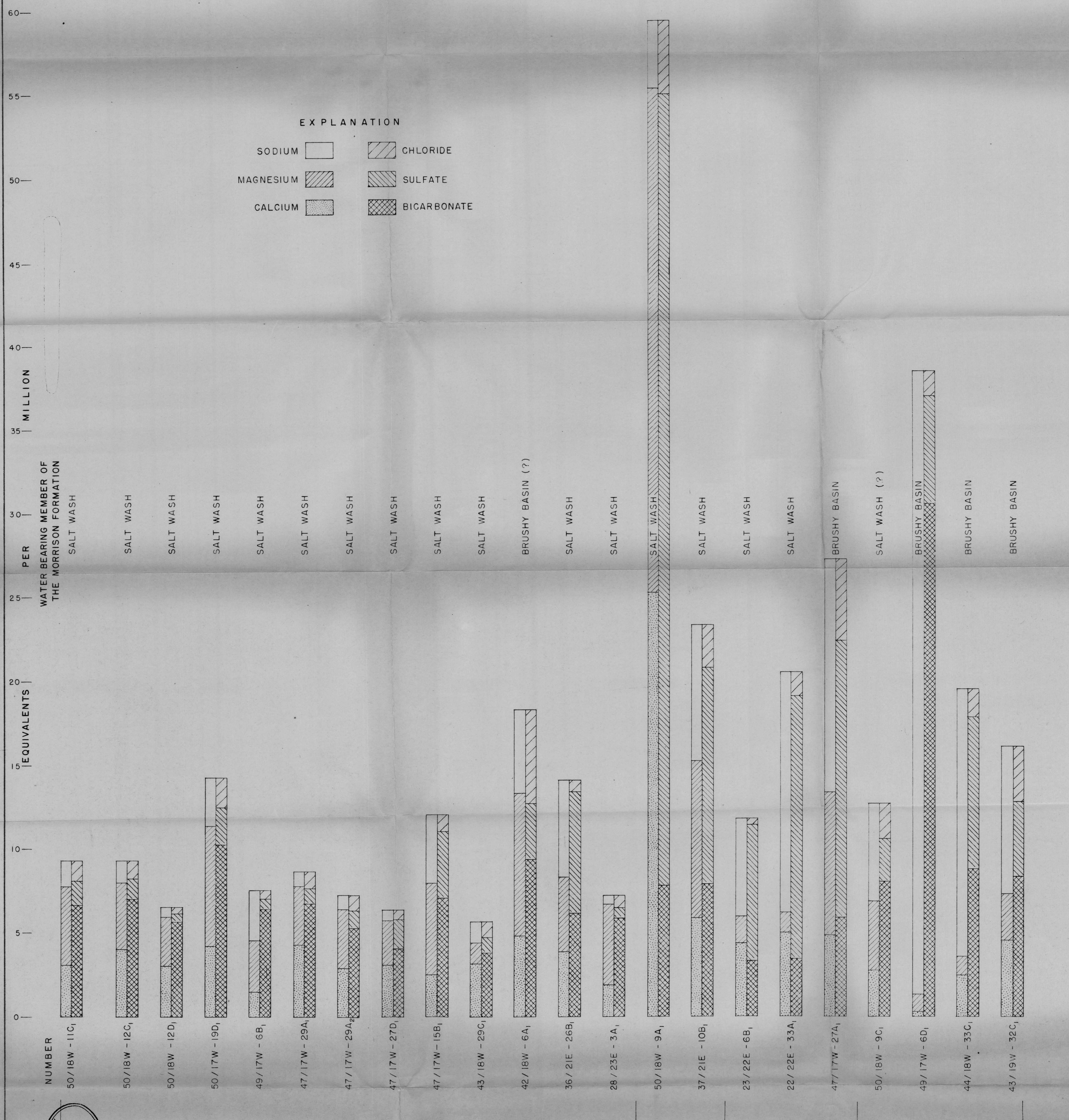

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Plate 8.--BAR GRAPH SHOWING ANALYSES OF GROUND WATER FROM THE MORRISON FORMATION IN EQUIVALENTS PER MILLION

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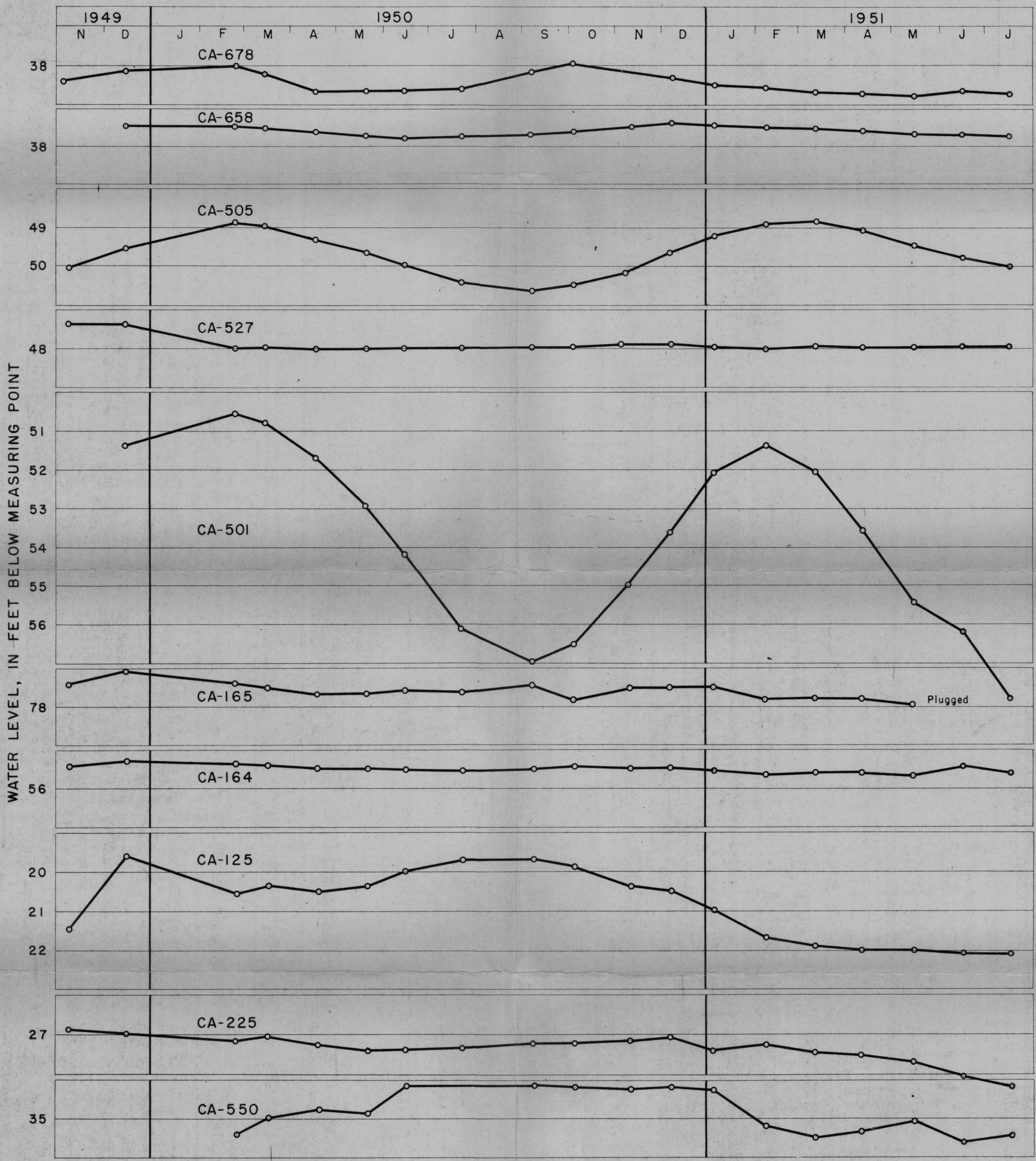

Plate 7.--HYDROGRAPHS OF WATER-LEVEL MEASUREMENTS IN 10 WELLS, CALAMITY GROUP AREA, MESA COUNTY, COLO., NOVEMBER 1949 TO JULY 1951