UTAH GEOLOGICAL AND MINERALOGICAL SURVEY
AFFILIATED WITH
THE COLLEGE OF MINES AND MINERAL INDUSTRIES
UNIVERSITY OF UTAH
SALT LAKE CITY, UTAH

Uranium-Vanadium Deposits Of the Thompsons Area Grand County, Utah

WITH EMPHASIS ON THE

Origin of Carnotite Ores

BY

WM. LEE STOKES

FEB. 28TH
MDCCCL

Published with the aid of a grant from the
University of Utah Research Fund

Bulletin 46 December, 1952

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FOREWORD

This bulletin is a masterful treatment of the intricate relationships observed in the uranium-vanadium deposits of the Thompsons area. In his characteristically scholarly fashion, Dr. Stokes has marshalled the evidence which to him indicates the close connection between the carnotite-type of uranium-vanadium ores and the accumulation of fossil plant remains in his area. To him this connection is not merely coincidental. It will be difficult for those familiar with the problem to doubt the validity of Stokes' reasoning.

According to Stokes, most of the vanadium and uranium in the Salt Wash member of the Morrison formation probably accumulated soon after the deposition of this member. For this conclusion he has also marshalled cogent evidence. Yet there is always the lurking suspicion that in view of the known migratory nature of these and related uranium and vanadium compounds, their implatation in the country rock might have occurred at a considerably later period of time along the same old pervious channels which Stokes so clearly shows were inherited from the aggrading streams of Salt Wash time. Several attempts have been made by others to fix the age of uranium deposition in the Colorado Plateau by radioactive methods. By this approach, it should be possible eventually, with improved techniques, to remove all reasonable doubt concerning the age of mineralization.

There is another and larger speculative problem about which the reader will wish that Dr. Stokes had given some inkling of his views. Whence came this flood of peculiar radioactive material? What was its original source? And how was it first removed from its matrix, rendered soluble, incorporated in the solutions which permeated the Salt Wash channel-fills, and redeposited as carnotite?

Since Dr. Stokes has shown quite conclusively that the streams which deposited the Salt Wash member of the Morrison formation in the Thompsons area came from the southwest and traveled toward the northeast, it must necessarily follow, if the ore minerals were precipitated by ground waters prior to lithification and the deformation of the beds, that the principal source of the uranium-vanadium minerals was from a southwesterly direction. One cannot help but speculate, if this be true, as to why it might not be scientifically justifiable, if not economically profitable, to prospect more intensively the area to the southwest. One might expect that the Morrison, the Entrada, the Chinle, and the Shinarump formations of southwestern Utah (of Wayne, Garfield, Kane, and Washington counties, where some of these formations are well-exposed), might offer some possible clues. Those interested in this aspect of the problem will find corroborative data of unusual significance in Bulletin 44 of this series by Dr. Paul Dean Proctor. (See list in the back of this bulletin.) One might also be tempted to explore carefully the Paleozoic and pre-Cambrian formations lying to the southwest as possible sources of the pre-existing uranium-vanadium minerals. Could these minerals have been derived from the pre-Cambrian complex of the Beaver Dam and Virgin ranges? Or did they come from still other land masses now hidden under mantles we cannot penetrate? Was there an intermediate rock sequence (analogous to the Phosphoria of northern Utah, Idaho Wyoming and Montana) which captured these elusive metals from the sea and effectively entombed them with disseminated phosphates until exhumed by erosion, decomposed by long continued weathering, and finally made available for reconcentration in late Jurassic time? All this to Dr. Stokes is pure speculation outside the evidence accumulated by his study. He is not given to letting his fancy outrun his facts. His field work was done eight years ago. Obviously, much of it is out of date, even before it is published, when compared with more recent studies of the Atomic Energy Commission. Had an earlier release been feasible, science would have benefited accordingly.

Fortunately, Dr. Stokes is still young, vgiorous, and active; he is thorough, and omnivorous in his reading of accumulated evidence and in his observation of field data. Let us hope that someday he may feel justified in enlarging upon the story he has here so tantalizingly placed before us.

ARTHUR L. CRAWFORD, Director
Utah Geological and Mineralogical Survey

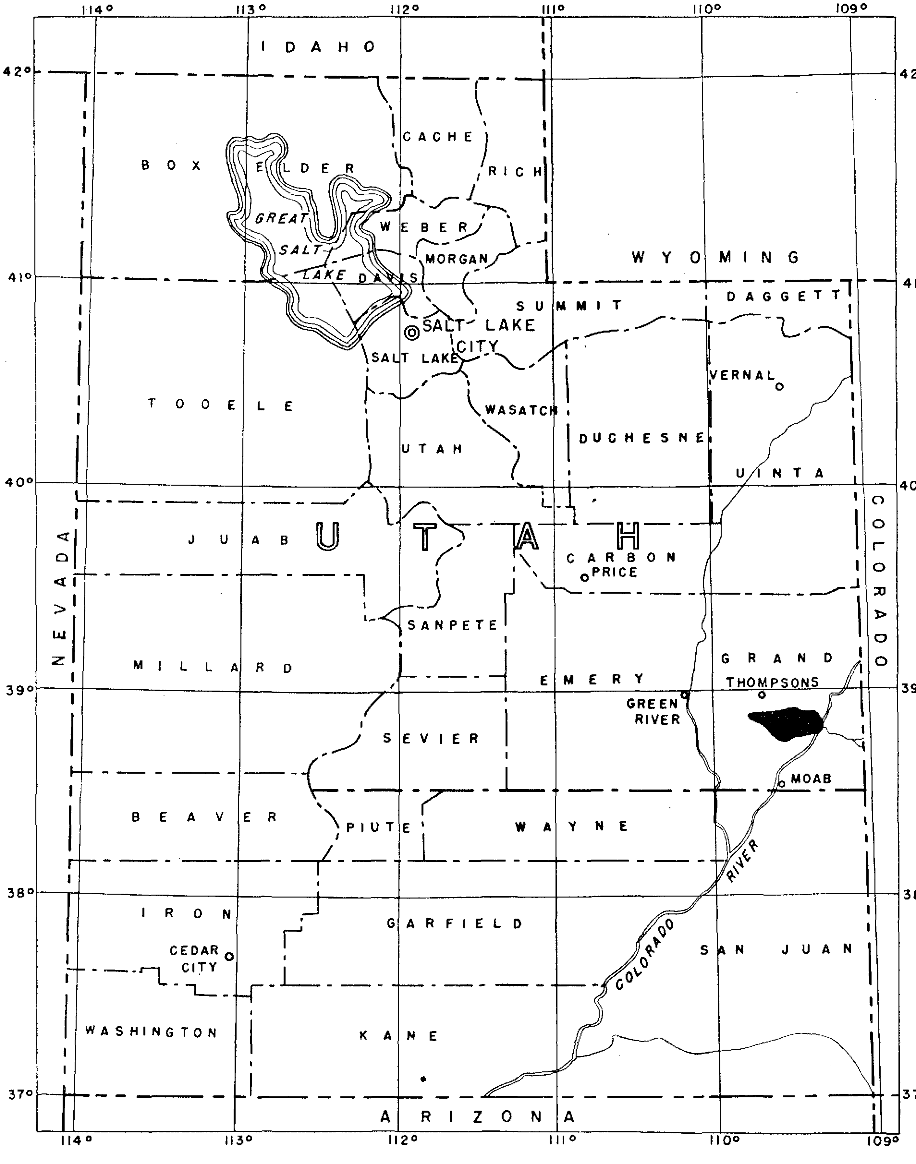

FIGURE I INDEX MAP OF UTAH SHOWING LOCATION OF THOMPSONS AREA

URANIUM - VANADIUM DEPOSITS

OF THE THOMPSONS AREA, GRAND COUNTY, UTAH WITH EMPHASIS ON THE ORIGIN OF CARNOTITE ORES[1]

By Wm. Lee Stokes[2]

ABSTRACT

The Thompsons area of about 200 square miles occupies most of the northeast flank of the Salt Valley anticline in north-central Grand County, Utah. The area has been a contributor of uranium and vanadium ores since about 1911. Exposed sedimentary rocks include the Navajo, Carmel, Entrada, Summerville, Morrison, Cedar Mountain, Dakota, and Mancos formations. The Morrison formation, which contains the ore deposits, consists of a lower unit, the Salt Wash sandstone member and an upper unit, the Brushy Basin shale member. Paleontology, paleogeography, and lithologic features of the Morrison formation indicate a fluvial origin on an aggrading flood plain.

The ore bodies consist of a concentration of various uranium and vanadium minerals in sand lenses. Most of the ore minerals occupy pore spaces in the sandstone. The largest and richest ore bodies are elongate and crudely semicylindrical "rolls" that occur in groups in the sand lenses. Studies of cross-bedding in the area show that the long axes of rolls are parallel to the direction of flow of the water that deposited the enclosing sandstone. The ore is nearly always accompanied by organic material of some kind, by limonite staining in associated sandstones, and by blue-green color alterations in the mudstones below the deposits.

It is assumed that the ore minerals were deposited from ground water in the vicinity of decaying organic materials shortly after the enclosing sandstones accumulated. As organic material seems to be essential to ore formation, considerable attention has been given to factors that favor the accumulation of plant material on flood plains.

It is concluded that the edges of thicker sand channels, especially along meander curves, are favorable sites for plant accumulation and hence for the formation of ore deposits.

INTRODUCTION

Deposits of uranium and vanadium near Thompsons, Grand County, Utah, have been mined intermittently since about 1911. Previous to 1923, the deposits were exploited mainly for uranium and the associated radium contained in the higher-grade ore. Discovery of the rich uranium deposits of the Belgian Congo in 1915 caused an almost complete cessation of mining activity in the region until about 1939. Subsequently, the deposits have been intensively worked for both uranium and vanadium, with emphasis shifting mainly to uranium since 1945.

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[1] Publication authorized by the Director, U. S. Geological Survey.

[2] Geologist, U. S. Geological Survey, Associate Professor, University of Utah.

The United States Geological Survey initiated a program of study in the Thompsons area in 1942 as part of a survey of domestic vanadium reserves; in subsequent years geologic studies have been made at various times in the area as part of the expanded program of research on radioactive materials. The present bulletin deals mainly with the stratigraphy of the area, the relation of the ore deposits to the larger features of the associated sedimentary rocks, and tentative suggestions as to possible guides to unexposed ore deposits.

Investigations of the area by the U. S. Geological Survey were under the direction of R. P. Fischer. The pertinent geologic features of the area were mapped on aerial photographs by the author in October and November 1943 and November 1944. A topographic map of the Yellow Cat claims, which include most of the important deposits of the area, was made by R. P. Rischer, D. C. Duncan, and the author in November 1943. Geologic features and ore deposits of the Yellow Cat area were added to the topographic map by the author and L. E. Smith in November 1944. The Red Vanadium and Flat Top claims were mapped and studied by members of the U. S. Geological Survey in 1943 in conjunction with a cooperative diamond-drilling project carried out by the Geological Survey and the U. S. Bureau of Mines.

The Thompsons area embraces about 200 square miles of territory in the Canyon Lands subdivision of the Colorado Plateau. Cuestas and dip slopes with moderate relief and dissection are the most common land forms in the area. Altitudes range from 4,090 feet at the junction of the Dolores and Colorado rivers to 5,450 feet on a high point at the northwest corner of the area. With the exception of the Colorado River, there are no perennial, through-flowing streams. There are a few springs of saline water that are adequate for most mining purposes, but culinary supplies are usually hauled from outside sources. Rainfall is light; the U. S. Weather Bureau records taken at Thompsons show an annual average precipitation of approximately 8.5 inches over a period of 33 years. Winters are not rigorous, and as both open-cut and underground mining are possible, operations of one type or the other can continue throughout the year. Vegetation is scanty and the area is primarily a winter grazing range for sheep.

A ranch near Dewey Bridge is the only permanent habitation in the area. Thompsons and Cisco, stations on the Denver & Rio Grande Railroad lie respectively 6 and 8 miles due north of the northern edge of the area, the distance from Thompsons to the chief mines being about 18 miles by road. Practically all of the ore so far mined has been trucked to Thompsons and then transferred to freight cars to be shipped to mills in Colorado. Several secondary roads lead from U. S. Highway 50 into various parts of the area, so that most of the mining properties are accessible by truck.

STRATIGRAPHY

Rocks exposed in the area consist entirely of sediments of Jurassic and Cretaceous age. The nearest outcrops of igneous and matamorphic rocks are those of pre-Cambrian age in Ryan Creek about 8 miles east of the east end of the area; intrusive rocks are exposed in the La Sal Mountains, roughly 25 miles to the southeast. An excellent discussion

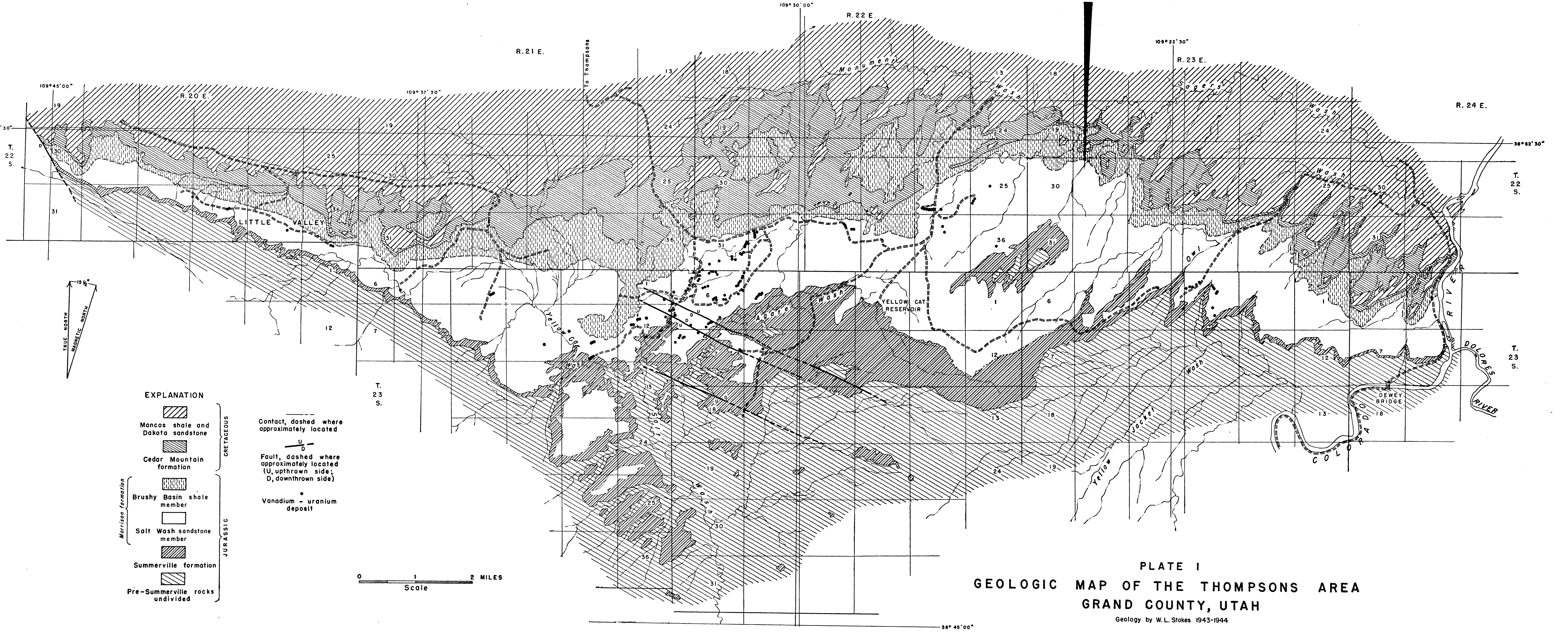


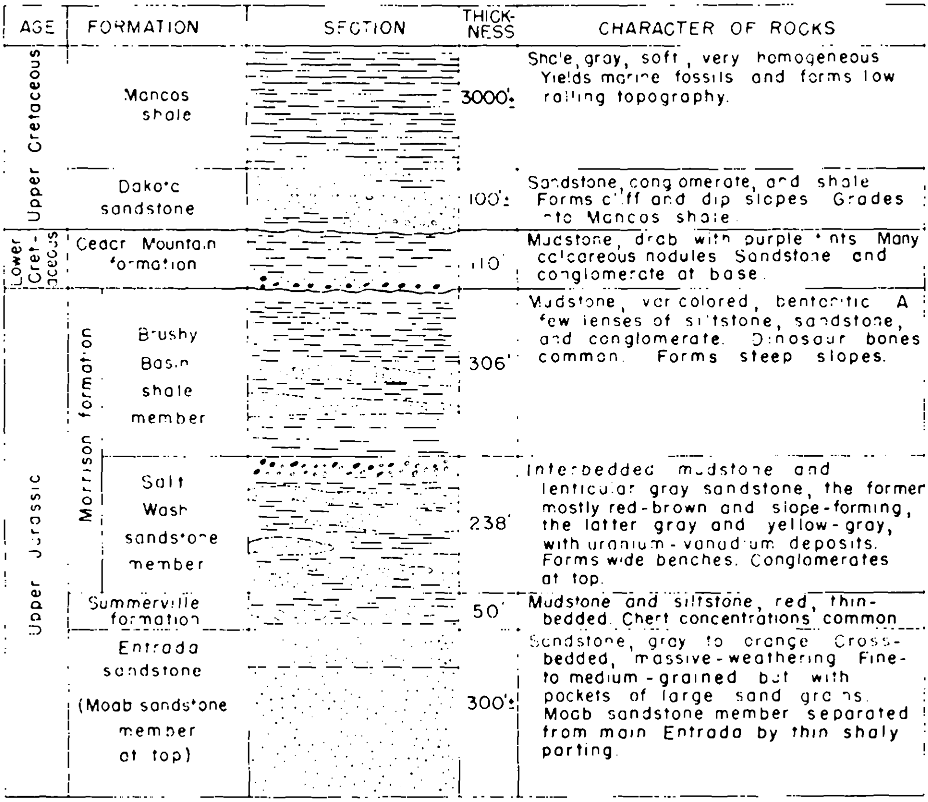
PLATE I

GEOLOGIC MAP OF THE THOMPSONS AREA GRAND COUNTY, UTAH

Geology by W. L. Stokes 1943-1944

of the stratigraphy of the area is contained in a report by Dane (1935, pp. 18-118). The Morrison formation of Jurassic age contains the mineral deposits that are the chief subject of this report, and it is therefore treated in greater detail than other formations. The distribution of the rock units is shown on the map of the area (pl. 1). Their geologic relations, lithologic features, and topographic expressions are discussed below and are also briefly summarized in table 1.

Table 1



AGE	FORMATION		SECTION	THICKNESS	CHARACTER OF ROCKS
Upper Cretaceous	Mancos shale			3000'±	Shale, gray, soft, very homogeneous. Yields marine fossils and forms low rolling topography.
	Dakota sandstone			100'±	Sandstone, conglomerate, and shale. Forms cliff and dip slopes. Grades into Mancos shale.
Lower Cretaceous	Cedar Mountain formation			110'	Mudstone, drab with purple tints. Many calcareous nodules. Sandstone and conglomerate at base.
Upper Jurassic	Morrison formation	Brushy Basin shale member		306'	Mudstone, varicolored, bentonitic. A few lenses of siltstone, sandstone, and conglomerate. Dinosaur bones common. Forms steep slopes.
		Salt Wash sandstone member		238'	Interbedded mudstone and lenticular gray sandstone, the former mostly red-brown and slope-forming, the latter gray and yellow-gray, with uranium-vanadium deposits. Forms wide benches. Conglomerates at top.
	Summerville formation			50'	Mudstone and siltstone, red, thin-bedded. Chert concentrations common
	Entrada sandstone (Moab sandstone member at top)			300'±	Sandstone, gray to orange. Cross-bedded, massive-weathering. Fine- to medium-grained but with pockets of large sand grains. Moab sandstone member separated from main Entrada by thin shaly parting.

GENERAL SECTION OF ROCKS EXPOSED IN THOMPSONS AREA

Pre-Summerville Rocks

Formations below the Summerville have not been differentiated on plate 1; the Navajo, Carmel, and Entrada formations are shown by a single map pattern. Outcrops of the Navajo sandstone and Carmel formation occupy only a very small part of the area but the Entrada forms the bedrock over many square miles south of the outcrops of the Summerville formation.

The Entrada of the Thompsons area is a clean, massive-appearing sandstone, generally weathering as smooth, rounded cliffs. It is distinctively color-banded in layers ranging from a few inches to 10 feet in thickness in various shades of red, gray, orange, and pink. Some of the color bands are original features of deposition, but most appear to be secondary. In general, the Moab sandstone member of the Entrada, which lies at the top of the formation, is lighter in color than the main Entrada. The formation consists of alternating cross-bedded and horizontally bedded layers, but sedimentary details are obscure and do not stand out as in the Navajo sandstone. The interval occupied by individual sets of cross-beds seldom exceeds 10 feet and averages perhaps 2 or 3 feet, and the laminations within the beds are usually very fine.

The Entrada sandstone is exposed either as cliffs or on wide bedrock benches and dip slopes. A striking feature is the excellent exposures of joint patterns on the barren rock surfaces. Weathering has accentuated the joints, and collection of moisture and consequent vegetation has caused them to stand out even more clearly. Weathering and erosion proceeding outward from the joint planes have produced large areas of symmetrical hummocks, walls, and occasional arches. In the eastern end of the area, where jointing has been less intense, the Entrada presents the more typical aspect of a single unbroken cliff.

The Entrada sandstone can be easily traced into western Colorado as a conspicuous light-colored, cliff-forming unit, called the slick-rim by miners and prospectors. It is equivalent to the lower La Plata of the older reports on the Colorado region and is widely known by that name. From its position in the San Rafael Swell between two well-dated fossiliferous marine formations, it is definitely known to be of Late Jurassic age (Gilluly and Reeside, 1928, p. 778). The double sorting of sand grains into two main sizes and the occurrence of faulted and contorted bedding have been discussed by Dane (1935) and are thought to have significant bearing on the problem of origin of the formation. Dane reported a thickness of 350 feet near the north end of Salt Valley and 290 feet at Dewey.

Summerville Formation

The Summerville formation near the type locality in the San Rafael Swell is from 125 to 331 feet thick (Gilluly and Reeside, 1928, p. 80) and is characterized by very persistent thin and regular bedding. In the Thompsons area the Summerville formation averages about 50 feet in thickness and displays more variation in lithology, texture, and bedding than at the type locality. In general it is reddish in varied hues, soft, and easily eroded, and displays little bedding except on fresh exposures. The formation consists of argillaceous and arenaceous fractions in varying proportions and mixtures so that true sandstones or mudstones are rare. Thus the rock types may be classified as sandy mudstones, muddy sandstones, silty sandstones, and silty shales with subordinate amounts of true shale and sandstone. There are scattered thin lenses of nodular limestone, large chert concretion, and a small amount of manganiferous material. The chert occurs in concretionary, roughly oval masses averaging 5 to 10 feet in diameter at about the middle part of the formation. It is light-colored, white, gray, blue, and pink; weathered fragments have locally accumulated to form "desert pavement."

The Summerville formation usually appears as a short, steep slope between outcrops of the Morrison and the Entrada formations, but locally it is exposed in broad, nearly level tracts.

The contact of the Summerville formation with the Entrada sandstone is sharp and conformable and can be located and mapped with little difficulty. The Morrison-Summerville contact, on the other hand, is somewhat gradational and difficult to determine. In general, the sediments involved in the transition zone reflect a gradual change from deposition in shallow, still, or slowly moving water to deposition under changing fluvial conditions which resulted in better sorting and greater lateral variation in sediments. The contact has been drawn where red, shaly, thin-bedded sediments give way upward to predominantly gray or brownish, sandy, lenticular types with distinct cross-bedding and less limestone and chert. Locally, however, sandstones of Morrison lithology cut into the Summerville and conversely, red Summerville-type rocks occur in the lower part of the Morrison.

To the west the Summerville formation grades in part into the fossiliferous Curtis formation and is also considered to be of Late Jurassic age (Gilluly and Reeside, 1928, p. 80).

Morrison Formation

The Morrison formation contains the carnotite deposits that constitute the chief subject of this report and for that reason the formation is treated in more detail than are the contiguous units. Specific problems relating to the sedimentation, paleogeography, and mineralization of the formation are discussed under sections of this paper dealing with ore deposits. The Morrison has received much attention from stratigraphers and paleontologists owing to its unusual lithology, its unique fossil content, and its involvement in the Jurassic-Cretaceous boundary dispute. Papers by Mook (1916), Simpson (1926) and Stokes (1944) deal specifically with these problems.

The formation consists of a diverse assortment of rock types including sandstone, mudstone, siltstone, shale, conglomerate, quartzite, and limestone, as well as all gradations between these types. The outcrop is correspondingly variegated and the topography developed on the beds is generally irregular and varied from place to place. The following section of the Morrison measured in the central part of the area (sec. 6, T. 23 S., R. 22 E., and sec. 32, T. 22 S., R. 22 E.) shows the details of lithology and relations and thicknesses of the various units.

Morrison formation:

Brushy Basin shale member:	Feet
Mudstone and shale, light red and pink, delicately banded and shaded; bentonitic, develops soft fluffy surface. Color fades somewhat toward summit with lighter shades of pink and red and a small amount of yellow and brown. Extreme summit shows some greenish-gray. Contact with basal part of Cedar Mountain formation mostly erosional. Forms steep, soil-free slope	207
Siltstone, gray nodular, weathers brown	3.5
Mudstone, light pink, red and gray, bentonitic; a few thin siltstones and sandstones	32

Morrison formation:

	Feet
Brushy Basin shale member (Continued):	
Sandstone, gray, coarse, very lenticular, has current bedding, contains small varicolored chert grains; forms hoodoos and vertical cliffs, shale partings in places	13.5
Shale and mudstone, purple, light red and pink, bentonitic, soft	50
Total Brushy Basin shale member	306.0
Salt Wash sandstone member:	
Conglomerate, yellow, brown and buff, chert pebbles up to ½ inch in diameter make up from 10 to 90 percent of total volume of the rock. Cross-bedded; contains much limonite stain, plant impressions, silicified bones and wood. Vanadium-bearing in several places	5
Mudstone, light red except immediately under conglomerate where it is greenish gray	20
Conglomeratic sandstone, gray, pebbles make up about 5 percent of total mass of rock, current bedded. Vanadium-bearing at several places	13
Mudstone, red	6
Sandstone, white to gray, medium grained, soft, weakly cemented, sugary, forms slope and cliffs	60
Mudstone, red	4
Silty sandstone, gray, clay pellets near base	4
Mudstone, mainly red, has a few green patches, also contains a few siltstone beds	14
Siltstone, gray to brown, contains a few green pellets	2
Mudstone, red with numerous gray-green patches, contains a few limy and silty beds	11
Sandstone, light gray to gray, massive, bedding mostly indistinct, has small gray clay pellets in layers ½ to 1 inch thick. Cliff forming; about 9 feet from base is a persistent layer of green clay that pinches and swells and has appearance of being at an unconformity. This layer is traceable over a wide area and appears to have about the same stratigraphic position as several thin ore bodies	45
Mudstone, red	6
Siltstone, gray, fairly continuous along outcrop	2
Mudstone, red	12
Siltstone, gray-brown, continuous along outcrop	3
Mudstone, lower part red, upper part gray-green	14
Siltstone	1
Mudstone, red	5
Siltstone, sandy, gray, lenticular	6
Mudstone, red	4
Siltstone	1
Total Salt Wash member	238
Total thickness of Morrison formation	544

As interpreted by previous investigators, the Morrison formation of the area includes an uppermost, unnamed unit which in the present study has been mapped separately as the Cedar Mountain formation.

The lower member of the Morrison formation, the Salt Wash sandstone member was first designated by Lupton (1914, p. 127) as the Salt Wash sandstone member of the McElmo formation in the area southwest of Green River, Utah, and has since been assigned to the Morrison and traced over wide areas in the Colorado Plateau. It consists of about equal proportions of gray, lenticular, cross-bedded sandstone, and gray and red mudstone with a few limestone and chert beds. The variability in lithology and arrangement of constituent lenses within the unit are shown on the map of the Yellow Cat area (pl. 2).

The upper limit of the Salt Wash sandstone member is not a definite stratigraphic plane or erosion surface. Its position is governed more or less arbitrarily by the local position of the uppermost sandstone or conglomerate lenses. Thus defined, the upper contact probably ranges through an interval of 50 to 100 feet.

The upper member of the Morrison, the Brushy Basin shale member, was designated by Gregory (1938, pp. 59-60) in the San Juan area of southeastern Utah. It has been traced away from the type section by field parties mapping the ore deposits of the contiguous Salt Wash sandstone member. The Brushy Basin shale member is mainly varicolored mudstone with a few lenses of sandstone and conglomerate. The color banding is distinctive; purple, red, pink, gray, green, yellow, and maroon are present in practically all good exposures. The mudstones consist of silt and clay-sized fragments in varying proportions; some of the beds are bentonitic and were probably derived by alteration of volcanic ash. The sandstones, siltstones, and conglomerates are distinctly lenticular. The lithologic characteristics of this unit are those usually thought of as being typically Morrison.

Each of the two members of the Morrison formation has its own fairly distinct topographic expression. Thus, the terrain between the base of the Morrison and the top of the Salt Wash sandstone member consists of benches, dip slopes, or shallow ravines, and is amenable to surface and subsurface prospecting at moderate depths. The ground between the outcrops of the top of the Salt Wash member and the top of the Brushy Basin member is almost without exception a steep slope where drilling would be difficult. In general there is a close relation between topography and lithology, especially in the erosion of the Salt Wash member. Erosion progresses more readily in the shales and leaves the irregular sandstones and conglomerates as benches, dip slopes, isolated mesas, and flats.

ORIGIN OF THE MORRISON FORMATION. Details of the paleogeography of Morrison time are imperfectly known, but the broader outlines of areas of erosion and sedimentation are fairly clear. One of the most significant clues to the distribution of high and low ground just previous to Morrison time is furnished by the marine deposits that were laid down during Carmel and Curtis time. The oceanic waters responsible for these deposits transgressed from the north and evidently had no immediate connections with the contemporaneous seas of the California-Nevada region or with the waters of the Gulf of Mexico area. This is indicated by the nature of the faunas. Carmel and Curtis deposits pass from typical calcareous marine facies in the vicinity of the Uinta Mountains southward into nonfossiliferous facies of lagoonal, estuarine, and littoral origin characterized by sandstone, shale, and gypsum. Deposits of this age thin markedly in west-central Colorado in the vicinity of the Ancestral Rockies, indicating that these mountains were still topographically high in Late Jurassic time. Marine deposits of Jurassic age are likewise absent along the eastern margin of the Front Range. Most of the area occupied by the marine waters, as well as vast expanses to the south and southeast, must have been very flat and stable as indicated by the lack of coarse clastics, the thin bedding and the relative uniformity of the sedimentary rocks of the San Rafael group. It is evident that during certain times in the Jurassic slight changes in relative position of sea level were capable of shifting the shore line over wide belts so that alternating conditions of submergence and emergence took place with consequent variations of sedimentation, local deposition of evaporites, and destruction of any marine organisms that attempted to establish themselves in the shallow waters. Pocket seas, playa lakes, lagoons, and sand dunes were common and certain areas probably received alternate supplies of fresh and saline waters.

The expulsion of the last Jurassic (Curtis) sea from the region may have been partly due to local diastrophism, as slight angular unconformities are found in the San Rafael area (Gilluly and Reeside, 1928, p. 81), but for the most part the beds are conformable and contacts gradational. The withdrawal may have been mainly due to the gradual filling of the basin, as the marine sediments merge into terrestrial sediments both laterally and vertically, and evidences of fluvial, lacustrine, and lagoonal environments gradually take the place of marine ones.

The withdrawal of the Curtis sea left a vast lowlying plain ending somewhat abruptly at the base of the highlands of the Mesocordilleran geanticline to the west and with restricted areas of old-age mountains marking the eroded remnants of the Ancestral Rockies to the east. Upon this vast plain the building up of the Morrison formation by fluvial agents commenced.

It is reasonable to suppose that drainage in Morrison time was controlled somewhat by the configuration of the unfilled basin left by the withdrawal of the Curtis sea, but changes brought about by orogenic activity to the west no doubt exercised both local and regional influences. The growth and intrusion of salt masses in the Utah-Colorado salt-dome region and the compaction of sediments over the Ancestral Rockies must also be considered as minor factors influencing drainage and sedimentation.

The sediments that now form the Morrison formation gradually filled the pre-existing basin and overlapped increasing areas of older rocks in the central Colorado region. The aggradation of the vast Morrison plain, even more extensive than that left at the close of the previous marine interval, was a slow process that occupied at least several million years. During this time drainage was generally eastward but the courses of the rivers shifted from place to place so as to maintain rather uniform grade and thickness of deposits. Probably during the final phases of Morrison sedimentation the Ancestral Rockies were almost completely buried, but during earlier phases the major rivers were deflected around or between the major units.

Paleogeography indicates two possible sources for Morrison sediments of eastern Utah, the Mesocordilleran geanticline to the west and the Ancestral Rockies to the east. Considering only the area of eastern

Utah and western Colorado, it is believed that the most important source of sediment was the highland mass to the southwest and west. Although the Ancestral Rockies were important sources of material in the late Paleozoic and early Mesozoic, they became less important and were finally almost completely buried by Morrison time. Igneous and metamorphic rocks are extremely rare in conglomerates of the Morrison of the Colorado Plateau, and the sandstones and shales show little evidence of having been derived directly from the decay of igneous rocks. The author has studied the fossil content and lithology of a widespread conglomerate at the top of the Morrison formation in east-central Utah (Stokes 1944, pp. 978-981). This conglomerate is composed largely of cherts derived from late Paleozoic and early Mesozoic rocks and considered to have been transported from the southwest. Coffin (1921, p. 108) reports Carboniferous fossils in the conglomerates near the top of the Morrison in Colorado. He also cites evidence to support the contention that the streams depositing the Morrison sediments were flowing eastward. Stokes (1944, p. 967) has also found in the beds immediately above the Morrison evidence supporting the idea of southwestern and western origin for the sediments, and the present study of cross-bedding seems conclusive, at least for the Thompsons area.

Although volcanic ash, now altered to bentonite, has locally been important and the detritus from pre-Cambrian and early Paleozoic rocks of the Ancestral Rockies may have been reworked locally into the Morrison of the Rocky Mountains, it seems probable that most of the material constituting the formation in the Colorado Plateau was brought in from the south, southwest, and west, and that Permian, Pennsylvanian, and Triassic formations were destroyed to supply sediment to the Morrison. Other sedimentary and igneous terrains may have been present within the drainage areas of the Morrison rivers, but evidence of these in the form of pebbles, heavy minerals, or reworked fossils has not been obtained.

FLUVIAL FEATURES OF THE MORRISON FORMATION. The Morrison formation is currently regarded as being a fluvial deposit with minor lacustrine and aeolian portions. It should be noted, however, that most early investigators, including some who have attempted to explain the genesis of the carnotite deposits in terms of paleogeography and stratigraphy, considered the Morrison to be lacustrine throughout and a few have advocated even a marine origin. These older ideas were utilized by Hess (1933, pp. 478-479) in formulating a comprehensive theory for the origin of the carnotite deposits and are still referred to by writers who are not informed as to more recent ideas regarding the origin of the formation.

It should be noted that the earlier writers were seeking to evolve a theory that would explain not only the deposits of the Morrison but also those of the Entrada and Shinarump formations, and that they were more interested in the type of lithology of the Salt Wash than in the more typical and widespread variegated facies of the Morrison formation with which most geologists are familiar. Nevertheless, it is evident that many students of uranium deposits are not acquainted with the contributions of paleontologists and stratigraphers toward an understanding of the problems of the Morrison.

Although the deposition of the Morrison formation may be broadly ascribed to the action of rivers, it must be borne in mind that fluvial action is extremely complex and variable. Twenhofel (1932, pp. 806-810) has subdivided the fluvial environment into (1) piedmont, (2) valley flat, and (3) some deltas. The Morrison formation is placed by him in the valley flat subdivision, which he defines as follows:

> An environment may be considered valley flat and not piedmont if the stream is situated in a valley, possesses a channel of fairly fixed position as opposed to one that is constantly changing, and has the channel bordered by a flood plain.

The Salt Wash sandstone member of the Morrison does not possess most of the qualifications imposed by the above definition, as it was not deposited in a valley by one main river keeping a constant position. On the other hand, the formation was mainly deposited too far from the highlands to be considered a piedmont deposit and too far from the ocean to be considered strictly deltaic. The nearest approach to conditions existing during the deposition of the Salt Wash to be found at present are on the great alluvial fans, flood plains, and deltas of such large rivers as the Hwang Ho, Yangtze, Indus, Ganges, and Nile.

In dealing with modern river sediments, Happ, Rittenhouse, and Dobson (1940, pp. 22-25) have evolved a system of classifying stream deposits that is based on genesis rather than on place of accumulation. The six genetic types given by them are as follows:

Colluvial deposits
Vertical accretion deposits
Lateral accretion deposits
Floodplain splay deposits
Channel-fill deposits
Channel lag deposits

They have found the six genetic types of deposits in four distinct associations as follows:

Normal floodplain or valley-flat association
Alluvial-fan, or alluvial-cone association
Valley-plug association
Delta association

The terms are mostly self-explanatory, but a more complete description may be had by consulting the publication cited. Happ, Rittenhouse, and Dobson evolved their classification for convenience in treating modern streams and stream deposits; whether this classification can be applied with profit to ancient fluvial deposits remains to be determined.

A further classification of flood plains based on the type of activity of the rivers occupying them has been proposed by Melton (1935):

> Floodplain streams are of two classes, single crest and double crest, the classification depending upon the performance of flood waters of a single or a double type of geologic activity.
>
> A single crest stream may produce one of three types of plains, (1) the *bar plain,* constructed by stream bed deposition during floods, the water being unconfined by a definite channel during the low stages, when the volume is insignificant (Canadian of Oklahoma and Platte of Nebraska); (2) the *covered plain,* constructed by the slow deposition of suspended sediment on the surface bordering a non-meandering low-water channel (Mississippi River near New Orleans); (3) the *meander plain* constructed by lateral cut and fill of the low water channel (Colorado River in California and the Connecticut near Haverhill, New Hampshire).

Double crest streams commonly form two types of floodplains; (1) bar plains with alluvial cover, which are low-level plains constructed by channel-bottom activity during ordinary floods, partly covered by alluvium deposited in extreme floods (the Missouri River in Nebraska and many streams in arid regions); (2) Meander plains with alluvial cover, which are low-level plains of lateral cut and fill covered by vertical accretion during unusually high water (common in humid regions).

Differentiation of meanders into bar scroll and bar plain are due to climatic changes or to other accidental causes (Little Colorado River).

The classification is further amplified to express the relative vigor of the two types of geologic activity at a given place.

It is not within the scope or purpose of the present paper to elaborate on the merits of the several schemes of classification outlined above. It is evident that a single river may pass through all of the environments of Twenhofel and build up all the types of deposits of Happ, Rittenhouse, and Dobson and take part in most of the forms of activity described by Melton, with the net result that a flood plain, even in the horizontal aspect, is usually extremely complex. A deposit such as the Salt Wash sandstone member which represents the vertical accumulations of many flood plains built up by rivers of different size, in flood and low water, engaged in alternate degradation and aggradation and under variations in climate and type of load, is clearly not susceptible to any simple all-embracing explanation or analysis.

In general, it should be sufficient to point out that the rivers of Salt Wash time were dominantly aggrading and consequently the deposits built by them are made up of interfingering, coarse and fine fractions segregated by currents of water. The coarser sediments were deposited by more rapidly flowing water in the stream channels and the finer portions were laid down in relatively quiet water between the channels. The accumulations of sand and conglomerate, because they represent ancient river beds may be termed channels. These bodies are lenticular in cross sections, show erosional contacts at the base, and interfinger laterally with finer sediments so that, as a general rule, the margins are not everywhere as sharply defined as they would be if created by dominantly degrading streams. The channels appear to be elongate in the direction of movement of the depositing streams, but they can seldom be traced as individual bodies for more than a mile. They are apparently best interpreted as discontinuous sand bodies accumulated in the beds of shifting rivers, at meander curves and in bars.

The proportions of sandstone and mudstone in the Salt Wash sandstone member of the Morrison formation are about equal, but in the Brushy Basin shale member the finer clastics predominate. Present-day flood plains show great variation in the grade of sediment being deposited; some are entirely sand or gravel, others are entirely clay or silt, others are mixed. The relative proportion of sand and of finer grades of material carried by a river has a profound influence upon the structure of its flood plain. Plains built up of sand only or clay only are probably relatively free of distinct channels whereas those receiving a mixture of materials contain more or less well defined lenses of fluvial sandstone surrounded by interstream deposits of finer material.

The map of the Yellow Cat area (pl. 2) illustrates the arrangement and structure of the sandstone channels insofar as these can be deduced from surface outcrops.

PALEONTOLOGY OF THE MORRISON FORMATION. Organic remains found in the Morrison formation clearly indicate a non-marine origin. The well-known dinosaur fauna is adjudged by experts to indicate a fairly well watered, low-lying terrane and a prevailing semitropical or at least temperate climate. Other faunal and floral elements support this interpretation. Isolated fragments of dinosaur bone are common throughout the Morrison formation of the Thompsons area, and collections complete enough for definite correlation with the type area of the Morrison have been made near Fruita and Grand Junction, Colo. (Riggs, 1901) and near Cleveland, Utah (Stokes, 1945). Near Fruita, bones of *Antrodemus* (Allosaur), *Stegosaurus, Brontosaurus, Camarasaurus,* and *Brachiosaurus* were found. At the quarry near Cleveland, remains of *Camptosaurus, Stegosaurus, Antrodemus, Diplodocus,* and *Brontosaurus* were collected.

No large collections appear to have been made from the Salt Wash sandstone member of the Morrison or its equivalents, but the author has seen diagnostic skeletal elements of *Stegosaurus, Brontosaurus, Diplodocus,* and *Antrodemus* in that member at several places, and of the above, all except *Brontosaurus* have been recognized from the Thompsons area.

The known vertebrate fauna of the Morrison formation is composed of aquatic, amphibious, terrestrial, and aerial forms, and as a whole seems to require an extensive, level, low-lying habitat where, locally at least, water was abundant.

Invertebrate remains have been collected from many localities in the Morrison formation (Branson, 1935, Yen, 1952). According to Holt (1942) well-preserved remains of several species occur in comparative abundance in the formation near Grand Junction, Colo. The list includes the gastropods, *Valvata scabrida,* which occurs about 115 feet below the Dakota sandstone and *Vorticifex stearnsi,* which occurs about 80 feet above the Entrada sandstone. In the lower fossil bed, Holt discovered a new species of *Vetulonaia,* which is distinguishable only in minor details from *Vetulonaia whitei* described by Branson. As shown by Branson, most of the species of Morrison fresh water clams are known only from specimens in which the dentition and ornamentation are poorly preserved or absent. In addition, the forms are so little known that they have practically no value for detailed correlation and serve only to indicate that their environment was that of fresh-water rivers and lakes. The author has found well-preserved *Unio* shells in the lower part of the Salt Wash sandstone member of the Morrison in the Thompsons area. These have been compared with paratypes from the Grand Junction area, and are also referred to *Vetulonaia.* The author has also collected *Unio* shells from the Morrison on the Triangle claim, Calamity Mesa, Grand County, Colo.; near Radium Hill, Montrose County, Colo.; and from East Canyon, San Juan County, Utah. Thus organic evidence from the Thompsons and adjacent areas agrees in indicating a fluvial or at least fresh-water origin for the Salt Wash sandstone member.

The Morrison formation has yielded few identifiable plant fossils, and those that are known have been insufficiently studied. Although the author has examined carbonaceous shales and sandstones of the Salt

Wash sandstone member at many places, he has seen no recognizable leaves or seeds. The only plant fossils that offer promise of being determined are the silicified trunks of trees that are relatively common. According to Hess (1933, p. 463), specimens of silicified wood from the Morrison have been identified by Knowlton as *Araucarioxylon*. The Araucarians are a declining group, at present inhabiting parts of the Southern Hemisphere, where they range from subtropical to temperate climates. It should be noted that the araucaria is a little branching tree with branches small for the size of the trunk and leaves small for the size of the branches. The apparent lack of cycads in the lower part of the Morrison is difficult to explain. Most of the larger trees were evidently drifted into the area, as the branches are broken off and the trunks seem battered and abraded. Roots, or at least the root bases, are usually discernible. Some of the trees are silicified, others are carbonized, and still others are replaced by ore minerals.

The only well-preserved plant remains, other than the silicified logs, consist of branches with short sharp thorns that were collected near the Memphis mine in the Yellow Cat area. These have been examined by R. W. Brown of the U. S. Geological Survey, who reported them to be unlike any remains in the collections of the U. S. National Museum from the Morrison or any other formation. It is significant that thick-leaved, thorn-bearing plants are characteristic of relatively dry areas.

Cedar Mountain Formation

The name Cedar Mountain formation was proposed by Stokes (1944) and as defined by him includes the uppermost beds formerly mapped as Morrison. At the base of the Cedar Mountain formation at its type locality near Cleveland, Utah, is a prominent clastic formation, the Buckhorn conglomerate of Stokes (1944), which is not represented in the Thompsons area. The separation and recognition of the Cedar Mountain formation seem desirable, not only for cartographic purposes, but also as a means of resolving the problem of placement of the Jurassic-Cretaceous boundary, which in this and contiguous areas has long been disputed.

In the Thompsons area, the basal part of the Cedar Mountain formation is variable and consists of wedges and lenses of conglomerate, quartzite, siltstone, and sandstone with many diastems and minor erosional unconformities. The sandstone is cross-bedded and in local irregular patches has been converted into dense, hard quartzite. Silicified fossil logs are abundant in parts of the unit. The conglomerates contain pebbles of types that could have been derived locally by erosion of subjacent beds and also well-rounded durable individuals that must have come from a distant source. From the nature of talus in some places, it is evident that this formation also contains lenses of bedded varicolored chert or silicified limestone. The upper part of the formation is light-colored shale or mudstone with occasional sandstone or conglomerate lenses. The predominant color is dull gray, but poorly defined bands of purple and green are also present. Stratification is obscure except on fresh exposures. Numerous irregular nodules and concretions of gray siliceous and calcareous material are characteristic.

Fossils collected from the Cedar Mountain formation on the southwest flank of the Salt Valley anticline and identified by R. E. Peck include the following:

Metacypris cf angularis
Cypridea cf C. brevicornis
Cypridea wyomingensis
Clavator harrisi

These fossils are considered to indicate an Early Cretaceous age for the formation.

The following section illustrates the detailed composition of the Cedar Mountain formation as measured in sec. 32, T. 22 S., R. 22 E.

Dakota sandstone:

Sandstone and conglomerate, yellow and gray. Chert and quartzite pebbles abundant in lower part. A resistant bed at the base forms a wide dip slope.

Cedar Mountain formation:	Feet
Mudstone, drab, light purple or lavender near base grading upward into gray, green, and yellow tints. Lower 50 to 60 feet contains abundant calcareous nodules. Slope-forming	81
Sandstone, quartzite, siltstone, and conglomerate subdivided as follows:	
(1) Sandstone, silty, brown, soft, even-bedded	7
(2) Siltstone, white, soft; weathers in rounded forms and generally occupies recess in cliff face	7
(3) Conglomerate and quartzite, gray; conglomerate consists of chert pebbles and fragments of limestone and shale. Locally lenses and irregular patches of very hard, gray quartzite, some silicified wood; very irregular in detail, varying as much as 100 percent in thickness in several miles. Forms a more persistent cliff and horizon marker than the Dakota sandstone	15
Total, Cedar Mountain formation	110

Dakota Sandstone and Mancos Shale

The Dakota sandstone is a widespread continental formation made up of interstratified shale, sandstone, and conglomerate, with minor carbonaceous beds. It ranges in thickness from 40 to 110 feet in the area (Dane, 1935, pp. 114-116). This variation in measured sections is mainly due to the difficulty of locating precise and consistent upper and lower boundaries. The Dakota is a relatively hard formation and caps irregular mesas and dip slopes above the more easily eroded Cedar Mountain formation. The Mancos is usually stripped away from the upper surface of the Dakota but extends up the dip slopes between the drainage lines in irregular tongues or has a poorly exposed transition zone in many places covered by the alluvial accumulations of streams that tend to follow the contact at the base of dip slopes.

The sandstones of the Dakota are usually coarse grained, buff or yellow in color, and pass by gradual stages into grits and conglomerates. Most of the pebbles in the conglomeratic portions are dark-colored cherts, but there are generally a few of gray or yellowish quartzite; the average diameter is about one inch, and the pebbles are fairly well rounded. The pebbles usually lie in thin lenses and constitute from 5 to 90 percent of the total mass of the conglomerates in which they occur. The interbedded mudstones are usually greenish gray and much more dull-colored than the mudstones of the Morrison or Cedar Mountain formations. Thin seams of carbonaceous material with vague impressions of plant tissues are fairly common. A silicified *Tempskya* trunk was found in place in the lower stratum of the Dakota in sec. 28, T. 22 S., R. 22 E. Owing to contradictory evidence as to the age of the Dakota sandstone a question mark has usually been applied to the name and correlation, but this practice has recently been discontinued.

Only the lower part of the thick Mancos shale is included in the map area. The Mancos consists of uniform gray shale of marine origin that has little resistance to erosion. Under the usual conditions of topography and climate, it erodes rapidly to low rolling hills with intricate drainage or to pediment surfaces. Where protection is afforded by overlying rocks, it forms steep talus-covered slopes. Fossil evidence proves the Late Cretaceous age of the unit. Near the lower contact there is usually much variation in organic content and certain beds are highly bituminous.

STRUCTURE

The Salt Valley anticline is the dominating structural feature of the region. This is essentially a northwest-trending anticline, the crest of which has been dropped by a complicated fault system into a structural trough. The Thompsons area is on the northeast flank of the fold outside of the central area of intense faulting. The shallow Sagers Wash syncline lies 1 to 2 miles north of the east end of the map area, but it dies out westward and has progressively less effect on the regular regional northward dip toward the Uinta Basin. Salt Wash, where it flows through the Entrada sandstone, occupies a shallow syncline developed between the northeast dip of the Salt Valley anticline and the northwest dip of the Dome Plateau. About 2 miles west of Squaw Park, a low anticline is developed in the northwest-dipping rocks. The Yellow Cat dome, with a reported closure of 100 feet, is near the southeast end of this anticline. The faults that are associated with the anticline and the dome were found by the present author to be more numerous and extensive than indicated by Dane (1935). Two of the faults form a graben in which is preserved a mass of carnotite-bearing Morrison strata. Although ore deposits occur near these faults, the bodies are no more numerous than at places remote from the faults, and the association is no more than is expectable in the relation in space of two otherwise unrelated features.

The joints and faults of the region appear to be related directly to the Salt Valley anticline. The joint patterns of a belt surrounding the central part of the anticline are perfectly shown on the aerial photographs of the region owing to the manner of weathering of the extensive bare-rock surfaces of the Moab sandstone member of the Entrada formation. Although many interesting hypotheses might be drawn from a study of the joint patterns, it is sufficient to note that for most of the region, and for that part adjacent to the Yellow Cat area in particular, the joints strike about N. 70° W. and are rather closely spaced. The direction and strength of joints have been noted during mapping of mines and mineral deposits, but no obvious relationship has been found to exist between the fracture and joint patterns and localization of ore bodies or mineralized areas.

The effects, if any, of the intrusion of salt masses into the rocks of the region upon the deposition of vanadium are not evident in the present study.

ORE DEPOSITS

Since their discovery in 1899, the uranium, vanadium, and radium deposits occurring in various sedimentary formations of the Colorado Plateau have been subjects of more than ordinary geologic interest. These deposits were once the principal source of radium in this country. Later, during World War II, they became the most productive domestic source of vanadium and still more recently of uranium. They have been intensively explored by prospectors and geologists, but relatively little of a scientific nature has been published regarding them.

Uranium and vanadium are widely disseminated in the earth's crust, but commercial concentrations, especially in sedimentary rocks, are rare. To explain the relatively large local concentrations of these elements in the Morrison, Entrada, and Shinarump formations of the Colorado Plateau, the following theories have been proposed: (1) They are the result of hydrothermal action and are therefore related to deep-seated fractures, with mineral constituents derived originally from deep within the earth. (2) They are syngenetic accumulations laid down in close association with organic materials. According to some observers, the metals were concentrated by the organisms during life and were integral parts of their bodies, but others claim that the metals were precipitated from surface water by dead organic material and buried with it shortly thereafter. According to either of these ideas, the minerals may have migrated short distances away from their original sites into the surrounding rocks. (3) They are syngenetic accumulations of detrital mineral particles laid down with the other inorganic constituents of the enclosing rocks. (4) They originated later than the enclosing rock by concentration from ground water in the proximity of organic accumulations or under the influence of obscure physical or chemical factors not now easily detected.

Accumulated observations now seem to favor the last-named theory. Practically no evidence has been discovered to indicate connection with igneous action of any kind, and the mineralization commonly cuts across the bedding and other original sedimentary features, precluding a syngenetic origin. The chief point of dispute concerns the possible time at which mineralization occurred. Some have concluded that mineralization took place in relatively unlithified sediment under only a few feet of cover with the percolating solutions still more or less freely communicating with the surface and the organic material in an early stage of decay. Others believe that the ore bodies formed under several hundred feet of cover as a minor phase of the cementation and lithification of the formation as a whole, and that the mineral-bearing ground water was confined to conduits well below the surface.

The present study was undertaken to determine the relation of the ore to the larger features of stratigraphy and lithology. Problems bearing on the chemistry and mineralogy of the ore and on the relation of gangue and ore minerals have not been investigated, although many details of genesis will have to be solved by studies of these more minute relations.

Mineralogy

The uranium-vanadium deposits of the Morrison formation have usually been referred to as "carnotite deposits" to distinguish them from similar deposits in the Entrada sandstone, which have been termed the "roscolite deposits." These terms have been carried over from the earlier period of mining when carnotite was the chief type of ore mined. The term "sandstone ore" may be used to include both types. The distinction between the ore of the Entrada sandstone and that of the Morrison formation is more of degree than of kind, for even the carnotite ore contains many times more vanadium than uranium and the mineral form of the vanadium in the two formations is apparently the same. Very few deposits consist entirely of vanadium minerals or entirely of uranium minerals. Practically all of the minerals occur in extremely fine grains or crystals and are usually intermixed and intergrown so that their study and exact determinations are difficult.

The ore ranges in grade from a fraction of a percent to 10 percent V_2O_5 and up to 0.4 U_3O_8. The ore minerals occur mostly in sandstone, coating the grains and partly or entirely filling the pore spaces. Finer grades of sediment, especially thin clay films or shale pebbles, are in places richly replaced by the uranium-vanadium minerals. Although the principal vanadium mineral is micaceous, its exact identity, composition, and properties have not been definitely established. The mineral is dark and colors the sandstone gray and greenish gray, and the color darkens as the vanadium content increases, so that an experienced miner can estimate the content of V_2O_5 within 0.5 percent. The yellow uranium minerals, carnotite (approximately $K_2O \cdot 2UO_3 \cdot V_2O_5 \cdot 3H_2O$) and tyuyamunite (approximately $CaO \cdot 2UO_3V_2O_5 \cdot 4H_2O$), are widely disseminated in the ore, and in places they constitute small high-grade bodies, either replacing fossil plants or impregnating sandstone. Corvusite ($V_2O_4 \cdot 6V_2O_5 \cdot nH_2O$), a purplish blue-black mineral, appears to form mainly in localities where gypsum and organic matter are plentiful in the sandstone. Vanoxite, a black hydrous vanadium oxide ($2V_2O_4 \cdot V_2O5 \cdot 8H_2O$), is thought to have constituted a large part of several very rich bodies mined in the Thompsons area, the ore from which is reported to have contained 15 to 20 percent V_2O_5. Hewettite and metahewettite, red hydrous calcium vanadates of the same composition, are present locally but contribute relatively little vanadium. Pascoite ($2CaO \cdot 3V_2O_5 \cdot 11H_2O$), rossite ($CaO \cdot V_2O_5 \cdot 4H_2O$), and metarossite ($CaO \cdot V_2O_5 \cdot 2H_2O$) are left in the form of local efflorescent coatings where vanadium-bearing waters evaporate. Pascoite is bright orange and rossite and metarossite are light yellow. Detailed discussion of the ore minerals may be found in publications by Hess (1933), Foshag and Hess (1927), and Fischer (1942).

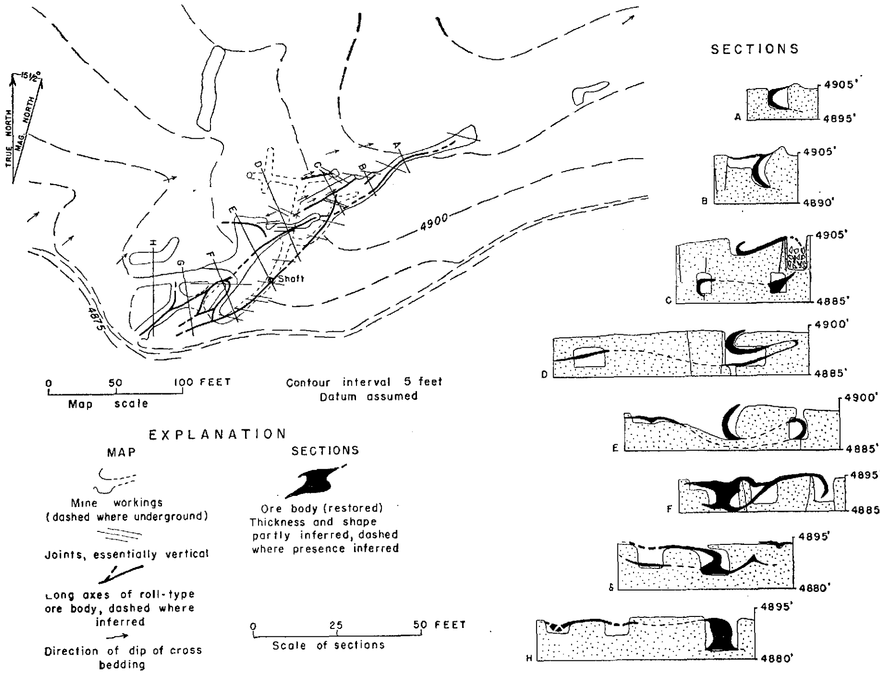


FIGURE 2

MAP AND SECTIONS
MINE AND ORE BODY ON ALLOR NO. 2 CLAIM
YELLOW CAT GROUP, GRAND COUNTY, UTAH

Topography by R. P. Fischer, W. L. Stokes, and L. E. Smith
Geology by W. L. Stokes and L. E. Smith
Nov. 1944

Ore Bodies

The ore was formed by selective mineralization of the sandstone, concentration of minerals around fossil organic remains, and adsorption by certain types of clay material. The distribution of the vanadium-bearing micaceous mineral, which is the most abundant constituent, varies in the different types and grades of ore. It may be uniformly distributed through sandstone, concentrated along bedding planes, or in irregular spots and blebs, or it may lie in curving zones that cut across the bedding.

The ore bodies are so varied that no simple classification is possible. They may, however, be roughly divided into two categories; those with well-defined boundaries and those with poorly defined boundaries. The cross-cutting type of mineralization is more characteristic of the bodies with well-defined edges, but a single deposit may consist of both types and all intermediate stages.

The shape and size of the individual ore deposits are governed primarily by the lithology, composition, and general arrangement of the sandstone bodies in which they lie. The presence or absence of plant or other organic remains appears also to have been important in localizing mineralization. In general, the thicker, more continuous sandstone lenses are more likely to contain uranium-vanadium deposits than are the discontinuous ones. Mudstone is barren except where it occurs as thin partings or lenses within sandstones, or lies at contacts of mineralized sandstones or in the form of rounded pellets, which may be more or less widely scattered or in local thin conglomerates. Fine-grained sandstones, siltstones, and limestones are rarely mineralized in the Morrison formation but sandstone with calcareous cement is apparently not unfavorable for mineralization. Most of the ore is contained in medium- and coarse-grained sandstone, but conglomerates in which siliceous pebbles constitute from 5 to 80 percent of the rock and range in size from ⅛ to ½ inch in diameter are well mineralized in several places. Ore does not appear to have been confined to sandstone with any particular type of bedding or original sedimentary structures, but sandstone that shows strong cross-bedding of any sort is considered less favorable than sandstone with moderate development of bedding and cross lamination.

The ore bodies range in size from thin irregular layers less than 5 feet across to bodies 200 feet in their long dimension, in which ore ranges through a vertical interval of 12 feet or more. The yield of ore ranges from a few tons to several thousand tons, depending on size and grade of the deposits. The variations in grade have already been noted. In a general way the smaller deposits are likely to be of higher grade than the larger ones, but the grade depends on many factors—the type of minerals making up the bulk of the ore, the amount of waste in the form of barren layers or siliceous pebbles, the amount and nature of the organic material present, and probably other factors not recognized at present.

The ore bodies characterized by curving zones of mineralization that cross the bedding planes are in many ways the most productive, as the ore they contain is usually of good grade and mining is relatively less costly and difficult. The form and relations of these cross cutting bodies have been well described and illustrated by Fischer (1942) but the mode of origin is not yet well understood (see figs. 2 and 3).

Where mineralization is especially strong, a curving plane of weakness or actual fracture usually separates heavily mineralized rock on one side from barren or weakly mineralized rock on the other. In a few places well-mineralized rock lies on both sides of the plane (Fischer, 1942, pls. 55 and 56). Although terminology is not uniform, the miners commonly call the elongate mass of ore adjacent to the plane of weakness a "roll" and the plane itself a "roll surface" or "skin." The ore and waste tend to separate along the roll surface, which greatly facilitates mining this type of body. Some deposits are made up of a single roll (fig. 6); others consist of many rolls (figs. 2 and 5).

As shown by the illustrations, the individual rolls of a group are oriented in a common direction and are connected by thin layers and patches of ore. Rolls or groups of rolls lie with their major axes parallel to the stratification planes of the enclosing sandstone, but the roll surfaces cut across the bedding at various angles. The three-dimensional aspect of a group of rolls may be very complex owing to the development of many curving planes and attendant ore bodies.

Typically, the curving plane or roll surface is crescent or C-shaped in cross-sections normal to the long axis. Cross-sections of S-shape are also common, and the variations may be visualized as the progressive stages in the deformation of the letter S from the normal upright position to a straight line, provided that the top and base of the letter are straight and remain essentially parallel. Ore may lie on either side or both sides of the plane of weakness, but in most places thickens progressively as the angle between the plane and the stratification increases. Generally the roll surface becomes essentially parallel with the stratification above and below and is lost among the bedding planes or along unconformities. The ore is usually richer at the roll surface, owing in part to the solution of sand grains and a consequent concentration of the ore minerals, but there is also a gradual diminution of the ore minerals away from the plane of weakness. A drift driven along a roll usually shows on one wall either a convex or concave smooth surface, formed by separation along the preexisting fracture or plane of weakness, the other wall of the drift being rough and irregular where the barren rock has been blasted away in the ordinary manner.

In areas where rolls are complex, elongate cylindrical or oval masses of sandstone may have been enclosed in the ore in such a manner as to have the form of concretions, but the ore is seldom if ever enclosed in planes that curve through more than 180°. Thus, although the shapes of these elongate bodies may be thought of as crudely cylindrical, they are more nearly analogous to hollowed-out half-sections of cylinders.

The presence or absence of rolls is not a hard and fast criterion for the classification of ore bodies, as the number of rolls may differ greatly, and all deposits show more or less elongation and contain patches of ore that vary in grade and thickness without being bounded by clearly defined edges. However, the deposits that lack rolls or have less well defined edges may be characterized as roughly tabular or lenticular in shape, with their long axes parallel to the bedding. The length and breadth of such bodies are many time greater than the thickness. Deposits in thin-bedded sandstones, in which the ore is concentrated mainly along the bedding planes, are usually of irregular or tabular form with high- and low-grade areas interfingering in an apparently haphazard manner.

Many ore bodies are simply single mineralized logs and the attendant aureoles of lower-grade ore. The shapes of others are evidently determined by irregular masses and bunches of plant material. Other high-grade masses appear to be replacements of shale beds and seams, and have inherited the shape of original beds.

Relation of Ore Deposits to Primary Sedimentary Features

Although a great amount of effort has been spent in mapping and studying the carnotite deposits, no clear-cut evidence of structural control has been found except that of more mobile and soluble uranium minerals whose migration has been directed by available cracks and joints. The distribution of the deposits in general seems to have no relation to faults or folds and numerous deposits occur in areas of little disturbed, flat-lying sediments many miles from igneous intrusions of any kind (Fischer, 1944). On the other hand, a general stratigraphic control is indicated by the restriction of the deposits to the Morrison formation over wide areas. More detailed stratigraphic control is shown by the restriction of the deposits to the sandstone facies in the Morrison and by the fact that thicker sandstones are more likely to be mineralized than are thin ones. These facts together with the concept of fluvial origin of the Morrison formation have been the basis for the belief that specific guides to ore deposits based on characteristics of river deposits may be detected.

The Yellow Cat area was chosen for a detailed stratigraphic study chiefly because of the excellence of the outcrops. The ore-bearing beds dip gently northward and the outcrop is locally several miles wide.

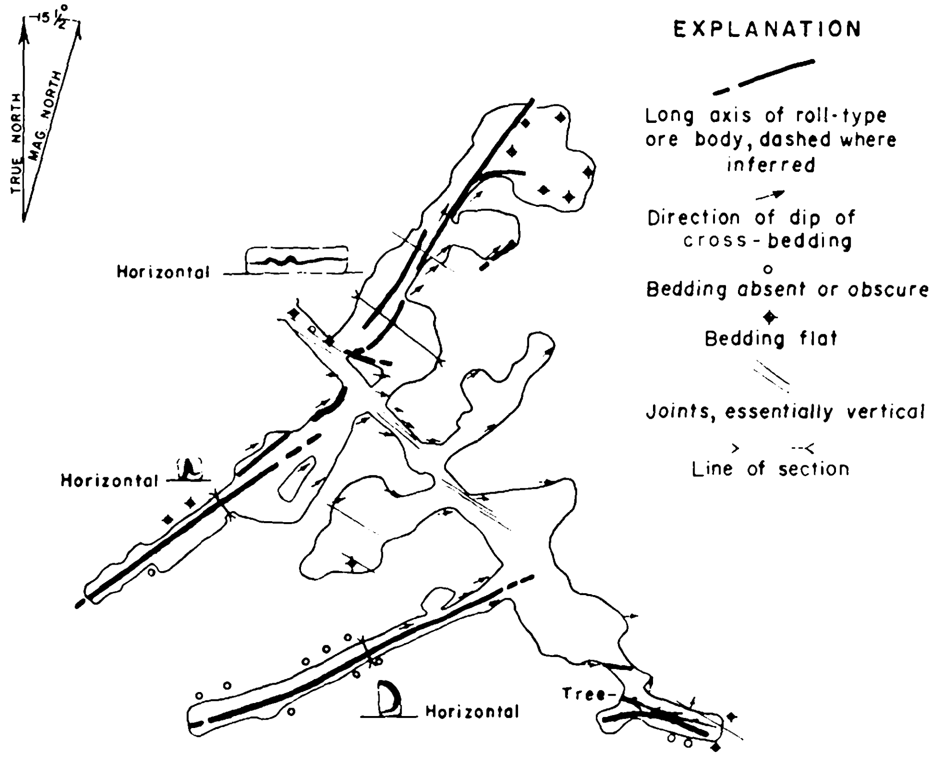


FIGURE 3 PLAN OF THE PITTS NO. 5 MINE
YELLOW CAT GROUP, GRAND COUNTY, UTAH

Showing cross-bedding and the long axes of rolls with vertical sections showing shape of representative parts of ore body.

Geology and mine plan by W. L. Stokes and L. E. Smith
Nov. 1944

0 100 200 FEET
Scale

The area has been dissected so that considerable three-dimensional detail is visible. Vegetation and soil mantle are comparatively light. Ore deposits occur in all the thicker sandstones through a stratigraphic interval of about 250 feet.

In this area the original shapes and distribution of channel and flood-plain deposits may be studied. As the rivers in Salt Wash time were dominantly aggrading, there are few wide-spread unconformities, and there has been little or no destruction of older channels by later ones. The river channels of Salt Wash time were, for the most part, not cut into previously deposited material but rather seem to have been built up simultaneously with the adjacent flood plain so that there is interfingering of coarser stream channel sand and finer flood-plain clays with no sharply defined boundaries. These ancient river courses are characterized by the following features:

(1) Relative abundance of sandstone lenses, expressed in stratigraphic sections by the high proportion of sandstone within the channel zone, compared with adjacent areas.

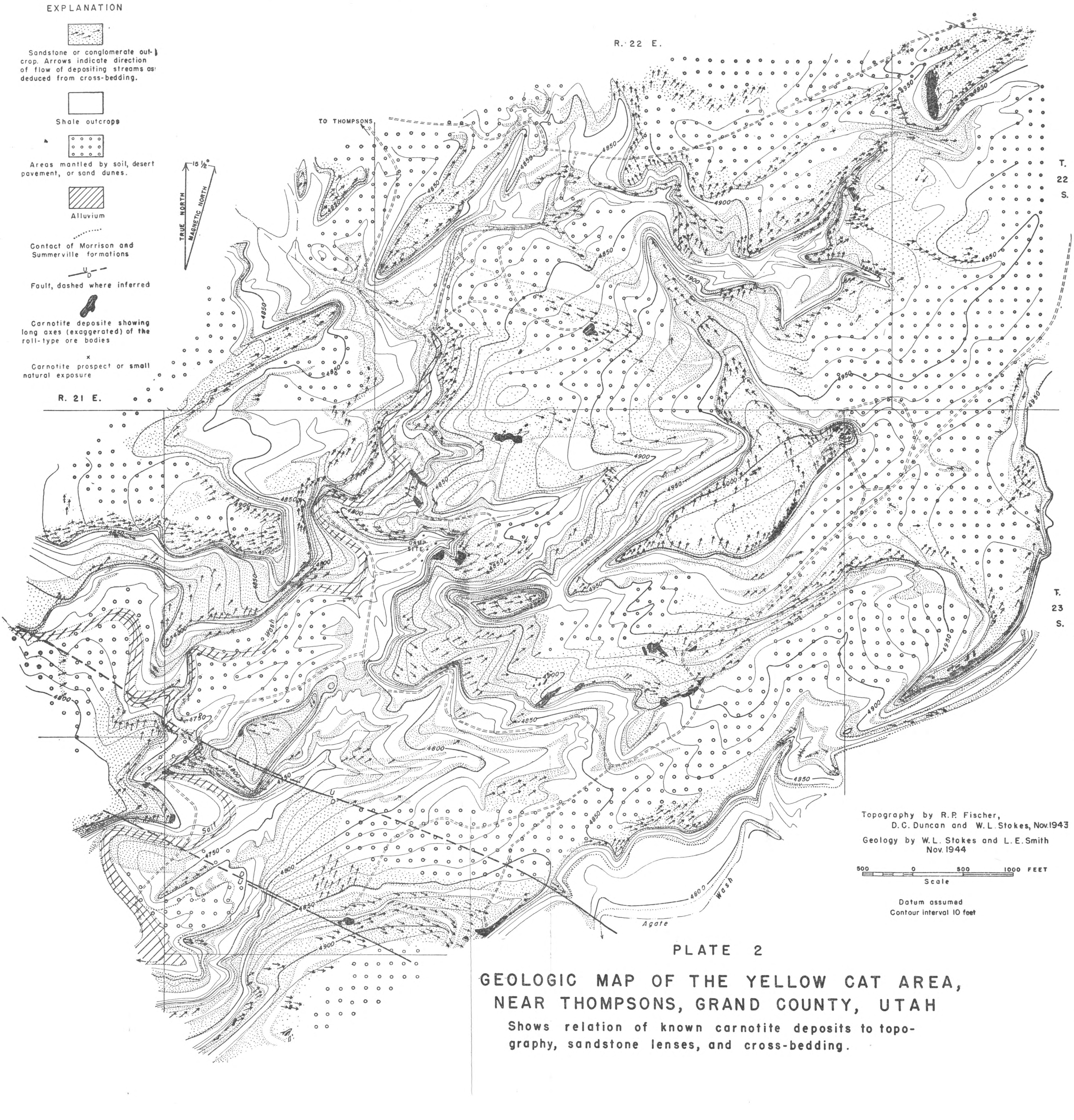
(2) A predominant direction of cross-bedding and elongation of sandstone lenses in the direction of flow of the streams responsible for the deposits.

(3) Evidences of meanders, bars, diastems, cut and fill, current-bedding, river-living organisms, etc.

The most significant mappable feature of the lenses and channels is the cross-bedding, which is abundantly present in practically all the coarser sandstones and can be studied on benches and cliff faces and in mine workings. The deductions based on a study of cross-bedding rest on the assumption that the direction of maximum inclination or dip of the inclined laminae is the direction of movement of the agent that transported and deposited the sediments. This assumption need not be supported by extensive argument; it is a matter of both observational and experimental record, and numerous geologists have accepted and used it as a basis for reasoning on paleogeographic, geologic, and lithologic problems. (See Beadnell 1910; Rubey and Bass, 1925; Knight, 1929; Reiche, 1938; and McKee 1939 and 1940.)

The type of bedding described by Knight (1929) as occurring in the Casper sandstone of Wyoming is similar in major aspects to that present in the Morrison formation of the Thompsons area. This type has been designated "festoon bedding" in allusion to the appearance in plan and vertical views. Knight (1929, p. 86) has briefly described his findings as follows:

> The Casper and Tensleep sandstones are characterized, over several thousand square miles and throughout their full thickness, by a type of cross-lamination which has been described as festoon cross-lamination.
>
> A detailed study of the various oriented vertical and adjacent horizontal rock faces has shown this type of cross lamination to be the result of (1) the erosion of plunging troughs, having the shape of a quadrant of an elongate ellipsoid, (2) the filling of the troughs by sets of thin laminae conforming in general to the shape of the trough floors, and (3) the partial destruction of the filling laminae by subsequent erosion, producing younger troughs. The plunging troughs are symmetrical transverse to their elongate axial planes. They vary in depth from 1 foot to 100 feet, in width, from 10 to 1000 feet, and in length from 50 to several



Topography by R.P. Fischer,
D.C. Duncan and W.L. Stokes, Nov.1943
Geology by W.L. Stokes and L.E. Smith
Nov. 1944

Datum assumed
Contour interval 10 feet

PLATE 2

GEOLOGIC MAP OF THE YELLOW CAT AREA, NEAR THOMPSONS, GRAND COUNTY, UTAH

Shows relation of known carnotite deposits to topography, sandstone lenses, and cross-bedding.

> thousand feet. The axes of the troughs plunge to the southwest varying through 120 degrees of the arc lying between N. 80° W. and S. 20° E. The average maximum angle of the slope of the sides of the trough is between 10 and 15°. The angle of plunge of the axis of each trough decreases rapidly away from the closed end of the trough and the axis becomes a horizontal line which is cut off by a younger erosion trough. The superposition, one upon another, of a series of cut-off troughs gives, on a horizontal side face, a characteristic overlapping or shingle pattern.
>
> Although the mechanics of the process by which the troughs were eroded and filled is not thoroughly understood, it is concluded that the same force operating through varying degrees of intensity, eroded and filled the troughs. The force is believed to have been oscillating currents in comparatively shallow water.

The bedding in the Morrison formation is similar to that described above, the only differences being in magnitude and relative degree of development of different component features. The filled troughs of the Morrison may be described as follows:

(1) They range from 5 feet long, 2 feet wide, and 6 inches deep to 50 feet long, 20 feet wide, and 5 feet deep.

(2) The troughs are usually symmetrical in transverse cross section, but the filling laminae are not necessarily so.

(3) The individual laminae may carry without appreciable change in thickness around the closed end and along the sides in some of the larger troughs, but in most cases the laminae are much thicker around the closed end and die out or grade into each other along the sides.

Figure 4 shows the aspect of bedding of the festoon type as displayed on the conventional planes. The chief purpose of this illustration is to demonstrate that the direction of cross-bedding can be determined by direct measurements on either upper or longitudinal exposures. It is obvious that measurements of orientation are subject to error, but each recorded direction in this study is an average of several readings taken along the axis of adjacent troughs. The outcrops provide unlimited opportunities for study of all possible cross sections of the troughs, and the typical scoop-shape of the individual laminae is everywhere evident.

The results of the study of cross-bedding are shown on the maps and graphs (see pl. 2 and figs. 3 and 5 to 8). The arrows on the maps indicate the direction of inclination of cross-bedding obtained by averaging the direction shown in several adjacent troughs; the variation of axial trend directions in one area of troughs is about 10° to 15°. Continuous readings along outcrops of each sandstone are considered most satisfactory to establish the average directions and the flow patterns. Large areas and thicknesses of sandstone are mostly massive and structureless but careful search usually reveals local patches where satisfactory readings may be obtained. Usually one direction or cross-bedding prevails through each sandstone lens but some cliffs show opposing or highly confusing directions. Observations made on cliff surfaces lying at right angles to the direction of flow are practically useless, and a cliff cut in this plane shows highly confusing lamination. It should be emphasized that figure 4 is idealized and shows complete and perfect development of all aspects of bedding. Slight variations of texture and hardness render the cross-bedding visible; when these are poorly shown the bedding is correspondingly obscure.

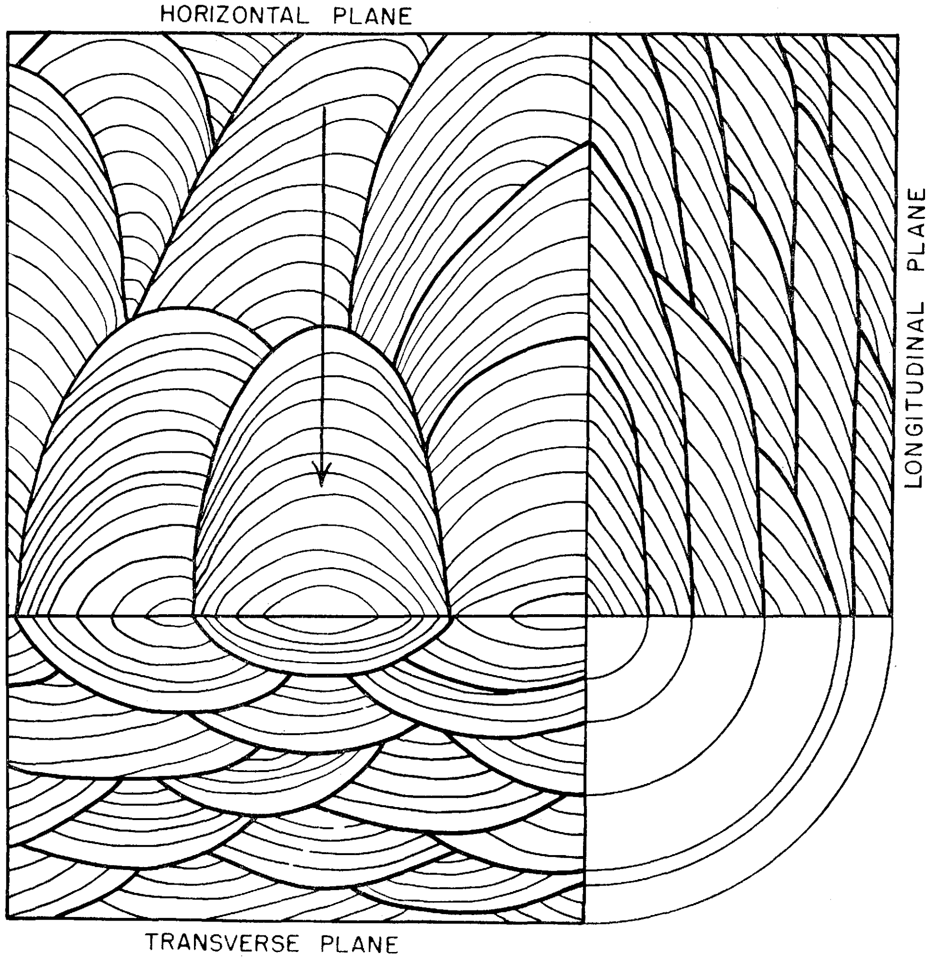


Figure 4. Diagram showing festoon-bedding as it appears on horizontal, transverse, and longitudinal planes. Arrow indicates directon of current movement.

The radial histogram (fig. 7) was prepared as follows: The map (pl. 2) was divided into squares, equal roughly to 6,000 square yards each, and the predominant direction within each square was taken as a unit observation. The information was tabulated by 10° sectors and the number of unit observations by sectors is indicated around the circumference of the graph.

The Salt Wash sandstone member of the Morrison formation differs in several ways from most of the other formations on which studies of cross-bedding have been attempted. The Casper, Navajo, Coconino, and Supai are relatively homogeneous formations, evidently built up under conditions that favor little variation in sedimentation or in source materials. The Salt Wash consists of a mixture of coarse and fine

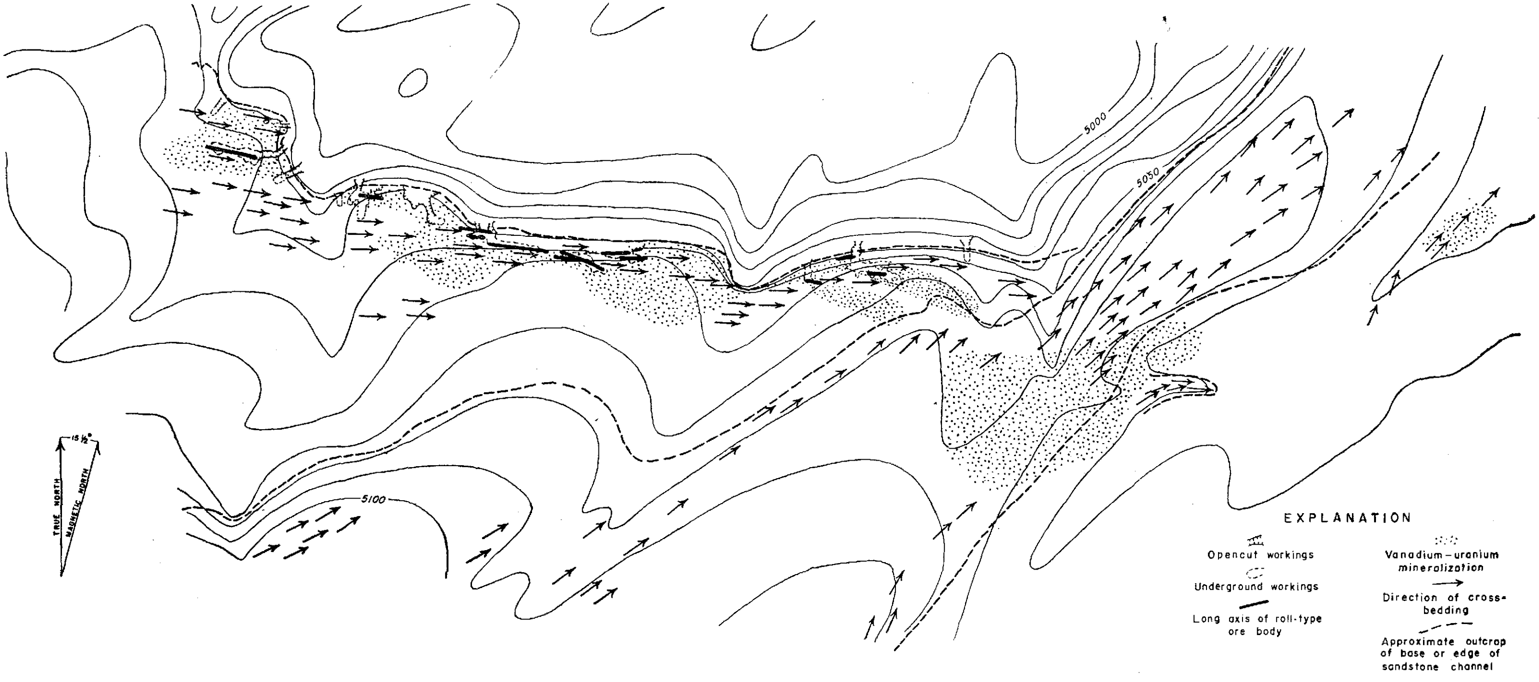


FIGURE 5

GEOLOGY AND ORE DEPOSITS OF THE RED VANADIUM CLAIMS

GRAND COUNTY, UTAH

0 100 200 FEET
Scale
Datum assumed
Contour interval 10 feet

Topography by R. P. Fischer and W. L. Stokes
Geology by W. L. Stokes – Oct. 1943

fragments that occur in lenses of various size and with great variations in color, texture, and degree of sorting. This range in lithologic features indicates corresponding variations in conditions of sedimentation, such as undoubtedly occur on flood plains undergoing alternate erosion and deposition and under contemporaneous subaqueous and subaerial conditions.

The large-scale maps of several mines and mining properties indicate the detailed relationship of cross-bedding and ore deposits. Because of the scale of the map, the detailed relationships of ore and cross-bedding in the Yellow Cat area cannot be shown. The radial histogram (fig. 7) summarizes the information on cross-bedding in terms of the distribution of observed directions for convenience in reference and discussion. The chief question arising from the known variability of deposition, and consequently in regard to the interpretation of the graph, is whether the direction having the maximum number of readings may be regarded as the true direction of flow of the rivers that deposited the sediments of the Thompsons area. A consideration of the various graphs or curves that might result from observations on rivers of various types shows that the direction of maximum number of readings does not necessarily indicate the direction of flow of any given river. A more reliable approach is evidently a negative one, for the source of the river is invariably toward the direction that shows relatively few or no readings. Thus, a graph of a river of extreme meanders shows a fairly even distribution of readings around the compass, but relatively fewer in the direction from which the river flows. The graph of a straight river

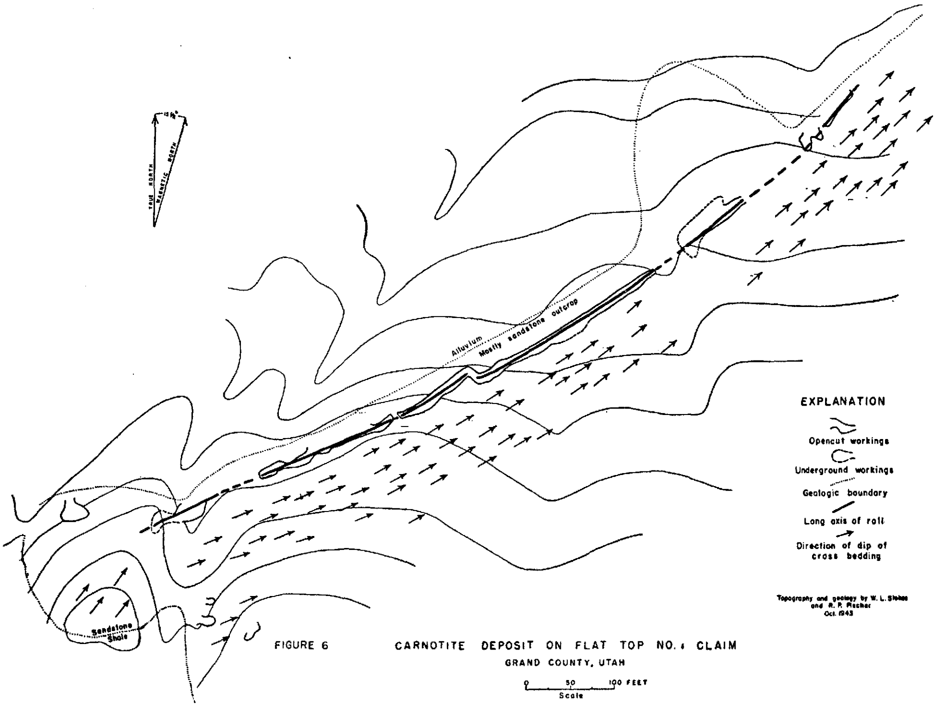


FIGURE 6 CARNOTITE DEPOSIT ON FLAT TOP NO. 1 CLAIM
GRAND COUNTY, UTAH

obviously shows only one direction; the intermediate stages from complex meanders to a straight course would be indicated by a gradual diminution of readings in the sector from which the river is flowing and their accretion in the opposite direction. As the graph of the Thompsons area is one of many possible intermediate stages between complex meanderings and a straight course, the rivers that deposited the Salt Wash sandstone member were probably relatively straight and certainly not complexly meandering. Furthermore, as the readings were taken on many separate lenses through an interval of about 250 feet of sediment, the relative predominance of one direction is even more significant and indicates that there was probably a preferred direction during most of Salt Wash time. A number of curving rivers entering and

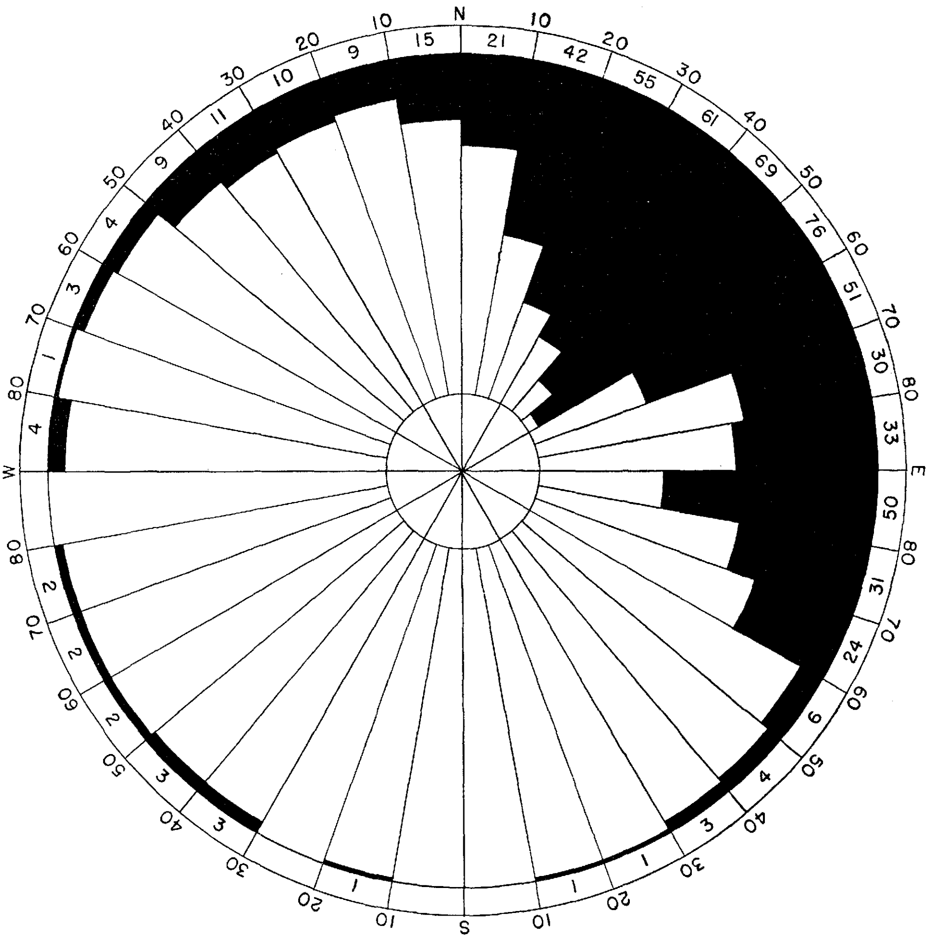


Figure 7. Diagram showing distribution of cross-bedding determinations in the Yellow Cat area. Observational unit is average current direction within a 250-foot square (see text). Inside figures give number of observations falling within the 10° sectors indicated by outside figures.

leaving the area in a haphazard and irregular manner would be expected to give a much more uniform distribution of readings than is apparent, and likewise a repetition of straight courses trending in different directions at different levels would result in a more uniform graph, or at least one with several maxima.

Although this short discussion by no means exhausts the possible inferences that could be drawn from the maps and graphs, it is assumed that the river system responsible for the introductions and deposition of the sediments of the Yellow Cat area entered from the southwest quadrant and left in the northeast. This is strictly in agreement with the broader aspects of paleogeography and paleogeology.

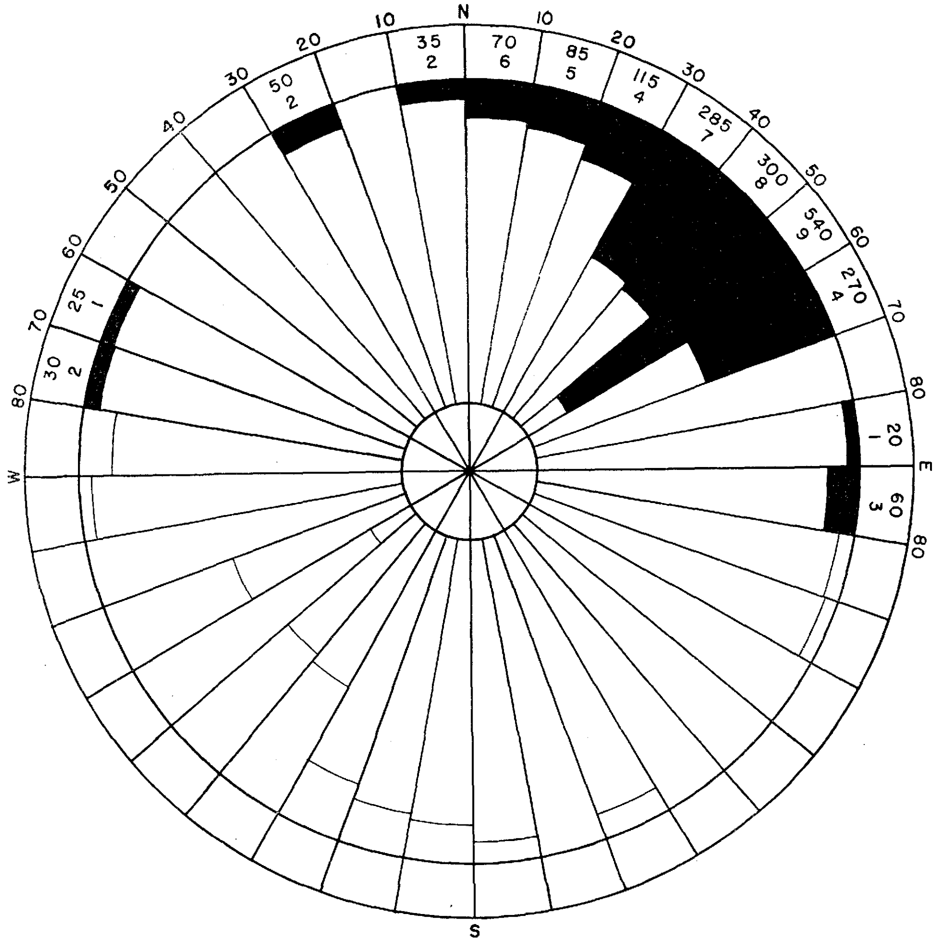


Figure 8. Diagram showing orientation of rolls in the Yellow Cat area. Outer figures indicate degrees of arc, middle figures linear feet of roll structure, and inner figure number of rolls or significant segments of rolls. See text for more complete explanation. All observations are tabulated in the 180° of arc between N. 80° W. and S. 80° E. to facilitate comparison with figure 7.

Although the detailed geologic maps of the various mines in the area show the local close agreement of cross-bedding and alinement of ore deposits, a broader, more general comparison is probably even more significant. A radial histogram showing the orientation of long axes of roll-type ore bodies has been prepared (fig. 8). In this, the unit observation is a linear foot of roll structure. Although a roll structure has two-way vector quality in comparison with the cross-bedding, which has one-way vector quality, data on both features have been plotted on similar graphs for ease of comparison. Instead of showing only a 180° graph for the rolls as is usually done for joints, with a north-south or east-west base, the graph is a full 360° with the rolls plotted as though observed from the N. 80° W. to S. 80° E. hemisphere. Where rolls show sharp curves of more than 15° or 20° the segments of the rolls have been measured separately, but if the curves are gentle and the different straight portions are more or less equal in length, the trend has been taken as the direction from one end to the other. Short segments of less than 10 feet have usually been disregarded. The outside figures on the periphery of the graph are the number of feet of roll structure having trends within each 10° sector; inside figures are the number of rolls or significant segments having trends within the corresponding sectors. The fact that the N. 50°-60°E. sector shows a maximum of roll structure as well as a maximum of cross-bedding trends is evident from a comparison of these two graphs. The secondary maximum of both features in the S. 80°-90°E. sector is also significant.

A second means of showing the relations between the original cross-bedding and the distribution of ore bodies is illustrated in Figure 9. This is a map showing the distribution in plan view of the 95 deposits constituting the Yellow Cat group. This covers a wider area than that shown in plate 2 and includes all deposits in the central, well-defined, mineralized trend of the Thompsons area. A line drawn through the mathematical center of all these deposits and expressing the direction of elongation of the whole group of deposits trends N. 52° E. This line was constructed by the same method as used in determining the mean or average line in ordinary scatter diagrams. Although this illustration is subject to many serious errors, it is nevertheless significant that the distribution of known deposits shows perfect agreement in trend with that shown by cross-bedding determinations and by the elongation of individual ore bodies. The effects of erosion in removing many deposits are not taken into account, but distribution of known deposits is probably a good sample of the distribution of eroded as well as undiscovered deposits.

In practically all cases, the trend of the festoon type of cross-bedding is in the same direction as the original long axis of the lens in which it occurs, and it follows that the cross-bedding is generally parallel with the original margins of the lenses. Thus, in an eroded cliff face, the direction of cross-bedding gives a clue as to whether the original edge of the channel or lens was parallel with the present cliff. The map of the Yellow Cat area (pl. 2) shows that many sandstone cliffs lie parallel with cross-bedding directions. In most of the higher lenses the parallelism is marked, but where the present stream channels have been in a sense superimposed upon underlying lenses, the agreement is less perfect.

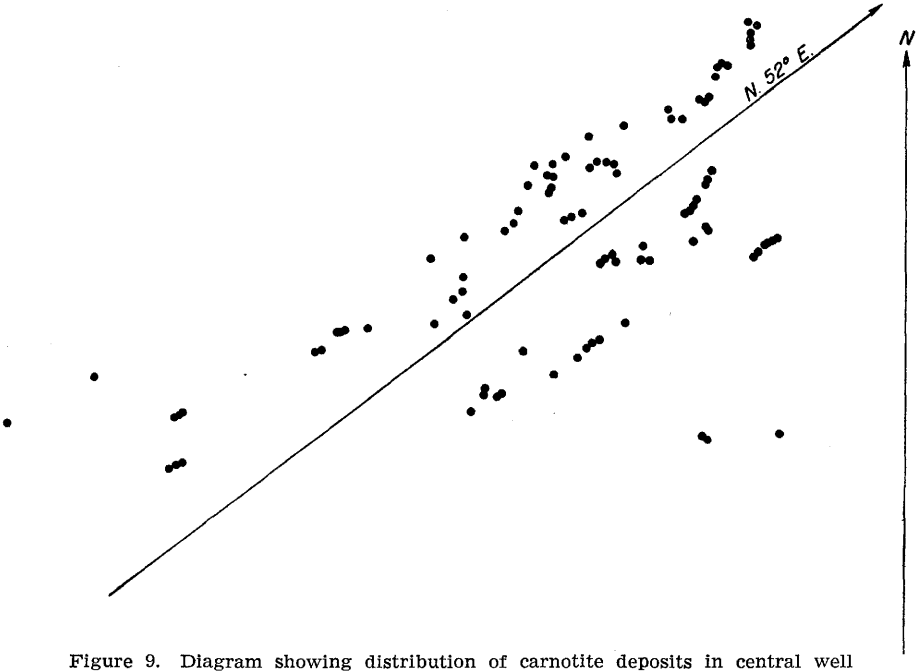


Figure 9. Diagram showing distribution of carnotite deposits in central well mineralized belt of Thompson area.

Trend line passes through mathematical center of group and is drawn by same methods as used in ordinary scatter diagrams.

The evidence of the graphs and maps may be summarized as follows: The rolls and elongate ore bodies lie with their long axes parallel with the directions of cross-bedding and practically always parallel with the long dimension of the sandstone lenses of which they are a part.

The experience of miners and drillers has been that thick sandstone lenses especially at their edge are relatively favorable for ore deposition. This relationship is well shown by several deposits in the Yellow Cat area, as well as in the Red Vanadium and Flat Top claims. (See figs. 5 and 6.) The mineralized area in the northeast corner of sec. 6, T. 23 S., R. 22 E., in the Yellow Cat area, and the one in the northeast corner of the map (pl. 2) both lie on the outer edge of curving sandstone lenses. The deposits of the Red Vanadium group are likewise located along the edge of a channel. The edge of this channel can be seen pinching out northward at both ends of the group of deposits. Extensive diamond drilling on the bench behind the rims failed to penetrate significant ore deposits except at the east, and more or less in line with the known rolls. Mining and prospect drilling here prove the concentration of ore along the edge of the channel. At the Flat Top claims, the edge of the channel is not well exposed, but drill-hole information and lithologic characters justify the conclusion that the unusually long roll is at the edge of a standstone lens trending with the roll. There are excellent exposures of cross-bedded conglomeratic sandstone south of the ore body, but the sandstone becomes less conglomeratic and has little bedding where it passes under the alluvium north of the ore body.

The foregoing observations seem to provide substantial verification for the so-called rim-rock theory that has been held by many miners and prospectors in the region since the earliest period of mining. According to this theory, ore is most likely to be found on the "rims" or cliff edges and may diminish in grade and quantity inward from the surface or edges of the sandstone ledges. This observation led many geologists as well as miners to suppose that the ore minerals had migrated toward the surface, and hence that deeply buried ore bodies are not to be expected.

A more scientific explanation now seems possible. The edges of sand channels appear to have been favorable sites of accumulation of plant material, and hence ore deposition, whereas central areas of sand channels were relatively less favorable. In exposed areas of flat-lying strata of the Salt Wash member differential erosion has etched out the shale so as to leave the sand lenses more or less in relief. The exposed edges of these lenses, now eroded to cliffs so as to constitute "rims," have consistently shown a somewhat higher proportion of mineralized rock than more deeply buried portions of the same beds. Erroneous interpretation of the observed facts has discouraged deeper prospecting in the past, but the rim-rock theory still holds useful possibilities in future exploration.

The Thompsons area is notable for the vertical stratigraphic range of the carnotite deposits. Several occurrences near Salt Wash are only 50 feet above the Summerville formation and the uppermost conglomerate is well mineralized at the north end of the Yellow Cat group and at the Cactus Rat claim. This apparent change in the stratigraphic position of the ore from a lower position at the southwest to a higher position in the northeast can be logically attributed to erosion which has planed away progressively lower and lower beds from north to south.

As pointed out by Fischer (1944) the position of the predominant ore-bearing horizon varies from place to place in the Colorado-Utah vanadium region. According to the author's interpretation, the mineralization is confined chiefly to the zone of thicker, more continuous sandstones regardless of their position in the Morrison. From the viewpoint of genesis, it is thought that this distribution is a reflection of the relative volume of underground circulation that has passed through any particular channel or area. The more continuous interconnecting lenses were evidently correspondingly more favorable for the passage of the ore-bearing or ore-precipitating solutions than were the discontinuous lenses.

In the Thompsons area the Salt Wash sandstone member of the Morrison formation has few continuous horizontal sandstone layers, but it does have many discontinuous channels or lenses that are superimposed one above another so as to constitute a veritable maze. This suggests that movement of ground water upward or downward from bed to bed was probably less hindered than in areas where sandstone and ore are restricted by stratigraphic conditions to better-defined horizontal levels or zones.

The evidence of cross-bedding supports the concept of a zone of superimposed channels running more or less consistently in the same general direction through the Thompsons area. The relative persistence of constructional channels in vertical zones is a subject on which little is known. Wanless' observations in the White River group of Oligocene age led him to write (1923):

> The streams of White River time seem to have confided their valleys to fairly limited belts, though their actual courses may have shifted 2 or 3 miles during the whole of the White River period. The abundant development of channels in the Corral-Quinn-Cottonwood Creek area through all the divisions of the White River and the absence of channels in all divisions in some of the Badlands northeast of Imlay, seems to indicate this.

In a discussion of the geology of Russell County, Kansas, Rubey and Bass (1925) have described the Rocktown channel sandstone member of the Dakota sandstone. The channel consists of very discontinuous, highly cross-bedded sandstone lenses which appear to lie in long, more or less sinuous belts a few miles or less wide. By mapping these now disconnected lenses, and by measuring the dip of current-bedding, Rubey and Bass were able to construct a map showing the original course and direction of flow of the ancient river. It is interesting to note that a second series of lower and less well exposed lenses has a more or less parallel course with the main Rocktown channel.

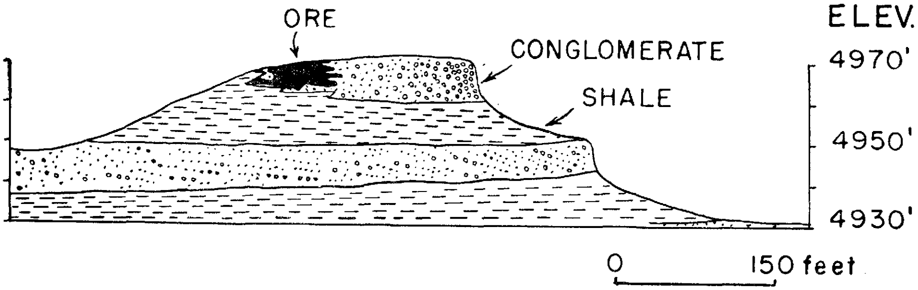


Figure 10. Cross section of ore deposit in northeast corner of Yellow Cat area (for plan view see Plate 2). Shows position of ore deposit near edge of conglomerate and sandstone lens.

Reference to the map of the Yellow Cat area will show that although many ore deposits lie along the edges of sandstone lenses, there are many that are not so located. Some ore bodies are not well enough exposed for a study of their relation to shale and sandstone lenses. Minor diastems have doubtless been important in the localization of some deposits, but the information on this relationship is insufficient for positive statements. Small deposits are found adjacent to single fossil logs or bunches of plant material, and these seem to have a haphazard distribution and positions that are unpredictable. The relationship of many significant deposits to edges of channels and also to accumulations of plant material seems to be important and may furnish useful clues in prospecting for new ore bodies. Several important deposits of the Gateway district in Colorado as shown in figures 11 and 12 have curving shapes suggestive of meander deposits, but cross-bedding studies of these deposits are not available. Figure 10 shows an example of ore lying at the edge of a curving lens of sandstone in the northeast part of the Yellow Cat area.

Relation of Ore Deposits to Secondary Sedimentary Features

The sandstone lenses of the Salt Wash sandstone member of the Morrison formation exhibit several types of secondary structures developed at different stages during deposition, compaction, and regional deformation. It is assumed that the foregoing sections of this paper have demonstrated that joints, faults, and folds, which have originated rather late in the geologic history of the region, have had no significant influence on the genesis or localization of the ore bodies. Attention will, therefore, be directed to secondary features originating early in the history of the formation. Among the secondary structures that must have been produced in unconsolidated material are sandstone "dikes" in shale, shale "dikes" in sandstone, contorted bedding in both shale and sandstone, and minor irregular disturbances of various sorts.

None of these structures have been observed to influence the localization of ore bodies, and certainly no genetic implications are evident. Although changes in porosity and permeability must have resulted from movements producing these features, there is no evidence that such disturbed areas thereby became favorable for ore deposition.

The roll surface, or skin, previously described which is intimately associated with the elongate type of ore body may be classed as a special type of secondary sedimentary structure, but it seems to be unique insofar as published descriptions are concerned and is apparently not amenable to experimental duplication. The following remarks are necessarily of a speculative nature.

Ground water has evidently been the agent responsible for bringing the constituents of the ore minerals to the sites of their accumulation, and it seems logical to seek an explanation for the roll surfaces by the same agency. The fact that the long axes of the roll-type ore bodies, the direction of cross-bedding, and the edges of sand lenses are parallel in orientation supports the conclusion that underground water probably percolated along essentially the same routes as the surface streams that originally deposited the sand bodies. Unhindered percolation was possible only during that period of the time following deposition and before the formation became thoroughly lithified. In terms of geologic time, original mineralization may have been accomplished while the Salt Wash sandstone member was under relatively light cover and still retained approximately its original inclination with respect to the earth's surface. This does not preclude the possibility that the essential elements may have not been recomposed or altered at a later time through the agency of heated waters or other forces.

Speculating further, it may be assumed that the curving planes of discontinuity termed roll surfaces and the associated ore bodies were formed either at the same time or at nearly the same time.

If the roll surfaces, either with or without actual fracturing, had developed in the rocks previous to, and independently of, mineralization, they should probably be found at many places in the formation remote from ore bodies, but such have not been observed. Roll structures might, however, be inconspicuous, or even invisible, on ordinary inspections if they were, for example, due to differences in distribution of light-colored calcareous cement or other interstitial material. They might also be formed at many places as an early phase of diagenesis and later healed or obliterated by continued cementation. Introduction of ore minerals during an early satge of cementation could prevent healing or further cementation by ordinary minerals, and would also bring about striking color differences. At any rate, it is possible that curving surfaces initially formed by ground water acted as dams against which concentration and precipitation of ore minerals occurred. These planes could have been accentuated by subsequent mineralization where such was favored by presence of organic accumulations and relatively large supply of ground water.

The fact that quartz sand grains have been more or less dissolved in the near vicinity of the roll surfaces may be variously interpreted. One consequence of this solution has been a sagging or settling of beds on one side of the roll surface, so that bedding planes have been slightly but noticeably displaced. Likewise the fine-grained ore minerals have been concentrated at and near the roll surface, apparently also by the solution of the sand grains. Whether solution occurred before, after, or during mineralization is an unsettled question, but the two processes were probably not widely separated in time.

In the absence of positive evidence, it seems permissible to assume that the secondary structures known as roll surfaces were created essentially at the same time as the ore bodies that attend them, and that both phenomena are manifestations of ground-water action.

Relation of Organic Material to Ore Deposits

The fact that rich concentrations of "carnotite" ore are commonly found in intimate association with recognizable fossil logs has been known to miners and prospectors from the days of earliest activity in the region. The high value of such "trees" makes them objects of special interest, and the sandstones in which they occur are known locally as "tree formations."

Geologists who first described and discussed the uranium-vanadium deposits from more than a strictly economic viewpoint were also impressed by the close association of plant remains and ore minerals.

As early as 1911 F. L. Hess visited and described the carnotite deposits near Green River, Utah, which are in the Morrison formation about 35 miles west of the Thompsons area. Hess (1913, p. 162) describes these as follows:

> All the deposits are in a coarse, loosely consolidated, cross-bedded sandstone which is in places finely conglomeratic. The sandstone is cemented with calcite and carries much petrified wood, many imperfect plant remains that appear to have been reeds and many fossil bones. Some of the petrified wood is in logs 2 or 3 feet in diameter and 10 feet or more long. The structure of the wood is, however, not well preserved. The supposed reeds are represented by cavities crossed by numerous septa suggestive of cat-tail leaves. In some of these cavities there is apparently some carbonized organic matter left; others are partly filled by manganese dioxide or iron oxide. None of the fossils seem well enough preserved to offer hopes of their identification. The bones are in part black from organic matter and retain much phosphorus in their composition. All seen were too fragmental to promise a possibility of identification. The plant remains seem to occur largely along one horizon in the sandstone and the carnotite is closely associated with them.

However, as shown by his conclusions (1913, p. 164), Hess then believed the association of plant remains and ore to be mostly accidental for he states:

> It is also to be noted that all the deposits examined, except one, visibly accompany faults. Their presence with the organic matter seems to be fortuitous and due to the convenient cavities provided by its decay and removal or to its cracking.

Gale (1907, p. 110) described the carnotite occurrences in Rio Blanco County, Colorado, as follows:

> In the principal group of deposits seen the carnotite occurs in association with fossil or silicified wood. The fossil wood layer is apparently an original stratum of the Dakota (now known to be Morrison), for it may be traced along the strike of the beds for a mile or more. The carnotite itself is in the form of a bright yellow film or crust—in only one place the mineral was found as an impregnation in the Dakota sandstone apparently without association of silicified wood.

Writing of the sedimentary ores of the eastern part of Utah, Butler (1920, p. 153) reports:

> Plant remains are characteristically associated with the deposits and in many places are abundant. They are commonly in part silicified and in part carbonized. . . . Silicified fossil plants contain little, if any, metal, but carbonized plants may contain much.

Hess (1914, p. 682) attempted to synthesize the known facts regarding the association of ore and plant remains as follows:

> The relation of the carnotite and the fossil vegetation in the sediments of the area may be summed up thus:
>
> (1) The carnotite deposits always contain fossil vegetation.
>
> (2) Spaces in the rocks, which were formerly occupied by vegetation, including large trees, are now occupied by carnotite and associated minerals.
>
> (3) The fossil wood was floated to its resting place and was not petrified until it had been buried rather deeply.
>
> (4) Neither carbonized nor silicified wood has been replaced by metallic minerals.
>
> (5) Carnotite is an oxidized mineral which may have migrated some distances from its original position. Aureoles show that under present conditions carnotite and other metallic minerals are moving away from rather than toward fossil wood.

In a later paper (1933, p. 480) Hess states:

> It seems probable that deposition from tenuous solutions was caused directly or indirectly by decaying vegetable matter.

A somewhat different opinion has been expressed by Fischer (1937, p. 943):

> It is the writer's opinion that the genetic role of the plant material in these ores has been overemphasized. Carbonized plant material, in appearance identical to that found with the ore, is commonly noted in the mine workings above and below the ore and this material generally shows no trace of mineralization. Plant fossils may or may not be as abundant in the non-mineralized sandstone as in the ore but they are present and show no mineralization.

Discussing the possible modes of origin of the ore and the effects of organisms other than those which leave fossil remains, Fischer continues (1937, p. 951):

> Possibly certain organisims, presumably of the lower forms of life, for they left no direct record of their existence, may have been effective in concentrating these metals in the past.

In a later paper, Fischer (1942, p. 389) reiterated his belief that plant remains may have no genetic relationship to the localization of ore bodies as follows:

> Shale pebbles, clay films along bedding planes, and fossil plants commonly localize high concentrations of the metals within ore bodies, but since these lithologic features are as abundantly present in the adjacent barren sandstone as they are in the ore, they cannot have controlled the position of the ore bodies.

Notestein (1918) conducted experiments which show that uranium and vanadium are precipitated from sulfate solution by calcite. He also placed rotten and fresh wood in solutions of the metals with no appreciable effects of concentration or precipitation. No claim was made that these experiments duplicated with any degree of accuracy the conditions that prevail within the earth under deep burial and over long periods of time.

In the absence of conclusive experimental evidence on the possible effects of organic material upon precipitation and concentration of the ore, observation made in the field must continue to form the basis for reasoning on the subject.

That ore deposits and plant remains occur together in many deposits cannot be doubted, but a causal relationship is more difficult to prove. As noted by Fischer, there are many accumulations of fossil plant material in the Salt Wash sandstone member that are unmineralized and the presence of organic material does not invariably produce mineralization. Granting that a complete quantitative treatment of this problem is difficult, if not impossible, certain observations made in the Thompsons area are nevertheless thought to be significant.

Within the area shown in plate 2, there are 70 separate known deposits of carnotite ore. The number is arbitrarily limited by the lumping together of small spots of ore that lie near each other in the same sandstone bed. Eight of the 70 deposits were not examined with enough care to establish with certainty the presence or absence of organic remains. Of the 62 deposits that were examined, 56 contain recognizable plant remains or carbonaceous matter. Most of the deposits in which no organic material was found are poorly exposed and some of them probably would show organic material if fully exposed, or if eroded portions could be restored. It seems safe to assert from general observation that the portion of ore deposits that contain organic materials (90 percent) is vastly greater than the proportion of unmineralized rock that contains or is near organic materials. In fact, plant fossils are very rare except in ore deposits; those that are found outside the deposits are usually silicified tree trunks. Carbonaceous shales and sandstones such as are common in the Pitts No. 5 mine (fig. 3) have been noted in no unmineralized outcrops.

It will probably be useful to indicate the types of plant remains and other organic accumulations that have apparently governed the deposition of ore, as all are not readily recognizable as being of organic derivation. The following classification of remains seems to apply quite generally to the Salt Wash sandstone member of the Morrison formation and its equivalents wherever the author has had the opportunity of examining them.

(1) Water-worn carbonaceous fragments: Accumulations of rounded, elliptical, and oval fragments of carbonaceous, woody material are fairly common. These are usually less than half an inch in the long dimension and occur mainly in thin-bedded sandstone, especially along the bedding planes. These are similar in shape, size, and evident mode of origin to the small water-worn fragments that may be observed in recent streams and lakes, especially after floods. These fragments seem to have been subjected to much abrasion by water, and they probably originated as dead, partly desiccated and broken fragments picked up in times of high water and were then transported for long distances during which they became rounded and smoothed. Fragments of this sort generally come to rest in shallow water and are probably not deposited where the velocity of the stream is sufficient to produce good cross-bedding. The small fossil fragments, although not known to be replaced by siliceous or calcareous material, occur in great abundance in some ore deposits, especially those of the tabular type in which the ore minerals are also concentrated along the bedding planes.

(2) Reedlike impressions: Molds of stems and branches and vague impressions of soft-bodied plants may or may not be associated with carbonaceous material. Straplike and reedy fragments which must have been originally soft and vascular, water-loving plants which were easily flattened and distorted by a light overburden of sediments occur in association with irregular masses of ore and yellow limonite stain. Some of these show only smooth surfaces, but others have a barklike texture; none with leaf-shaped outlines has been seen by the writer and specific identifications can hardly be expected. None has been observed in silicified form, but gymsum in some cases fills the cracks and openings left by the plants. These remains are thought to have been buried near or at the places of growth, as their comparatively fragile nature would not allow for long transportation.

(3) Trees and logs: Petrified and mineralized pieces of wood are the most easily recognized fossils of the Salt Wash sandstone member of the Morrison formation. As noted by most observers, the original logs appear to have drifted into the area from more or less distant sources. Roots and branches appear to have been battered and broken off as if by long transportation. Knowlton (as reported by Hess, 1933, p. 479) has identified silicified specimens as *Araucarioxylon,* a coniferous genus common throughout the Mesozoic era and surviving in restricted habitats in the Southern Hemisphere at the present time. It should be noted that this type of tree is characterized by straightness of the trunk and relatively small branches which are clustered near the crown. The wood in many species is tough and resinous. The habitat ranges from subtropical to temperate, and if this can be taken as an indi-

cation of former climatic conditions, it suggests that the Morrison was probably not deposited under tropical conditions and could have originated in a semiarid temperate climate.

The fossil logs may be replaced with, or represented by casts and molds of, various materials including calcite, dolomite, silica, ferruginous sandstone, ore minerals, coal, jet, and unidentified bituminous substances. Generally speaking, the siliceous specimens are the least crushed and are in most cases perfectly preserved. Trunks that are preserved as carbonaceous residues are crushed to mere sheets and those represented by calcite, ore, and limonite are intermediate in degree of deformation. Generally, the "high-grade" pieces containing rich masses of carnotite ore are partly flattened and the space occupied originally by woody material is now filled by soft incoherent masses of iron-stained sand, ore, and fragments of siliceous and calcareous material, and it is not uncommon for several types of replacing and residual material to be present in the same cavity.

The trunks range from 10 to 50 feet in length and from 6 inches to 1½ feet in diameter, but the poor preservation and loss of detail, as well as the crushing, render exact measurement difficult. There appears to have been little branching of the trunks and such branches as were present were small.

The logs occur generally in the cross-bedded sandstones and usually their long axes are parallel with the direction of cross-bedding, but may be at various angles with it. No large group of trunks is known in the Thompsons area but several are present in the adjoining Gateway district (Stokes and Fischer, 1945). All logs observed are parallel with the stratification and no stumps or roots in position of growth have been seen. All evidence agrees in indicating that the trees grew at some place more or less distant from the area in which they were buried and that they were floated by rivers into the area and lodged in shallow water.

The implications of the types of preservation, coalification, silicification, and mineralization, degree of replacement, deformation, and other features probably cannot be fully evaluated until more is known of the process of petrifaction of organic material in general. It has been noted by Butler and others that silicified trees are generally barren and that such carnotite as is present occurs as mere coatings and crusts in cracks and on the surface of the silicified wood. With this the author is in full agreement. It is believed that completely silicified trees in which no carbonaceous material is present are essentially barren of uranium and vanadium minerals.

The production of coaly, jetlike, and more or less structureless material from original woody tissues is a subject that is out of place in this report, but the form, texture, and occurrence of these materials indicate clearly that the parent source was woody or other organic tissue.

Dinosaur bones are common in the ore deposits and are frequently observed replaced by high-grade minerals. The thin, black, high-grade ore bodies are evidently composed mainly of fine-grained ore and clay minerals, but there is also much carbonaceous material associated with them. The shapes of these thin layers suggest that some may have been originally oozelike accumulations, rich in organic material, deposited in local ponds of stagnant water.

Observations made in other areas previous to detailed study of the Thompsons area suggested a definite connection between uranium-vanadium ore and blue-green color in associated mudstones. Evidence gathered in the Thompsons area indicates this association to be a significant one that may be useful in prospecting for hidden ore bodies. The blue-green color seems to be a secondary feature imposed on originally red argillaceous sediments generally lying below and in the near vicinity of ore bodies. The areas affected are commonly several times larger in plan view than the associated mineralized rock and thus, for practical purposes, they offer more sizable "targets" in exploration. Depth of alteration ranges from a few inches to 10 feet; there seems to be relatively little alteration above ore-bearing layers, but thin lenses or detached fragments within the sandstones are invariably of a blue-green color in the vicinity of ore bodies. This type of alteration was observed in 62 of the 70 deposits examined in the Thompsons area and has been widely noted in connection with ore bodies in other districts. Much additional detailed work is necessary to determine the chemical changes that have taken place and in what respect these changes are related to organic materials, ore minerals, and ground water.

The association of limonite and limonite-staining with the ore and plant remains is likewise significant. Of the 70 deposits in the area, pronounced yellow or brown limonite-staining of the associated sandstone is present in 64. The association of organic material and limonite is more readily understandable and the reactions involved are probably less complex than between vanadium and organic materials.

It is logical to suppose that chemical reactions involving the products of decay of buried organic tissues in saturated rocks are not restricted to the immediate surfaces or internal cavities of the material. Thus, in the precipitation of ferric oxide and probably in the precipitation of vanadium and uranium compounds, the effect of the migration of the humic acids and complex colloids resulting from decay must be considered. If complex organic colloidal materials acted to precipitate the ore, it is evident that reactions could take place not only in the actual decaying materials but also in their near vicinity, probably the effects diminish away from the organic matter owing to gradual weakening and dilution of the organic products. Thus, the observation that unmineralized plant impression, fragments, and carbonaceous material occur in barren mine workings does not preclude the probability that the process of decay of these same plants provided the necessary chemical environment for the concentration of nearby ore masses. If the ore is not actually in contact with the remains, it is at least generally in the very near vicinity of them.

In this connection it is also necessary to bear in mind the complex nature of the channels and lenses in which ore deposition has taken place. Not all of the lenses or channels were open to circulating solutions; many were no doubt sealed off and surrounded by shale. Although these isolated sand bodies are structurally and lithologically suited for ore deposition and may even possess the necessary accumulations of fossil logs and plant materials, the all-important factor of large volumes of mineral-bearing waters was absent and ore bodies are consequently lacking. These considerations may explain why ore minerals are not always in direct contact with the organic materials in their vicinity. Hess (1914) and Coffin (1921) believe that the ore minerals, originally highly concentrated in the organic remains, have migrated outward into the surrounding rock. The author suggests the alternative idea that this grading away or fading out of mineralization may be explained as the result of the migration, not of ore minerals, but of the organic products released from the decaying material whose reactions with the through-flowing solutions were necessary for ore formation.

The subject of the behavior of uranium and vanadium compounds in the presence of organic material in the colloidal state is not well understood. The conditions of heat and pressure and the time factor, which are available geologically, are difficult to duplicate in the laboratory and so the whole series of reactions may not be susceptible of experimental demonstration. Nevertheless, the occurrence of ores of uranium and vanadium with plant remains, iron stain, and blue clay indicates, in the author's opinion, that the association is of fundamental importance in the genesis of the ore deposits in the Morrison formation. So common is the association of organic material and ore that any clues leading to the location of possible sites of deposition of fossil remains are also clues to the location of possible ore deposits.

Conclusions

As previously indicated, the correlation of deposits of organic debris with ore accumulations is close enough to warrant the assumption that any guides leading to the discovery of sites of deposition of organic material may also be valuable in prospecting for ore. The only line of approach so far evident is an indirect one through the study of the configuration and distribution of sand lenses and channels.

The curving or crescentic pattern of many of the sandstone lenses in the Salt Wash sandstone member of the Morrison formation indicates that they are associated with meander growth. These lenses, studied in conjunction with what may be observed of present day meandering rivers, suggests that certain organic accumulations are likely to occur more commonly at meander curves and therefore have characteristic curving shapes.

During meandering the concave bank of a river is subject to erosion while sand and gravel bars are accumulating along the convex bank. Trees, if they are present, are undercut on the concave bank and fall into the river. As a general rule, if aggradation is progressing the bars of the convex banks become permanent additions to the river deposits so that the flood plain becomes a complex maze of curving deposits which may show great variations in texture both laterally and vertically. With moderate meandering, such as appears to have characterized the rivers in Salt Wash time, there is a mixture of straight and curving elements at various levels.

In connection with the present investigations the chief point of interest is the fate of plant remains during the accumulation of the flood-plain sediments. Large trees appear to represent a special instance where not only the sites of accumulation but also the final orientation may, in many cases, be traced to meander action. One of the first effects of river transportation upon a fallen tree is the removal of twigs and branches. This battering effect usually continues until only a much-abraded log with stumps of branches and roots remains. Owing to difference in weight, the root-bearing end of a floating log is usually oriented upstream. Likewise a log floating in shallow water is likely

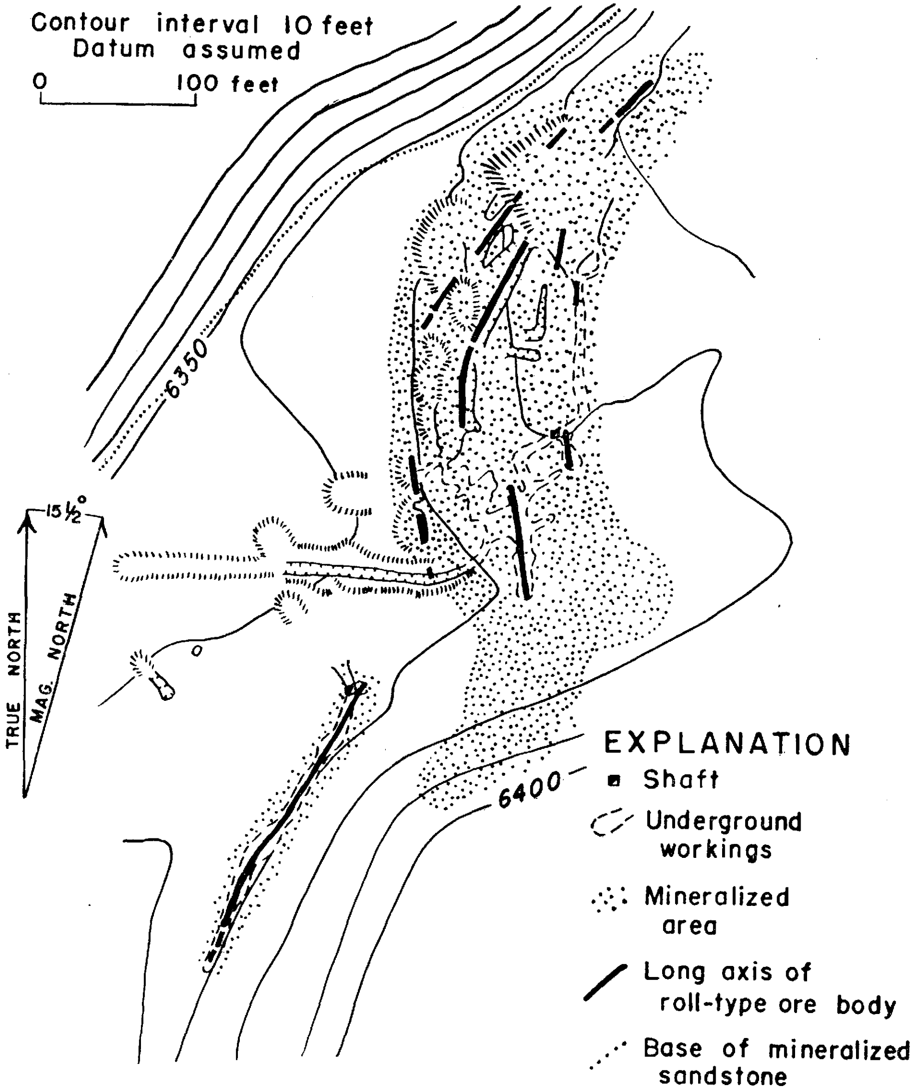


FIGURE 11 CARNOTITE DEPOSIT ON THE HUMMER-GREAT HESPER CLAIMS, CALAMITY MESA, MESA COUNTY, COLORADO

Topography and geology by D. C. Duncan and W. L. Stokes
June 1943

to catch first by the root end and to swing down current so as to come to rest with the roots upstream. It is obvious that large numbers of floating logs in very turbulent water may be involved in log jams and come to lie in a disorganized mass. Likewise, logs that have lost their roots or branches so as to have more or less equal diameter throughout may be rolled rather than dragged in shallow water and thus come to rest at right angles to the current. In meandering rivers under ordinary conditions of flow, floating logs usually become lodged upon the bars or against the banks in the meander curves and are less common where the channel is straight.

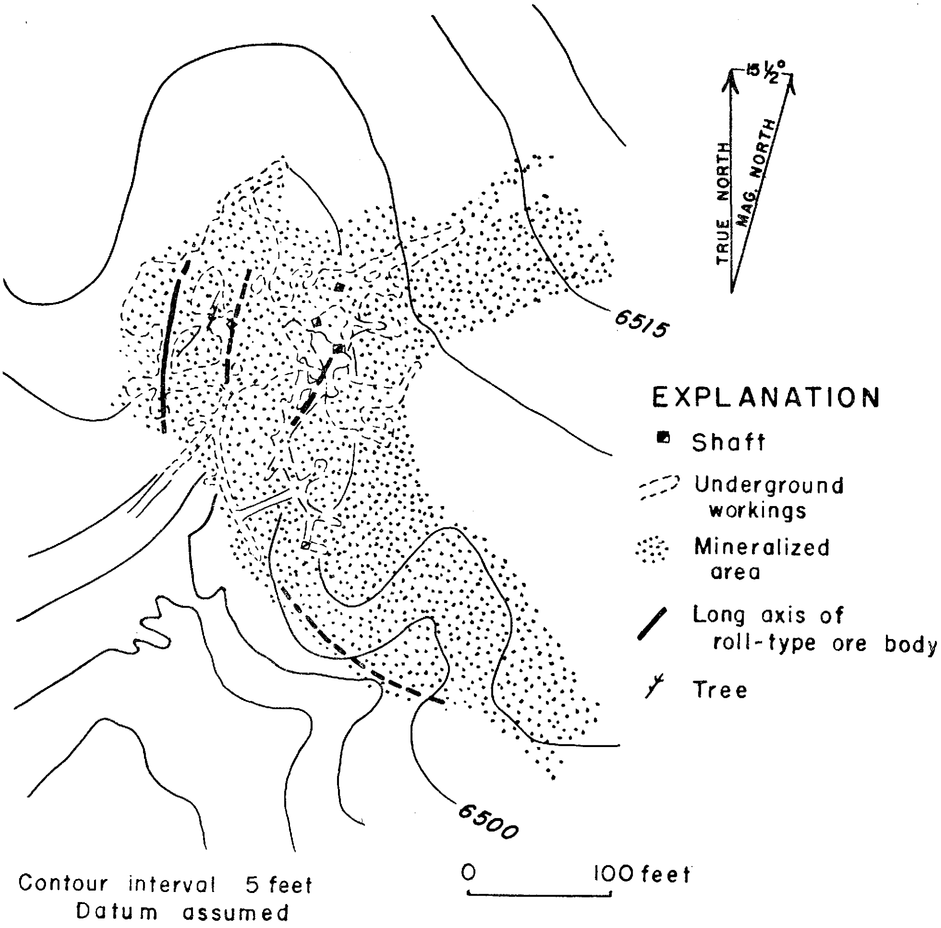


FIGURE 12 CARNOTITE DEPOSIT AT THE HIDDEN TREASURE MINE, CALAMITY MESA, MESA COUNTY, COLORADO

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Ore-bearing fossil logs are relatively common in the Salt Wash sandstone member of the Morrison formation where they occur either singly or in groups. When in groups the fossil logs usually lie in curving bands within the rocks. (See Stokes and Fischer, 1945.) Observations of miners and detailed mapping by geologists in many ore deposits have conclusively shown that the orientation of fossil logs is the same as that of the roll-type ore bodies when the two occur together; also the direction of the current flow as indicated by cross-bedding whenever mapped coincides with the long axes of the fossil trees. The map of the Club mine near Uravan published by Fischer (1942) indicates some of the foregoing observations in an excellent manner.

What has been said about the orientation and burial of logs in fluvial deposits may also be applied to other accumulations of organic material. As meandering is one of the most common features of aggrading streams, it leaves its impress, not only on the distribution of the coarser clastic sediments, but on the finer ones as well. Oxbow lakes, left by the shifting of the river channel, become sites of accumulation for fine sediments and for the growth of plants. The deposits of oxbow lakes later become curving bodies of fine sediment markedly higher in organic content than surrounding materials.

In times of flood, when the river deposits sediments more or less blanket-like over wide areas, plants may be buried where they grow. Such masses of buried plant materials will usually lie in the margins of sand lenses, curving or otherwise, as these represent the banks of streams where organic growth is most abundant.

The foregoing brief argument serves to indicate that organic material, if it is buried by fluvial action, may be expected most commonly along the edges of sand lenses and also that curving bodies of sand, representing ancient meanders, are more favorable than relatively straight channel segments. What is known of the organic accumulations of the Salt Wash sandstone member of the Morrison formation supports these conclusions and provides a possible basis for exploration for additional hidden deposits.

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