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PRELIMINARY REPORT ON THE STRATIGRAPHY OF THE MORRISON AND RELATED FORMATIONS OF THE COLORADO PLATEAU REGION

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This preliminary report is released without editorial and technical review for conformity with official standards and nomenclature, to make the information available to interested organizations and to stimulate the search for uranium deposits.

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ABSTRACT AND SUMMARY

The Jurassic rocks of the Colorado Plateau region are divided into three units: the Glen Canyon group, the San Rafael group, and the Morrison formation in ascending order. The Glen Canyon group consists mainly of eolian and fluvial sediments; the San Rafael group of marine and marginal marine sediments; the Morrison formation of fluvial and lacustrine sediments.

The Morrison formation of central and eastern Colorado cannot be differentiated into members. In eastern Utah, northeastern Arizona, northwestern New Mexico, and part of western Colorado, the Morrison may be divided into a lower part and an upper part, each of which has two members differentiated on a lithologic basis.

The lower part of the Morrison consists of the Salt Wash sandstone member and the Recapture shale member. These intertongue and intergrade over a broad area through the vicinity of the Four Corners. The Salt Wash member is present through eastern Utah and parts of western Colorado, northeastern Arizona, and northwestern New Mexico. It was formed as a large alluvial plain or "fan" by an aggrading system of braided streams diverging to the north and east from an apex in south-central Utah. The major source of the Salt Wash was southwest of south-central Utah, probably in west-central Arizona. The Salt Wash deposits grade from predominantly coarse-textured sediments at the apex of the "fan" to predominantly fine-textured sediments near the margin of the "fan".

The Salt Wash has been arbitrarily divided into four facies: the conglomeratic sandstone facies, the sandstone and mudstone facies, the claystone and lenticular sandstone facies, and the claystone and limestone facies. The Salt Wash was derived mainly, if not completely, from pre-existing sedimentary rocks.

The Recapture shale member is present in northeastern Arizona, northwestern New Mexico, and small parts of southeastern Utah and southwestern Colorado near the Four Corners. It was formed as a large alluvial plain or "fan" by an aggrading system of braided streams. The Recapture deposits grade from predominantly coarse-textured sediments to predominantly fine-textured sediments, and have been arbitrarily divided into three facies: the conglomeratic sandstone facies, the sandstone facies, and the claystone and sandstone facies. The distribution of the facies indicates that the major source of the Recapture was south of Gallup, N. Mex., probably in west-central New Mexico. The Recapture was derived from a mixed source of intrusive and extrusive igneous rocks, metamorphic rocks, and sedimentary rocks.

The upper part of the Morrison formation consists of the Westwater Canyon sandstone member and the Brushy Basin shale member. The Westwater Canyon member forms a lower part of the upper Morrison in northeastern Arizona, northwestern New Mexico, and in places in southeastern Utah and southwestern Colorado near the Four Corners, and it intertongues and intergrades northward into the Brushy Basin member. The Westwater Canyon member was formed as a large alluvial plain or "fan" by an aggrading system of braided streams. The Westwater deposits grade from predominantly coarse-textured sediments to somewhat finer-textured sediments, and have been arbitrarily divided into two facies: the conglomeratic sandstone facies and the sandstone facies. The distribution of the facies indicates that the major source of the Westwater was south of Gallup, N. Mex., probably in west-central New Mexico. The Westwater was derived from a mixed source of intrusive and extrusive igneous rocks, metamorphic rocks, and sedimentary rocks. The similarity of the distribution and composition of the Westwater to the Recapture indicates that the Westwater essentially represents a continuation of deposition on the Recapture "fan" but contains considerably coarser materials.

Whereas the Salt Wash, Recapture, and Westwater members may be characterized as monotonous sequences of interstratified sandstone and red or green claystone, the Brushy Basin consists mainly of variegated claystone with uncommon lenticular conglomeratic sandstone. The Brushy Basin shale member is present in eastern Utah and parts of western Colorado, northeastern Arizona and northwestern New Mexico. It consists of sediments formed in fluvial and lacustrine environments and contains large amounts of clay, part of which is bentonitic and was probably contributed by volcanic ash falls. The source area for many of the fluvial deposits of the Brushy Basin may have been the same as that for the Salt Wash member, to the southwest in west-central Arizona. No lithologic facies with restricted areal distribution can be distinguished in the Brushy Basin. At the conclusion of deposition of the conglomeratic sandstone and sandstone of the Westwater, Brushy Basin deposition spread southward over at least part of the area of the Westwater. The original extent of the Brushy Basin to the south and west is not known, for it has been removed by pre-Dakota erosion from most of northeastern Arizona.

The undifferentiated Morrison of eastern and central Colorado has lithologic characteristics similar to those of the Brushy Basin. It contains representatives of both the upper and lower parts of the Morrison to the west, but these units cannot be distinguished, and no other lithologic units have sufficient continuity to warrant member status.

Lower Cretaceous beds, mainly of fluviatile and lacustrine character, have been recognized above the Morrison over most of the Colorado Plateau region. In places they are so similar to the Morrison that the formations are difficult or impossible to separate. Upper Cretaceous formations consist of intertonguing continental and marine beds which mark widespread transgressions and regressions of the strand line. The Dakota sandstone, at the base of the Upper Cretaceous, overlies an erosional unconformity which increases to the southwest, and in western New Mexico and northeastern Arizona the Dakota progressively overlies older and older formations.

The carnotite deposits of the Morrison formation are essentially confined to the Salt Wash member and lie entirely within the sandstone and mudstone facies of the Salt Wash. Lithofacies studies delimit an area of relative favorability for ore localization within the area of the sandstone and mudstone facies. Most of the carnotite deposits occur in areas where sandstones of the Salt Wash have low logarithmic standard deviations, and probably a relatively high permeability. The resultant dip directions of cross laminae in the sandstones of the Salt Wash and the trends of ore "rolls" show about the same radial regional pattern and may indicate a large-scale influence by primary sedimentary structures on the shapes of carnotite deposits; however, the ore deposits show little detailed control by sedimentary structures, for in many places the ore cuts across the bedding and lamination.

Three sources for the uranium of the carnotite deposits may be postulated: 1) from the rocks of the source area of the Salt Wash, 2) from a post-Salt Wash hydrothermal source in the Colorado Plateau region, and 3) from disseminations in post-Salt Wash sedimentary rocks.

INTRODUCTION

Purpose and methods

In July 1947, a program of stratigraphic studies was begun by the Colorado Plateau project of the U. S. Geological Survey on behalf of the Atomic Energy Commission.

The general purpose of the stratigraphic studies has been 1) to determine the paleogeography of the uranium-bearing formations of the Colorado Plateau with the ultimate goals of establishing possible sources of the ore minerals, their means and routes of transportation and controlling factors for their localization in ore bodies as an aid to guiding exploration for these deposits; and 2) to provide a sound foundation for stratigraphic nomenclature within the areas of the geologic mapping and exploration programs.

The first phase of the stratigraphic studies has been concerned with the Morrison formation of Upper Jurassic age, which contains most of the carnotite deposits of the Colorado Plateau and has shown the most promise for development of ore reserves. Study of the Morrison is nearing completion. This report summarizes the results and interpretations warranted at this stage of the work. Many of the ideas resulting from this work are new. This is due to the development of new methods, to a more widespread application of old methods, and to standardization of descriptions and techniques.

The work has been divided into four studies, two of which deal with the Morrison formation and adjacent formations, and two of which deal mainly with the carnotite-bearing Salt Wash sandstone member.

1. Regional stratigraphic study, concerned with establishing and interpreting the stratigraphic sequence, physical continuity, and color, composition, texture, structure and thickness variations of the members of the Morrison formation and adjacent formations.

2. Sedimentology, concerned with the laboratory analysis of samples of the Morrison and adjacent formations to determine detailed lithologic characteristics and variations. Particular emphasis has been placed on the Salt Wash member to determine not only the regional variations but also any relation of the carnotite deposits to sedimentary parameters.

3. Lithofacies study, concerned with determining the distribution and variation of the sediments formed in the two main depositional environments of the lower part of the Morrison.

4. Study of sedimentary structures, concerned with determining the current directions during deposition of the Salt Wash member and the relation of the resulting sedimentary structures to ore structures.

The region of study includes more than 5,000 miles of linear outcrop of the Morrison formation. This outcrop is so extensive that all parts of the stratigraphic studies were required to resort to sampling techniques. All the studies yielded quantitative as well as qualitative results and all except the regional stratigraphic study supplied data which are amenable to statistical treatment.

Work was begun in the carnotite-producing area of westernmost Colorado and was extended radially outward from this area with decreasing concentration. The region of study extends sufficiently beyond the limits of recognizable Salt Wash to permit a thorough understanding of the geologic history of the member.

Region of study and geologic setting

The region of study encompasses the western two-thirds of Colorado, the northwestern quarter of New Mexico, the eastern half of Utah, and the northeastern quarter of Arizona. It includes all except the southwestern margin of the Colorado Plateau province, all the Southern Rocky Mountain province, and the western edge of the Great Plains province as these physiographic provinces are outlined by Fenneman (1931).

In the Colorado Plateau, sedimentary beds are flat-lying or gently warped except where pierced by laccolithic mountains, volcanic plugs, and salt-anticlines or sharply folded along large monoclines. The Morrison formation crops out in long, continuous but serrate patterns (fig.1). In the Southern Rocky Mountain part of the region, the rocks exposed are dominantly igneous and metamorphic and are faulted, folded, and uplifted to form mountains of complex structure. In this area the Morrison crops out in shorter disconnected belts that forms sinuous or straight patterns. In the Great Plains province, sedimentary beds are nearly flat-lying, and, where exposed, the Morrison crops out in long, continuous but serrate patterns.

The rocks exposed in the region of study range from pre-Cambrian to Cenozoic in age. Igneous and metamorphic rocks constitute the pre-Cambrian, whereas later rocks are predominatly sedimentary. The lower Paleozoic is represented by relatively thin marine limestones and clastics. These grade upward to the thick terrestrial and marginal marine

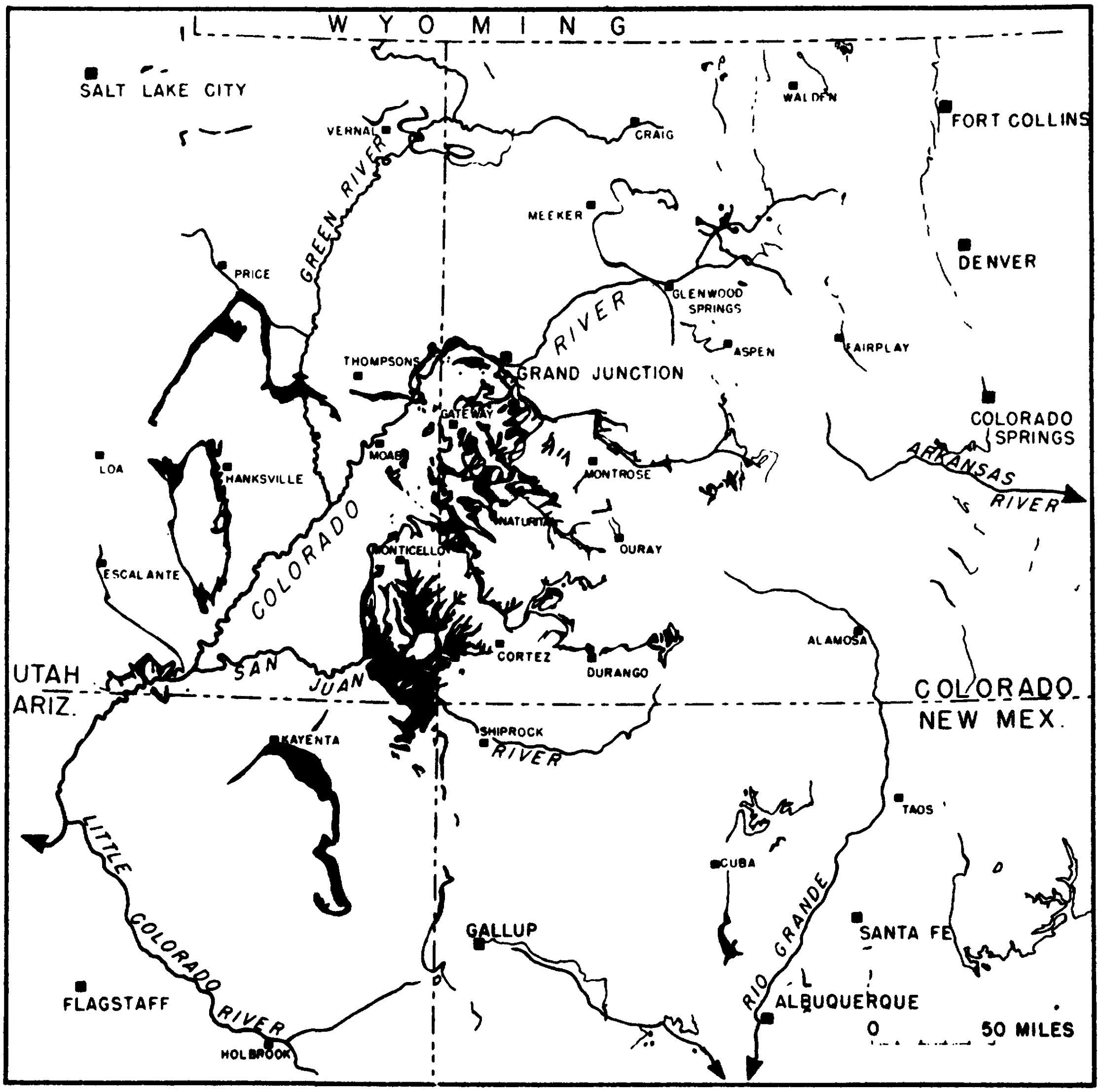


Figure 1.--Index map of the Colorado Plateau region showing the outcrop pattern of the Morrison formation.

clastics and evaporites of the upper Paleozoic. Rocks of Mesozoic age are mainly clastic; they were deposited under terrestrial conditions throughout the Triassic, Jurassic, and Lower Cretaceous except for two marine units of Middle and Upper Jurassic age. The Upper Cretaceous is represented by thick marine clastics. Tertiary sediments are mainly clastic; Tertiary igneous activity is represented by volcanics such as those of the Shiprock area, the San Juan Mountains and the Spanish Peaks, and by isolated laccolithic intrusive masses of the Colorado Plateau, such as the Henry Mountains.

STRATIGRAPHY OF JURASSIC AND CRETACEOUS ROCKS

The Jurassic rocks (table 1) of the Colorado Plateau are subdivided into three major units: the Glen Canyon group, the San Rafael group, and the Morrison formation in ascending order. This classification may be applied throughout the region of study. Baker, Dane, and Reeside (1936, 1947) have discussed the Jurassic stratigraphy of the Colorado Plateau and their papers cite most of the basic references dealing with this subject.

Pre-Morrison formations

Glen Canyon group

The Glen Canyon group consists of the Wingate sandstone, Kayenta formation, and Navajo sandstone, in ascending order. Assignments of the group to the Jurassic is tentative because of the lack of diagnostic fossils. The Wingate sandstone forms a broad lens-shaped deposit extending through all southeastern Utah, into southwestern Colorado and part of northeastern Arizona and northwestern New Mexico adjacent to

Table 1.—Generalized section of Jurassic and Cretaceous Strata in southwestern Colorado and adjoining parts of Utah

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

the Four Corners. The Wingate is mostly eolian in the center of this area but shows increasing characteristics of deposition in a standing water body to the north and east and fluvial deposition to the southeast.

The Kayenta forms a broad lens-shaped deposit through all of southeastern Utah and part of northeastern Arizona, and extends into western Colorado. The Kayenta is fluvial in origin. The marginal relations of both the Wingate and Keyenta are poorly understood.

The Navajo sandstone forms an irregular wedge of predominantly eolian sandstone extending through all of southern and eastern Utah, into western Colorado and part of northeastern Arizona. The Navajo is thickest in southwestern Utah and is represented by the even thicker Aztec sandstone in southern Nevada. The limit of the Navajo is along an irregular northeast-southwest trending line through southwestern Colorado and northeastern Arizona.

In Colorado and Utah the Glen Canyon group is conformable on the underlying Upper Triassic Chinle formation, but in New Mexico and Arizona an erosional disconformity is indicated at the base of the Glen Canyon. The formations of the Glen Canyon group are separated in most places by gradational contacts.

The Glen Canyon group reflects a period of aridity during which terrestrial clastics accumulated over the region of the Colorado Plateau. The dominant eolian deposition characterizing the group was broken by a period of widespread stream deposition in Kayenta time. Data as to sources of the formations are incomplete. The Wingate was probably derived from the west in Utah and eastern Nevada. Baker, Dane, and Reeside (1936, p. 44) suggest that the Kayenta had an important local source from the east, from the Ancestral Uncompahgre Highland of of western Colorado, but no major source has been recognized. The Navajo probably was derived from western and southern Nevada. Analyses of the orientation of sedimentary structures in the Navajo indicate that the sands were deposited by winds blowing from the west and northwest across eastern Utah and northeastern Arizona.

San Rafael group

The San Rafael group is divided into four formations: the Carmel formation, Entrada sandstone, Curtis formation, and Summerville formation, in ascending order. The Carmel has been dated as early Upper Jurassic and the Curtis as middle Upper Jurassic from marine invertebrate fossils. The Entrada and Summerville lack diagnostic fossil remains.

The Carmel formation was deposited throughout southern Utah and northeastern Arizona. It thins to the northeast and reaches a feather edge in southwestern Colorado. A partly marine limestone- and gypsum-bearing sandstone and shale facies in central and southwestern Utah has been distinguished from a marginal marine red shale facies in northeastern Arizona and a marginal marine red silty sandstone facies in eastern Utah. The extent of the Carmel into New Mexico has not been determined. This problem can only be solved by detailed studies of facies relations in the Four Corners area.

The Entrada sandstone was deposited throughout southern and eastern Utah, most of Colorado, and all of northeastern Arizona and northern New Mexico. A red earthy sandstone facies in central and southwestern Utah has been distinguished from a clean sandstone facies in Colorado, eastern Utah, northeastern Arizona, and northern New Mexico. The earthy sandstone facies is largely of subaqueous origin and the clean sandstone facies was deposited in an alternating subaqueous and subaerial marginal marine environment. The Entrada is absent in parts of central Colorado on the Ancestral Highlands.

The interval between the top of the Entrada sandstone and the base of the Morrison formation is complicated by many facies changes and a number of formation and member names. The Curtis and Summerville formations are the main units occupying the interval. The Curtis is grayish to greenish glauconitic sandstone; the Summerville is red silty shale with minor light-colored sandstone. The Curtis has been recognized in southwestern, central, and northeastern Utah and in northwestern Colorado. Thin-bedded sandstones and shales along the northern part of the Front Range in Colorado, and limestone and gypsum deposits in southwestern Colorado and northwestern New Mexico, may be equivalent to the Curtis. The Curtis and these possible equivalents are regarded as predominantly marine in origin. The Summerville formation has been recognized throughout south-central and southeastern Utah, and parts of southwestern Colorado, northeastern Arizona, and northwestern New Mexico. Where both formations are present the Summerville overlies the Curtis or possible equivalents of the Curtis. In northeastern Utah and northwestern Colorado the Curtis occupies the entire interval between the Entrada and the Morrison. The Summerville is regarded as a marginal marine deposit formed in relatively quiet shallow water. It contains the Moab tongue of the Entrada sandstone in part of southeastern Utah, a sandstone deposit that may have formed as an offshore bar.

In southern Utah, southwestern Colorado, northwestern New Mexico, and northeastern Arizona, the upper part of the Summerville is replaced by a sandstone unit that has been named the Bluff sandstone and the Junction Creek sandstone. Both have been considered as basal members of the Morrison (Gregory, 1938, p. 58; Goldman and Spencer, 1941, p. 1751), but the Junction Creek has also been considered either as a separate formation (Eckel, 1949, p. 29), or, most recently, a member of the Wanakah formation (Read, Wood, Wanek, and MacKee, 1949), a unit that occupies the interval between the Entrada and Morrison in parts of Colorado and New Mexico. In accordance with this latest usage, both the Bluff and the Junction Creek are tentatively assigned to the upper part of the San Rafael group. Southward in the area west of Gallup, N. Mex. the entire San Rafael group above the Carmel becomes sandstone similar to the Entrada and the Entrada and post-Entrada beds are inseparable.

The base of the Carmel is marked by an erosional break probably of little time duration. The irregularities of the underlying Glen Canyon were beveled and the top deposits were rewonked into the basal few feet of the Carmel. The remainder of the San Rafael group is essentially conformable. Local angular unconformities are common in central and south-central Utah as well as in the Four Corners area at various horizons in the San Rafael group, and are regarded as minor breaks of little importance.

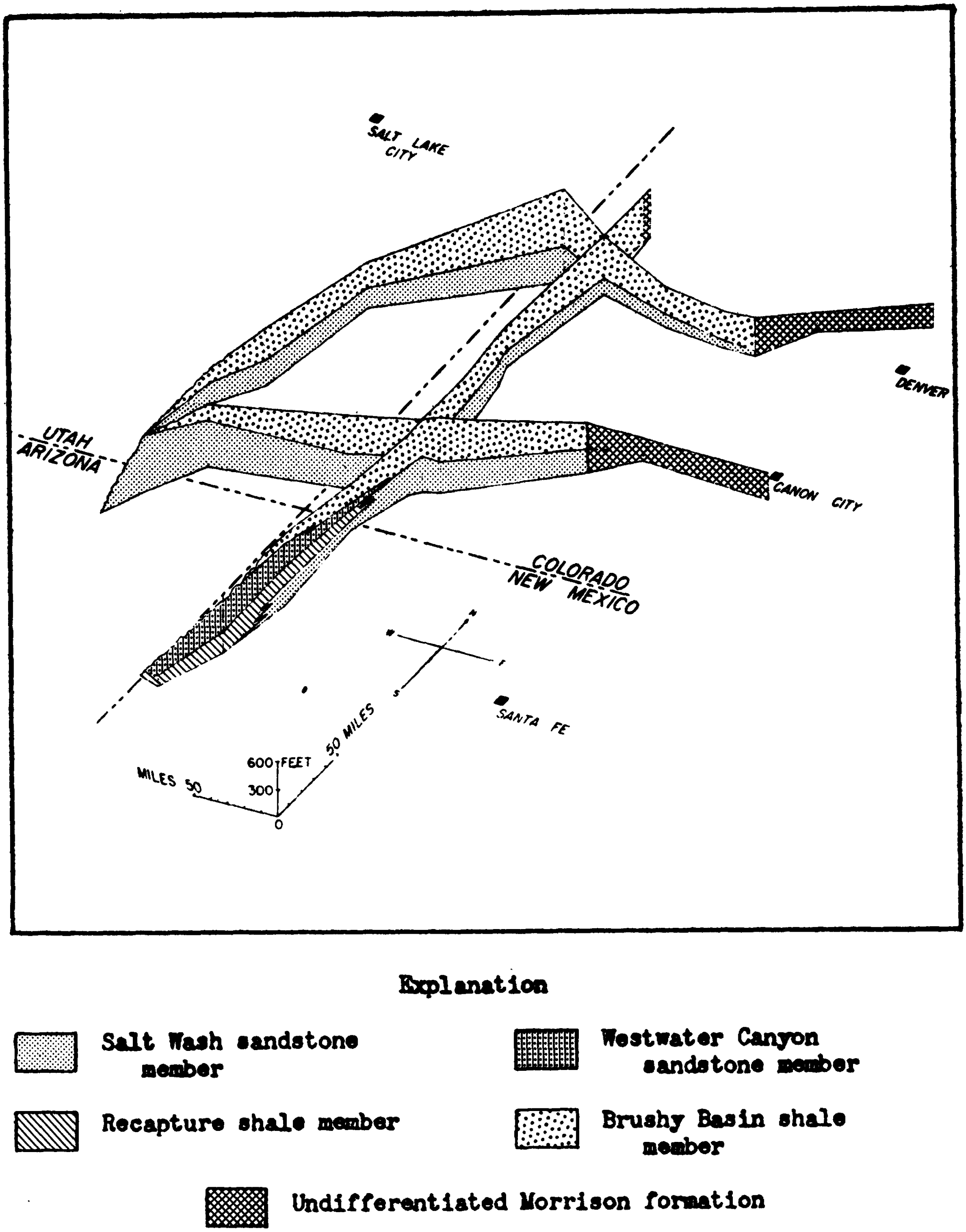
Morrison formation

The Morrison formation (Cross, Whitman, 1894, p. 2) has been recognized over most of the western interior of the United States, and, except where removed by erosion, it is present over all of Colorado, eastern Utah, northwestern New Mexico, and part of northeastern Arizona (fig. 1). The Morrison consists of lenticular strata of variegated mudstones and claystones and light-gray, cross-laminated sandstones. Over most of the western interior the Morrison cannot be divided into members; lithologic units or discrete facies are not sufficiently continuous or distinct to warrant recognition of members. In western Colorado, eastern Utah, northeastern Arizona, and northwestern New Mexico, however, the Morrison can be separated into a lower part and an upper part, each of which has two members differentiated on lithologic criteria (fig. 2). An arbitrary line separating undifferentiated Morrison of central Colorado from the subdivided Morrison to the west extends irregularly from northwestern Colorado to south-central Colorado. In figure 3 this line is shown as the limit of recognizable Salt Wash.

The base of the Morrison is defined as the base of the terrestrial fluviatile Jurassic deposits overlying beds of the marine or marginal marine San Rafael group. Detailed criteria for selecting the contact vary from one area to another.

Lower part of the Morrison formation

The lower part of the Morrison consists of the Salt Wash sandstone member in eastern Utah and western Colorado and the Recapture shale member in northeastern Arizona and northwestern New Mexico. These members interfinger and grade into each other over a broad area in the vicinity of the Four Corners (fig. 2).



Explanation

Salt Wash sandstone member

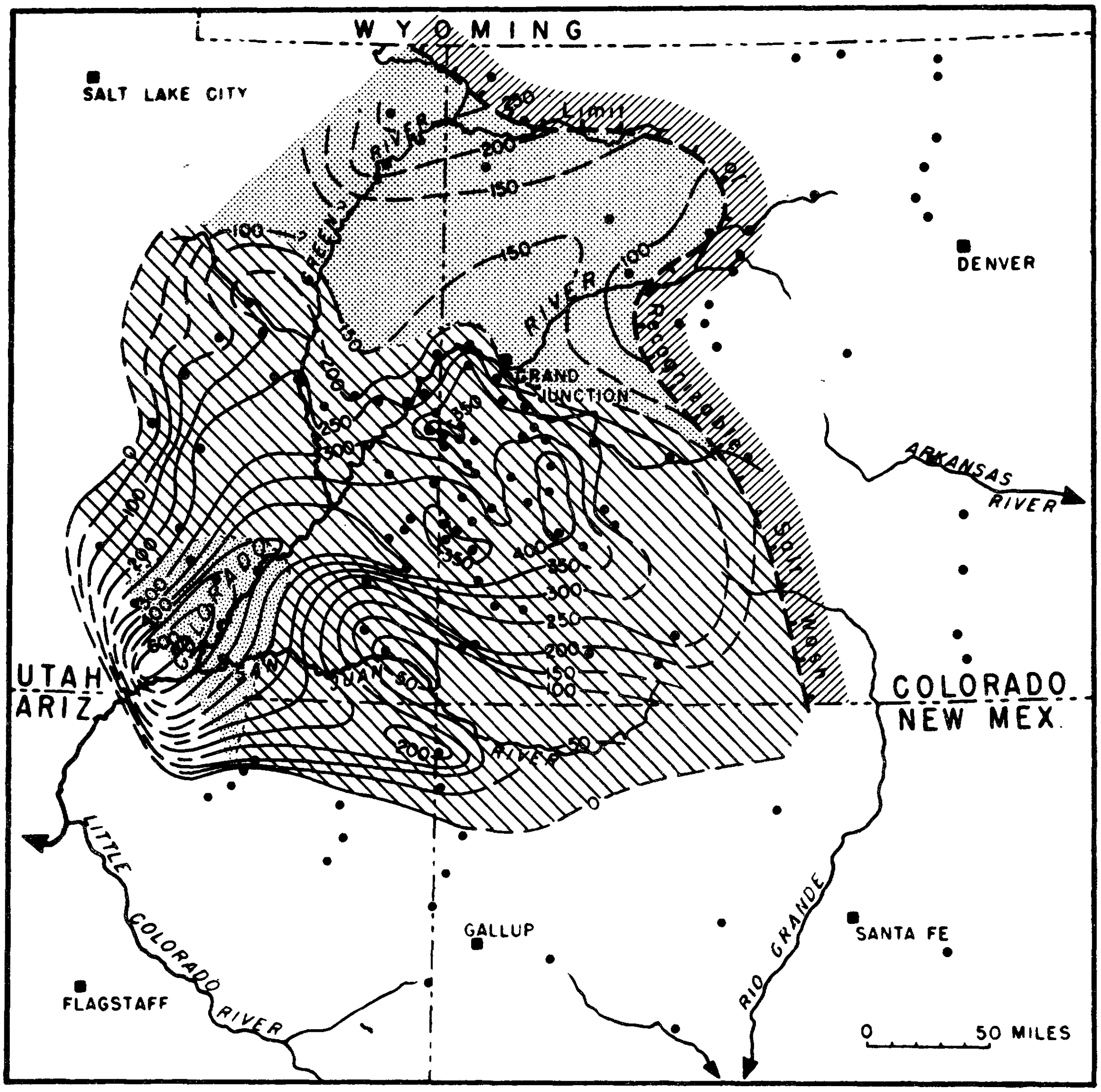
Recapture shale member

Westwater Canyon sandstone member

Brushy Basin shale member

Undifferentiated Morrison formation

Figure 2.—Fence diagram of the Morrison formation of the Colorado Plateau region



Explanation

Conglomeratic sandstone facies

Claystone and lenticular sandstone facies

Sandstone and mudstone facies

Claystone and limestone facies

• Location of measured section

Contour interval 50 feet

Figure 3.--Isopachous and facies map of the Salt Wash sandstone member of the Morrison formation.

Regional stratigraphy

Salt Wash sandstone member.--The Salt Wash sandstone member (Lupton, 1914, p. 127; Gilluly and Reeside, 1928, p. 82) occupies the lower part of the Morrison over a large fan-shaped area shown in figure 3. The blunt apex of the fan lies along the northwest-southeast trending line in south-central Utah and north-central Arizona. This line is a limit of preservation southwest of which the Salt Wash has been removed by erosion. The south side of the fan-shaped area is a limit of deposition. South of Blanding, in southeastern Utah, the upper part of the Salt Wash intertongues with and grades into the Recapture shale member. In the Carrizo Mountains area, northeastern Arizona, lower parts of the Salt Wash intertongue with the Recapture, and farther south along the Chuska Mountains, a basal tongue of Salt Wash reaches to the limit of deposition, a feather edge of the Salt Wash along the zero isopach. The western edge of the fan-shaped area is a poorly defined limit of deposition trending almost north-south along the zero isopach in south-central Utah. The rounded margin of the fan is the irregular line extending from northwestern to south-central Colorado beyond which the Salt Wash cannot be distinguished from the upper part of the Morrison.

The Salt Wash member is composed dominantly of interstratified units of sandstone and claystone. The sandstone intervals consist of grayish yellow, very pale orange, and white (Goddard, et al, 1948), fine-to medium-grained sandstone, which locally contain stringers of pebbles. The sandstone forms strata composed of a single lensing bed, 1 to 20 feet thick, or strata composed of many lensing beds which may have a total thickness of 80 feet or more. The beds are cross-laminated and generally show a slightly irregular to sharply channeling scour surface at the base. The sandstone strata form cliffs on steep ledgy slopes.

The claystone strata consist of interbedded claystones and minor clayey sandstones. The claystones are variably silty and sandy and in much of the area studied can properly be called mudstones. They are pale reddish brown, grayish red, and light greenish gray. The thin sandstone interbeds are pale red to light gray and fine-grained. In some places the claystone intervals contain thin nodular zones or platy to slabby beds of gray limestone which locally contain remains of algae, fresh-water mollusks, and ostracods. Bedding within the claystone strata is gently to sharply lenticular, but scouring features are not common.

The base of the Salt Wash is the base of terrestrial fluvial beds above the marine and marginal marine deposits of the San Rafael group. The top of the Salt Wash is based on a change of lithology and composition that reflects a minor variation in the fluvial environment.

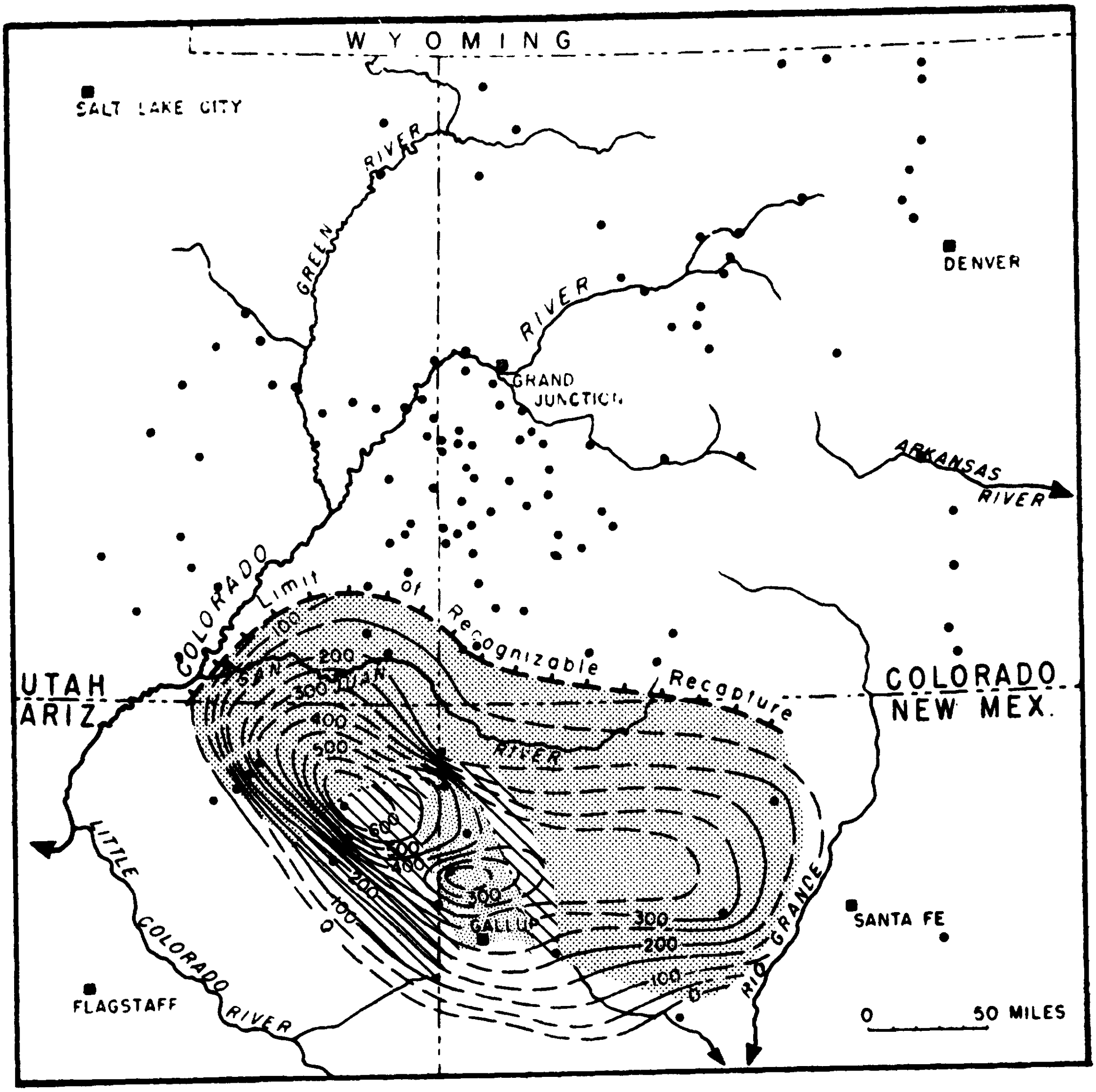
Areal changes in the texture and composition of the Salt Wash permit the separation of four major facies (fig. 3). A conglomeratic sandstone facies, confined to south-central Utah, consists mainly of scour-fill sandstones containing chert pebbles as much as 4 inches in diameter. A sandstone and mudstone facies, consisting of interstratified scour-fill sandstones and variably impure claystones, surrounds the conglomeratic sandstone facies on the northwest, north, and east. A claystone and lenticular sandstone facies consisting of sparse lenses of sandstone in a dominant matrix of claystone, is present in northeastern Utah and part of northwestern Colorado. The fourth facies, the claystone and limestone facies, lies east of the limit of recognition of the Salt Wash and thus strictly is not a facies of the member. However, the gradual decrease in sandstone content and increase in claystone and limestone content indicate that beds continuous and essentially contemporaneous with the typical Salt Wash were deposited east of the limit of recognition. It is only our inability to distinguish these claystones and limestones from similar lithologies in the upper part of the Morrison that prevents eastward extension of the Salt Wash member as a recognizable unit.

The thickness distribution of the Salt Wash sandstone member is shown on figure 3. From a maximum thickness of over 600 feet in south-central Utah, the Salt Wash in general thins radially to the north and east. The thinning is fairly regular except in several marginal areas. In the Vernal area of northeastern Utah the Salt Wash is moderately thick, reaching a maximum thickness of 285 feet. This thickening is poorly understood at present but may represent an accumulation of sediment from a source unrelated to the main source of the Salt Wash. In westernmost Colorado, the isopach lines show irregularities that are thought to represent irregular independent sinking of the basement. The irregularity cannot be related to either the variation of thickness nor to differential compaction of underlying formations. A thin area of Salt Wash in the Bluff area of southeastern Utah is related to the thickness of the underlying Bluff sandstone, for as the Bluff thickens the Salt

Wash thins in this area.

Recapture shale member.--The Recapture shale member (Gregory, 1938, p. 58) forms the lower part of the Morrison formation over a part of northeastern Arizona and northwestern New Mexico (fig. 4). To the north it intertongues with and grades into the Salt Wash sandstone member; the upper part is the most extensive and is recognized almost to Blanding in southeastern Utah. On the southwest the Recapture pinches out along the zero isopach line passing south of Gallup, N. Mex. Both to the east and to the west this line is the limit of deposition of the Recapture, but in the middle, south of Gallup, the Recapture may have been cut out by later erosion and thus may have been originally more extensive in this area. The eastward extent of the Recapture in north-central New Mexico is not yet known.

The Recapture shale member is composed of interstratified sandstone and claystone. The sandstone strata consist of pinkish-gray to light-brown, fine- to medium-grained sandstone, which locally contains granules and pebbles disseminated in the sand-sized matrix or concentrated in stringers along the laminations. The sandstones are uniformly quite friable and sedimentary structures are poorly displayed. However, where structures are preserved, the sandstone strata are seen to comprise lenticular, cross-laminated, scour-fill beds similar to those of the sandstone strata of the Salt Wash member. Along the east side of Black Mesa, Ariz., and in the Fort Defiance-Gallup area, some sandstone strata exhibit sweeping, wedging, cross-lamination and lack the scour-fill structures. The claystone strata consist of pale-red, grayish-red, and very-dusky-red, variably silty and sandy claystone. The bedding in the claystone strata exhibits the same gentle lensing shown in the bedding in the claystone strata of the Salt



Explanation

Conglomeratic sandstone facies

Sandstone facies

Claystone and sandstone facies

• Location of measured section

Contour interval 50 feet

Figure 4.--Isopachous and facies map of the Recapture shale member of the Morrison formation.

Wash. The friable character of the Recapture sandstones causes the member to weather to a steep earthy slope and in most places where the Salt Wash is present a bench is developed at the foot of the slope on the more resistant sandstones of the Salt Wash member.

Three distinctive facies, based on variations in texture and composition, have been recognized in the Recapture (fig.4). A conglomeratic sandstone facies occupies a narrow lobate area north of Gallup, N. Mex. The pebbles occur in rare stringers and consist mainly of quartz feldspar, granite, and minor gray and black chert. These pebbles are as much as 1 inch in diameter. A sandstone facies surrounds the conglomeratic sandstone facies on the west, north, and east, and differs from it mainly in the absence of pebbles. The third and most extensive facies of the Recapture is the claystone and sandstone facies. It surrounds the sandstone facies on the west, north, and east, and consists of interstratified variably impure claystone and nonconglomeratic sandstone.

The thick part of the Recapture occupies an elongate curving area from northeastern Arizona into northwestern New Mexico (fig. 4). A maximum thickness of 680 feet was measured near Rough Rock, Ariz. The Recapture is erratically thin in the area of the conglomeratic sandstone facies north of Gallup. The thickness variations are regarded as a result of differential sinking of the basement. The northward thinning shown in figure 4 results from intertonguing with the Salt Wash and the southward thinning from depositional convergence, and, near Gallup, from later erosion.

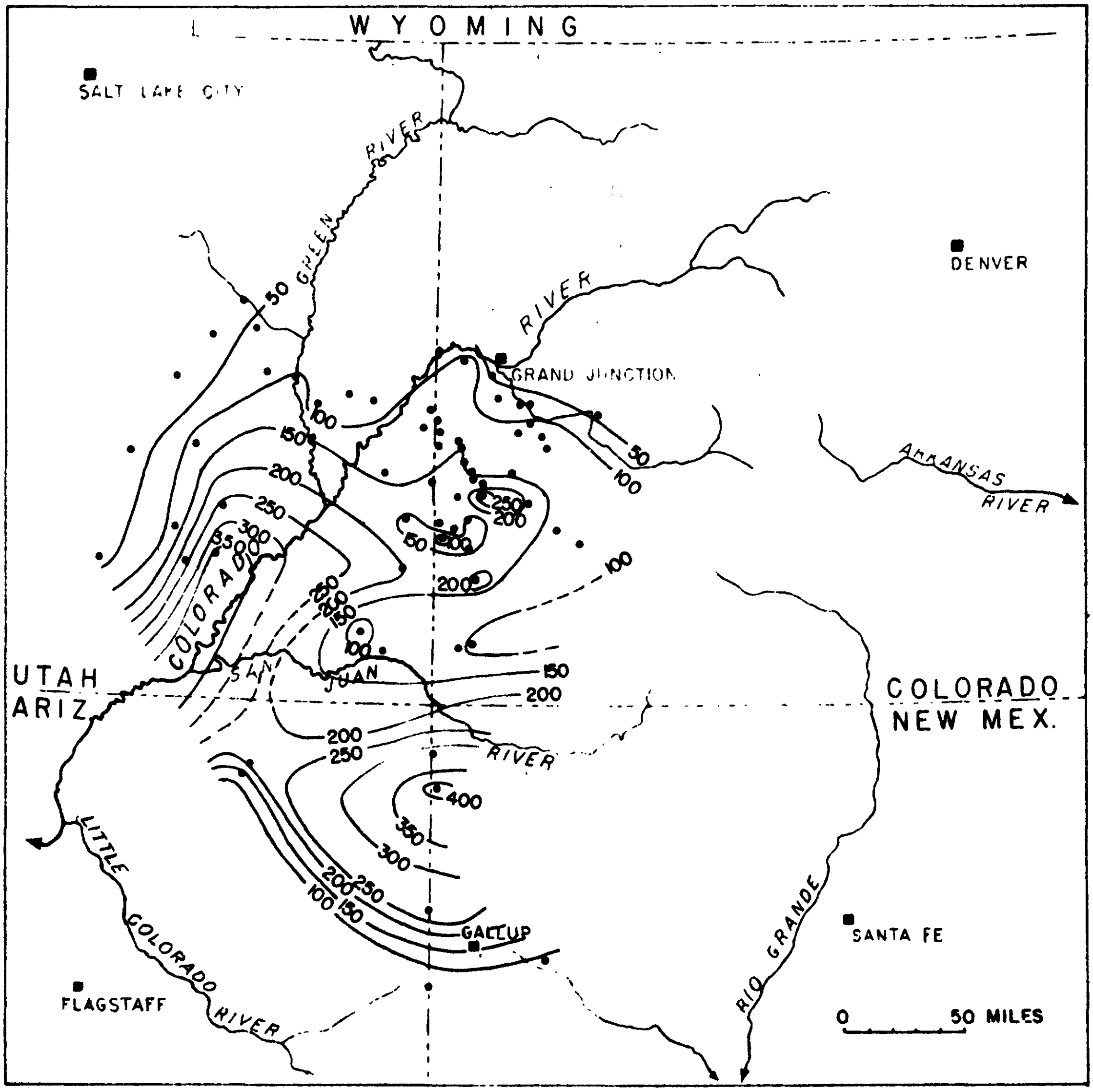
Lithofacies

The lower part of the Morrison consists of cross-laminated sandstone and conglomeratic sandstone lenses, which were deposited in a stream environment, and of claystones and horizontally bedded sandstones, which accumulated in a flood-plain environment. The areal variation of thickness, relative proportion, and continuity of the stream deposits and flood-plain deposits is the subject matter of the lithofacies study of the Morrison.

The lithofacies studies have been restricted mainly to the lower part of the Morrison formation, for the Salt Wash and Recapture members are particularly amenable to ratio studies. The usual practice in ratio studies of comparing the thickness of one or more rock types to the thickness of different rock types has not been followed because of the complete gradations between sandstone and claystone that are common in the lower part of the Morrison, and because of the possibilities of paleogeographic reconstruction offered by a classification based on environment of deposition.

The areal variations in lithofacies were determined by measuring the thickness of the stream and flood-plain deposits at 66 localities. Five sections were measured through the lower part of the Morrison formation at each locality in order to permit computation of average data on the thickness and relative proportions of the two types of deposits and to allow a measure of the continuity of the stream deposits. Isolith maps showing the areal variations of these aspects were prepared from the collected data.

The areal distribution of the total thickness of the stream deposits in the lower part of the Morrison formation is shown by figure 5,



Explanation

Location of lithofacies section

Isopachous interval 50 feet

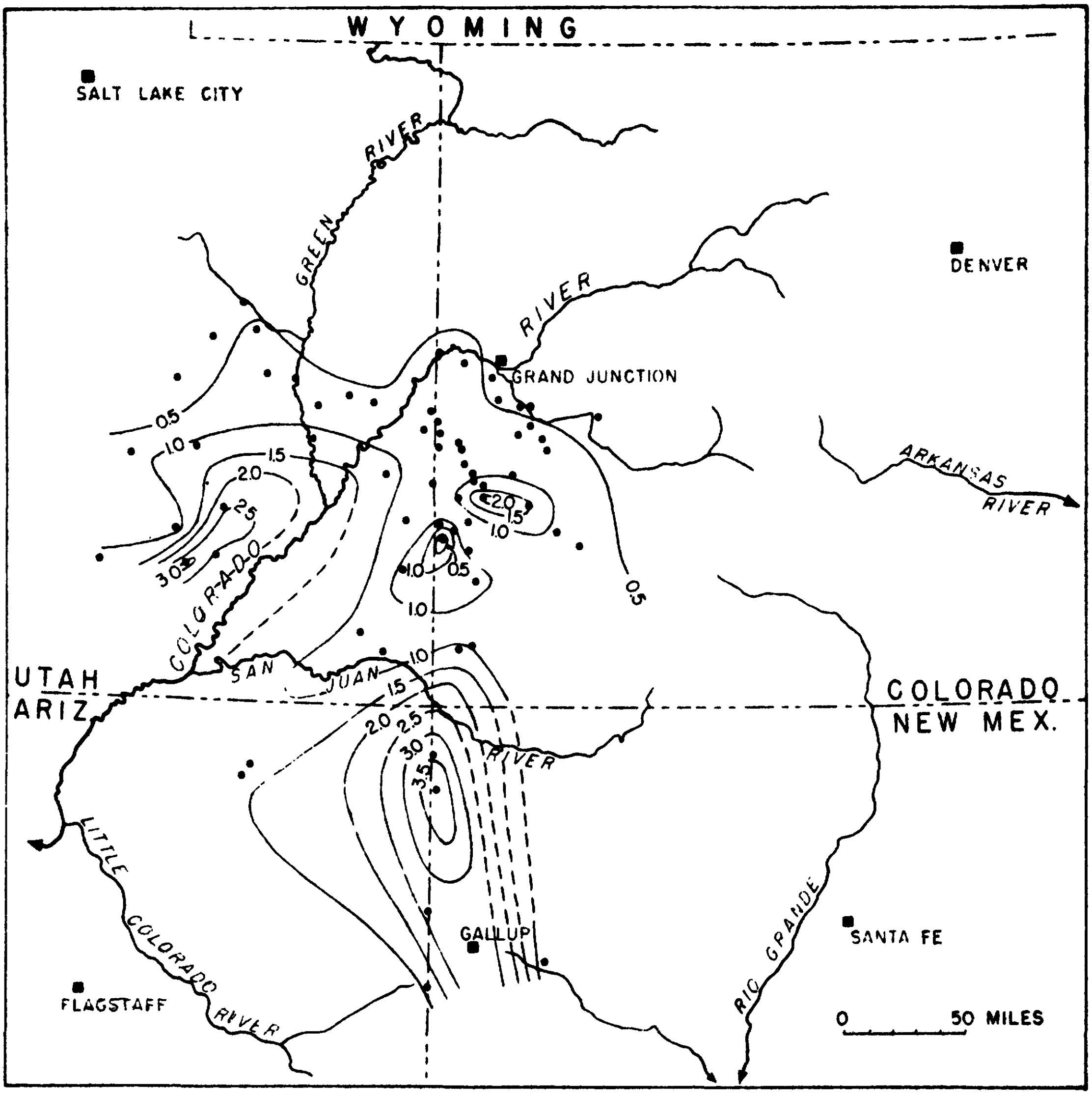
Figure 5.--Isopachous map of stream deposits in the lower part of the Morrison formation.

an isopachous map of the stream deposits.

The areal distribution of the relative proportions of the stream and flood-plain deposits is shown by figure 6, an isolith map of the ratio of stream deposit thickness to flood-plain deposit thickness. A high ratio indicates a high proportion of stream deposits.

The areal distrubution of the relative continuity of the stream deposits is shown by figure 7. This is an isolith map of the percentage mean deviation of the stream deposit thickness. The relative continuity at each locality is determined by computing for each locality the average of the deviation of the total thickness of the stream deposits in each section from the average thickness for the five sections and expressing the deviation as a percentage. A low percentage of deviation is interpreted to indicate high continuity of the stream deposits.

The three maps are remarkably similar. The pattern of the isoliths show that the total thickness of stream deposits, relative proportion of the stream deposits to the flood-plain deposits, and relative continuity of the stream deposits decrease rather uniformly away from two centers, one in south-central Utah and one along the northern part of the Arizona-New Mexico state line. Values of all three factors decrease to the north and east of the Utah center and the isolith lines, concentric to this area, form an asymmetric fan-shaped pattern with a prominent lobe extending eastward. Thickness of stream deposits, proportion of stream to flood-plain deposits, and continuity of the stream deposits decrease to the north, south, and west of the northern Arizona-New Mexico area. The isoliths concentric to this area form a fan-shaped or ellipsoidal pattern with the long axis trending slightly west of north. All three maps show that the two areas of high values are separated by an area of low values that trends northeast-southwest through southeastern Utah. In southwestern Colorado and eastern Utah irregularities in the isolith lines interrupt the uniformity of the major fan-shaped pattern extending outward from south-central Utah.

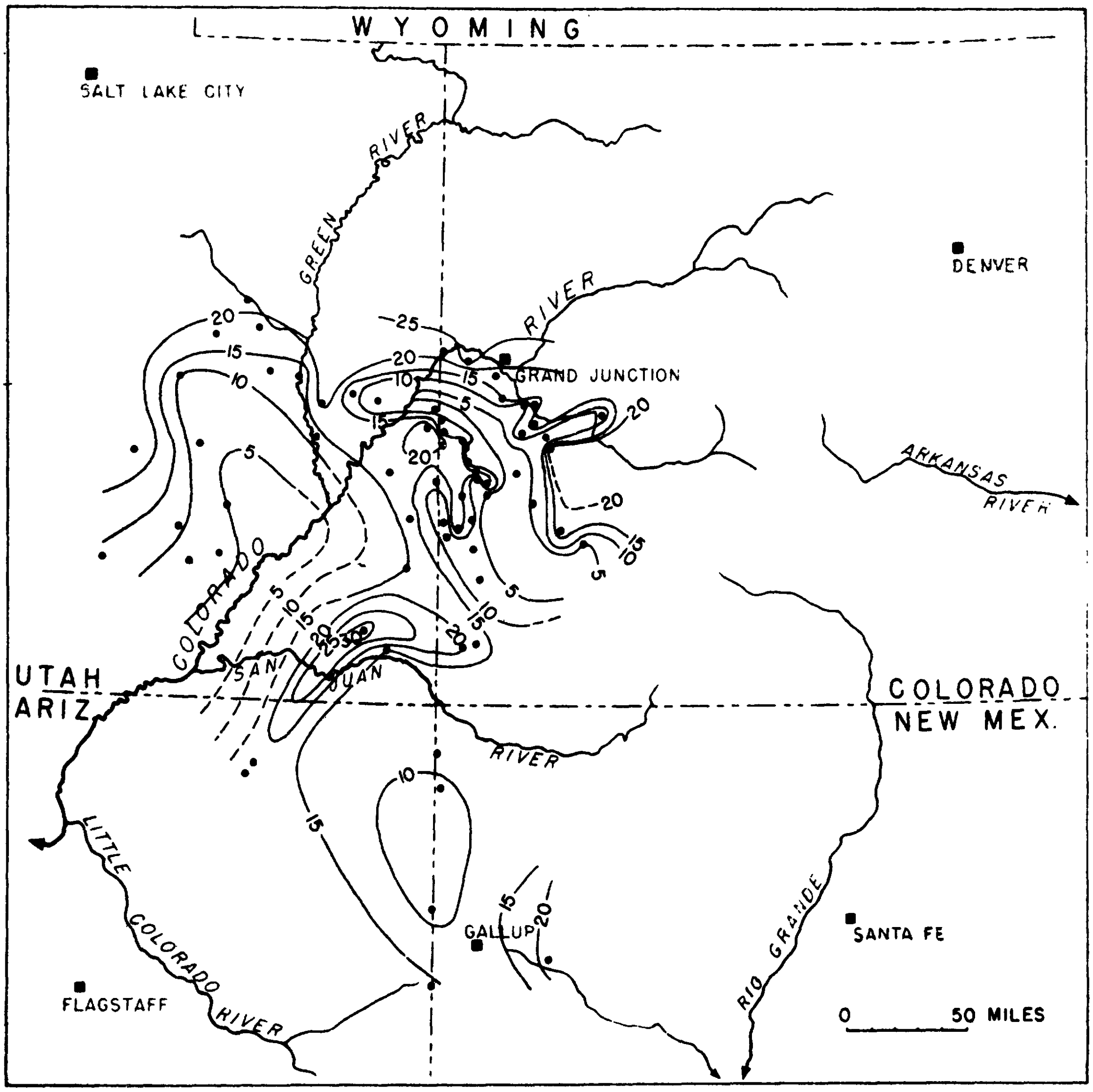


Explanation

Location of lithofacies study

Isolith interval 0.5

Figure 6.—Isolith map of the ratio, $\frac{\text{thickness of stream deposits}}{\text{thickness of flood-plain deposits}}$, in the lower part of the Morrison formation.



Explanation

• Location of lithofacies study

Isolith interval 5 percent

Figure 7.—Isolith map of percentage mean deviation of stream deposit thickness in the lower part of the Morrison formation.

Sedimentary structures

Sedimentary structures in the lower Morrison include cross-lamination, current lineation, contorted bedding, ripple marks, and mud cracks. Horizontally bedded and structureless units are also common in the lower Morrison. Emphasis of the sedimentary structure study was on the Salt Wash sandstone member.

Sedimentary structures are amenable to two types of analysis--description and measurement. A brief description of the important sedimentary structures of the lower Morrison follows.

Cross-lamination in the Salt Wash sandstone is a complex of several types. Using the terminology of McKee (1948), as illustrated by Kiersch (1950), the most prevalent types are festoon cross-lamination, wedge "torrential" cross-lamination, and low-angle compound cross-lamination. Festoon cross-lamination, the most common type in the Salt Wash, is produced by channeling action and subsequent deposition. In plan view festoons are semi-ellipsoidal, resembling half a canoe. Dips are highest near the closed end or "prow"; away from the closed end the laminae gradually flatten. The closed end is interpreted to be in the upstream direction; the open end to be in the downstream direction. Wedge "torrential" cross-lamination is formed by deposition of cross-beds that are subsequently beveled by scour surfaces. Low-angle compound cross-lamination is the result of simple accumulation of cross-beds with cross-laminae of moderate to low dip without any truncating surfaces.

Current lineation (Stokes, 1947) is the result of a streaming effect of sand particles to form low ridges parallel with the current. Current lineation is generally perpendicular to ripple marks where both are present in the same depositional unit. Current lineation has not been observed directly superimposed on ripple marks. Ripple marks occur in both the sandstone and the mudstone of the Salt Wash member. They are always the current type. Rarely, superposed sets of ripple marks in the mudstone form a false cross-lamination, the "ripple cross-lamination" of McKee (1939). Contorted laminae occur locally in the cross-laminated sandstone and represent the slumping of water-saturated sand. Mud cracks are rare in the Salt Wash, but have been noted on the surfaces of mudstone partings.

Sedimentary structures in the Recapture shale member are similar to those described for the Salt Wash sandstone member. However, festoon cross-lamination appears to be less common in the Recapture; horizontally laminated units and units with low-angle compound cross-lamination are more common.

Directional features of sedimentary structures that may be measured with precision include the strike and dip of cross-laminae, the plunge directions of festoon axes and of current lineation, and the strikes of ripple-marks. If adequately sampled, the average of measurements of trends of any of these structures will give an approximate indication of the main current direction. Cross-lamination is the sedimentary structure most amenable to statistical analysis because it is the only structure that can be measured in areas of poor to fair exposure.

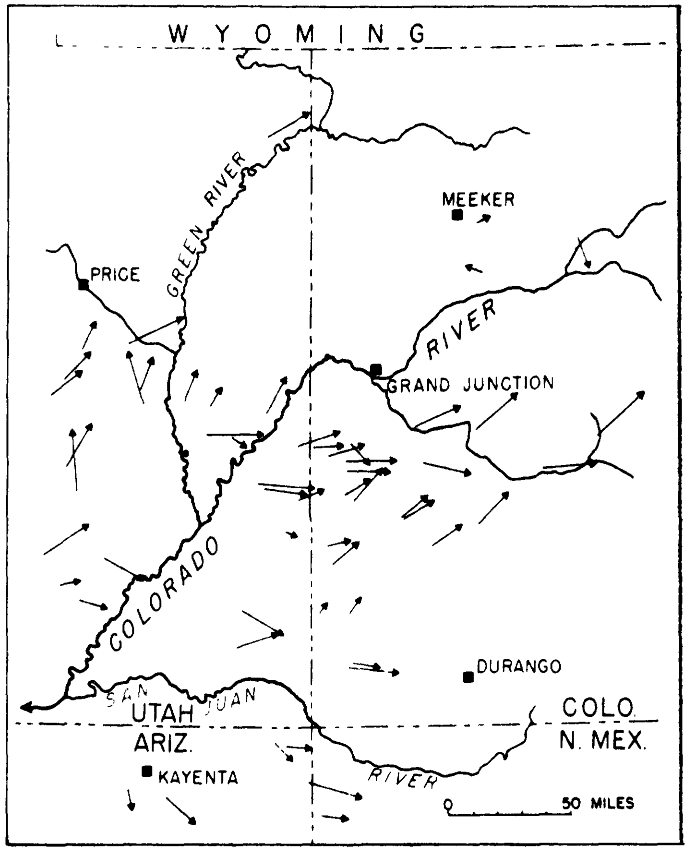
In the field study of cross-lamination, a measurement is made of the azimuth of dip of one cross-lamina in each separate cross-laminated unit conformable within itself. The study is made along the outcrop of a single sandstone stratum.

The statistical methods of treatment of the field data are adapted from Reiche (1938). Each dip azimuth may be considered a unit vector; the vector sum of a number of dip azimuths gives a resultant dip azimuth. The resultant dip azimuth is vectoral "average" of the directions of dip of all cross-laminae measured at a locality. A numerical expression for the consistency of direction of the individual dip azimuth vectors is obtained by dividing the resultant length by the number of measurements. If all observations were identical, the consistency factor would be unity; if the vectors were disposed at random, the consistency factor would be zero.

Figure 8 shows the pattern of cross-lamination in the Salt Wash sandstone member. The arrows on this map show the resultant dip azimuths of cross-laminae for studies at 55 localities. The length of the arrow is proportional to the consistency factor. The map shows a pattern of arrows which diverges to the north and east from an apex in south-central Utah.

Based on the premise that each cross-lamina has a component of dip azimuth down-current, the resultant dip azimuth is interpreted as the average drainage direction. The consistency factor is regarded as a measure of the relative persistency of direction of drainage at the place of study.

The resultant dip azimuths of cross-laminae indicate that the streams depositing the Salt Wash sandstone member flowed north, east, and southeast from the south-central part of Utah. No contemporaneity is implied by the map. It is a "multiple exposure" of drainage directions throughout the time of deposition of the Salt Wash. Studies at different positions in the Salt Wash were made at each of four localities.



Explanation

Direction of arrow is resultant dip direction of cross-laminae.

Length of arrow is proportional to consistency factor.

Tail of arrow marks location of cross-lamination study.

Figure 8.—Map of resultant dip directions of cross-laminae in sandstones of the Salt Wash member of the Morrison formation.

These show that the resultant dip azimuths are about the same regardless of stratigraphic position in the member and imply that about the same drainage directions prevailed throughout Salt Wash deposition.

No regional study was made of cross-lamination in the Recapture shale member.

Sedimentary petrography

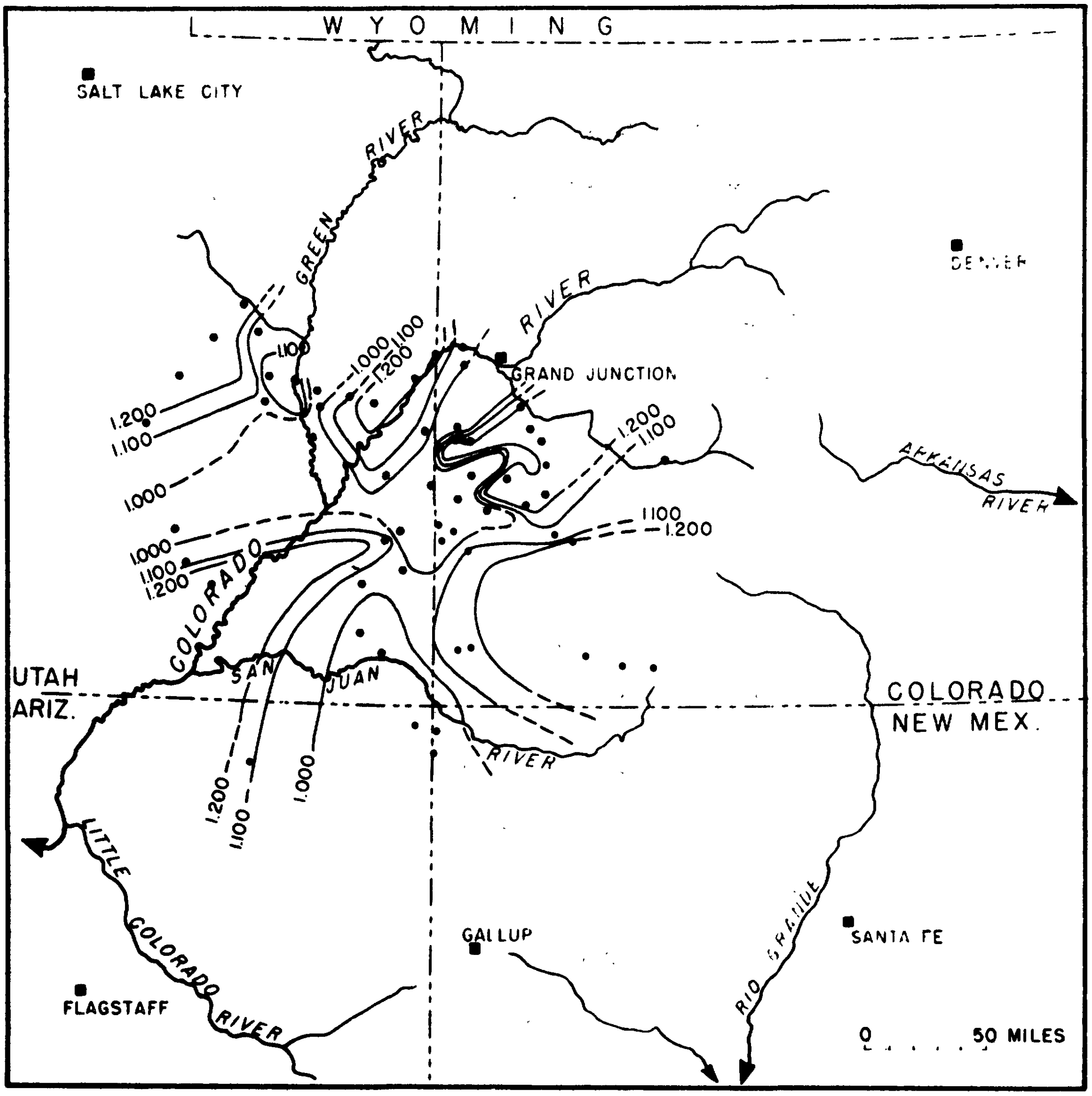
The contribution to this report by the sedimentary petrography laboratory of the Colorado Plateau project in Grand Junction, Colo., is based on the results of the analysis of 202 sandstone samples from the Salt Wash member of the Morrison. An investigation of the shales and siltstones of the Salt Wash and other members of the Morrison is under way in the project laboratory and in the Trace Elements Section Washington Laboratory. Samples of sandstones from other members of the Morrison, as well as samples of sandstone from adjoining formations, are in various stages of analysis.

Methods used in the laboratory study of the sandstones of the Salt Wash may be divided into two groups: preparation and measurement. Preparation involves the use of standard methods of disaggregation of consolidated sediments, separation of heavy mineral fractions, and the preparation of mineral grain slides for petrographic examination. Measurement involves the determination of grain-size distribution for each sample by means of graduated sieves and pipette elutriation, computation of the statistical analysis of the grain-size distribution of each sample, determination of the proportions of light (sp. gr. < 2.90) and heavy (sp. gr. > 2.90) minerals, and determination of amounts of cements and soluble detrital fractions.

Averages of the analytical results show that sandstones of the Salt Wash may be classified as fine-grained, quartzitic sandstones. The average modal diameter of the sand is 0.176 mm. Of the detrital grains, 93 percent are of sand size, and 7 percent are of silt or clay size. The average composition of the sandstones is: cement (calcite), 13 percent; secondary silica (cement and overgrowths), 4 percent; detrital grains, 83 percent. Of the detrital grains, quartz (grains and overgrowths) comprises 86 percent; feldspar (orthoclase to albite), 7 percent; chert (chalcedony and opal), 7 percent. Only a small suite of light and heavy minerals is present. Quartz, the dominant mineral, occurs in three varieties. Other light detrital minerals are chert, feldspar, gypsum, calcite, and dolomite. Heavy minerals are zircon, tourmaline, garnet, rutile, anatase, staurolite, biotite, spinel, and apatite.

The statistical analysis of the grain-size distribution of each of the samples yielded a number of measurements of sorting, grain-size averages, lack of symmetry of the distribution, and other properties of petrologic interest. The most significant measurements of the grain-size distribution turned out to be the logarithmic standard deviation and percentile skewness, the former a coefficient of sorting, and the latter a measure of the deviation of the distribution of the grain sizes from the familiar symmetrical bell-shaped curve.

The logarithmic standard deviation of a perfectly sorted sand is 0.000. The averages of the samples of Salt Wash taken at each locality studied vary between 0.500 and 1.500. The regional distribution of the logarithmic standard deviation is illustrated in figure 9. The figure shows that there are regional differences in the sorting of the Salt Wash sands, and that the differences fall into a distinct pattern as



Explanation

• Location of sampled section

Isopleth interval 0.100

(Only the 1.000, 1.100, and 1.200 isopleths are shown.)

Figure 9.—Isopleth map of logarithmic standard deviation of grain-size distribution in sandstones of the Salt Wash member of the Morrison formation.

outlined by isopleths of the 1.000, 1.100 and 1.200 values.

The map shows a central area of relatively well-sorted sand on the boundary between southwestern Colorado and southeastern Utah. Extensions radiate outward to the north, east, south and west from the central area.

These zones of better sorted sand may represent concentrations of channel deposits.

The precentile skewness is significant because it explains and supports the conclusions suggested by the regional sorting pattern. Support is offered by the fact that the regional pattern of the skewness duplicates that of the sorting as shown in figure 9. Explanation is provided by the variations in the readings; areas of better sorted sand have low positive skewness readings, which is normal; areas of poorer sorted sands have either high positive readings or low negative readings, that is, a lack of symmetry due to the presence of too many fines, or a lack of symmetry due to the presence of too large a coarse fraction.

Sandstones of the Salt Wash contain a relatively high proportion of feldspar in northern Arizona and New Mexico, in a corridor along the Colorado-Utah border, and in northwest Colorado and northeast Utah. The sandstones in southwest Colorado and southeast Utah outside of the corridor contain less feldspar. Some samples from south of the Four Corners area contain substantial fractions of fresh angular feldspar and quartz, which indicates the presence of a local granitic source. The decrease in the amount of the fresh material northward suggests that the source was to the south.

Samples from several locations on the extreme western edge of the Salt Wash in central Utah contain large amounts (as much as 86 percent of the detrital fraction) of fresh angular to rounded opaline chert. The chert grains are much less weathered and show less sphericity than the chalcedony-opal chert characteristic of the Salt Wash to the east and suggests a local source to the west, possibly quite close to the region of investigation.

Garnet is absent from most of the samples from western Colorado, and present in almost all samples from west of the Colorado-Utah border. The garnet-bearing sandstones seem to intertongue eastward with sandstones in which garnet is absent or rare. Owing to the high specific gravity of garnet and its tendency to fracture into grains of high sphericity, it tends to settle out in the placer-type concentrations, which, in an aggrading system, are soon buried. Thus, the distribution indicates that the source of the garnet was to the west or southwest. The apparent intertonguing of garnet-bearing sandstone with non-garnet-bearing sandstone is explained by settling out and burial of the garnet in the western part of the area rather than by a true intertonguing of two different sandstones.

Staurolite has an areal distribution similar to that of garnet. The general absence of the mineral from the sandstones of Colorado is probably the result of attrition, for the splintery cleavage makes staurolite vulnerable to abrasion and solution. A western or southwestern source is indicated.

Apatite is present throughout the sandstones of the Salt Wash in northeastern Utah and in a relatively narrow belt extending diagonally southeastward to south-central Colorado. A possible source to the northwest is suggested.

Interpretation

The collected data of the stratigraphic investigations yield a well-defined concept of the paleogeography of the lower part of the Morrison.

Two major source areas are indicated by the facies and isopachous maps of the lower Morrison. One major source area lay southwest of south-central Utah, probably in west-central Arizona. It produced most of the sediments comprising the Salt Wash sandstone member. The other major source area lay south of Gallup, probably in west-central New Mexico. It produced most of the sediments comprising the Recapture shale member. The mineralogy of the members of the lower Morrison indicate that the rocks exposed in the source area of the Salt Wash were quite different from those exposed in the source area of the Recapture. The Salt Wash was derived mainly from older sedimentary formations and received only minor contributions from igneous and metamorphic rocks. Fossils in chert pebbles from the conglomeratic sandstone facies of the Salt Wash have been identified as late Paleozoic in age. These were derived either directly from upper Paleozoic beds or from younger beds formed by reworking of the upper Paleozoic formations. The Recapture was derived from a mixed source of pre-existing sedimentary, igneous, and metamorphic rocks. The abundance of feldspar, quartz, and granite pebbles found in the conglomeratic sandstone facies indicates that acid igneous rocks comprised a large part of the rocks exposed in the source area. The erratic distributions of opaline chert, feldspar, and apatite in the

Salt Wash represent contributions from minor sources to the west and northwest of central Utah; similarly the Recapture member may have had contributions from minor sources east and west of the major source in west-central New Mexico. The presence of angular fresh feldspar and quartz in the Salt Wash of the Four Corners area suggests that material from the Recapture source may have mixed with materials of the Salt Wash in this area.

Structures and textures of the lower part of the Morrison indicate that both the Salt Wash and Recapture members were deposited in a dominantly fluvial environment and are composed of alternations of stream-deposited sediments and flood-plain deposited sediments. Slight epeiric uplift probably caused northward retreat of the marine and marginal marine deposition which characterizes the San Rafael group. Moderate orogenesis in the source area of the Salt Wash and Recapture members initiated the spread of clastics northward and eastward across the Colorado Plateau region. Streams of low gradient transported and deposited detritus on the almost flat surface of the San Rafael group. Although some time is required to transport detritus from one location to another, the spread of the lower Morrison across the region is thought to have been essentially synchronous geologically.

The Salt Wash and Recapture members are regarded as two broad fan-shaped alluvial plains or "fans" constructed simultaneously by deposition from two separate aggrading stream systems. The two "fans" coalesced along a common margin which passes a wide belt through the Four Corners area. In this belt the two members intertongue and intergrade.

The isopachous and isolith maps of the Salt Wash member (figs. 2, 5, 6, 7) show similar fan-shaped patterns. The sedimentary structure orientations (fig. 8) show a pattern of drainage directions which diverges northward and eastward from the apex of the Salt Wash "fan" in south-central Utah. Salt Wash streams probably formed an alluviating distributary system of braided channels which changed position on the "fan" by lateral migration.

The distribution of facies (fig. 3) and the distribution of the streams deposit thickness relative to flood-plain deposit thickness (fig. 6) indicate a decrease in transporting capacity of the streams outward from the apex of the "fan". Either decrease in gradient or decrease in volume of the streams or both would produce the decrease in transporting capacity. The uniform distribution of facies (fig. 3) and the gradual change from one facies to another suggest that any decrease in stream gradient must have been quite gentle. Loss of volume of the streams may have resulted from evaporation, absorption by the sediments, or by subdivision of streams to form successively smaller distributaries outward across the surface of the plain. The thick Salt Wash (fig. 3) at the apex of the "fan" is thought to represent an accumulation of sediments close to the source. Irregular thick and thin areas in the vicinity of Four Corners probably reflect topographic features of the top of the San Rafael group; the Salt Wash streams impinged on, beveled, and reworked the underlying Bluff and Junction Creek sandstones and only thin deposits of Salt Wash were formed in areas where these underlying sandstones are thick. The lack of uniform thickness in the Salt Wash in the area south of Grand Junction, Colo., probably resulted from local subsidence and filling of the consequent depressions. The poorly defined thickening of the Salt Wash in Utah and Colorado near the Wyoming boundary also may have resulted from local subsidence; however, it may represent an accumulation of sediment from a source unrelated to the major source of the Salt Wash.

The isopachous and isolith maps of the Recapture member (fig. 4, 5, 6, 7) do not show as prominent a fan-shaped pattern as do the maps of the Salt Wash. However, the facies distribution (fig. 4) supports the concept of an alluvial plain or "fan" with an apex near Gallup, N. Mex. The irregular distribution of Recapture thickness is thought to reflect differential subsidence. Recapture streams probably formed an alluviating distributary system of braided channels, similar to the streams on the Salt Wash "fan".

The climate during lower Morrison deposition is difficult to define with much certainty from evidence in the rocks. A semi-arid climate is suggested by the preservation of sand dunes in the Recapture member in northeastern Arizona. Stokes (1945) has reported remains of thorny plants from the Salt Wash of east-central Utah, a discovery which supports the concept of semi-aridity. However, sufficient moisture was present to support growth of grasses, reeds, and large trees, at least along the stream courses, and to permit the existence of small bodies of standing water in which thin beds of limestone were deposited. Casual observation suggests a greater abundance of fossil tree remains near the apex of the Salt Wash "fan" than away from it. This distribution may reflect a greater abundance of vegetation in this area as a result of slightly higher elevation and proximity to a greater water supply in the uplands of the source area.

Upper part of the Morrison formation

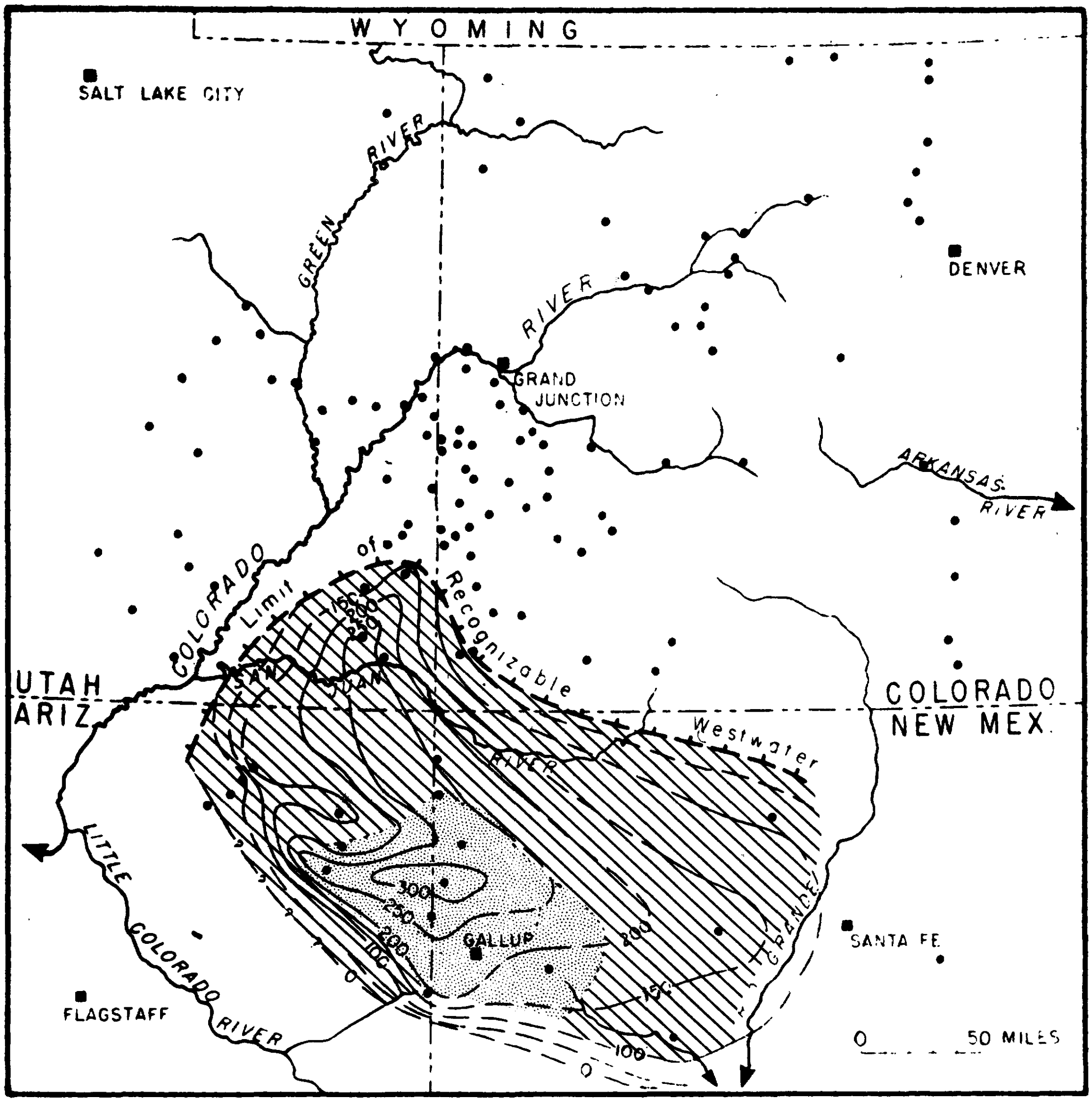
The upper part of the Morrison consists of the Westwater Canyon sandstone member and the Brushy Basin shale member. The Westwater Canyon member constitutes a lower portion of the upper Morrison in the southern part of the region of study. The Brushy Basin shale member is present over most of the region of study (fig. 2).

Regional stratigraphy

Westwater Canyon sandstone member.--The Westwater Canyon sandstone member (Gregory, 1938, p. 59) is present over a part of northeastern Arizona and northwestern New Mexico (fig. 10). To the north, at least a part of the Westwater Canyon intertongues with and grades into the lower part of the Brushy Basin shale member along a limit of recognition that passes just south of Monticello in southeastern Utah. In most of northwestern New Mexico and a small part of northeastern Arizona the upper part of the Brushy Basin member overlies the Westwater Canyon, but to the southwest post-Morrison erosion has removed the Brushy Basin, and the Westwater Canyon is the only part of the upper Morrison preserved. The Westwater Csnyon thins to extinction along the zero isopach on the south and southwest, mostly as a result of increasing magnitude of the post-Morrison erosion. True depositional convergence may also contribute to this thinning. The eastward extent of the Westwater Canyon in north-central New Mexico is not yet known.

The Westwater Canyon member is composed of interstratified sandstone and minor amounts of claystone. The sandstone is yellowish gray, pale yellowish-orange, or light brown, fine- to medium-coarse-grained, and locally contains stringers and lenses of pebbles. The sandstone forms strata composed of many lensing cross-laminated beds, which exhibit slightly irregular to deep channeling scour surfaces at their base. The claystone strata consist of light-greenish-gray or pale-red to grayish-red, variably silty and sandy claystone, and have the gently lensing sub-parallel bedding similar to that observed in the claystone strata of the Salt Wash member. The sandstones of the Westwater are more resistant than those of the underlying Recapture and the member forms nearly vertical cliffs or very steep ledgy slopes with small reentrants or narrow benches marking the position of the thin and less resistant claystone strata.

The Westwater Canyon member may be separated into two facies (fig. 10), mainly based on textural differences. A conglomeratic sandstone facies



Explanation

Conglomeratic sandstone facies

Sandstone facies

• Location of measured section

Contour interval 50 feet

Figure 10.—Isopachous and facies map of the Westwater Canyon sandstone member of the Morrison formation.

occupies a wide lobate area north of Gallup, N. Mex. The pebbles are predominantly quartz, feldspar, granite, and quartzite with minor amounts of gray and black chert. This facies may be subdivided into a central area, where pebbles as much as 4 inches in diameter are common, and a peripheral area, where pebbles are generally less than 1 inch in diameter. The second facies, a sandstone facies, surrounds the conglomeratic sandstone facies on the west, north, and east. It differs from the conglomeratic facies mainly in the absence of pebbles. Both facies contain thin strata of claystone but the sandstone facies generally contains a greater percentage of claystone (10 to 40 percent) than does the conglomeratic sandstone facies (5 to 20 percent).

The Westwater Canyon forms an arcuate belt of relatively thick sediment extending from northwestern New Mexico through the northeastern corner of Arizona into southeastern Utah (fig. 10). A maximum thickness of 330 feet was measured 30 miles north of Gallup, N. Mex. No studies of the orientation of sedimentary structures have been made on the Westwater Canyon sandstone member and sedimentological analyses are incomplete.

Brushy Basin shale member.--The Brushy Basin shale member (Gregory, 1938, p. 59) is present in western Colorado, eastern Utah, northern New Mexico, and part of northeastern Arizona (fig. 11). To the southwest it has been removed by post-Morrison erosion, leaving only the partially equivalent Westwater Canyon member. The eastern and northeastern boundary is an arbitrary line drawn where the lower Salt Wash member loses its identity and cannot be distinguished from the upper part of the Morrison. To the east of this arbitrary line the Morrison is not differentiated into members.

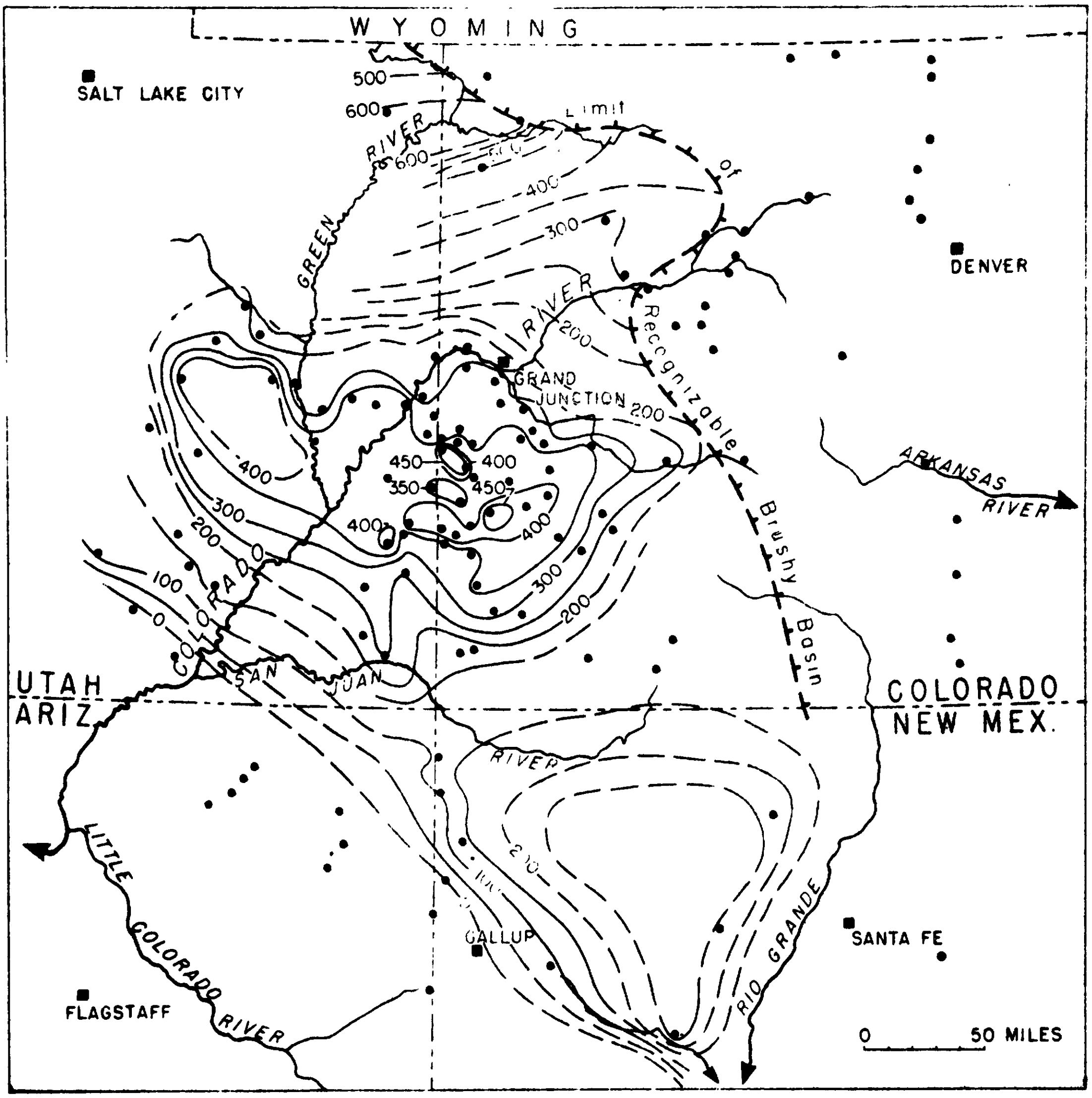
The Brushy Basin member is composed predominately of variegated claystone containing varying amounts of silt and sand. Fissile shale is rare. Impure bentonitic clay forms much of the Brushy Basin and is in part volcanic in origin. Lenses of conglomeratic sandstone are common. The pebbles consist mainly of red, green, white, and black chert and are as much as 2 inches in diameter. The lenses are rarely over several hundred feet wide, and pinch out laterally in the main mass of claystone. A few thin-bedded, discontinuous limestone beds occur in the Brushy Basin and were probably deposited in temporary fresh-water lakes.

A lensing conglomeratic sandstone containing red, green and white chert pebbles has a wide distribution at the bottom of the Brushy Basin in western Colorado and eastern Utah. The base of this bed has been used as the basal contact of the member in this area. Where the basal conglomerate is absent in western Colorado, the top of the uppermost scour-fill sandstone of the Salt Wash is used as the contact between the Brushy Basin and the underlying Salt Wash sandstone member.

Distinct facies with limited areal distribution have not been recognized in the Brushy Basin, for the lithologic components show no regularity. However, colors of red, purple, and gray predominate in northeastern Utah and western Colorado and colors of light greenish gray and pink predominate in southeastern Utah, northeastern Arizona, and northwestern New Mexico. This may be only a secondary weathering feature.

Petrified dinosaur bones and wood are abundant, particularly at the base of the Brushy Basin. Other fossils are rare; fresh water gastropods and algae have been found at only a few localities.

The thickness of the Brushy Basin varies considerably over the Plateau (fig. 11). A thickness of over 1,000 feet of variegated shale has been reported in northeastern Utah, but part of these beds may be Lower Cretaceous in age. Over 600 feet of Brushy Basin has been measured at Vernal, Utah. In southwestern Colorado, 450 feet of Brushy Basin has been measured; in



Explanation

• Location of measured section

Isopachous interval 50 feet

Figure 11.—Isopachous map of the Brushy Basin shale member of the Morrison formation.

this area the member varies considerably in thickness in contrast to the more gradual thickness changes elsewhere.

Interpretation

The members of the upper part of the Morrison form two relatively distinct groups of sediments. The facies distribution of the Westwater Canyon member (fig. 10) indicates a major source south of Gallup, probably in west-central New Mexico. The feldspar, quartz, granite, quartzite, and chert pebbles in the conglomeratic sandstone facies indicate a mixed source of pre-existing sedimentary, igneous, and metamorphic rocks. The source of the Brushy Basin is not clearly indicated from any of the collected data. The coincidence in distribution of the basal conglomeratic sandstone of the Brushy Basin with the distribution of the sandstones of the Salt Wash suggests that the Brushy Basin may have been derived from essentially the same source as the Salt Wash. Similar conglomeratic sandstone higher in the Brushy Basin may also have had the same source. The prevalence of chert pebbles and almost complete absence of other varieties suggests that at least the sandstones were derived mainly from a source of sedimentary rocks.

Structures and textures in the Westwater Canyon sandstone member and in the sandstones of the Brushy Basin indicate that they were deposited in a fluvial environment. Much of the bentonitic clay of the Brushy Basin probably accumulated as ash falls; limestone, as well as some of the clay, may have been deposited in a lacustrine environment.

The facies distribution in the Westwater Canyon member (fig. 10) indicates that it formed as broad fan-shaped alluvial plain or "fan" similar to that of the Recapture. It was formed by an alluviating distributary system of braided channels and represents essentially a continuation of

Recapture deposition. The Westwater differs, however, in that it consists predominantly of much coarser material than the Recapture. This is thought to reflect a rejuvenation in the source area, in west-central New Mexico. As the source area was reduced and ceased contributing coarse materials, Brushy Basin deposition spread southward to cover the area of Westwater deposition. The original southward extent of the Brushy Basin is not known for the member has been removed by pre-Dakota erosion south of a line (the zero isopach) extending from northwestern New Mexico to south-central Utah (fig. 11).

The greater abundance of fossil plant and dinosaur remains suggests that the climate was more humid during deposition of the upper Morrison than during deposition of the lower Morrison. In contrast with the Recapture member, the Westwater Canyon member contains no extensive windblown deposits in northeastern Arizona. This may also support a concept of increased humidity during upper Morrison time.

Undifferentiated Morrison of Colorado

Regional stratrigraphy

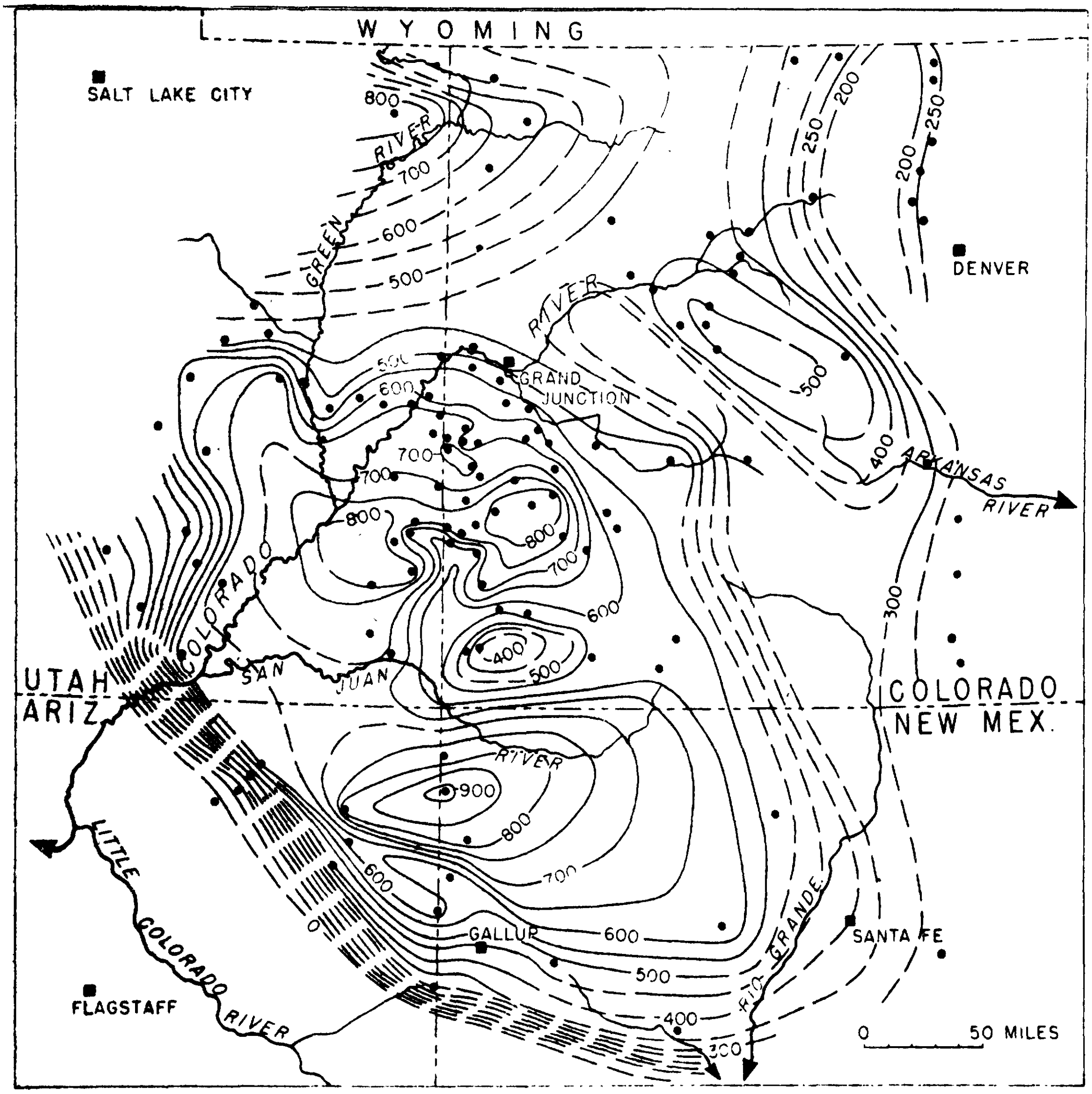
The Morrison formation cannot be separated into members east and north of the arbitrary line marking the limit of recognizable Salt Wash. Lithologic units do not have sufficient continuity to warrant member status. The area of undifferentiated Morrison includes all of central and eastern Colorado and extends eastward into western Kansas to a subsurface pinch-out of the formation. This area includes the type section of the Morrison formation near the town of Morrison in central Colorado.

Eldridge's (Emmons, Cross, and Eldridge, 1896) original definition of the formation includes an upper sandstone and shale unit that is now assigned to the Lower Cretaceous and excluded a basal sandstone now assigned to the basal Morrison. The beds near Morrison form a typical section of undifferentiated Morrison. At the new type section, described by Waldschmidt and LeRoy (1944, pp. 1097-1114), a basal lenticular sandstone 17 to 30 feet thick is overlain by 55 feet of gray and red shale with Aclistochara and fresh water gastropods, 50 feet of gray clay and limestone, 52 feet of gray shale and sandstone with dinosaurian remains, 37 feet of red shale, and 77 feet of variegated shale and sandstone. The total thickness is approximately 300 feet.

Northward from the type section, along the Front Range near Loveland, Colo., and into Wyoming the Morrison can be divided roughly into three units: a lower unit of thin-bedded gray shale and limestone with charophyte oogonia and ostracods, a medial unit of cross-bedded sandstone and conglomerate with dinosaurian remains, and an upper unit of variegated shale. Overlying the variegated shale unit lie sandstones and conglomerates of Lower Cretaceous age.

West of the type section in the central Colorado basin, the Morrison consists of claystone beds with thin intercalated limestone and sandstone beds. Dense limestones are abundant in the basal Morrison in this area but these are lenticular and cannot be individually correlated from section to section. The ancestral Uncompahgre uplift to the west, which has a northwesterly trending axis through Gunnison, Colo., may have served as a barrier, retarding the easterly flowing Salt Wash streams so that only the finer sediments crossed the highland into the central basin. The Morrison thins appreciably over the crest of this uplift (fig. 12).

The isopach map of the Morrison formation of the Colorado Plateau region (fig. 12) combines the thicknesses of the separate members of the "western"



Explanation

• Location of measured section

Isopachous interval 50 feet

Figure 12.--Isopachous map of the Morrison formation.

differentiated Morrison and the thickness variations of the western part of the map are known to result from more than one factor in some areas. In central and eastern Colorado, the map shows thicknesses of the undifferentiated Morrison. The variations may be the result of a complex history which cannot be interpreted because distinct units within the formation cannot be recognized from one area to another.

Interpretation

The undifferentiated Morrison is lithologically similar to the Brushy Basin shale member of the "western" Morrison and depositional environments are thought to have been the same. The structures of the sandstones suggest fluvial deposition; limestones and some of the clays were probably deposited in shallow temporary lakes; some of the clay is bentonitic and probably represents volcanic ash falls. The main source of the undifferentiated Morrison was probably to the south and west, the same source as those of the members of the "western" Morrison.

Post-Morrison formations

Lower Cretaceous formations

Lower Cretaceous formations overlie the Morrison formation in Colorado, eastern Utah, a small corner of northeastern Arizona, and northern New Mexico. In the past these beds have been included in either the Morrison formation or with the Dakota (?) sandstone, depending on their characteristics and affinities in different areas. The Purgatoire formation in southeastern Colorado and northeastern New Mexico separates the Morrison and Dakota. In north-central Colorado, beds usually called Dakota probably contain equivalents of the Lower Cretaceous, Cloverly formation, Wyoming. In the Four Corners area and northward through western Colorado and easternmost Utah, the Burro Canyon formation has been recognized as a separate formation of Lower Cretaceous age. In central Utah, the Buckhorn conglomerate locally forms a lower part, and the Cedar Mountain shale forms a widespread upper part to the Lower Cretaceous. All these formations are composed of interstratified conglomeratic sandstone and variegated claystone in varying proportions and sequence. The basal contact is prominent only in those areas where basal channel sandstones are present. Where these are absent it is exceedingly difficult or impossible to separate the Lower Cretaceous variegated shales from those of the upper part of the Morrison. No field evidence for a major disconformity has been recognized at the base of the Lower Cretaceous beds. The sandstones and claystones are thought to represent various combinations of fluvial and lacustrine deposition.

Upper Cretaceous formations

Dakota (?) sandstone

The Dakota (?) sandstone is recognized as a lithologic unit throughout most of the region of study and forms a sequence of interstratified conglomeratic sandstone and gray carbonaceous shale or coal. These reflect deposition in alternating stream and swamp environments. The Upper Cretaceous age of the Dakota (?) sandstone has been established in southwestern Colorado (Brown, 1950, p. 45), but faunal evidence indicates that the lithologic unit called the Dakota (?) sandstone in parts of central Utah is Lower Cretaceous in age (Katich, 1951). Throughout western Colorado and eastern and central Utah, the Dakota (?) sandstone is separated from underlying Lower Cretaceous formations by only an erosional disconformity but to the south and west in New Mexico and northeastern Arizona, this unconformity increases and the Dakota (?) sandstone overlies progressively older and older beds; and pre-Dakota warping and subsequent erosion has removed Lower Cretaceous formations, the Morrison formation, and part of the San Rafael group along the southern and southwestern margin of the region of study.

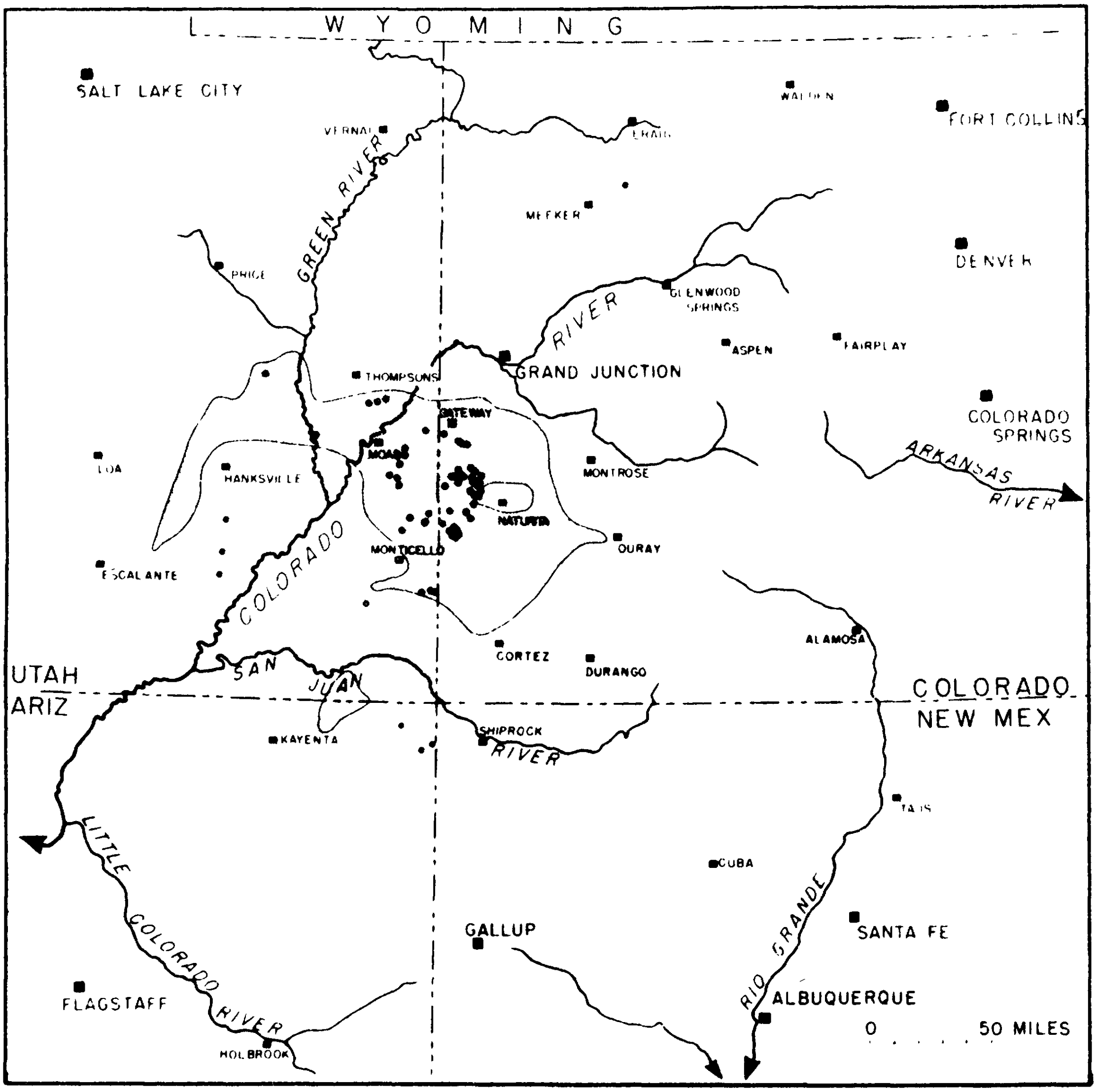
Mancos shale

The Mancos shale consists of gray calcareous and gypsiferous marine claystones and minor sandstones. Marine invertebrate fossils are common. The Mancos lies conformably on the Dakota (?) sandstone; the contact is gradational and in many places is only arbitrarily located.

RELATION OF ORE DEPOSITS TO THE STRATIGRAPHY OF THE MORRISON FORMATION

Information concerning the relation of carnotite deposits to the stratigraphy of the Colorado Plateau region and particularly to that of the Morrison formation has been collected by the regional studies as well as by a number of detailed studies in the vicinity of ore deposits. Many of the results are negative but are valuable in that they eliminate possible lines of research.

The distribution of major groups of carnotite deposits is shown in figure 13. The carnotite deposits of the Morrison formation are nearly confined to the Salt Wash sandstone member and lie entirely within the sandstone and mudstone facies of the Salt Wash (fig. 3). Most carnotite deposits are in areas where the Salt Wash member is more than 240 feet thick (fig. 3). The lithofacies studies show that most of the carnotite deposits are in areas where the stream deposits (essentially the channel sandstones) constitute 40 to 55 percent of the thickness of the Salt Wash member; that most of the carnotite deposits are in areas where the total thickness of the stream deposits in the Salt Wash is 90 to 200 feet (fig. 5); and that most of the carnotite deposits are in areas where the thickness of the stream deposits shows a percentage mean deviation of 5 to 18 percent.



Explanation

• Location of major carnotite deposit

☐ Area of favorable environment for ore deposition as delimited by lithofacies criteria:
Salt Wash sandstone member over 240 feet thick.
Stream lithotope comprises 40 to 55 percent of thickness of member.
Total thickness of stream lithotope in member is 90 to 200 feet.
Percentage mean deviation of stream lithotope is 5 to 18 percent.

Figure 13.—Map showing the location of major carnotite deposits in the Salt Wash sandstone member of the Morrison formation and the areas of favorable environment for ore deposition as delimited by lithofacies criteria.

These observations suggest that an area of relative favorability for ore localization may be delimited (fig. 13) within the area of the sandstone and mudstone facies (fig. 3). It is generally agreed that the ore was not deposited at the time of accumulation of the sediments but was introduced before regional deformation by mineral-bearing solutions that percolated through the more permeable layers. Before the Salt Wash member was regionally deformed, it must have varied areally in its quality as an aquifer. Near the apex of the "fan" in south-central Utah it must have been an excellent aquifer for it is relatively thick and contains a high percentage of relatively continuous permeable, stream deposited sandstone. To the north and east, in the areas of the claystone and lenticular sandstone facies and the limestone and claystone facies, the Salt Wash must have been a poor aquifer for it is thin and contains a very low percentage of relatively discontinuous stream deposited sandstones. Within the area of the sandstone and mudstone facies, the Salt Wash must have had intermediate properties as an aquifer. Ore-bearing solutions might have "flushed" through the highly permeable part of the Salt Wash without appreciable opportunity for deposition and concentration of the ore minerals. In the marginal facies of the Salt Wash, ore-bearing solutions perhaps would have moved too slowly to have brought in much uranium and vanadium in solution. Optimum conditions of supply and movement of mineral-bearing solutions must have occurred within the sandstone and mudstone facies.

The petrography of the Salt Wash sandstone shows no detailed or regional relation between ore deposits and the heavy-mineral distribution or any of the parameters of grain-size distribution except the sorting as measured by the logarithmic standard deviation (fig. 9). Most of the carnotite deposits occur in areas where the Salt Wash sandstones are relatively well-sorted (low logarithmic standard deviation). In general well-sorted sands have greater permeability than those that are poorly sorted. A greater permeability of the Salt Wash sandstone may have influenced migration of ore-bearing solutions and contributed to the development and localization of deposits in the area of relatively well-sorted sandstone.

Detailed control for the localization of ore deposits is probably the result of the interplay of a number of environmental factors. The coincidence of several physical features of the Salt Wash with the ore deposits has been studied and summarized by Blackman (1950). The variations of the Salt Wash in the vicinity of the Uravan mineral belt (Fischer and Hilpert, 1951), "A narrow, elongate area in southwestern Colorado in which the carnotite deposits . . . have a closer spacing, larger size, and higher grade than those in adjoining areas." have been studied and summarized by E. J. McKay (1951). The parallel orientation of the long axes of ore "rolls" to the elongation of ore deposits and fossil logs has been noted by R. P. Fischer (1942, p. 387) and indicates a large-scale controlling influence by primary sedimentary features on the shape of ore bodies. However, sedimentary structural studies show considerable divergence between the resultant dip direction of cross-laminae in some mineralized areas and the orientation of ore "rolls" in the mines of the same areas. This may be a result of sampling technique, for the sedimentary structural study may average the orientation of many different stream channels and the orientation of ore deposits may be influenced by only a few channels in the area studied. Nevertheless, the resultant dip directions of cross laminae (fig. 8) and the trends of ore "rolls" show about the same radial regional pattern. Ore deposits show little detailed control by sedimentary structures for in many places the ore cuts across the bedding and lamination.

To date the stratigraphic studies have yielded little information on the original source of the uranium in the carnotite deposits of the Morrison. Three sources may be postulated: 1) from the sedimentary rocks of the source area of the Salt Wash, 2) from a post-Salt Wash hydrothermal source in the Colorado Plateau region, or 3) from post-Salt Wash sediments, possibly tuffaceous beds, either in the immediate vicinity of the present ore deposits or away from the present ore deposits.

The pre-Morrison sedimentary rocks have been entirely removed from the area of the major source of the Salt Wash in west-central Arizona and evidence of pre-existing uranium deposits in these rocks is lacking. Evidence of the origin of these hypothetical uranium deposits might be found in the pre-Cambrian rocks of this area. Two deposits of moderate uranium content have been cited in the pre-Cambrian of Arizona (Kaiser, 1951). One of these, the Jim Kane mine in Mohave County, is in the area considered as the probable source area of the Salt Wash member. Uranium deposits have been reported in the Triassic Chinle formation of Arizona not far from the source area of the Salt Wash. Both the upper Paleozoic Kaibab and Madison limestones of Utah have "strong traces" of uranium (Webber, 1947, p. 234) and might have formed a low-grade source of the uranium concentrated in the Salt Wash. Argall (1943, pl 19) suggests that the uranium of the Salt Wash might have been derived from the vanadiferous beds of the Permian Phosphoria formation, a phosphate-bearing formation of northern Utah, southern Idaho, and southwestern Wyoming. Pebbles of the Phosphoria have been reported in the Salt Wash of central Utah. This formation contains low percentages of uranium in Wyoming and Idaho and might have yielded uranium which, by concentration, formed the relatively rich deposits of the Salt Wash. However, this would have involved migration of uranium-bearing solutions from the west and northwest to the south and southeast across the grain of the Salt Wash structures (fig. 8). Such migration seems improbable unless a regional tilting to the southeast forced ground-water movement across the structures. Evidence for this tilting is lacking. The absence of phosphatic material in the Salt Wash suggests that the

Phosphoria was neither an important source during the accumulation of the Salt Wash sediments nor an important source of mineral-bearing solutions during formation of the carnotite deposits.

No evidence is known that directly relates the Salt Wash carnotite deposits to a hydrothermal origin.

Migration of uranium and vanadium from minerals disseminated in overlying sediments, particularly tuffaceous clays, is possible, but it appears unlikely, first because these overlying beds are rather impervious, and second because they generally do not appear to contain more metal than is normal.

FUTURE PLANS

Stratigraphic field work on the Morrison formation will be completed during the field season of 1951. This work will consist of several aspects; study of areas not yet investigated in northeastern Utah and northeastern New Mexico, completion of control and solution of specific problems in areas already studied, a limited extension of Morrison pebble studies, and reconnaissance inspection of possible Morrison source areas. Office work in the winter of 1951-52 will be directed to the completion of an official detailed final report on the stratigraphy of the Morrison formation. This final report will be modified for public release as a Geological Survey Professional Paper or Bulletin.

Stratigraphic studies of the Triassic Shinarump conglomerate began in May 1951 in Monument Valley, Utah-Arizona. Stratigraphic study of the Shinarump will be continued on a full-time basis in the field season of 1952 and following field seasons.

REFERENCES

Argall, G. O., Jr., 1943 , The occurrence and production of vanadium: School of Mines Quart., vol. 38, no. 4, p. 19.

Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., 1936, Correlation of Jurassic formations of portions of Utah, Arizona, and Colorado: U. S. Geol. Survey Prof. Paper 183.

Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., 1947, Revised correlations of Jurassic formation of parts of Utah, Arizona, New Mexico, and Colorado: Bull. Amer. Assoc. Petrol. Geol., vol. 31, pp. 1664-1668.

Blackman, D. H., 1950, Geologic guides to carnotite deposits on the Colorado Plateau: U. S. Geol. Survey Trace Elements Mem. Rept. 170.

Brown, R. W., 1950, Cretaceous plants from southwestern Colorado: U. S. Geol. Survey Prof. Paper 221-D, p. 45.

Cross, Whitman, 1894, U. S. Geol. Survey Geol. Atlas, Pikes Peak folio no. 7, p. 2.

Eckel, E. B., 1949, Geology and ore deposits of the La Plata district, Colorado: U. S. Geol. Survey Prof. Paper 219, pp. 29-30.

Emmons, S. F., Cross, Whitman, and Eldridge, G. H., 1896, Geology of the Denver Basin in Colorado: U. S. Geol. Survey Mon. 27.

Fenneman, N. M., 1931, Physiography of western United States, McGraw-Hill Book Co.

Fischer, R. P., 1942, Vanadium deposits of Colorado and Utah: U. S. Geol. Survey Bull. 936-P, p. 387.

Fischer, R. P., and Hilpert, L. S., 1951, U. S. Geol. Survey Bull., in preparation.

Gilluly, James, and Reeside, J. B., Jr., 1928, Sedimentary rocks of the San Rafael Swell and some adjacent areas in eastern Utah: U. S. Geol. Survey Prof. Paper 150, p. 82.

Goddard, E. N., et al., 1948, Rock-color chart: National Research Council.

Goldman, M. I., and Spencer, A. C., 1941, Correlation of Cross' La Plata sandstone, southwestern Colorado: Bull. Amer. Assoc. Petrol Geol., vol. 25, pp. 1745-1767.

Gregory, H. E., 1938, The San Juan Country: U. S. Geol. Survey Prof. Paper 188, pp. 58-59.

Kaiser, E. P., 1951, Uraniferous quartzite, Red Bluff prospect, Gila County, Arizona: U. S. Geol. Survey Trace Elements Mem. Rept. 120.

Kaiser, E. P., 1951, Radioactivity at the Jim Kane Mine, Mohave County, Arizona: U. S. Geol. Survey Trace Elements Mem. Rept. 216.

Katich, P. J., 1951, unpublished thesis, Ohio State University.

Kiersch, G. A., 1950, Small scale structures and other features of Navajo sandstone, northern part of the San Rafael Swell, Utah: Amer. Assoc. Petrol. Geol. Bull., vol. 34, pp 923-942.

Lupton, C. T., 1914, Oil and gas near Green River, Grand County, Utah: U. S. Geol. Survey Bull. 541, p. 127.

McKay, E. J., 1951, Large-scale geologic guides to carnotite deposits in the Uravan and Gateway districts, Montrose and Mesa Counties, Colorado: U. S. Geol. Survey Trace Elements Mem. Rept. 271.

McKee, E. D., 1939, Some types of bedding in the Colorado River delta: Jour. Geology, vol. 47, pp. 64-81.

McKee, E. D., 1948, Classification and interpretation of cross-lamination (abstract): Geol. Soc. Amer. Bull., vol. 59, p. 1378.

Moore, R. C., 1949, Meaning of facies: Geol. Soc. America Mem. 39, pp. 8-16.

Read, C. B., Wood, G. H., Wanek, A. A., and MacKee, R. V., 1949, Stratigraphy and geologic structure in the Piedra River Canyon, Archuleta County, Colorado: U. S. Geol. Survey Oil and Gas Invs. Prelim. Map 96.

Reiche, Parry, 1938, An analysis of cross-lamination; Coconino sandstone: Jour. Geology, vol. 46, pp. 905-932.

Stokes, W. L., 1947, Primary lineation in fluvial sandstones: A criterion of current directions: Jour. Geology, vol. 55, pp. 52-54.

Stokes, W. L., 1945, unpublished U. S. Geological Survey manuscript.

Waldschmidt, W. A., and LeRoy, L. W., 1944, Reconsideration of the Morrison formation in the type area, Jefferson County, Colorado: Geol. Soc. America Bull., vol. 55, no. 9, pp. 1097-1114.

Webber, B. N., 1947, Geology and ore resources of the uranium-vanadium depositional province of the Colorado Plateau region: Union Mines Develop. Corp. unpublished report, p. 234, pp. 177-178.