Stratigraphy of the Morrison and Related Formations, Colorado Plateau Region A Preliminary Report

GEOLOGICAL SURVEY BULLETIN 1009-E

A CONTRIBUTION TO THE GEOLOGY OF URANIUM

STRATIGRAPHY OF MORRISON AND RELATED FORMATIONS, COLORADO PLATEAU REGION, A PRELIMINARY REPORT

By Lawrence C. Craig and Others *

ABSTRACT

Three subdivisions of the Jurassic rocks of the Colorado Plateau region are: the Glen Canyon group, mainly eolian and fluvial sedimentary rocks; the San Rafael group, marine and marginal marine sedimentary rocks; and the Morrison formation, fluvial and lacustrine sedimentary rocks.

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

Where differentiated, the lower part of the Morrison consists either of the Salt Wash member or the Recapture member or both; these are equivalent in age and intertongue and intergrade over a broad area in the vicinity of the Four Corners area of New Mexico, Colorado, Arizona, and Utah. The Salt Wash member is present in 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 area of the Salt Wash was to the southwest of south-central Utah, probably in west-central Arizona and southeastern California. The member was derived mainly from sedimentary rocks. The Salt Wash deposits grade from predominantly coarse texture at the apex of the "fan" to predominantly fine texture at the margin of the "fan".

The Salt Wash member has been arbitrarily divided into four facies: a conglomeratic sandstone facies, a sandstone and mudstone facies, a claystone and lenticular sandstone facies, and a claystone and limestone facies.

The Recapture member of the Morrison formation is present in northeastern Arizona, northwestern New Mexico, and small areas of southeastern Utah and southwestern Colorado near the Four Corners. It was formed as a large

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alluvial plain or "fan" by an aggrading system of braided streams. The Recapture deposits grade from predominantly coarse texture sedimentary rocks to predominantly fine texture and have been arbitrarily divided into three facies: a conglomeratic sandstone facies, a sandstone facies, and a claystone and sandstone facies. The distribution of the facies indicates that the major source area of the Recapture was south of Gallup, N. Mex., probably in west-central New Mexico. The Recapture was derived from an area of intrusive and extrusive igneous rocks, metamorphic rocks, and sedimentary rocks.

The upper part of the Morrison formation consists of the Westwater Canyon member and the Brushy Basin member. The Westwater Canyon member forms the lower portion of the upper part of the Morrison in northeastern Arizona, northwestern New Mexico, and places in southeastern Utah and southwestern Colorade 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 sedimentary rocks to somewhat finer textured sedimentary rocks, and have been arbitrarily divided into two facies: a conglomeratic sandstone facies and a sandstone facies. The distribution of the facies indicates that the major source area of the Westwater was south of Gallup, N. Mex., probably in west-central New Mexico. The Westwater was derived from an area 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 represents essentially a continuation of deposition on the Recapture "fan"; the Westwater contains, however, considerably coarser materials.

Whereas the Salt Wash, Recapture, and Westwater members of the Morrison formation are characterized by sequences of interstratified sandstone and red or green claystone, the Brushy Basin member consists mainly of variegated claystone with a few lenticular conglomeratic sandstone strata. The Brushy Basin 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 derived from falls of volcanic ash. The source area for many of the fluvial deposits of the Brushy Basin member may have been the same as that for the Salt Wash member. No lithologic facies with restricted areal distribution can be distinguished in the Brushy Basin member. At the conclusion of deposition of the conglomeratic sandstone and sandstone of the Westwater member, deposits of the Brushy Basin were spread southward over at least part 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 formation of eastern and central Colorado has lithologic characteristics similar to those of the Brushy Basin member. It is thought to contain beds equivalent to both the upper and lower parts of the Morrison to the west, but these parts cannot be distinguished, and no other lithologic units have sufficient continuity to warrant member status.

Lower Cretaceous beds, mainly of fluvial and lacustrine character, have been recognized overlying the Morrison formation throughout most of the Colorado Plateau region. In places the beds are so similar to the beds of 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; in western New Mexico and northeastern Arizona the Dakota progressively overlies older and older formations.

Most of the carnotite deposits of the Morrison formation are in the Salt Wash member. They are found entirely within the sandstone and mudstone facies of the Salt Wash member. Lithofacies studies have delimited an area relatively favorable for the occurrence of ore within the area of this facies. Most of the carnotite deposits occur in areas where sandstones of the Salt Wash are relatively well sorted and probably have a relatively high permeability. The resultants of dip directions of cross-laminae in the sandstones of the Salt Wash and the trends of ore "rolls" show similar radial patterns and may indicate that the shapes of carnotite deposits were influenced by primary sedimentary structures; however, the ore deposits show little detailed control by sedimentary structures, for in many places the ore cuts across the bedding and lamination.

Three distinct possible sources for the uranium of the carnotite deposits may be postulated: 1) the rocks of the source area of the Salt Wash member of the Morrison formation, 2) a post-Salt Wash hydrothermal source in the Colorado Plateau region, and 3) 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 Late 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 and adjacent formations, and two of which deal mainly with the carnotite-bearing Salt Wash member of the Morrison formation, as follows:

1. Regional stratigraphic study, concerned with establishing and interpreting the stratigraphic sequence, physical continuity, color,

composition, texture, structure, and thickness variations of the members of the Morrison 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 these variations.

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

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

The region of study includes more than 5,000 linear miles of outcrop of the Morrison formation. Outcrops are so extensive that it was necessary to resort to sampling methods in all the phases of the stratigraphic studies. All the studies yielded quantitative as well as qualitative results, and all except the regional stratigraphic study supplied data which can be studied statistically.

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

REGION OF STUDY AND GEOLOGIC SETTING

The region of study includes the western two-thirds of Colorado, the northwestern quarter of New Mexico, the eastern half of Utah, and the northeastern quarter of Arizona (fig. 19). This region 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 intruded by laccoliths, pierced by volcanic plugs, and warped in salt anticlines, or where sharply folded along large monoclines. The Morrison formation crops out in long, continuous serrate patterns (fig. 19). In the Southern Rocky Mountain part of the region the rocks exposed are dominantly igneous or metamorphic and are faulted, folded, and uplifted to form mountains of complex structure. In this area the Morrison crops out in short disconnected

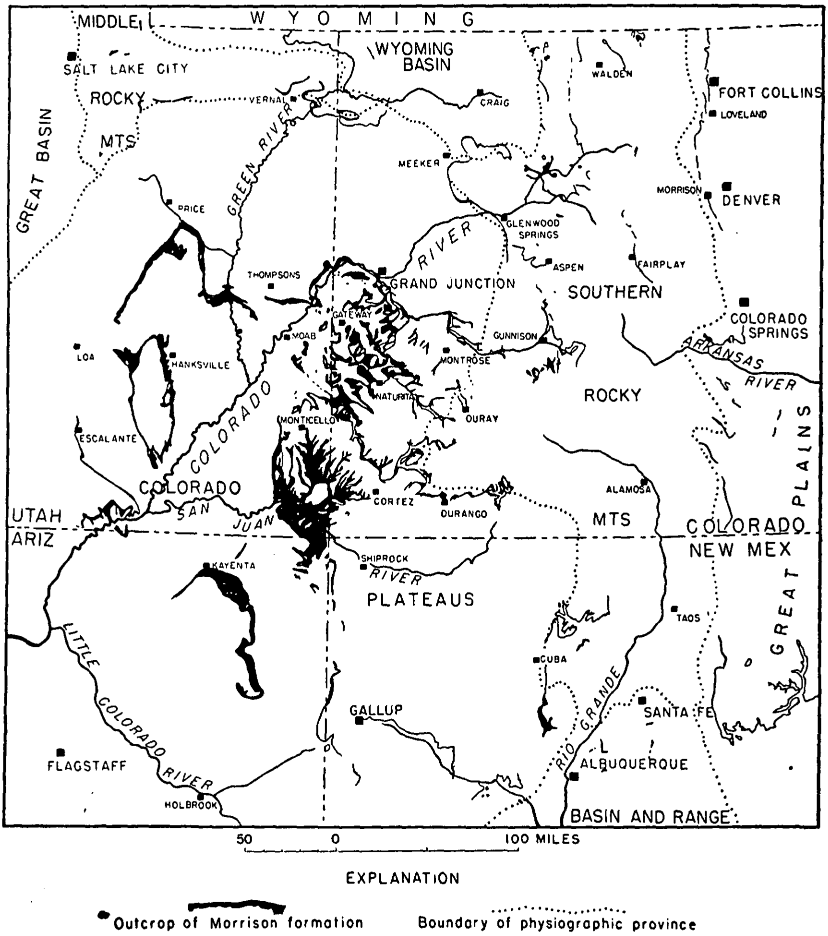

FIGURE 19.—Index map of the Colorado Plateau region, showing the outcrop pattern of the Morrison formation.

belts that form 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 serrate patterns.

The rocks exposed in the region of study range in age from pre-Cambrian to Cenozoic. Igneous and metamorphic rocks constitute the pre-Cambrian, whereas younger rocks are predominantly sedimentary. The early Paleozoic is represented by relatively thin marine limestones and clastics. These grade upward to the thick terrestrial and marginal-marine clastics and evaporites of the late Paleozoic. Rocks of Mesozoic age are mainly clastics; they were deposited under terrestrial conditions throughout the Triassic, Jurassic, and Early Cretaceous with the exception of two marine units of Middle and Late

Jurassic age. The Late Cretaceous is represented by thick, dominantly marine clastics. Tertiary sedimentary rocks are mainly nonmarine clastics; Tertiary igneous activity is represented in many forms in places in the region studied.

STRATIGRAPHY OF JURASSIC AND CRETACEOUS ROCKS

The Jurassic rocks (table 1) of the Colorado Plateau are subdivided into three major units. In ascending order these are: the Glen

TABLE 1.—*Generalized section of the Wingate sandstone and Jurassic and Cretaceous strata in part of southwestern Colorado and adjoining parts of Utah*

System	Group	Formation	Thickness (feet)	Character and distribution
Cretaceous		Mesaverde formation	1,000±	Light-colored sandstone and gray shale; coal-bearing; cliff-forming; wide-spread.
		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.
		—Unconformity— Burro Canyon formation	50–250	Light-colored conglomeratic sandstone and maroon and green mudstone; mesa-capping.
Jurassic		Morrison formation	300–500	Brushy Basin member: varicolored shale (or mudstone), some sandstone lenses; forms slopes; widespread.
			200–400	Salt Wash member: light-colored sandstone and red mudstone; forms cliff 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.
	Glen Canyon group	—Unconformity— Navajo sandstone	0–2,000	Light-colored, massive sandstone; cliff-forming; thins to extinction in western Colorado; thickens westward.
Jurassic(?)		Kayenta formation	0–300	Red sandstone, irregularly bedded; bench-forming; absent in eastern part of region.
Triassic		Wingate sandstone	0–400	Red, massive sandstone; cliff-forming; absent in eastern part of region.

Canyon group, the San Rafael group, and the Morrison formation. 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 in ascending order of the Wingate sandstone, Kayenta formation, and Navajo sandstone. Assignment of the group to the Jurassic is tentative because of the lack of diagnostic fossils.[1] The Wingate sandstone forms a broad lens-shaped deposit extending throughout southeastern Utah, and into southwestern Colorado and the Four Corners. In the center of this area the Wingate is mostly of eolian origin but to the north and east shows increasing characteristics of deposition in a standing body of water and to the southeast, of fluvial deposition.

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

The Navajo sandstone forms an irregular wedge of sandstone, predominantly eolian in origin, extending throughout southern and eastern Utah into western Colorado and part of northeastern Arizona. The Navajo is thickest in southwestern Utah and is represented by the Aztec sandstone of even greater thickness in southern Nevada. The eastern limit of the Navajo is along an irregular north-south trending line through western Colorado and northeastern Arizona.

In Colorado and Utah the Glen Canyon group is generally conformable on the underlying Upper Triassic Chinle formation, but in parts of New Mexico and Arizona an erosional disconformity is indicated at the base of the Glen Canyon (Harshbarger, Repenning, and Jackson, 1951, p. 96). 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 interrupted by a period of widespread stream deposition in Kayenta time. Data as to source areas of the formations are incomplete. The Wingate sandstone was probably derived from areas to the west in Utah and eastern Nevada. Baker, Dane, and Reeside (1936, p. 44) suggest that the Kayenta formation had an important local source from the east, the Ancestral Uncompahgre Highland of western Colorado, but no major source area has been recognized. The Navajo sandstone probably was derived from a source area in western and southern Nevada. Analyses of the orientation of sedimentary structures in

[1] The Geological Survey now treats the Wingate sandstone as Triassic in age, the Kayenta formation as Jurassic(?), and the Navajo sandstone as Jurassic. See table 1.

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, the Curtis formation, and the Summerville formation, in ascending order. The Carmel has been dated as Middle and early Late Jurassic and the Curtis as middle Late 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 to a feather edge in southwestern Colorado. In central and southwestern Utah a partly marine sandstone and shale facies containing limestone and gypsum 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 in New Mexico has not been determined. This problem can be solved only by detailed studies of facies relations in southeastern Utah.

The Entrada sandstone was deposited throughout southern and eastern Utah, most of Colorado, and all 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 environment of alternating subaerial and subaqueous marginal marine conditions. The Entrada is absent in parts of central Colorado over 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 by 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 and shale; 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. 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.

In the vicinity of the Four Corners and as far west as south-central Utah a prominent sandstone unit is present at the top of the Summerville formation and at the base of the Morrison formation. This unit has received various assignments in the geologic literature. Gregory (1938, p. 58) designated the sandstone unit as the Bluff sandstone member of the Morrison formation in southeastern Utah. Goldman and Spencer (1941, p. 1750) defined it as the Junction Creek sandstone member of the Morrison in southwestern Colorado. The Junction Creek has been treated as a separate formation (Eckel, 1949, p. 29) and, most recently, has been treated as a member of the Wanakah formation (Read, Wood, Wanek, and McKee, 1949), a unit that occupies the stratigraphic position of the Summerville formation in parts of Colorado and New Mexico.

Goldman and Spencer (1941, p. 1759) suggested that the Junction Creek correlates with the Bluff. This correlation seems certain on the basis of similarity of lithology, stratigraphic position, and detailed stratigraphic sequence, but the outcrops of this sandstone in southwestern Colorado are separated from those of the Bluff in adjacent states, and the unit is treated here as a separate formation, the Junction Creek sandstone of southwestern Colorado.

The Bluff sandstone has been traced southward from the Four Corners area into northeastern Arizona and northwestern New Mexico. In the area west of Gallup, N. Mex., the Bluff constitutes an inseparable part of the Cow Springs sandstone (Harshbarger, Repenning, and Jackson, 1951, p. 97–98). The Cow Springs occupies the entire stratigraphic interval of the Summerville formation and part of the Morrison formation. Inasmuch as the Bluff of the Four Corners area has been identified as an extension of the thicker and more complete sandstone section to the south, the Bluff is recognized as a tongue of the Cow Springs sandstone.

The Bluff has been observed to tongue and grade into the Summerville formation in southeastern Utah, and a part of the Bluff has been observed to tongue with the overlying Salt Wash member of the Morrison formation in northeastern Arizona a short distance west of the Four Corners. Thus the sandstone unit is related to both the Summerville and Morrison formations. Both the Bluff sandstone and the correlative Junction Creek sandstone are assigned here arbitrarily to the San Rafael group. This is appropriate, for the Bluff and Junction Creek exhibit bedding and lithologic characteristics quite similar to those found in the San Rafael group and quite dissimilar to those of the bulk of the Morrison of the Colorado Plateau region.

Southward from the Four Corners the rocks in the stratigraphic interval of the Summerville formation, as well as most of the Morrison formation, grade into the Cow Springs sandstone. In places west and south of Gallup, the Entrada and Cow Springs sandstones are essentially inseparable. Similarly, to the northwest of the Four Corners, in south-central Utah, the stratigraphic interval of the Summerville formation becomes sandstone and constitutes the Winsor formation (Gregory, 1951, p. 30–53).

The base of the San Rafael group is marked by an erosional break, probably of little time duration. The irregularities of the underlying Glen Canyon group were beveled and the uppermost deposits were reworked into the basal few feet of the Carmel formation. 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, 1894, p. 2) has been recognized over most of the western interior of the United States; except where removed by erosion, it is present over all of Colorado, eastern Utah, northwestern New Mexico, and part of northeastern Arizona (fig. 19). The Morrison consists of lenticular strata of variegated mudstones and claystones and light-gray, cross-laminated sandstones. Over most of the western interior of the United States the Morrison has not been divided into members. In western Colorado, eastern Utah, northeastern Arizona, and northwestern New Mexico, however, the Morrison can be separated into a lower and an upper part, each of which has two members, differentiated on lithologic criteria (fig. 20). An arbitrary line separating the undifferentiated Morrison of central Colorado from the subdivided Morrison to the west extends irregularly from northwestern Colorado to south-central Colorado. In figure 21 this line is shown as the limit of recognizable Salt Wash.

The base of the Morrison formation is defined in the Colorado Plateau region as the base of the terrestrial, fluvial 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 solely of the Salt Wash member in most of eastern Utah and western Colorado and solely of the Recapture member in most of 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. 20).

REGIONAL STRATIGRAPHY

Salt Wash member.—The Salt Wash member (Lupton, 1914, p. 127; Gilluly and Reeside, 1928, p. 82) constitutes the lower part of the Morrison formation over the large fan-shaped area shown in figure 21. 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 it the Salt Wash has been removed by erosion. The south side of the fan-shaped area is a limit of deposition. South of Monticello, in southeastern Utah, the upper part of the Salt Wash intertongues with and grades into the Recapture member. In northeasternmost Arizona lower parts of the Salt Wash intertongue with the Recapture, and farther south 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.

Gregory (1938, p. 58–59) did not recognize the Salt Wash member in the southeastern corner of Utah, but subsequently Stokes (1944, p. 963–964) recognized the member in the lower part of Gregory's Recapture member in this area as well as in the Carrizo Mountains area of northeastern Arizona. The extension of the Salt Walsh member as a recognizable unit through southeastern Utah and into northeastern Arizona and northwestern New Mexico constitutes a restriction of Gregory's original definition of the Recapture member.

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 sandstones, which locally contain stringers of pebbles. The sandstone may form strata composed of a single, lensing bed, 1 to 20 feet thick, or it may form strata composed of many lensing beds, which may have a total thickness of 80 feet or more.

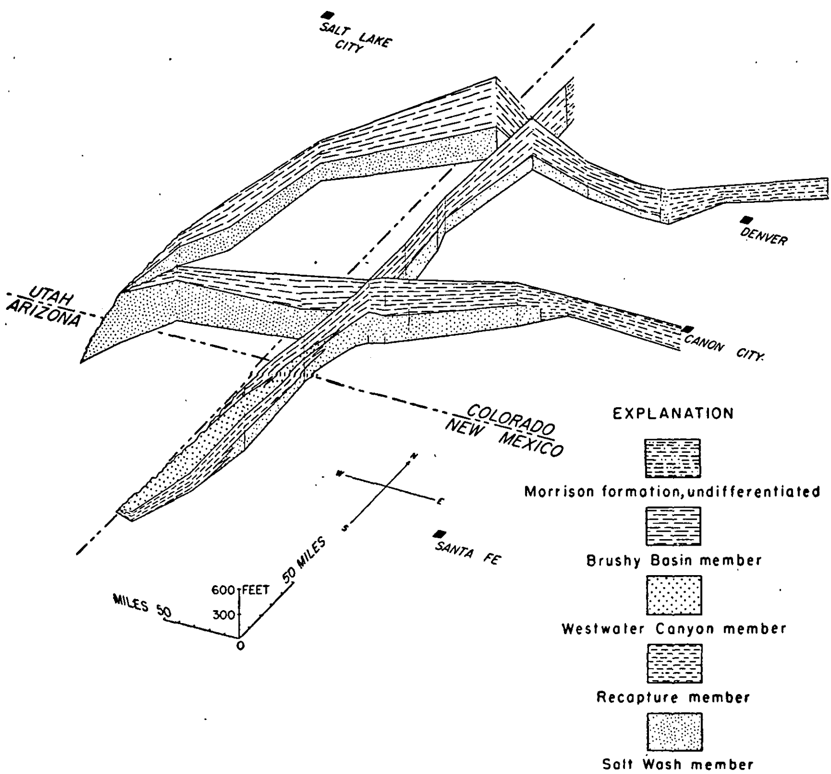

FIGURE 20.—Fence diagram of the Morrison formation of the Colorado Plateau region.

The beds are cross-laminated and generally show a slightly irregular to sharply channeled 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, and scour features are uncommon.

The base of the Salt Wash member of the Morrison formation 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 characterized by 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 member permit the separation of four major facies (fig. 21). 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, a 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. The difficulty of distinguishing these claystones and limestones from similar lithologies in the upper part of the Morrison formation prevents eastward extension of the Salt Wash member as a recognizable unit.

The thickness distribution of the Salt Wash member is shown on figure 21. From a maximum thickness of more than 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 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 thought to represent irregular independent sinking of the basement. The irregularity cannot be related to either the variation of thickness or to differential compaction of underlying formations. A thin area of Salt Wash in southeastern Utah is related to the thickness of the underlying Bluff sandstone, for, in general, as the Bluff thickens, the Salt Wash thins in this area. However, the complementary thickness relations are inexact; they probably result both from simple depositional thickness changes within the Salt Wash and the Bluff and, as observed in northeastern Arizona, from intertonguing of the two units.

Recapture member.—The Recapture member (Gregory, 1938, p. 58) forms the lower part of the Morrison formation over a part of northeastern Arizona and northwestern New Mexico (fig. 22). To the north it intertongues with and grades into the Salt Wash member; the upper part is the most extensive and is recognized to the south of

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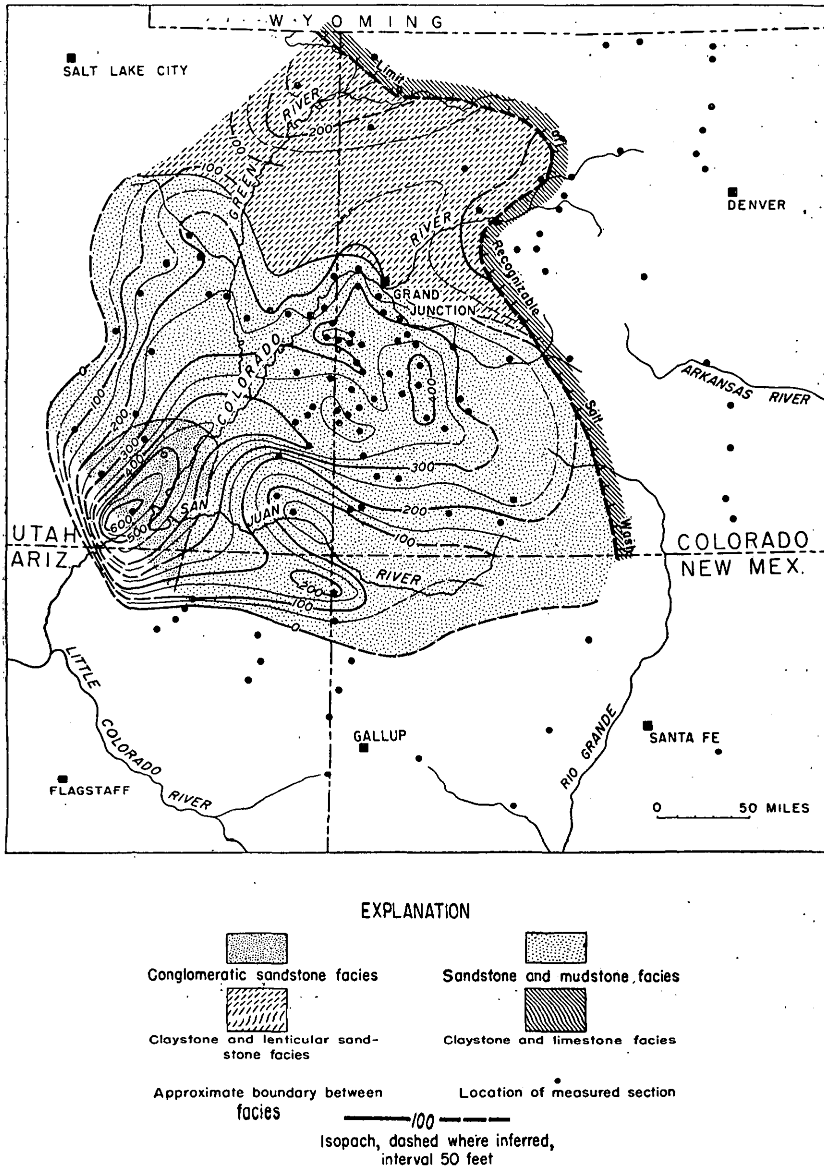


FIGURE 21.—Isopachous and facies map of the Salt Wash member of the Morrison formation.

Monticello in southeastern Utah. To the southwest the Recapture pinches out along the zero isopach line passing south of Gallup, N. Mex. Both at the northwestern and southeastern extremities of this zero isopach the line marks the apparent limit of deposition of the Recapture, but in the middle, south of Gallup, beds equivalent to the Recapture have been removed by subsequent erosion, and, thus,

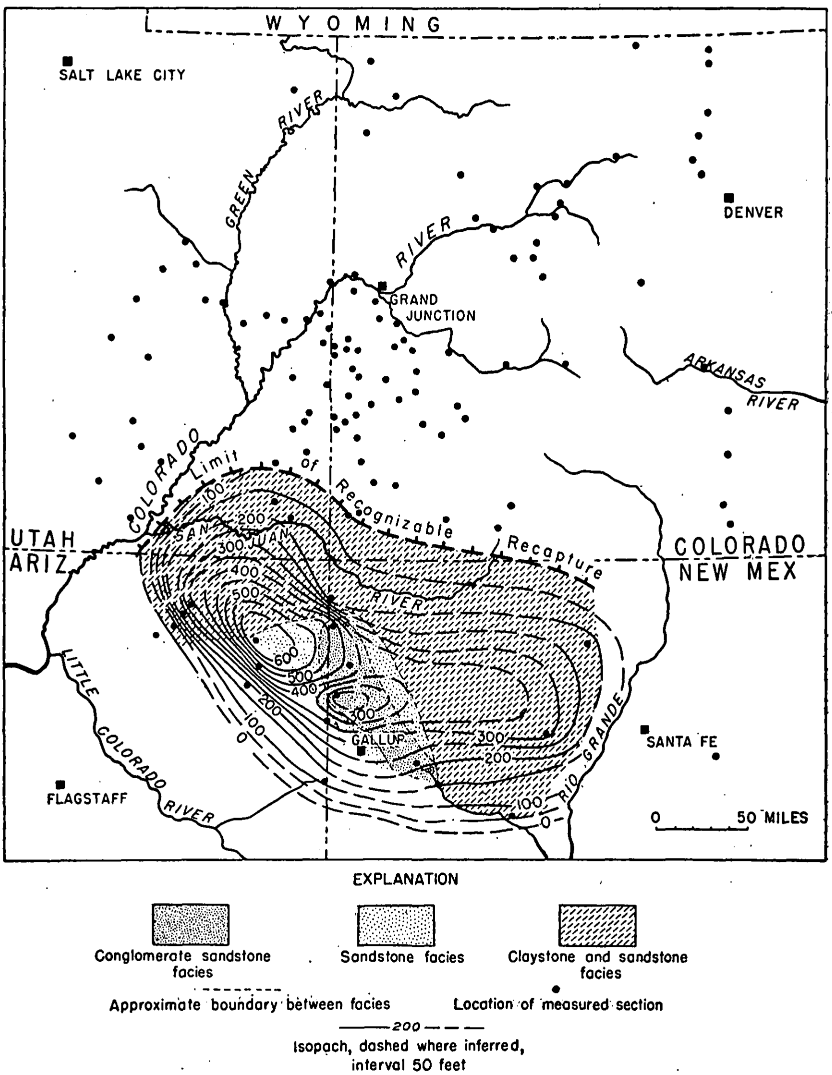


FIGURE 22.—Isophachous and facies map of the Recapture member of the Morrison formation.

this unit originally may have been more extensive in this area. The eastward extent of the Recapture in north-central New Mexico is not yet known.

The recognition of the Recapture member as a distinct lithologic unit through much of northeastern Arizona (Harshbarger, Repenning, and Jackson, 1951, p. 98), and northwestern New Mexico constitutes an appreciable areal extension of the member beyond its previously known limits.

The Recapture member is composed of interstratified sandstone and claystone. The sandstone strata consists of pinkish-gray to light-brown, fine- to medium-grained sandstone, which, locally, contains granules and pebbles disseminated in the sand 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. In Arizona, west and northwest of Gallup, N. Mex., the Recapture member is gradually replaced southward by sandstone strata that exhibit sweeping, wedging, cross-lamination and lack the scour-fill structures. These sandstones constitute an upper part of the Cow Springs sandstone (Harshbarger, Repenning, and Jackson, 1951, p. 97–98). The claystone strata of the Recapture member consist of pale-red, grayish-red, and very dusky red, variably silty and sandy claystone. The bedding in the claystone strata exhibit the same lensing shown in the bedding in the claystone strata of the Salt Wash. The friable character of the sandstone of the Recapture causes the member to weather to a steep earthy slope; a bench is developed at the foot of the slope on the more resistant sandstones of the Salt Wash in most places where that member is present.

Three distinctive facies, based on variations in texture and composition, have been recognized in the Recapture member (fig. 22). A conglomeratic sandstone facies occupies a narrow lobate area north of Gallup. The pebbles occur in rare stringers and consist mainly of quartz, feldspar, granite, and minor black and gray chert. These pebbles are as much as 1 inch in diameter. A sandstone facies surrounds the conglomeratic sandstone facies on the west, north, and, possibly, on the 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 member occupies an elongate curving area from northeastern Arizona into northwestern New Mexico (fig. 22). A maximum thickness of 680 feet was measured in northeastern Arizona. The Recapture is erratically thin in the area of the conglomeratic sandstone facies north of Gallup. The variations in thickness are regarded as a result of differential sinking of the basement. The northward thinning shown in figure 22 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 formation 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 floodplain environment. The areal variation of thickness, relative proportion, and continuity of the stream deposits and floodplain 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 floodplain deposits at 64 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 23.

The areal distribution of the relative proportions of the stream and floodplain deposits is shown by figure 24. A high ratio indicates a high proportion of stream deposits.

The areal variation in the relative continuity of the stream deposits is shown by figure 25. 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 floodplain 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

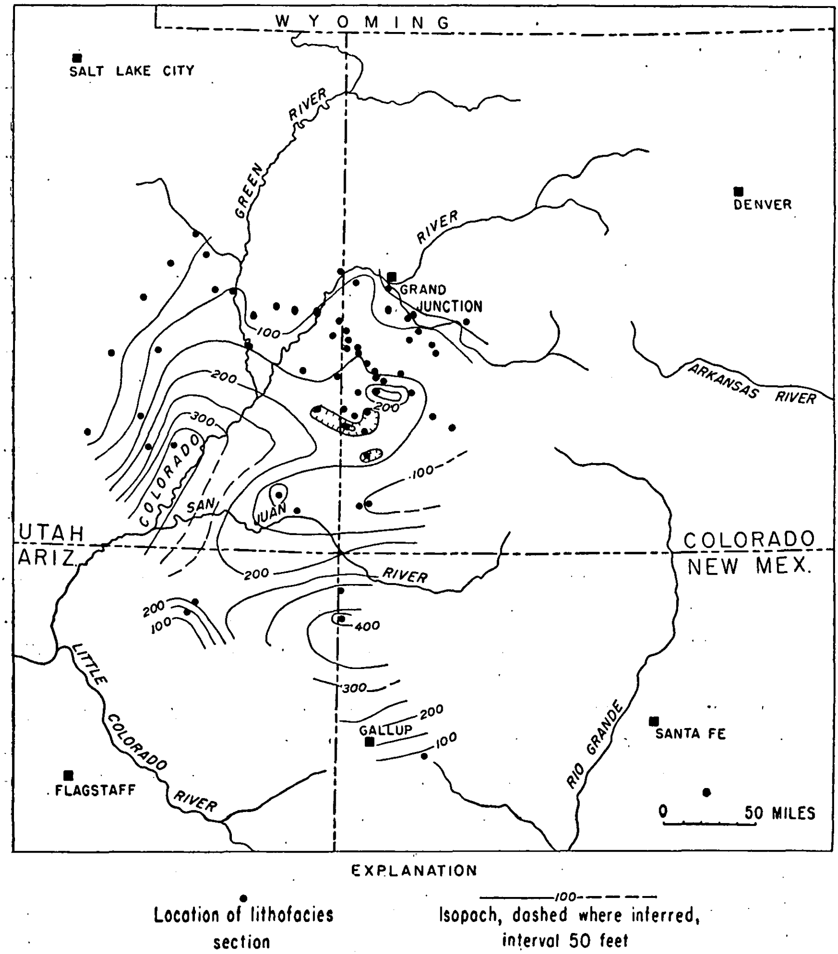
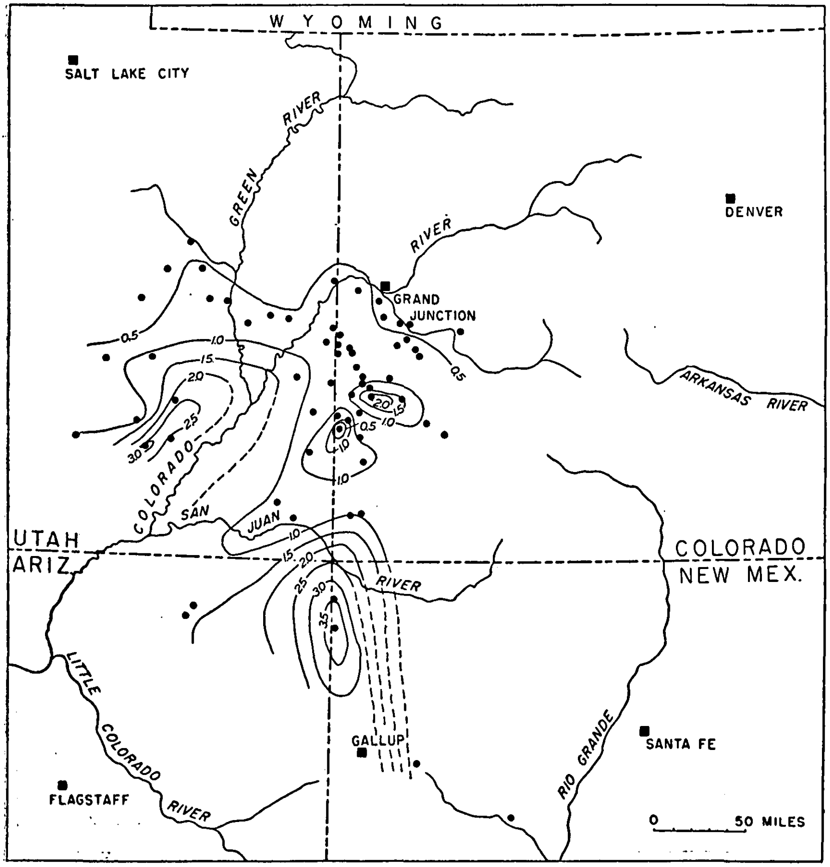


FIGURE 23.—Isopachous map of stream deposits in the lower part of the Morrison formation.

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 floodplain deposits, and continuity of the stream deposits decrease to the north, south, and west of the northern Arizona-New Mexico area. The isolith lines 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

—2.0— — — Isolith, dashed where inferred, interval 0.5

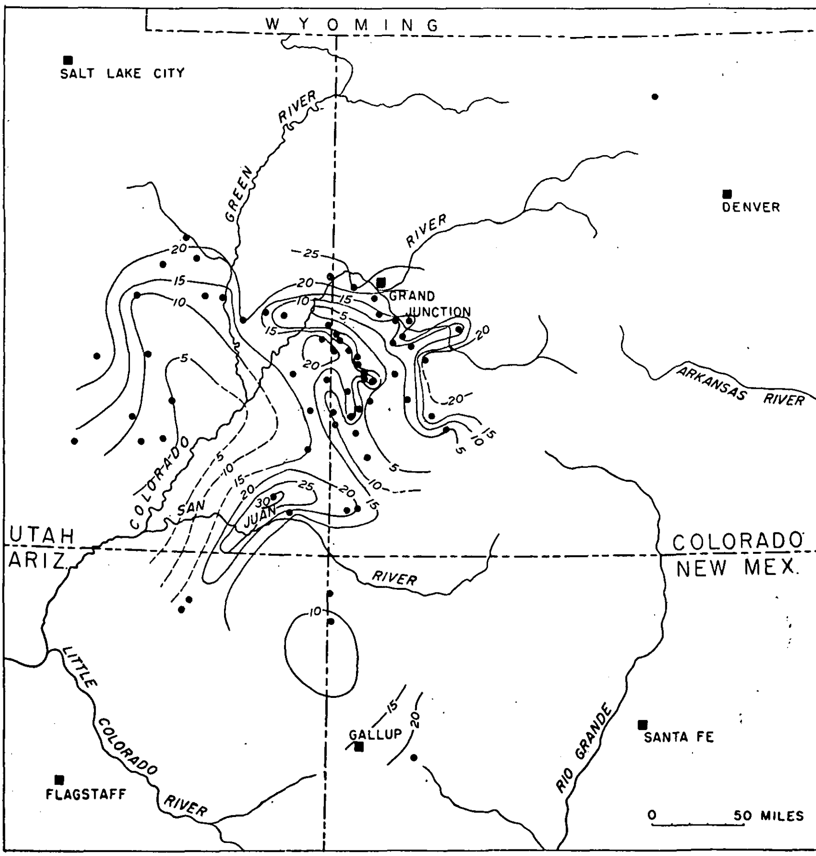
FIGURE 24.—Isolith map of the ratio of thickness of stream deposits to thickness of flood-plain deposits in the lower part of the Morrison formation.

SEDIMENTARY STRUCTURES

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

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

Cross-lamination in the Salt Wash member is a complex of several types. Classified according to the terminology of McKee (1948), as



EXPLANATION

• Location of lithofacies study

—10— - - - Isolith, dashed where inferred, interval 5 percent

FIGURE 25.—Isolith map of percentage mean deviation of stream deposit thickness in the lower part of the Morrison formation.

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 semiellipsoidal, 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 crossbeds that are subsequently beveled by scour surfaces. Low-angle compound cross-lamination is the result of simple accumulation of crossbeds 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 to the current. Current lineation is generally perpendicular to ripple marks where both are present in the same depositional unit. Current lineation has not been

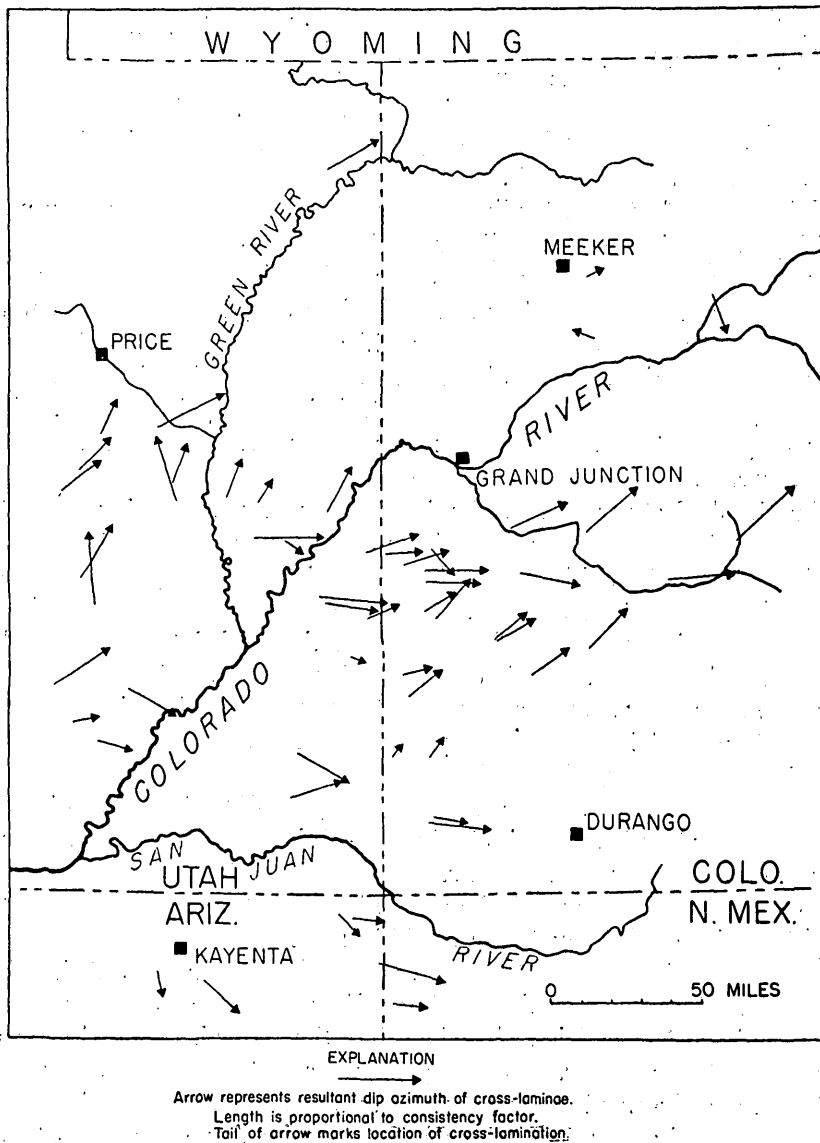


FIGURE 26.—Map of resultant dip directions of cross-laminae in sandstones of the Salt Wash member of the Morrison formation.

observed directly superimposed on ripple marks. Ripple marks occur in both the sandstone and the mudstone of the Salt Wash member. They are always of 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 member are similar to those described for the Salt Wash 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 strikes and dips 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 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 the 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 26 shows the pattern of cross-lamination in the Salt Wash member. Arrows 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 that 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 member flowed north, east, and southeast from the south-central part of Utah. No contemporaneity of deposition 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 horizons in the Salt Wash were made at each of four localities. 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.

Regional study of cross-lamination orientations in the Recapture member are incomplete.

SEDIMENTARY PETROGRAPHY

The sedimentary petrography contained in this preliminary report is based on the results of the study of 202 sandstone samples from the Salt Wash member of the Morrison formation. An investigation of the claystones and siltstones of the Salt Wash and other members of the Morrison was made by [2] A. D. Weeks (1953).

Methods used in the laboratory study of the sandstones of the Salt Wash member may be divided into two groups: preparation and measurement. Preparation includes the use of standard methods of disaggregation of consolidated sedimentary rocks, separation of heavy mineral fractions, and the preparation of mineral grain slides for petrographic examination. Measurement includes 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 member 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: calcite (cement), 13 percent; secondary silica (cement and overgrowths), 4 percent; detrital grains, 83 percent. Of the detrital grains, quartz (grains and over-

[2] Weeks, A. D., 1953, Mineralogic study of some Jurassic and Cretaceous claystones and siltstones from western Colorado and eastern Utah: U. S. Geol. Survey Trace Elements Investigations Rept. 285.

growths) comprises 86 percent; feldspar (orthoclase to albite), 7 percent; chert (silicified tuff and chert), 7 percent. Only a small suite of light and heavy minerals is present. Light detrital minerals other than quartz 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, average grain-size, asymmetry of the distribution, and other properties of petrologic interest. The results of the statistical analysis showed that the most significant measurements of the grain-size distribution are the logarithmic standard deviation and the percentile skewness, the former is a coefficient of sorting, and the latter a measure of the deviation of the distribution of the grain sizes from a 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. Figure 27 shows that there are regional differences in the sorting of the sands of the Salt Wash member and that the differences fall into a distinct pattern as 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 areas in which the stream-deposited sand had been reworked more than in adjacent areas.

A map of percentile skewness is similar to the map of sorting as shown by the logarithmic standard deviation (fig. 27). In general, the areas of better sorted sand have low positive skewness values; areas of poorer sorted sands have either high positive values or low negative values, that is, a lack of symmetry due to the presence either of too many fine grains or too many coarse grains respectively. Negative skewness values were obtained mainly along the southwestern margin of the Salt Wash member in south-central Utah and northeastern Arizona. These negative values indicate that sandstones of this area tend to have an excess of coarse material and are probably proximal to the source area of the Salt Wash.

Sandstones of the Salt Wash member contain a relatively high proportion of feldspar in northern Arizona and New Mexico in an elongate area along the southern part of the Colorado-Utah border, and in northwest Colorado and northeast Utah. The sandstones in southwest Colorado and southeast Utah outside of the elongate area contain less feldspar. Some samples from south of the Four Corners

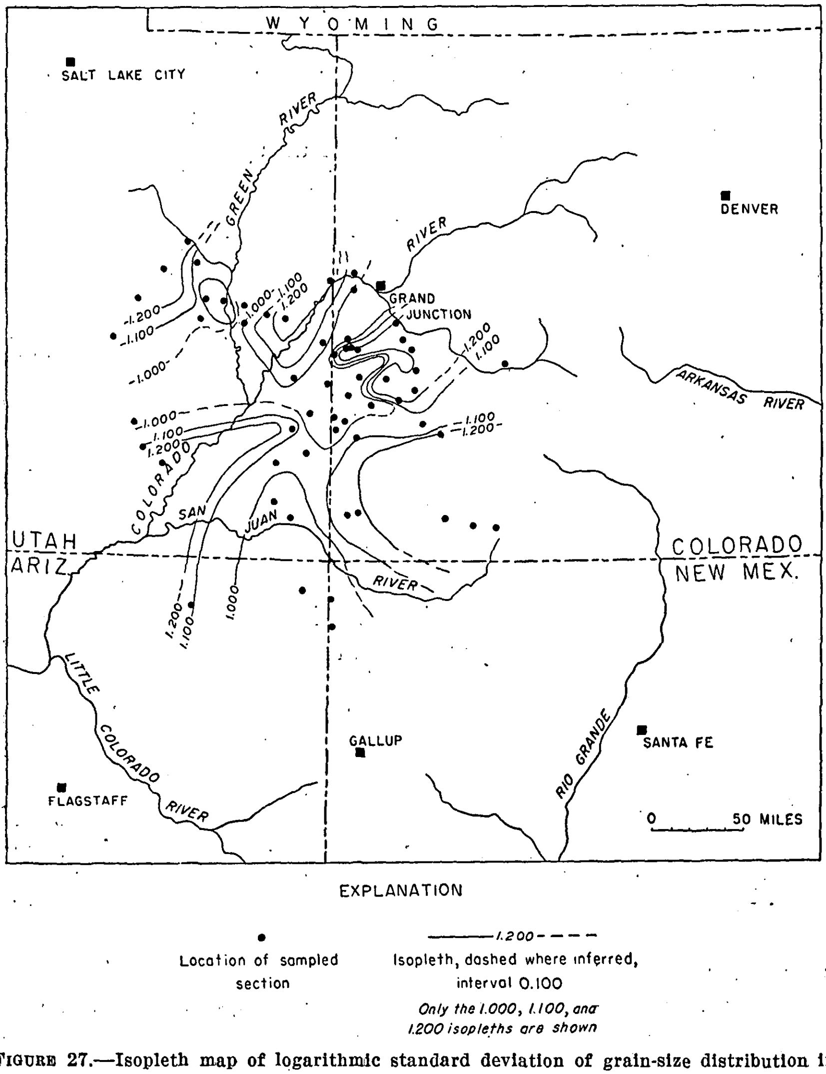


FIGURE 27.—Isopleth map of logarithmic standard deviation of grain-size distribution in sandstones of the Salt Wash member of the Morrison formation.

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 localities on the extreme western edge of the Salt Wash member in central Utah contain large amounts (as much as 86 percent of the detrital fraction) of fresh, angular to rounded, opaline tuff. The grains are much less weathered and show less sphericity than the silicified tuff and chert characteristic of the Salt Wash to the east and suggest 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, but is present in almost all samples from west of the Colorado-Utah border. Owing to the high specific gravity of garnet and the 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.

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 member 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 formation.

Two major source areas are indicated by the facies and isopachous maps of the lower part of the Morrison formation. One major source area was southwest of south-central Utah, probably in west-central Arizona and southeastern California. It furnished most of the sediments comprising the Salt Wash member. The other major source area was south of Gallup, probably in west-central New Mexico. It furnished most of the sediments comprising the Recapture member. The mineralogy of the members of the lower part of the 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 an area of preexisting 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 distribution of opaline tuff, 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 formation 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 floodplain-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 areas 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 locality to another, the spread of the lower part of the 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 as 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. 21, 23, 24, 25) show similar fan-shaped patterns. The sedimentary structure orientations (fig. 26) show a pattern of drainage directions which diverges northward and eastward from the apex of the Salt Wash fan in south-central Utah. During the time of Salt Wash deposition, streams probably formed an aggrading distributary system of braided channels which changed position on the fan by lateral migration.

The distribution of facies (fig. 21) and the distribution of the stream-deposit thickness relative to floodplain-deposit thickness (fig. 24) 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. 21) 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 could have resulted from evaporation, absorption by the sediments, or from subdivision of streams to form successively smaller distributaries outward across the surface of the fan. The thick Salt Wash member (fig. 21) at the apex of the fan is thought to represent an accumulation of sediments near the source area. 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 locally impinged on, beveled, and reworked the sands of the upper part of the Bluff and Junction Creek sandstones, and only relatively 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 area unrelated to the major source area of the Salt Wash.

The isopachous and isolith maps of the Recapture member (figs. 22–25) do not show as prominent a fan-shaped pattern as do the maps of the Salt Wash member. However, the facies distribution (fig. 22) 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 result from differential subsidence. During Recapture deposition, streams probably formed an aggrading distributary system of braided channels similar to the streams on the fan of the Salt Wash.

The climate during deposition of the lower part of the Morrison is difficult to define with much certainty from evidence in the rocks. A semiarid climate is suggested by the preservation of sand dunes in the Recapture member in northeastern Arizona. Stokes [3] has reported remains of thorny plants from the Salt Wash member of east-central Utah, a discovery which supports the concept of semiaridity. 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 fan of the Salt Wash than away from it. This distribution may reflect a greater abundance of vegetation in this area resulting from a slightly higher elevation than the rest of the fan 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 formation consists of the Westwater Canyon member and the Brushy Basin member. The West-

[3] Stokes, W. L., 1945, unpublished U. S. Geol. Survey report.

water Canyon member constitutes the lower unit of the upper part of the Morrison in the southern part of the region of study. The Brushy Basin member is present over most of the region of study (fig. 20).

REGIONAL STRATIGRAPHY

Westwater Canyon member.—The Westwater Canyon member (Gregory, 1938, p. 59) is present over a part of northeastern Arizona and northwestern New Mexico (fig. 28). To the north the Westwater Canyon intertongues with and grades into the lower part of the Brushy Basin 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 part of the Morrison preserved. The Westwater Canyon and equivalent beds thin 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 eastern limit of the Westwater Canyon in north-central New Mexico is not yet known.

The recognition of the Westwater Canyon member as a distinct lithologic unit through much of northeastern Arizona (Harshbarger, Repenning, and Jackson, 1951, p. 98) and northwestern New Mexico constitutes an appreciable areal extension of the member beyond its previously known limits.

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 deeply channeled scour surfaces at their base. South and west of Gallup in a narrow belt along the margin of the member the scour-fill sandstones are replaced gradually by sandstone strata that exhibit sweeping, wedging, cross-lamination and lack the scour-fill characters. These sandstones constitute the uppermost part of the Cow Springs sandstone (Harshbarger, Repenning, and Jackson, 1951, p. 97–98). The claystone strata of the Westwater Canyon member consist of light-greenish-gray or pale-red to grayish-red, variably silty and sandy claystone and have a gently lensing subparallel bedding similar to that observed in the claystone strata of the Salt Wash member. The sandstones of the Westwater Canyon member are more resistant than those of the underlying Recapture member and form nearly vertical cliffs or very steep

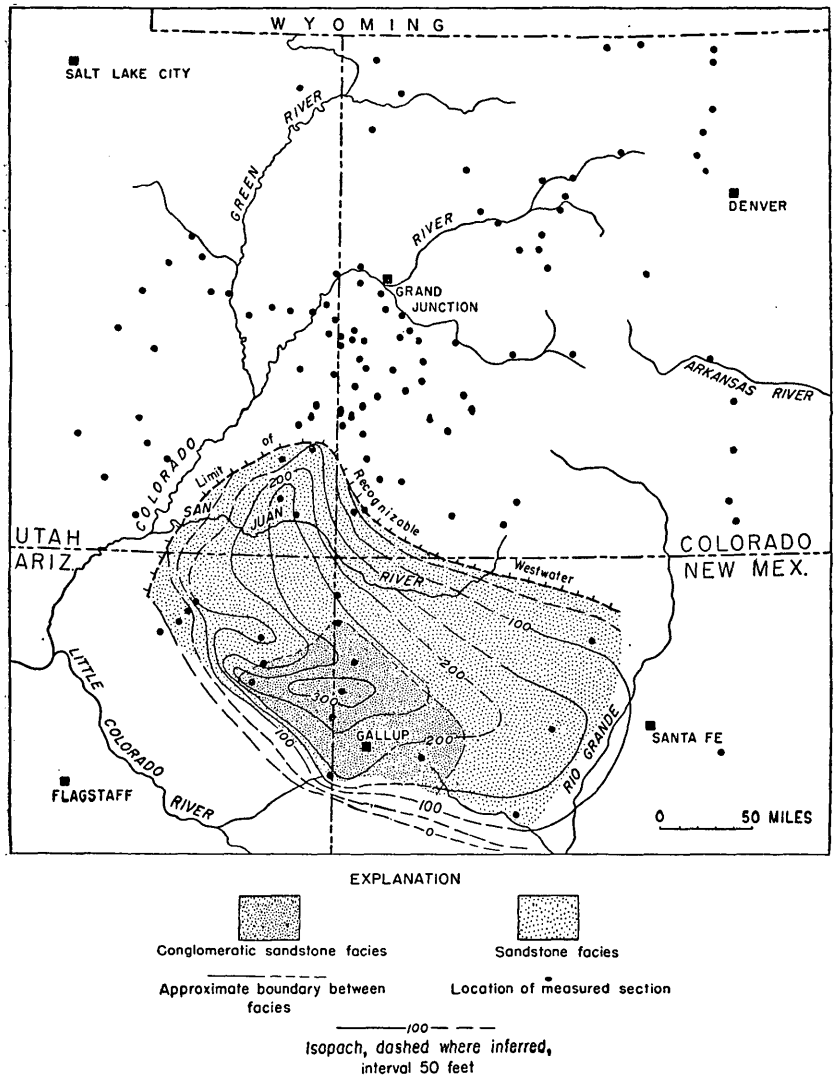


FIGURE 28.—Isopachous and facies map of the Westwater Canyon member of the Morrison formation.

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. 28), mainly based on textural differences. A conglomeratic sandstone facies 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 percent of claystone (10–40) than does the conglomeratic sandstone facies (5–20).

The Westwater Canyon member forms an arcuate belt of relatively thick sedimentary rocks extending from northwestern New Mexico through the northeastern corner Arizona into southeastern Utah (fig. 28). A maximum thickness of 330 feet was measured 30 miles north of Gallup, N. Mex. Studies of the orientation of sedimentary structures and sedimentological analyses of the Westwater Canyon member are incomplete.

Brushy Basin member.—The Brushy Basin member (Gregory, 1938, p. 59) is present in western Colorado, eastern Utah, northern New Mexico, and part of northeastern Arizona (fig. 29). To the south-

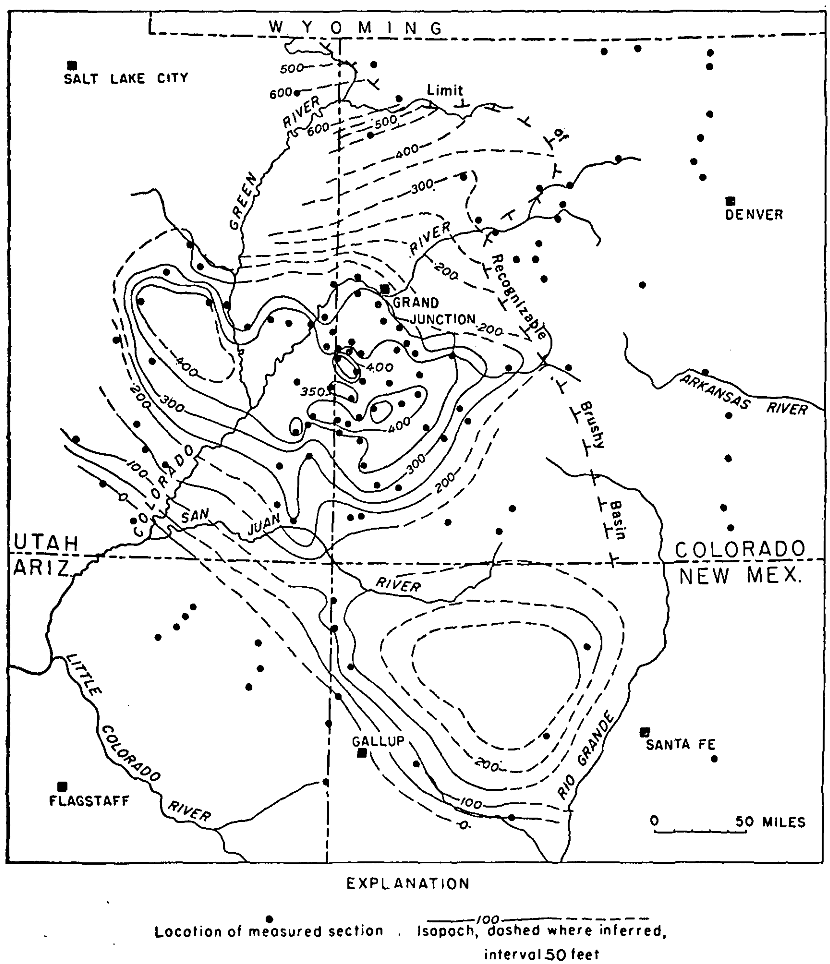


FIGURE 29.—Isopachous map of the Brushy Basin member of the Morrison formation.

west it has been removed by post-Morrison erosion, leaving only the partly equivalent Westwater Canyon member. The eastern and northeastern boundary is an arbitrary line drawn where the Salt Wash member loses its identity and cannot be distinguished from the upper part of the Morrison formation. East of this arbitrary line the Morrison is not differentiated into members.

The Brushy Basin member is composed predominantly 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 more than several hundred feet wide, and pinch out laterally in the main mass of claystone. A few thin-bedded, discontinuous beds of limestone 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 base of the Brushy Basin member 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 member is used as the contact between the Brushy Basin and the underlying Salt Wash member.

Distinct facies with limited areal distribution have not been recognized in the Brushy Basin member, for the lithologic components show no regularity. Colors of red, purple, and gray predominate in northeastern Utah and western Colorado and light greenish gray and pink predominate in southeastern Utah, northeastern Arizona, and northwestern New Mexico.

Petrified dinosaur bones and wood are common in the Brushy Basin member. Other fossils are rare; fresh water gastropods and algae have been found at only a few localities.

The thickness of the Brushy Basin member varies considerably over the Plateau (fig. 29). More than 600 feet of Brushy Basin has been measured at Vernal, Utah. In southwestern Colorado 450 feet of Brushy Basin has been measured; in 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 formation form two relatively distinct groups of sedimentary rocks. The facies distribution of the Westwater Canyon member (fig. 28) 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 as the source an area of preexisting sedimentary, igneous, and metamorphic rocks. The source area of the Brushy Basin member 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 member suggests that the Brushy Basin may have been derived from essentially the same source area as the Salt Wash. Similar conglomeratic sandstone higher in the Brushy Basin may also have had the same source area. The area of thick Brushy Basin in northeastern Utah may reflect a source area to the north or northwest, but the conglomeratic sandstones in that area have lithologic similarities to those to the south. The prevalence of chert pebbles and the almost complete absence of other varieties suggest that at least the sandstones were derived mainly from a source area of sedimentary rocks.

Structures and textures in the Westwater Canyon member and in the sandstones of the Brushy Basin member indicate that they were deposited in a fluvial environment. Much of the bentonitic clay of the Brushy Basin accumulated from falls of volcanic ash. 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. 28) indicates that it formed as a broad fan-shaped alluvial plain or "fan" similar to that of the Recapture member. 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 of the source area, in west-central New Mexico. As the source area was reduced and ceased furnishing coarse material, Brushy Basin sediments were spread southward over the area of deposition of the Westwater. The original southern limit 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. 29).

Greater abundance of fossil plant and dinosaur remains suggests that the climate was more humid during deposition of the upper part of the Morrison formation than during deposition of the lower part of the Morrison. In contrast to the Recapture member, the Westwater Canyon member contains much less extensive windblown deposits in northeastern Arizona. This may also support a concept of increased humidity during late Morrison time.

UNDIFFERENTIATED MORRISON OF COLORADO

REGIONAL STRATIGRAPHY

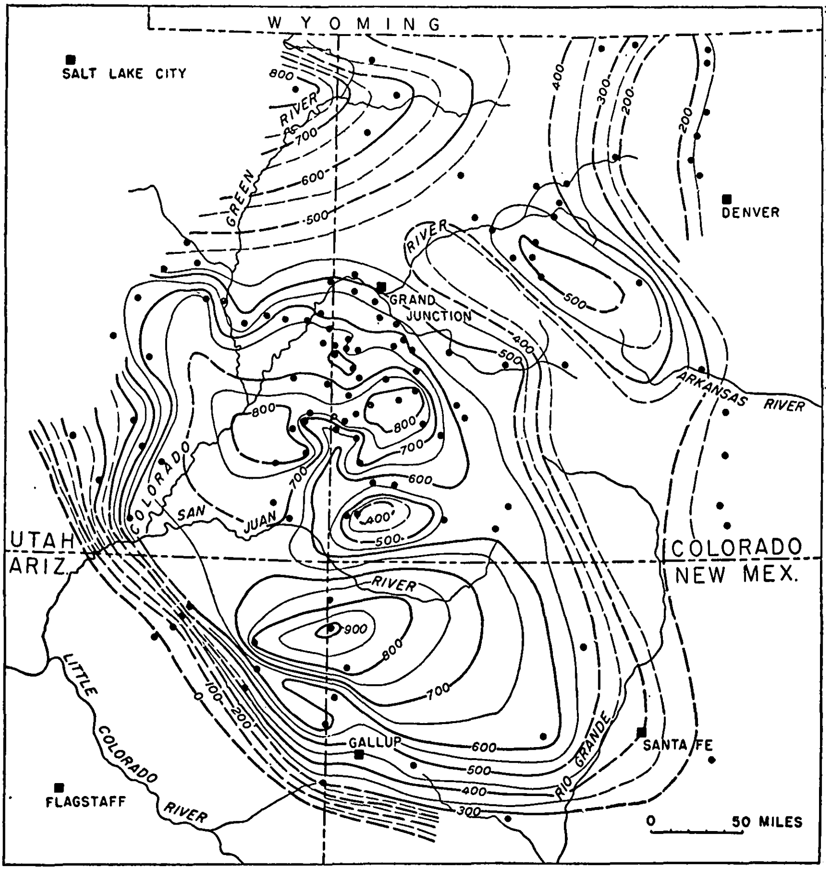
The Morrison formation has not been separated into members east and north of the arbitrary line marking the limits of recognizable Salt Wash member. Lithologic units do not have sufficient continuity in central and eastern Colorado to warrant member status. The area of undifferentiated Morrison includes all 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 included an upper sandstone and shale unit that is now assigned to the Lower Cretaceous and excluded a basal sandstone now assigned to the basal part of the Morrison. The beds near Morrison form a typical section of undifferentiated Morrison formation. At the new type section, described by Waldschmidt and LeRoy (1944, p. 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 formation can be divided roughly into three units: a lower unit of thin-bedded gray shale and limestone with charophyte oögonia and ostracods, a medial unit of crossbedded sandstone and conglomerate with dinosaurian remains, and an upper unit of variegated shale. Overlying the variegated shale unit are sandstones and conglomerates of Early Cretaceous age.

West of the type section, in the central Colorado basin the Morrison formation consists of claystone beds with thin intercalated limestone and sandstone beds. Dense limestones are abundant in the basal part of the Morrison in this area, but these are lenticular and cannot be individually correlated from section to section. The ancestral Uncompahgre uplift, which has a northwesterly trending axis through Gunnison, Colo., may have served as a barrier, retarding the easterly flowing streams during Salt Wash deposition so that only the finer sediments were carried eastward across the highland into the central basin. The Morrison thins appreciably over the crest of this uplift (fig. 30).

The isopachous map of the Morrison formation of the Colorado Plateau region (fig. 30) shows the combined thickness of the separate



EXPLANATION

• Location of measured section

——500—— — — Isopach, dashed where inferred, interval 50 feet

FIGURE 30.—Isopachous map of the Morrison formation.

members of the "western" differentiated Morrison; the thickness variations of the western part of the map are, in some areas, known to result from more than one factor. In central and eastern Colorado, the map shows thickness of the undifferentiated Morrison; here, variations may be the result of a complex history, which cannot be interpreted because distinctive units in one area cannot be recognized in others.

INTERPRETATION

The undifferentiated Morrison formation is lithologically similar to the Brushy Basin member of the "western" Morrison and the depositional environment is 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, recording falls of volcanic ash. The main source areas of the undifferentiated Morrison were probably to the south and to the west, the same source areas as those of the members of the "western" Morrison.

POST-MORRISON FORMATIONS

LOWER CRETACEOUS FORMATIONS

Lower Cretaceous beds 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 the Dakota sandstone, depending on the basis of their characteristics and affinities in different areas. In southeastern Colorado and northeastern New Mexico the Purgatoire formation separates the Morrison and Dakota. In north-central Colorado, beds usually called Dakota probably contain equivalents of the Lower Cretaceous Cloverly formation of 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 Early Cretaceous age. In central Utah the Cedar Mountain formation of Stokes (1944, p. 965) forms a widespread Lower Cretaceous unit. These formations are composed of interstratified conglomeratic sandstone and variegated claystone in varying proportions and sequence. The basal contact is conspicuous only in those areas where basal channel sandstones are present. Where these are absent it is exceedingly difficult or impossible to differentiate the variegated shales of the Lower Cretaceous 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 strata. 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, gray carbonaceous shale, and coal. These reflect deposition in alternating stream and swamp environments. The Late 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 Early Cretaceous in age (unpublished thesis by

P. J. Katich, 1951, Ohio State University). Throughout western Colorado and eastern and central Utah the Dakota sandstone is separated from underlying Lower Cretaceous formations by an erosional disconformity, but in New Mexico and northeastern Arizona pre-Dakota warping and subsequent erosion have 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. Consequently the Dakota sandstone progressively overlies older and older formations to the south and west.

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 MORRISON STRATIGRAPHY

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 during the regional studies as well as during a number of detailed studies in the vicinity of ore deposits. Many of the results are negative but are of value in that some lines of research can be eliminated.

The distribution of major groups of carnotite deposits is shown in figure 31. Most of the carnotite deposits of the Morrison formation are confined to the Salt Wash member. The carnotite deposits of the Salt Wash member lie almost entirely within the sandstone and mudstone facies (fig. 21); most are in areas where the Salt Wash member is more than 240 feet thick (fig. 21). The lithofacies studies show that most of the carnotite deposits are in areas where the stream deposits (essentially the channel sandstones) constitute from 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 from 90 to 200 feet (fig. 23); and that most of the carnotite deposits are in areas where the thickness of the stream deposits shows a percentage mean deviation of from 5 to 18 percent.

These observations suggest that an area of relative favorability for ore localization may be defined (fig. 31) within the area of the sandstone and mudstone facies (fig. 21). It is generally agreed that most of the ore was introduced by mineral-bearing solutions that percolated through the more permeable layers at sometime after the accumulation

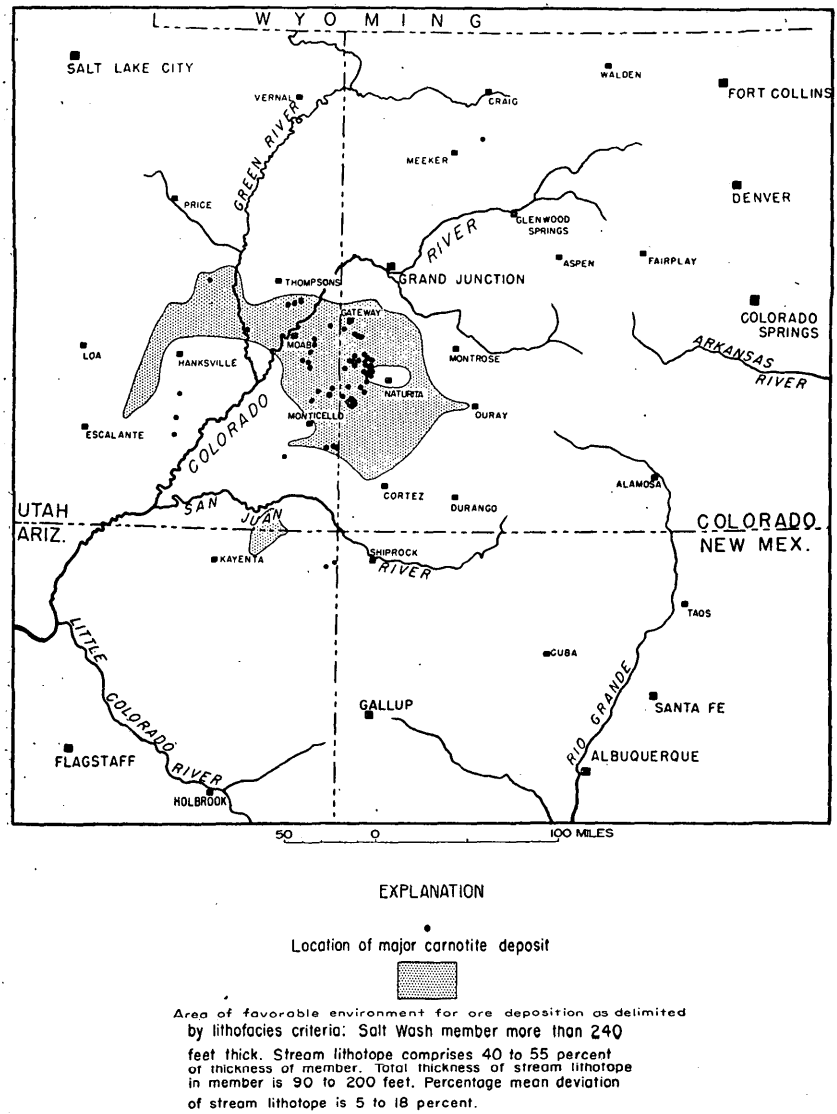


FIGURE 31.—Map showing the location of major carnotite deposits in the Salt Wash member of the Morrison formation and the areas of favorable environment for ore deposition, as delimited by lithofacies criteria.

of the sediments. 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 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 stream-deposited sandstone beds, which are mostly discontinuous. Within the area of the sandstone and mudstone facies, the Salt Wash must have had intermediate properties as an aquifer. If ore-bearing solutions were introduced prior to regional deformation, they 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 could have occurred within the sandstone and mudstone facies.

The petrography of the Salt Wash member of the Morrison formation shows no detailed or regional relation between ore deposits and the heavy-mineral distribution or between any of the parameters of grain-size distribution except the sorting as measured by the logarithmic standard deviation (fig. 27). Most of the carnotite deposits occur in areas where the sandstones of the Salt Wash 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 member 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 member with the ore deposits has been studied and summarized by Weir (1952). The variations of the Salt Wash in the vicinity of the Uravan mineral belt (Fischer and Hilpert, 1952), "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 McKay.[4] The parallel orientation of the long axes of ore "rolls" with the elongation of ore deposits and the orientation of fossil logs has been noted by 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

[4] McKay, E. J., 1955, Large-scale geologic guides to carnotite deposits in the Uravan and Gateway districts, Montrose and Mesa Counties, Colorado: U. S. Geol. Survey Bull. 1009J (in press).

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. 26) 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.

Three possible distinct sources of the uranium in the carnotite deposits may be postulated: the sedimentary rocks of the source area of the Salt Wash member; a post-Salt Wash hydrothermal source in the Colorado Plateau region; or post-Salt Wash sedimentary rocks, possibly tuffaceous beds, either in the immediate vicinity of or away from the present ore deposits. The stratigraphic studies of the Morrison formation have furnished little evidence for determining the most probable original source.

The pre-Morrison sedimentary rocks have been entirely removed from the probable area of the major source of the Salt Wash member of the Morrison formation in west-central Arizona and evidence for pre-existing uranium deposits in these rocks is lacking. Evidence for the origin of such 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 [5] [6]). 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 probable source area of the Salt Wash. Both the upper Paleozoic Kaibab and Madison limestones of Utah have "strong traces" of uranium (Webber [7], 1947, p. 234) and might have formed a low-grade source of the uranium concentrated in the Salt Wash. Argall (1943, p. 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. In Wyoming and Idaho this formation contains low percentages of uranium and might have yielded uranium that, 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. 26). Such migration seems im-

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

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

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

probable unless a regional tilting to the southeast forced ground-water movement across the structures. Evidence for this postulated 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.

Much field evidence has been cited as supporting a hydrothermal origin of the carnotite deposits of the Morrison formation. Much of this evidence is inconclusive. Perhaps the greatest support to the hypothesis rests in age determinations (Stieff, Stern, and Milkey, 1953) that indicate the uranium was emplaced at about the beginning of the Tertiary.

Migration of uranium into the Morrison from minerals disseminated in overlying sediments, particularly tuffaceous clays, is possible. However, it appears unlikely: first, because these overlying beds are quite impervious, and second, because they generally do not seem to contain more metal than is normal in a sedimentary rock.

Regardless of the source of the carnotite deposits of the Colorado Plateau region, mineral-bearing solutions must have migrated laterally through the sandstone beds to emplace most, if not all, deposits. The migration of these solutions through the Morrison formation and the emplacement of the deposits were undoubtedly affected by the orientation and character of the sedimentary structures and the facies variations of the Salt Wash member. These stratigraphic features serve to focus attention on broad areas favorable for carnotite deposits and may serve to provide expectable orientations of the ore bodies within the Salt Wash member.

LITERATURE CITED

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

Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., 1936, Correlation of Jurassic formations of parts 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: Am. Assoc. Petroleum Geologists Bull., v. 31, p. 1664–1668.

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

Cross, Whitman, 1894, Description of the Pikes Peak sheet: U. S. Geol. Survey Geol. Atlas, folio 7.

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

Emons, 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.

Fischer, R. P., and Hilpert, L. S., 1952, The Uravan mineral belt: U. S. Geol. Survey Bull. 988–A.

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.

Goddard, E. N., and others, 1948, Rock-color chart: National Research Council.

Goldman, M. I., and Spencer, A. C., 1941, Correlation of Cross' La Plata sandstone, southwestern Colorado: Am. Assoc. Petroleum Geologists Bull., v. 25, p. 1745–1767.

Gregory, H. E., 1938, the San Juan Country: U. S. Geol. Survey Prof. Paper 188, p. 58–59.

Gregory, H. E., 1951, The geology and geography of the Paunsaugunt region, Utah: U. S. Geol. Survey Prof. Paper 226.

Harshbarger, J. W., Repenning, C. A., and Jackson, R. L., 1951, Jurassic stratigraphy of the Navajo country: New Mexico Geol. Society Guidebook of the San Juan Basin, New Mexico and Arizona, p. 95–99.

Kiersch, G. A., 1950, Small scale structures and other features of Navajo sandstone, northern part of the San Rafael Swell, Utah: Amer. Assoc. Petroleum Geologists Bull., v. 34, p. 923–942.

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

McKee, E. D., 1939, Some types of bedding in the Colorado River delta: Jour. Geology, v. 47, p. 64–81.

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

Moore, R. C. 1949, Meaning of facies: Geol. Soc. America Mem. 39, p. 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 Inv. Prelim. Map 96.

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

Stieff, L. R., Stern, T. W., and Milkey, R. G., 1953, A preliminary determination of the age of some uranium ores of the Colorado Plateaus by the lead-uranium ratio: U. S. Geol. Survey Circular 271.

Stokes, W. L., 1944, Morrison and related deposits in and adjacent to the Colorado Plateau: Geol. Soc. America Bull., v. 55, p. 951–992.

Stokes, W. L., 1947, Primary lineation in fluvial sandstones: A criterion of current directions: Jour. Geology, v. 55, p. 52–54.

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

Weir, D. B., 1952, Geologic guides to prospecting for carnotite deposits on Colorado Plateau: U. S. Geol. Survey Bull. 988–B.

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