Geologic History of the Slick Rock District and Vicinity, San Miguel and Dolores Counties, Colorado

GEOLOGICAL SURVEY PROFESSIONAL PAPER 576-E

Prepared on behalf of the U.S. Atomic Energy Commission

Geologic History of the Slick Rock District and Vicinity, San Miguel and Dolores Counties, Colorado

By DANIEL R. SHAWE

GEOLOGIC INVESTIGATIONS IN THE SLICK ROCK DISTRICT, SAN MIGUEL AND DOLORES COUNTIES, COLORADO

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A review of the origin of sedimentary rocks and geologic history of the region indicates that formation of uranium-vanadium deposits was a natural result of the deposition of the rocks, the occurrence of intrastratal waters therein, and the postdepositional movement of the waters resulting from evolution of the sedimentary rock environment

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1976

UNITED STATES DEPARTMENT OF THE INTERIOR

THOMAS S. KLEPPE, *Secretary*

GEOLOGICAL SURVEY

V. E. McKelvey, *Director*

Library of Congress Cataloging in Publication Data
Shawe, Daniel R. 1925-
Geologic history of the Slick Rock district and vicinity, San Miguel and Dolores Counties, Colorado.
(Geologic investigations in the Slick Rock District, San Miguel and Dolores Counties, Colorado) (Geological Survey Professional Paper 576-E)
Bibliography: p.
Supt. of Docs. no.: I 19.16:576-E
1. Geology—Colorado—San Miguel Co. 2. Geology—Colorado—Dolores Co.
I. United States. Atomic Energy Commission. II. Title. III. Series. IV. Series: United States Geological Survey Professional Paper 576-E.
QE75.P9 no. 576-E [QE92.S35] 557.3'08s [557.88'23] 76-608133

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402
Stock Number 024-001-02830-1

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GEOLOGIC HISTORY OF THE SLICK ROCK DISTRICT AND VICINITY, SAN MIGUEL AND DOLORES COUNTIES, COLORADO

By Daniel R. Shawe

ABSTRACT

At the close of Precambrian time in the region surrounding the Slick Rock district, basement gneisses and schists had been beveled by erosion and were being downwarped along a north-trending axis farther west to receive the basal sediments of the great Cordilleran geosyncline. Coarse clastic sediments of Cambrian age were the first sediments to be deposited in the vicinity of Slick Rock. Sediments then became finer grained upward, and deposition ceased in Ordovician and Silurian time, the hiatus indicating stability of the low land masses east and southeast of the district.

During Devonian and Mississippian time the region lay on the shelf of the Cordilleran geosyncline on which miogeosynclinal sediments were being deposited. Mild northwest-trending folds were formed on the shelf coincident with the extreme deformation that occurred during the Antler orogeny in the region of the present Great Basin to the west. Temporary emergence occurred in Late Mississippian time.

In Pennsylvanian time the northwest-trending Paradox Basin formed on the shelf as a result of depression of a graben and rise of adjacent land along faults bounding the Uncompahgre uplift northeast of the district and underlying Disappointment Valley in the district. Development of the basin coincided with reactivation of a Precambrian-age northeast-trending structure at the southeast end of the basin—the Glade subsurface zone of faults. Northwest-oriented folding continued during the Middle Pennsylvanian in the Paradox Basin as stagnant marine sediments, including thick evaporites, were deposited.

In the middle part of Permian time the Uncompahgre uplift rose rapidly, shedding coarse clastic debris westward. This event coincided with renewed movement on the Glade subsurface fault zone and with pronounced flow of salt into the salt anticlines. Deposition of thick Permian sediments, some subaerially, displaced the border of the Cordilleran geosyncline westward.

During Early and Middle Triassic time, sediments were deposited in the Paradox Basin, were folded, and were then eroded upon emergence. Middle Pennsylvanian to Early Triassic deformation in and around the Slick Rock district coincided with tectonism of the Sonoma orogeny occurring in the region of the present Great Basin.

In Late Triassic time a depositional basin formed, centered in southern Utah and northern Arizona, in which continental fluvial and lacustrine sediments were laid down. Provenance was sedimentary and granitic rocks lying east, southeast, and south, and possibly a newly emergent volcanic island arc to the west.

Jurassic and Early Cretaceous deposition, mostly terrestrial and some marginal marine, took place in a basin centered variously in the region extending from southern Nevada to eastern Utah. Sources of sediment were toward the east, but they shifted to the west with emergence, during the Late Jurassic, of land in the general region of volcanic centers to the west, and then shifted to the south in the Early Cretaceous. Also during Late Jurassic time, mild renewal of Paradox Basin deepening modified the deposition of the Salt Wash Member of the Morrison Formation in the region of the Uravan mineral belt which extends northward from Slick Rock, resulting in development of lithologies favorable to later deposition of uranium-vanadium ores. Abundant carbonaceous plant material, preserved where sediments lay below a water table, afforded the critical reducing environment necessary for later formation of the ores.

In Late Cretaceous time a large seaway encroached northward from Mexico onto the continent—marine black shale was deposited in this geosyncline. Pronounced deepening of the seaway coincided with strong tectonism on both sides of the seaway: the Sevier orogeny to the west in the region of the present Great Basin during most of the Cretaceous, and the Laramide orogeny to the east in the region of the present Rocky Mountains in latest Cretaceous time. Volcanic sources to the west, in addition to the eroding lands both east and west, continued to supply debris to the region of the Colorado Plateau in Late Cretaceous time.

It seems likely that marine black shale (Mancos Shale) of Late Cretaceous age shortly after deposition contained a large volume of saline, reducing, carbonated, and slightly alkaline water that carried complex ions of uranium and vanadium. Upon deposition of overlying thick, largely terrestrial strata of latest Cretaceous and Eocene (Mesaverde, Wasatch, and Green River Formations), much of the pore water of the black shale was driven out by compaction into overlying formations and along zones of faults into underlying formations. Wide-scale epigenetic alteration accompanied passage of the water, and where the solutions moving in and near the zones of faults encountered carbonaceous strata in the Salt Wash Member, uranium-vanadium deposits were formed.

Igneous activity occurred during the early to middle Tertiary at scattered laccolithic centers on the Colorado Plateau, and large sills of igneous rock were emplaced during the middle Tertiary, mostly in Pennsylvanian sedimentary strata near the eastern border of the plateau.

General uplift of the Colorado Plateau took place in the middle Tertiary. Extensive erosion since then has exposed some of the previously deeply buried ore deposits.

Salt anticlines in and near the Slick Rock district whose growth was initiated tectonically almost at the time of deposition of the salt in Pennsylvanian time grew mostly by buoyancy from the Jurassic onward, and this growth has continued to the present.

Pleistocene and Holocene glacial, glacial-outwash, windblown, mass-wasting, and fluvial deposits are scattered throughout the district and surrounding region.

INTRODUCTION

This report is a narrative summary and interpretation, in the form of a geologic history of the Slick Rock district and vicinity, of four previously published chapters in this series dealing with stratigraphy of the Slick Rock district and vicinity (Shawe and others, 1968), petrography of sedimentary rocks of the district (Shawe, 1968a), structure of the district and vicinity (Shawe, 1970), and altered sedimentary rocks of the district (Shawe, 1976) and of other previously published reports on the district. It forms the background, with the earlier reports, for presentation of a final report in the series describing the uranium-vanadium ore deposits. A broad knowledge of the regional geologic history—the evolution of specific lithologic environments and the geologic processes that affected the rocks—is essential to an understanding of the origin and genesis of uranium-vanadium ores in sedimentary strata of the Colorado Plateau.

Details of the geology of the Slick Rock district have been given in the earlier chapters, but some general information will be reviewed briefly here. The location of the Slick Rock district in its regional setting is shown in figure 1. A generalized geologic map of the district is presented in figure 2. The consolidated sedimentary rocks in the district are briefly summarized in table 1. Familiarity with much of the detailed information reported previously will not be required for a comprehension of this report; the reader wishing documentation on which the inferences and conclusions of this report are based should refer to the earlier reports.

The geologic history encompasses a discussion of successive rock units, from Precambrian basement rocks through Quaternary surficial deposits.

PRECAMBRIAN ROCKS AND EVENTS

Little is known of the Precambrian history of the region that surrounds the Slick Rock district. Northeasterly alined geophysical discontinuities underlying the Blanding basin, Utah, west of Slick Rock (Case and Joesting, 1961, p. D287-D291 and figs. 393.1, 393.2), suggest that Precambrian basement rocks contain a northeast-trending structural zone formed in Precambrian time before sedimentary rocks of Cambrian and younger age were deposited. This zone, termed the "Glade subsurface fault zone" by Shawe (1970, p. C2), passes beneath the south end of the Slick Rock district. It was a zone of significant deformation at times during the Paleozoic Era and throughout the Mesozoic Era. At the beginning of the Paleozoic Era, in the region surrounding the Slick Rock district, Precambrian igneous and metamorphic basement rocks were eroded to a nearly flat plain before sedimentary rocks were deposited. This Precambrian detritus probably was transported westward into the region of the present Great Basin where it contributed to the thick upper Precambrian clastic sequence that was filling the newly forming Cordilleran geosyncline.

CAMBRIAN ROCKS AND EVENTS

Basal Cambrian rocks in the region are conglomeratic arkose deposited on weathered granitic Precambrian rocks; this relationship probably indicates that the base-leveled, subaerially weathered Precambrian rocks were gradually tilted and so parts of the region were lowered beneath the sea and were covered by coarse debris swept out from a nearby source area—the ancestral Zuni and Uncompahgre highlands south and east of the district. Hematite stain in the sediments just above the Precambrian indicates that initially the sediments probably were laid down subaerially when some oxidation and redistribution of iron took place, or that, if deposited in water, the sediments later emerged and were oxidized. As indicated by southeastward thinning of the Cambrian rocks, tilting of the coastal plain was toward the northwest, and the source of the sediments lay to the southeast. The coarseness and freshness of the detritus suggest that the highlands adjacent to the region around the Slick Rock district tended to rise while that region subsided. The next higher Cambrian rocks in the region, however, were less coarse and include some shale, indicating that the source areas had become more stable and were being more deeply weathered, thus providing a greater proportion of argillaceous debris. Of course, distance from source, mode of transport, and environment of deposition may have been important factors in determining the nature of the deposited sediment, but these factors cannot be well evaluated on present knowledge. Interlayered fine- to coarse-grained marine sandstone and conglomerate, shale, and dolomite above the basal arenaceous rocks in the region suggest a period of alternating uplift and quiescence of the adjacent highlands. During uplift coarse clastic material flooded the coastal plain in the region; during intervening periods of quiescence deep chemical weathering of the highlands probably took place and fine clastic and chemical sediments were deposited in the region. The dominance of shale, siltstone, and dolomite and the lesser amounts of sandstone in younger Cambrian rocks suggest that the highlands were less frequently uplifted during the later stages of the episode of denudation and nearby sedimentation, and the reddish colors of parts of these sediments suggest that deposition was partly subaerial or was in oxygenated tidal or mudflats marginal to the sea.

Deposition of Cambrian rocks in the region surrounding the Slick Rock district signifies eastward expansion of the Cordilleran miogeosyncline.

The advent of argillaceous sediments in the region near the end of the Cambrian indicates tectonic stabilization of the region. During the Ordovician and Silurian Periods either the region must have remained stable and no rocks

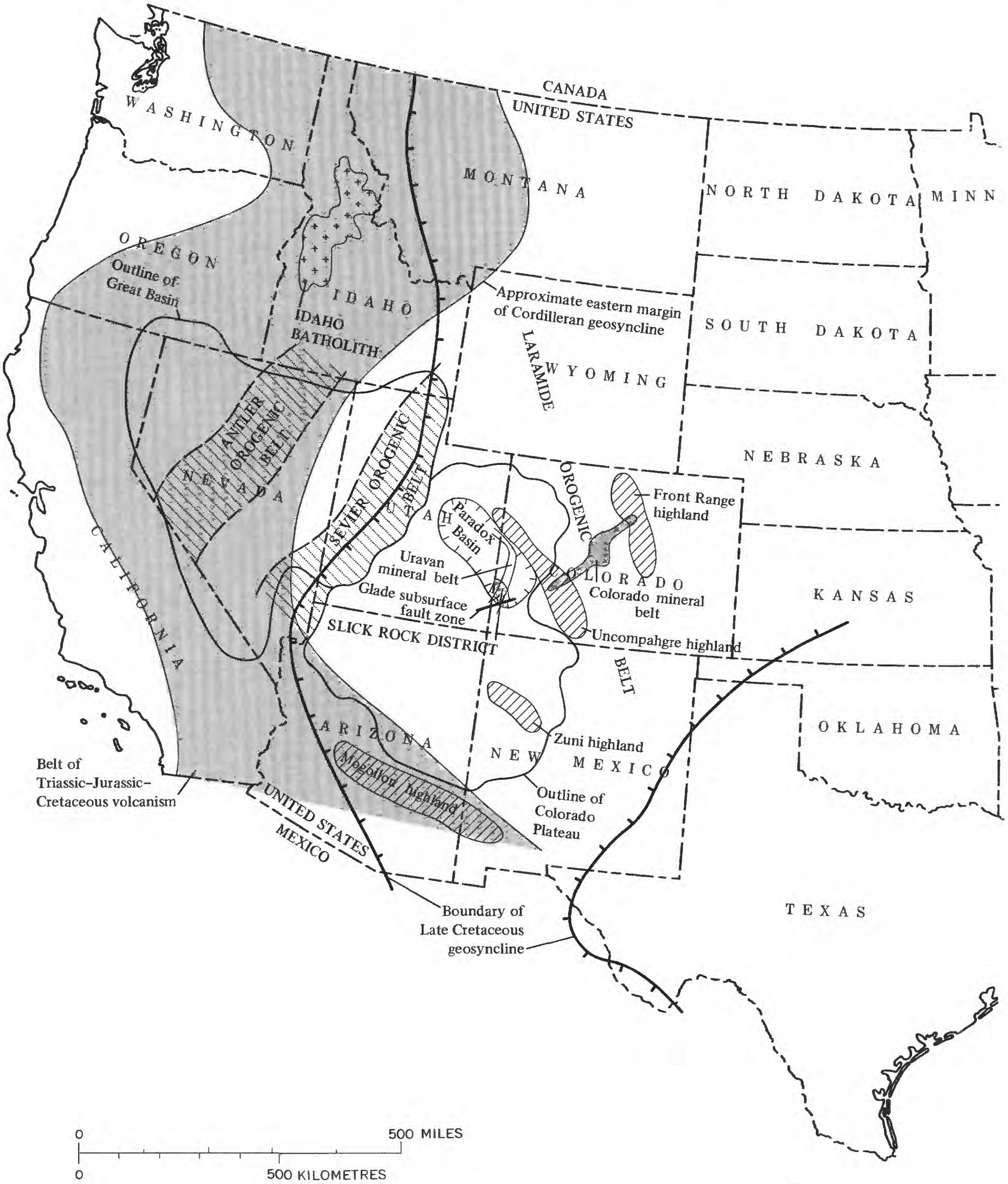

FIGURE 1.—Location of the Slick Rock district, and major tectonic elements in the Western United States referred to in the text.

of these periods were deposited in the region or the thin sediments that were laid down were swept away before younger sediments could bury them.

DEVONIAN ROCKS AND EVENTS

Marine inundation in the Devonian Period resulted in the deposition of several hundred feet of argillaceous, clastic, and carbonate sediments of Late Devonian age. The source areas to the east and south remained stable relative to the marine basin, as judged from the high proportion of chemical precipitates among these rocks. Mild downwarping of the region was accompanied by low-amplitude folding along northwest-trending axes. This folding foreshadowed the development of the

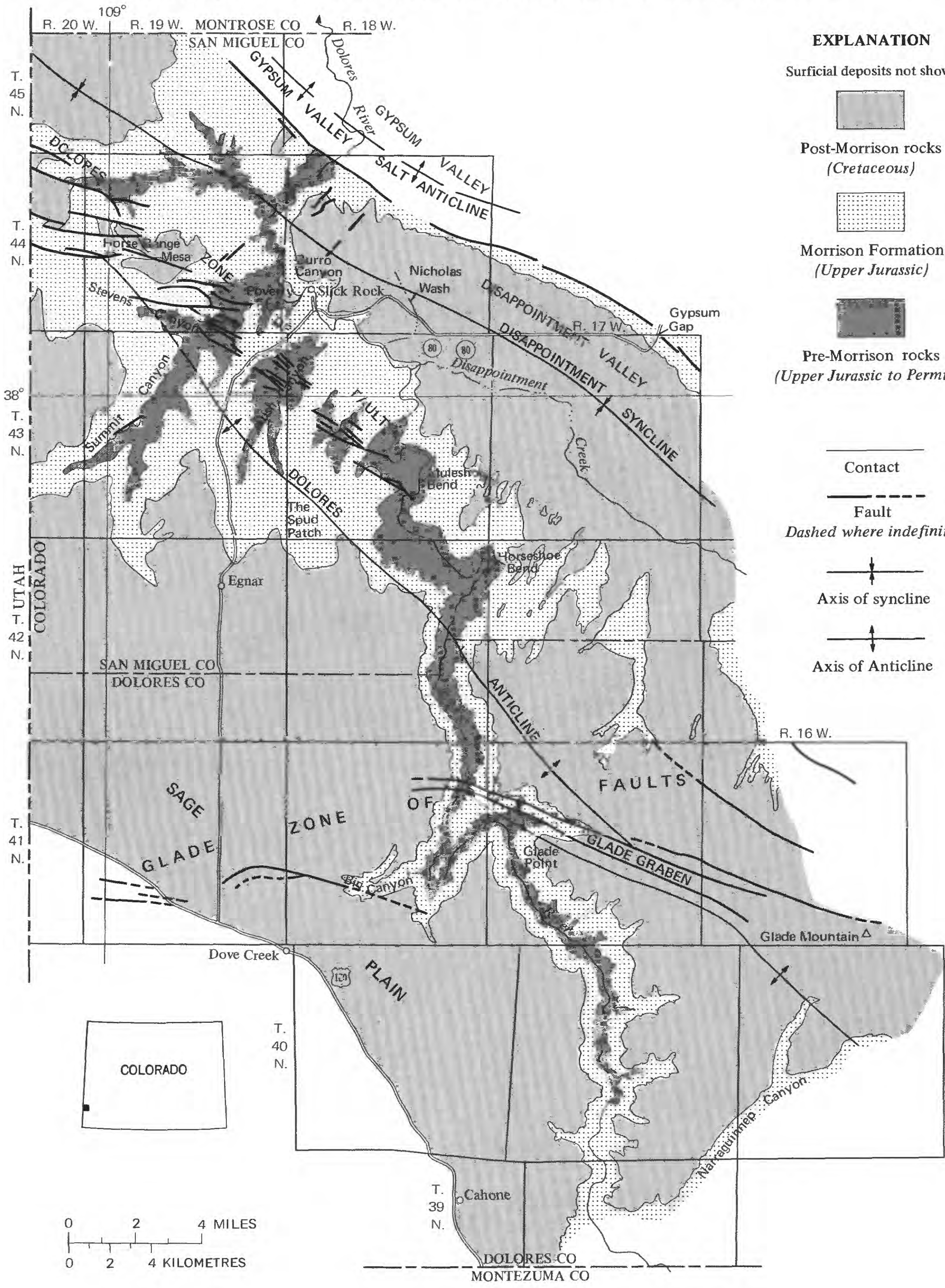

Figure 2.—Generalized geologic map of the Slick Rock district.

TABLE 1.—*Generalized section of consolidated sedimentary rocks*

Age	Formation and member		Thickness (feet)	Description
Late Cretaceous	Mancos Shale		1,600-2, 300	Dark-gray carbonaceous calcareous marine mudstone and minor amounts of gray limestone, greenish-gray bentonitic shale, and light-buff sandstone. Contains abundant invertebrate fossils.
Late Cretaceous	Dakota Sandstone		120-180	Light-buff fine-grained quartzose marginal marine and fluvial sandstone, dark-gray carbonaceous shale, coal, and, locally, light-buff conglomeratic sandstone.
	Unconformity			
Early Cretaceous	Burro Canyon Formation		40-400	Light-gray to light-buff fine-grained to conglomeratic quartzose fluvial sandstone, greenish-gray flood-plain shale and siltstone, and greenish-gray to gray lacustrine(?) limestone and chert.
Late Jurassic	Morrison Formation	Bushy Basin Member	300-700	Predominantly reddish-brown and greenish-gray bentonitic flood-plain mudstone and some light-reddish-brown, light-buff, and light-greenish-gray fluvial siltstone, sandstone, and conglomerate.
Late Jurassic	Morrison Formation	Salt Wash Member	275-400	Light-reddish-brown, light-buff, and light-gray quartzose fluvial sandstone and reddish-brown flood-plain mudstone. Sandstone lenses in top part are dominantly light buff or light gray and contain abundant carbonaceous plant material; lenses in lower part are mainly light reddish brown and contain sparse carbonaceous material.
Late Jurassic	Junction Creek Sandstone		20-150	Light-buff fine-grained quartzose sandstone with sweeping eolian crossbeds at south end of district. Changes northward to light-reddish-brown fine-grained tidal-flat(?) sandstone with horizontal beds; merges laterally with Summerville Formation.
Late Jurassic	Summerville Formation		80-160	Reddish-brown quartzose horizontally bedded marginal marine siltstone and fine-grained sandstone.
Late Jurassic	Entrada Sandstone	Slick Rock Member	70-120	Light-buff to light-reddish-brown fine-grained quartzose eolian sandstone.
Late Jurassic	Entrada Sandstone	Dewey Bridge Member	20-35	Reddish-brown very-fine-grained silty tidal-flat sandstone.
	Unconformity			
Jurassic and Triassic(?)	Navajo Sandstone		0-420	Light-buff and locally light-reddish-brown fine-grained quartzose eolian sandstone.
Late Triassic(?)	Kayenta Formation		160-200	Purplish-gray to purplish-red fluvial siltstone and sandstone, and locally shale, mudstone, and conglomerate.
Late Triassic	Wingate Sandstone		200-400	Light-buff and light-reddish-brown very fine grained to fine-grained quartzose eolian sandstone.
Late Triassic	Chinle Formation	Church Rock Member	340-500	Reddish-brown, purplish-brown, and orangish-brown, mostly lacustrine, horizontally bedded quartzose sandstone, siltstone, and mudstone, and a minor amount of dark-greenish-gray conglomerate.
Late Triassic	Chinle Formation	Petrified Forest(?) Member.	0-100	Greenish-gray fluvial and flood-plain mudstone, siltstone, and shale, and minor amounts of reddish-brown mudstone and greenish-gray sandstone and conglomerate.
Late Triassic	Chinle Formation	Moss Back Member	20-75	Light-greenish-gray limy arkosic and quartzose fluvial sandstone and gray to greenish-gray limy fluvial sandstone and conglomerate, containing abundant carbonaceous plant material, and minor amounts of greenish-gray and reddish-brown, mudstone, siltstone, and shale.

TABLE 1.—*Generalized section of consolidated sedimentary rocks*—Continued

Age	Formation and member	Thickness (feet)	Description
Middle(?) and Early Triassic	Moenkopi Formation	[1]0-200	Light-reddish-brown micaceous tidal-flat(?) siltstone and sandy siltstone.
Permian	Cutler Formation	1,500-3,000 (240 exposed)	Reddish-brown, orangish-brown, and light-buff arkosic fluvial and flood-plain sandstone, siltstone, mudstone, and shale.
Pennsylvanian	Rico Formation	[1]130-240	Transitional between underlying marine Hermosa Formation and overlying terrestrial Cutler Formation; and including marine evaporites.
Pennsylvanian	Hermosa Formation: Upper limestone	[1]1,000-1,800	Light- to dark-gray fossiliferous marine limestone interbedded with lesser amounts of gray, greenish-gray, and reddish-gray shale and sandstone.
Pennsylvanian	Hermosa Formation: Paradox Member: Upper unit	[1]300-500	Gray marine limestone, dark-gray shale, gypsum, anhydrite, halite, interbedded.
Pennsylvanian	Hermosa Formation: Paradox Member: Salt unit	[1]2,900-4,150	Dominantly halite; minor amounts of interbedded gypsum, anhydrite, limestone, black shale, sandstone.
Pennsylvanian	Hermosa Formation: Paradox Member: Lower unit	[1]50-200	Dark- to light-gray marine anhydrite, gray dolomite and limestone, dark-gray shale, gypsum, and halite, interbedded.
Pennsylvanian	Hermosa Formation: Lower limestone member.	[1]100-150	Medium-gray marine limestone; some thin dark-gray shale interbeds.
Pennsylvanian and Mississippian	Molas Formation	[1]100	Reddish-brown, dark-gray, and greenish-gray shale and silty shale, and gray limestone.
Mississippian	Leadville Limestone	[1]240	Medium-gray marine limestone overlying dolomite.
Devonian		[1]250-550	Gray marine dolomite and limestone interbedded with grayish-green and reddish sandy shale
Cambrian		[1]500-700	Interbedded marine shale, siltstone, dolomite, and sandstone grades downward into light-gray to pinkish-conglomeratic arkosic sandstone.
Precambrian			Granite, amphibolite, and other metamorphic rocks.

[1]None exposed.

Paradox Basin and the northwesterly alined salt anticlines of the region. The orientation of fold axes suggests that downwarping was related to compression that caused the folding. In Late Devonian time the Antler orogeny was initiated in the region of the present Great Basin. The orogeny and the initiation of folding farther east in the region of the Slick Rock district may have been correlative events.

The facts that the source area of the youngest Cambrian rocks known in the region had become stable relative to the marine basin and that a hiatus of considerable duration developed with seemingly conformable relation between Cambrian and Devonian strata suggest a long period of crustal stability in the region. Land areas in the region probably underwent prolonged weathering; evidence for this is the first sediments deposited in the area around the Slick Rock district following the long period of crustal stability. Arenaceous and argillaceous detritus in the lower part of the Devonian rocks, including that of the sandstone of the McCracken Member of Knight and Cooper (1955) of the Elbert Formation, indicates occasional uplift of the land areas peripheral to the region. These indications of crustal stability following the long hiatus support the most likely position of the Ordovician-Silurian-Early Devonian unconformity at the base of the Upper Devonian Aneth Formation of Knight and Cooper

(1955) rather than between the Cambrian Ignacio Quartzite and younger rocks that are lithologically similar to the Ignacio (Baars, 1958, p. 95–97).

LOWER MISSISSIPPIAN ROCKS AND EVENTS

Deposition of marine carbonate rocks continued into the Mississippian Period. The relatively thin layer of Lower Mississippian strata—the Leadville Limestone—confirms the persistence of a miogeosynclinal environment. The source areas continued to be low stable land masses, which were attacked principally by chemical weathering. However, deposition of marine limestone during the Mississippian Period represents maximum transgression of Paleozoic seas into the region, and land sources were likely a great distance east of the continental shelf on which the carbonate sediments were deposited. Northwesterly folding in the region surrounding the Slick Rock district continued in Early Mississippian time, possibly in step with the culmination of the Antler orogeny in the region of the present Great Basin.

UPPER MISSISSIPPIAN AND PENNSYLVANIAN ROCKS AND EVENTS

Before deposition of Molas strata in the region around Slick Rock the sea regressed briefly, possibly in Late Mississippian time, and older rocks were eroded. Detritus from this erosion was incorporated in the basal marginal marine sediments of the Mississippian and Pennsylvanian Molas Formation. Northwesterly folding persisted into the Early Pennsylvanian, and in addition, deformation of the rocks took place along the northeasterly alined Glade subsurface fault zone passing through the south part of the Slick Rock district. Probably this was the first reactivation in Paleozoic time of the ancient Precambrian regional structure; this reactivation was characterized by strike-slip deformation, extending from the Colorado Plateau northeastward along the Colorado mineral belt in the Rocky Mountains. Folding along northwest-trending axes probably was related to horizontal movement on the northeasterly structure, particularly southwest of the northwesterly oriented Uncompahgre highland, in an incipient Paradox Basin. Folding occurred on the northwest side of the Glade subsurface fault zone as a result of horizontal compression; rocks slipped horizontally along the Glade zone and virtually no compressional deformation took place southeast of the zone.

Still in Early Pennsylvanian time, a shallow basin probably with limited connection to the seas farther west began to form in the region around the Slick Rock district which was then near the eastern edge of the miogeosyncline "shelf" of the Cordilleran geosyncline. Deposition of carbonate rocks continued, but in addition, deposition of organic shales began, indicating a stagnant bottom environment resulting from a nearly closed depositional basin. These carbonate rocks and shales compose the lower limestone member of the Hermosa Formation and mark the onset of a depositional cycle that is identified with development of the Paradox Basin.

By Middle Pennsylvanian time the Paradox Basin was well established as a nearly closed or isolated basin dominated by a stagnant bottom environment. A few hundred feet of organic shale, carbonate, and evaporite beds was deposited in the basin, followed by many hundreds to several thousands of feet of dominantly evaporite strata, mostly halite. Evaporites accumulated to greatest thickness along the northeast edge of the Paradox Basin adjacent to the ancestral Uncompahgre highland which in Middle Pennsylvanian time was a low stable landmass succumbing chiefly to chemical weathering. An extended, rather slow and even subsidence of the Paradox Basin during deposition of the thick salt section was interrupted occasionally by slight uplift of surrounding lands that caused influx of detrital material into the basin. The grabenlike deepest part of the basin was bounded on the northeast side by a fault along the Uncompahgre highland and on the southwest side by a parallel fault of less displacement in the present position of the northeast side of Disappointment Valley. Evaporites of great thickness in this part of the Paradox Basin caused the later development of the Paradox fold and fault belt. Following deposition of salt, another relatively thin layer of stagnant bottom sediments—organic shale, carbonate, and thin evaporite strata—was deposited. Despite the conditions favorable for chemical sediment deposition, argillaceous sediments were derived from nearby deeply weathered and low-lying lands, such as the Uncompahgre, which had not yet assumed the topographic dominance that it would in later geologic periods. These Middle Pennsylvanian beds make up the Paradox Member of the Hermosa Formation. Coincident with deposition of the overlying rocks, the salt deposits of great thickness began to flow into the axial regions of anticlines, whose locations and orientations were first initiated by compression that had already established a northwest-oriented structural grain in the region. Once established, the anticlines continued to rise, in part because of the buoyant effect of low-density salt that occupied the cores of the anticlines. Renewed orogenesis in the region of the present Great Basin and in land farther west may have been related to folding in the Paradox Basin during the Middle Pennsylvanian.

UPPER PENNSYLVANIAN AND PERMIAN ROCKS AND EVENTS

Deposition of dominantly carbonate sediments—the upper limestone member of the Hermosa Formation and, locally, the Rico Formation—continued into Late Pennsylvanian time and Early Permian time. Probably the sea in the Paradox Basin was again more freely open to seas farther to the west. Folding continued, however, and may have been more pronounced because of the mobility of the great volume of salt in the section. Influx of abundant clastic material into the basin near the beginning of Permian time suggests uplift of land farther east; this was the onset of the period of main growth of the Uncompahgre highland.

After the Paradox Basin lost its closed character, and before the influx of vast quantities of detritus from the rising Uncompahgre landmass, marginal-marine deposition occurred. Free circulation of shallow aerated waters, possibly at the seaward edge of a coastal plain, permitted oxidation of argillaceous and carbonate sediments in the Rico Formation, with the result that much of the material deposited during this interval was dominantly reddish and yellowish. Some sporadic restriction of the outlet of the basin to the open ocean would have caused deposition of local layers of evaporites.

The restricted distribution of the Rico Formation in the vicinity of the Slick Rock district delineates a local basin of chemical sedimentation; this basin was surrounded by areas that received chiefly clastic material typical of most of the intertonguing and overlying Cutler Formation. Most of the Rico Formation is a transitional facies that records a gradual change from marine deposition that characterized the Hermosa Formation to continental deposition that typified the Cutler Formation. The upper contact of the Rico is therefore arbitrarily placed and even where the Rico has not been recorded the transitional nature of the Hermosa-Cutler boundary is generally evident.

Much of the remainder of the Permian Period saw the rapid subsidence of the Paradox Basin region and the rise of the Uncompahgre, which caused a great wedge of clastic debris—the Cutler Formation—to spread westward. At its eastern limit, deposition of the Cutler was chiefly subaerial. Farther west, the debris becomes increasingly finer grained, and in the eastern part of the region of the present Great Basin, sediments that were deposited at this time are fine-grained clastic strata that are interlayered with miogeosynclinal marine carbonate rocks. In Utah, the presence of evaporites in a restricted area in the Cutler attests to a local closed basin similar to those basins in which Rico sediments accumulated. The sudden and rapid uplift of the Uncompahgre highland in Cutler time, together with the buildup of an alluvial plain sloping southwestward from the highland, displaced the Cordilleran geosyncline westward. Also during the time that thick layers of arkosic debris were shed from the rapidly rising Uncompahgre, the salt anticlines were folded strongly, and large-scale deformation occurred along the Glade subsurface fault zone. A causal relationship among all three contemporaneous events seems plausible. Compression continued to shorten the crust on the northwest side of the northeast-trending structure; this deformation was permitted—where comparable deformation did not occur southeast of the northeast-trending structure—by strike-slip movement on the Glade subsurface fault zone. Rapid uplift of the Uncompahgre highland and folding of the salt anticlines may have been corollary responses to crustal shortening. Termination of the southeast end of the Paradox fold and fault belt against the Glade zone seems a natural consequence of the suggested deformation. Structural events in the Paradox Basin region may be correlative with recurrent deformation in the region of the Cordilleran geosyncline during the Permian Period.

TRIASSIC ROCKS AND EVENTS

After deposition of thick layers of arkosic debris during the Permian Period, uplift of the Uncompahgre source area ceased and erosion removed the upper part of the sedimentary pile. The salt anticlines continued to grow during this episode, and most of the axial parts of the anticlines were beveled by erosion. Fine clastic debris, largely derived from erosion of underlying Permian sediments, spread westward into a marginal marine environment which was dominant during Early and Middle(?) Triassic time, to make up the Moenkopi Formation. Stewart and others (1959, p. 499) stated that the eastern part of the Moenkopi was "derived from the granitic Uncompahgre highland" and "partly from the conglomeratic facies of the underlying Cutler formation" and was deposited under marginal-marine and tidal-flat conditions. Some of the detritus was deposited in the region around Slick Rock, but locally it was washed away to the west at a later time, as indicated by the absence of exposures of the Moenkopi at the surface in the district but by the presence of the Moenkopi in the subsurface nearby. Lower and Middle(?) Triassic rocks were beveled by considerable erosion preceding deposition of Upper Triassic sediments in the region that surrounds the Slick Rock district. Apparently, mild folding of the salt anticlines and especially deformation along the Glade subsurface fault zone continued during this time, as indicated by thick Moenkopi preserved along the zone (Shawe, 1970, fig. 3).

The region surrounding the Slick Rock district was largely emergent in Late Triassic time, and several hundred feet of largely fine grained continental fluvial and lacustrine sediments was brought in from the east, southeast, and south (Stewart and others, 1959; 1972) and was deposited as the Chinle Formation. Uplift of land east of the district may have centered on the ancient Front Range highland; uplift of land to the southeast may have centered on the Zuni highland or the area coinciding with the southeast part of the Uncompahgre highland; that in the south centered on the ancient Mogollon highland. As indicated by the general coarseness of some layers in the lower part of the Chinle, either the source area was probably not far distant or the material was transported rapidly from the source. Sediments in the lower part of the

Chinle (Moss Back and Petrified Forest? Members) were derived from a source area that contained granitic, metamorphic, and sedimentary carbonate and argillaceous rocks. Interbedded crossbedded sandstone and conglomerate layers and horizontally bedded mudstones and bentonitic shales are interpreted as representing fluvial channel-fill deposits and lacustrine or marsh deposits with some layers consisting of ash-fall material probably derived from volcanic island arcs west of the area of Upper Triassic sediments. The large proportion of quartzose clastic sediments as compared to limy clastic debris in the middle part of the Chinle (units 1 and 2 of the Church Rock Member) probably indicates a smaller amount of carbonate sediments in the source area, but occasional beds of limestone conglomerate indicate short intervals of time when carbonate sediments, probably of Paleozoic age, were being eroded in the source area. Volcanic material continued to make up an appreciable part of the sediments, not only in the sandy layers, such as part of the so-called Black Ledge, but also in bentonitic beds in the middle part of the Chinle. Fluvial deposition still was considerable during deposition of the middle part of the Chinle, but perhaps lacustrine or marsh deposition was predominant. Smaller amounts of clayey sediments in the upper part of the Chinle (unit 3 of the Church Rock Member) indicate less volcanic ash-fall material, although some beds no doubt had such an origin. Some fluvial deposition occurred from time to time in different places, but lacustrine deposition appears to have been the most widespread. Also near the end of Chinle time some thin layers of crossbedded dune sands which are interbedded with possibly lacustrine deposits and which are lithologically similar to the Wingate Sandstone that overlies the Chinle were deposited in advance of the main period of dune deposition that marked the formation of the Wingate.

The central part of the Late Triassic sedimentary basin lay southwest of Slick Rock in southern Utah and northern Arizona, as indicated by the thickening of these rocks into that area. Also, the basin seems to have filled gradually from the south, as indicated by progressively younger units at the base of the Upper Triassic farther north.

Local accumulations of abundant carbonaceous material (carbonized plant remains) in some of the coarser beds in the Upper Triassic, especially the Moss Back Member of the Chinle, caused diagenetic changes in the rocks that reflect a reducing environment. Most of the Upper Triassic rocks were subjected to an oxidizing diagenesis, with the result that they are dominantly of red-beds type. At some time after the development of the diagenetic types of lithology, epigenetic alteration, and deposition of uranium-vanadium deposits in parts of the Moss Back Member that exhibit carbon facies lithology, occurred when altering solutions from an extraneous source moved through the beds. Inadequate information prevents a determination of the time of the epigenetic alteration and the source of the altering solutions.

During and following the deposition of fluvial, lacustrine and marsh deposits of Late Triassic age the salt anticlines were again folded. In addition, after these rocks were deposited, renewed movement on the Glade subsurface fault zone that passes through the south end of the Slick Rock district caused local uplift and erosion of strata. Again, the apparent contemporaneity of deformation of the anticlines and the northeast-trending structure points to causal relationship: slippage took place along the northeast-trending Glade zone and folding of rocks occurred on the northwest side of the zone.

The land was close to sea level near the end of Late Triassic time, following local erosion of Upper Triassic sediments. Fine-grained detrital material probably derived from the east was reworked by onshore winds in vast dune fields adjoining tidal flats farther west, to form the Wingate Sandstone. According to Harshbarger, Repenning, and Irwin (1957, p. 23), the Wingate in the vicinity of what is now northeastern Arizona derived source material from the east; this material consisted dominantly of reworked older sediments, probably Triassic, and some new material from metamorphic terranes, which perhaps included the Uncompahgre highland. Stewart and others (1959, p. 524, 525) indicated that the Wingate was deposited by winds that blew dominantly southeastward. Minor oscillations in sea level, or perhaps transitory recurrence of shallow lakes, resulted in frequent inundation of the dune fields and so the dunes were leveled. Subsequent withdrawals of water permitted renewal of the formation of dunes as more material was carried in from the east, until several hundred feet of eolian deposits had piled up. During this time, or shortly following it and prior to deposition of younger sediments, deformation occurred on the Glade subsurface fault zone, and mild folding of the salt anticlines resumed.

The close of the Triassic Period saw uplift of land northeast of the region around Slick Rock, which caused influx of coarse clastic sediments, carried mostly by streams. A source for these sediments is inferred to the northeast on the basis of both sedimentary structures and lateral differences in composition of the sediments that make up this Upper Triassic(?) deposit, the Kayenta Formation (Stewart and others, 1959, p. 524). The region was covered by a thin blanket of fluvial channel-fill and crossbedded sediments as far south as the position of the Glade subsurface fault zone. If sediments were deposited farther south, they were later eroded. Deformation along the Glade zone recurred, and mild folding of the salt anticlines continued. If the salt anticlines were rising during Kayenta time, they must have formed only islands in the depositional basin, thus permitting transportation of sediments southwestward into the district. Perhaps most of the

Kayenta was deposited before the anticlines resumed growth; cyclic growth of the salt anticlines may have been related to more wide-scale tectonic events which in turn governed changes in lithology of successive formations.

TRIASSIC(?) AND JURASSIC ROCKS AND EVENTS

After accumulation of the thin sequence of fluvial strata making up the Kayenta Formation of Late Triassic(?) age, probably when the highland source of the fluvial sediments finally wore away, conditions reverted to those near the end of Wingate time. A second great wedge of eolian sand, the Navajo Sandstone, was deposited during the Triassic(?) and Jurassic. Its eastern limit now is not far east of Slick Rock, and its greatest thickness of a few thousand feet is at the center of the basin far to the west near southern Nevada. According to Harshbarger, Repenning, and Irwin (1957, p. 25), the Navajo Sandstone of northeastern Arizona was derived from a western source; as suggested by Stewart and others (1959, p. 525), largely on the basis of dominant cross-strata orientation, the source for the Navajo of southeastern Utah was to the northwest. Perhaps the higher feldspar content of the Navajo Sandstone in southwestern Colorado indicates a closer source, to the east or northeast. Streams may have brought detritus from the east that became distributed in a lowland, water-saturated environment and that was subsequently reworked by westerly winds. Horizontal layers that alternate with crossbedded layers and that are common in the Navajo likely reflect periods of subaqueous (lagoonal?) deposition; some transport of material from source areas may have been by water. Upon withdrawal of water, westerly winds reworked the detritus into dunes.

The salt anticlines again were folded appreciably, after deposition of the sand, and in many places on the crests of the anticlines the entire thickness of several hundred feet of eolian strata of the Navajo was removed by erosion. Erosion occurred in other regions outside the Paradox fold and fault belt. The general uplift thus implied by widespread erosion must have been related to the events that terminated the influx of sand into the region, as well as to the renewed folding of the salt anticlines.

Deformation in the western part of the region of the present Great Basin resumed its intensity during the Early Jurassic, and deformation recorded in the Colorado Plateau during this time possibly was related to it.

The sedimentary basin west of the Slick Rock district in the western part of the Colorado Plateau subsided after erosion of lower Middle Jurassic rocks and was inundated by the sea near the end of Middle Jurassic and at the start of Late Jurassic time. During deposition of limy marine strata of the Carmel Formation in a north-trending trough in central Utah in Middle and Late Jurassic time, reddish-brown silty rocks of the Dewey Bridge Member of the Entrada Sandstone (the red earthy siltstone unit of Wright and Dickey (1958) or medial silty member of Harshbarger, Repenning, and Irwin (1957)) were deposited in the vicinity of the district (Wright and others, 1962) on tidal flats and in lagoons near the eastern boundary of the sea. Local cherty limestone pans likely were deposited in freshwater lakes but may have been formed in erosional hollows on top of the Navajo Sandstone or may have been deposited during Navajo time as were similar limestone layers in eastern Utah (Wright and Dickey, 1957, p. 352). Because of resistance to erosion, those pans survived in places at the top of the remnant Navajo. Before the main deposition of silty Dewey Bridge sediments, some of the troughs in the eroded unconformable Navajo surface became filled with lag gravels that formed conglomeratic sandstone containing fragments of the Navajo Sandstone as well as pebbles of chert presumably eroded from scattered limestone layers not far distant. Such deposition apparently partly filled up irregularities in the old Navajo surface to form a nearly flat surface which received the silts typical of the Dewey Bridge. Horizontal and massive bedding of the siltstone and sandstone of the Dewey Bridge Member is here interpreted as indicating a tidal-flat or lagoonal environment of deposition. Position of the Slick Rock district near the eastern margin of the Carmel depositional basin, as well as uplift of rocks to the east, points to an eastern source for the Dewey Bridge Member.

The massive and horizontally bedded character of the massive unit of the Slick Rock Member of the Entrada Sandstone is suggestive of generally tidal-flat or lagoonal conditions of deposition similar to those envisaged for the underlying Dewey Bridge Member. A few scattered layers of eolian-type crossbedded strata in the massive unit indicate that during deposition parts were at times above water and dried out, and therefore small areas of windblown dune sands developed. These all appear to have been ultimately leveled at the top, and many probably were destroyed, by submergence in lagoonal waters. Eventually, much of the area of the Slick Rock district was drained of water and dried out and so dune sands could again accumulate. This period saw the deposition of the middle (crossbedded) unit of the Slick Rock Member which, as indicated by Shawe, Simmons, and Archbold (1968, fig. 20), was built up in increments comprising individual dune layers that were periodically submerged briefly and at that time were beveled at the top by water. In a few places where dunes were not submerged, dune layers were swept away, probably by wind action (deflation), and were replaced by windblown sand. Toward the close of the period of Slick Rock Member deposition the entire Slick Rock district was submerged, and the uppermost dune layer was beveled and reworked. Much of the upper (horizontally bedded) layer of the Slick Rock Member consists probably of reworked dune sands that were brought in from outside the district after the first horizontal bed covered the beveled dunes. Depositional conditions at the end of sedimentation of the horizontally bedded layer may have changed gradually to develop the alternating layers of shale and sandstone of the lower part of the Summerville Formation. More likely, however, a change in conditions or in position of the source area caused periodic and increasing influxes of clay with the sediments, resulting in progressively more abundant shale upward and transition into the Summerville Formation.

The source area of the Slick Rock Member suggested by southeastward thinning of the member was generally southeast of the district. Wright (1959, p. 61) indicated that the direction of transport of Entrada Sandstone and the Carmel Formation was from the east. During deposition of the crossbedded unit, minor amounts of airborne material of volcanic origin apparently were laid down in the district. Perhaps some volcanic material is also present in the other units of the Entrada. Cadigan (1958, p. 48) indicated the presence of important amounts of volcanic material in equivalent rocks in south-central Utah and suggested that volcanic material in the Slick Rock had a westerly source.

Ultimately, subsidence exceeded the accumulation of eolian sand, and clayey marine strata of the Summerville Formation were deposited widely in the region of the Colorado Plateau. Thin horizontal bedding and oscillatory ripple marks that widely characterize the Summerville suggest a shallow marine or a tidal-flat environment of deposition. The dominant easterly orientation of ripple-mark troughs indicates chiefly northward or southward wave motion and implies either northerly or southerly winds. Because of the probable marine origin of the Summerville and associated Curtis Formation farther west in Utah (Gilluly and Reeside, 1928), the source landmass undoubtedly lay other than to the west.

Harshbarger, Repenning, and Irwin (1957, p. 48, 51) indicated that the southward equivalent of the Junction Creek Sandstone, the Bluff Sandstone, formed as barchan dunes and moved northward from the main area of deposition of the Cow Springs Sandstone in northeastern Arizona. Certainly the great sweeping crossbeds displayed by the Junction Creek south of the Slick Rock district suggest origin in immense barchan dunes. The movement of dunes northward terminated in the southern part of the Slick Rock district, where the Junction Creek merges with the Summerville Formation. As suggested by Shawe, Simmons, and Archbold (1968, pl. 6), individual dune layers were probably reworked by the marine waters in which the Summerville was laid down, as evidenced by the change northward from the crossbedding to the horizontal bedding of the individual layers. Water probably periodically covered the dune layers, beveled them, and then deposited horizontally bedded clayey layers.

Material derived from the initial and farthest advance of the dunes probably was reworked for a long time and was spread northward by wave action and currents in the Summerville sea, or simply was blown northward and dropped in tidal estuaries, to form a "marker bed."

Two major events outside the Colorado Plateau near the end of Late Jurassic time strongly influenced sedimentation within the Plateau. A large landmass rose in west-central Arizona and southern California—possibly a westward extension of the Mogollon highland. It exposed to erosion clastic sedimentary rocks probably of Permian, Triassic, and Early and Middle Jurassic ages, detritus from which was shed northward, northeastward, and eastward onto the level plain formed of the Late Jurassic marine and tidal-flat strata. A second event, concurrent with uplift of the landmass, was vigorous volcanic activity that began in the island arcs west of the Jurassic basin. Prevailing westerly winds carried volcanic ash into the basin and deposited it in small to large amounts at various levels in the sediments that were laid down during the rest of Late Jurassic time.

The Salt Wash Member of the Morrison Formation was deposited in the region of the Colorado Plateau in Late Jurassic time. As Craig and others have pointed out (1955, p. 150), "the Salt Wash was derived mainly from older sedimentary formations and received only minor contributions from igneous and metamorphic rocks." It was deposited by aggrading streams as a broad fan-shaped alluvial plain. The source area of the Salt Wash, indicated by orientation of sedimentary structures, by facies changes, and by the position of the apex of the alluvial fan, was probably in west-central Arizona and southeastern California (Craig and others, 1955, p. 150–155). Sedimentary rocks in the provenance of the Salt Wash apparently were chiefly clastic, and these were probably derived in an earlier cycle of erosion from nearby igneous and metamorphic rocks of late Precambrian age. The conglomerate facies of the Salt Wash in Utah, however, contains very abundant silicified carbonate rock pebbles, indicating abundant carbonate rocks in the Salt Wash provenance (T. E. Mullens, written commun., 1973). According to Bowers and Shawe (1961, p. 184–186, table 2) zircons in the Salt Wash Member, chiefly the ore-bearing sandstone, consist of principally colorless spheroidal and egg-shaped grains and of small amounts of colorless worn euhedral and subhedral crystals, pink spheroidal and egg-shaped grains, colorless sharply euhedral crystals, and pink worn euhedral and subhedral crystals. The pink spheroidal and egg-shaped grains were almost certainly derived from Precambrian rocks, and so also were the colorless spheroidal and egg-shaped grains, judged from their extreme roundness and the late Precambrian-Cambrian average age of Morrison zircons (Shawe and others, 1968, table 4). The occurrence of the zircons indicates that more than 90 percent of the ore-bearing sandstone was derived ultimately by erosion of Precambrian rocks. Colorless sharply euhedral zircons probably had a volcanic origin, and colorless worn euhedral and subhedral crystals likely were derived from erosion of volcanic rocks.

Possibly the sedimentary rocks that were the immediate source of the Salt Wash deposited in the vicinity of the Slick Rock district were the Triassic Chinle Formation, inasmuch as the Chinle is known to underlie Jurassic rocks in the general source area of the Morrison Formation. (For example, see McKee and others, 1956, pl. 2.) Although older Jurassic rocks may also have been possible sources of the Salt Wash, grain size, sorting, and composition of such formations generally do not match those characteristics of the Salt Wash, suggesting that they were not a likely source. Rocks older than Triassic that may have been exposed in the source area and that are a likely source of the Salt Wash are clastic red beds of Permian age (described by Longwell, 1949, p. 930). Other older strata that may have been exposed in the general area are chiefly carbonate rocks, and silicified parts of these may have been sources of some Salt Wash detritus.

Just before deposition of Salt Wash sediments, the present area of the member must have been virtually a flat plain underlain by horizontal strata of the Summerville Formation. As interpreted from the data of Craig and others (1955), uplift of land in the vicinity of west-central Arizona and southern California instigated movement of detritus northward, northeastward, and eastward into the area of the Salt Wash, forming a great alluvial fan, or aggrading plain, with apex near the source area. If the interpreted source area is assumed to have been the sole provenance of the Salt Wash, irregularities in thickness of the alluvial fan reflect structural modifications during deposition. Evidence that post–Salt Wash erosion was negligible precludes attributing observed thickness variations to structural modification after the member was deposited and before overlying sediments were deposited. Shawe (1962) inferred that thickness variations in the Salt Wash Member indicated local subsidence of an area roughly coinciding with the Paradox Basin but encroaching northeastward into the area of the Uncompahgre highland. Subsidence of the area approximating the Paradox Basin caused the development of a smaller alluvial fan upon the much larger fan of the Salt Wash Member. The apex of the smaller fan is in a position that may have permited "capture" of a main trunk of Salt Wash distributary streams. Significantly the area of the smaller alluvial fan coincides with the area of principal development of lithologies that were favorable for deposition of uranium-vanadium deposits in the Salt Wash Member. (See Craig and others, 1955.) The toe of the smaller fan is the position of the Uravan mineral belt, which extends northward from Slick Rock. The belt itself is characterized by generally continuous ore-bearing sandstone that contains abundant carbonaceous material and is typically crossbedded and abounding in cut-and-fill structures. Eastward from the position of the mineral belt, strata at the horizon of the principal (topmost) ore-bearing sandstone are more flatbedded and contain a higher proportion of mudstone, suggestive of deposition under conditions of quieter water. (For example, see Fischer and Hilpert, 1952, p. 6; McKay, 1955, p. 272 and pl. 13.) The area within the basin east of the Uravan mineral belt is thus interpreted as containing sediments of flood-plain and perhaps lacustrine type; those in the mineral belt and westward to the end of the basin are interpreted as being fluvial deposits formed on a smaller aggrading fan localized on the larger Salt Wash alluvial fan by local subsidence during Salt Wash deposition.

According to L. C. Craig (written commun., 1961) the regional gradient of Salt Wash streams was probably about 5 feet per mile. As determined in a very small area in the Slick Rock district, at the Cougar mine (Shawe and others, 1968, fig. 31), the local gradient of streams just before deposition of the ore-bearing sandstone was approximately 50 feet per mile. This gradient is a rough estimate, and probably high, inasmuch as the area from which it was determined is small. Nevertheless, it suggests that toward the end of Salt Wash deposition the local gradient of streams in the vicinity of the district was higher than the regional gradient. It may indicate that the proposed smaller fan that was localized on the larger regional Salt Wash fan presented a slightly different environment of deposition, and this aberrant environment was partly responsible for later deposition of uranium-vanadium ore deposits.

Individual sandstone layers in the Salt Wash Member probably were reworked after initial deposition, and the ore-bearing sandstone in the Uravan mineral belt area may have been reworked extensively. Widespread scour-and-fill features in the relatively thin and laterally persistent upper unit indicate extensive reworking without addition of much new sediment. The ore-bearing sandstone interval likely was first deposited rapidly as sand and minor amounts of mud, after an abrupt and short-lived subsidence of the area approximating the Paradox Basin. These strata composed an alluvial fan whose average gradient may have been as much as 50 feet per mile, or about a degree, and whose toe occupied the position of the Uravan mineral belt. During a following period of quiescence the strata were considerably reworked by distributary and braided streams coursing down the fan, developing additional and extensive scour-and-fill characteristics and winnowing out much clay that was carried eastward into the local basin.

Abundant vegetation probably covered the whole of the area of Salt Wash deposition. The abundance of vegetation is now evidenced only in strata that were submerged beneath the water table just after deposition; lack of oxygen in such an environment permitted plant debris to be preserved.

Restriction of carbonaceous material dominantly to the area of the Uravan mineral belt seems anomalous in some respects. For example, locally at the west edge of the mineral belt carbonaceous material disappears abruptly in sandstone that laterally shows no other detectable lithologic or structural differences (John E. Motica, oral commun., 1961). Drilling done by the U.S. Geological Survey in the western Dissappointment Valley area shows that the ore-bearing sandstone in one place where it is about 30–40 feet thick changes from abundantly carbonaceous to noncarbonaceous within 1,000 feet laterally. Carbonaceous material may have been originally abundant throughout the ore-bearing sandstone, and may have been destroyed in many places some time after deposition, and preserved locally, as in the Uravan mineral belt. R. P. Fischer has suggested (oral commun., March 1961) that places in which carbonaceous material survived (that is, was not oxidized) were below the water table just after deposition, such as at the foot of an aggrading slope; upslope above the water table, aeration allowed oxidation and destruction of carbonaceous material. Such a mechanism readily accommodates itself to the conditions pictured for an alluvial fan, the toe of which may have been close to or under the water table that occupied the subsided area which nearly coincides with the Paradox Basin. Upper reaches of the fan, being alternately wet and dry, lost most of the original carbonaceous material by oxidation, although local accumulations of organic debris may have survived in perched water tables. The toe of the fan retained its carbonaceous material, being effectively submerged beneath the water table in most places. Perhaps absence of carbonaceous material in the upper part of the ore-bearing sandstone in many places and its abundance in the lower part can best be explained by oxidation above a water table. General absence of carbonaceous material east of the Uravan mineral belt may have resulted from nondeposition due to change of conditions eastward from the toe of the fan. Coarse plant material that was moved easily by streams on the aggrading fan may not have been transported farther eastward into the low-gradient flood-plain and lacustrine environment.

Diagenetic alteration of two types, related to presence or absence of carbonaceous material, affected the fluvial strata of the Salt Wash Member, commencing almost at the time they were deposited. Generally the beds were subjected to alternate wetting and drying and thereby became rapidly oxidized. Plant material that was buried with the sediments was destroyed, and black opaque minerals, largely magnetite and ilmenite, were oxidized to hematite and leucoxene, still retaining their detrital form. At the same time that the black opaque minerals were oxidized, some iron moved out of them and was redeposited as a hematite film on other detrital grains, or was dispersed as dustlike hematite throughout finely divided clayey material. If the redeposited iron was in the form of a hydrated oxide it was later dehydrated, inasmuch as all the reddish stain in these rocks now appears to be hematite. Where abundant carbonaceous material survived in the fluvial sediments beneath the water table, diagenesis proceeded differently. In this environment the black opaque detrital minerals were not oxidized, but some of them were destroyed by reduction and the iron was reprecipitated in pyrite.

After subsidence of the area that nearly coincides with the Paradox Basin; renewed folding of the salt anticlines occurred; the subsidence and folding may have been partly a result of compression. Southwest of the basin and nearly parallel to it is a west-northwest-alined uplift (Shawe, 1962, fig. 62.2); both basin and uplift may represent gross folding of deeper rocks through compression. Growth of the salt anticlines may have been merely triggered by such stress, and was perpetuated by salt flow resulting from differential loading by overlying strata. Sand of the lower unit of the Salt Wash was probably buried rapidly beneath the mud of the middle unit, because it did not receive the extensive reworking that affected the sand of the upper unit. Subsidence of the basin continued to a minor extent during deposition of the middle unit, but it may have been neither as great nor as rapid as during deposition of the lower unit. Folding of the salt anticlines was retarded, and may have consisted solely of local growth of salt cupolas, as suggested by the localization of a thinner middle unit along one segment of the Dolores anticlinal axis. Slower subsidence of the basin may account for the much higher proportion of mudstone in the middle unit. Deposition of the upper unit followed an abrupt but minor subsidence of the basin, and it was not buried immediately by mud as was the lower unit. Instead, relative quiescence in the basin permitted considerable reworking of the upper unit on the alluvial fan that filled the west end of the basin. Flood-plain and lacustrine conditions farther east permitted deposition of more evenly bedded sand, with a higher proportion of mud, partly derived from clay winnowed from the reworked upper unit on the fan.

Craig and others (1955, p. 157) concluded that the coarser clastic sediments of the Brushy Basin Member overlying the Salt Wash Member of the Morrison Formation "were derived mainly from a source area of sedimentary rocks." The position of the source area is not clearly evident, but was suggested by Craig and coworkers to have been generally that of the Salt Wash source area (1955, p. 157). Cadigan (1967, p. 84) suggested that much of the volcanic material in the Brushy Basin originated from a westerly or southwesterly source, inasmuch as the percentage of this material in the member increases generally in those directions.

Deposition of sediment continued without significant interruption following the formation of the ore-bearing sandstone of the Salt Wash Member, but at that time the area in eastern Utah and western Colorado approximating the Paradox Basin had slowed its rapid subsidence, and again became nearly filled with dominantly mud and silt strata deposited under flood-plain conditions. The salt anticlines continued to be active near the end of Late Jurassic time, but their growth was restricted largely to individual cupolas. For example during the deposition of several hundred feet of the Brushy Basin sediments, considerable salt flowed from beneath the axis of the Disappointment syncline into a large cupola underlying the adjacent Gypsum Valley anticline. The relatively rapid flow of evaporites from the synclinal area resulted in basining which induced diversion of streams into the low area and concomitant deposition of abundant sand along the synclinal axis, whereas deposition of mud and silt dominated elsewhere. Flow of salt probably slowed somewhat after initiation of Brushy Basin sedimentation, so, although folding continued, the ground surface remained level and streamflow was not confined to the synclinal axial regions. Folding of the salt anticlines accompanied a general downwarping of the Paradox Basin, and at the same time deformation continued along the northeasterly Glade subsurface fault zone.

In the Slick Rock district the lower brown unit of the Brushy Basin records an influx of volcanic material that diluted sediments typical of the underlying Salt Wash Member. Sporadic lenses of chert-rich conglomeratic sandstone mostly in the upper part of the lower brown unit may reflect addition of material derived from newly elevated areas of volcanic rocks or from sedimentary terrains west of the Colorado Plateau. The coarser rocks in the lower part of the Brushy Basin suggest occasional accelerated uplift of source areas on the western periphery of the plateau.

The middle green unit of the Brushy Basin contains abundant volcanic material derived both from ash falls and from erosion of volcanic source areas. Nearly half the material in the unit is detritus derived from the erosion of older sedimentary rocks. The abundance of clastic lenses in the middle green unit reflects marked uplift in the provenance of the Brushy Basin which possibly coincided with the advent of volcanic activity in these areas.

During deposition of the upper brown unit the amount of coarse clastic sediment in most places decreased appreciably, and probably the amount of volcanic material in the fine sediments was less than that in the middle green unit. Bentonitic clay seems to be less abundant in the upper brown unit, especially near the top, than in the middle green unit. Much of the fine clastic material in the upper brown unit was probably derived from erosion of sedimentary terranes, and less than half the unit consists of volcanic material. Near the end of Brushy Basin sedimentation, quartzose detritus similar to that which characterizes the overlying Burro Canyon Formation began to come into the region around the Slick Rock district. This detritus is local in distribution and is evident chiefly in greenish-gray parts at the top of the upper brown unit. The new material signifies the advent of another source area which became dominant in Burro Canyon time—probably a more southerly provenance nearly devoid of volcanic rocks. Craig (1961, p. 1584) cited evidence for northward-flowing streams that deposited the Burro Canyon. This gradual shifting of source areas was the main factor in the change from Morrison to Burro Canyon lithology; the general depositional environment changed little, with the result that the contact between the formations is in many places arbitrary and difficult to place because of intertonguing or transitional relations.

The greenish-gray or brownish-gray rocks in the Brushy Basin Member show more evidence of volcanic origin than do the reddish-brown rocks. Nevertheless, these rocks include abundant permeable sandstone layers that have been altered by reducing solutions—as indicated by sparsity of detrital black opaque minerals—suggesting that much of the greenish-gray and brownish-gray colors of the Brushy Basin resulted from epigenetic alteration.

CRETACEOUS ROCKS AND EVENTS

Terrestrial sedimentation in the region surrounding the Slick Rock district continued uninterrupted into Early Cretaceous time. The great abundance of coarse clastic material deposited in the Burro Canyon Formation during that time resulted from the rise of land farther south of the district and east of the source area of the Morrison Formation. Abundant scour-and-fill structures in sandstone strata in the Burro Canyon Formation show that these rocks were deposited under fluvial conditions. Mudstone layers interbedded with the sandstone are interpreted to be lacustrine or flood-plain deposits similar to those in the Morrison Formation. The much higher proportion of sandstone to mudstone in most of the Burro Canyon as compared to the underlying Morrison indicates greater influx of coarser clastic material, with no appreciable difference in the environment of deposition. The new source area to the south provided a great abundance of quartzose debris that became intermixed with the diminished sediment from the source area of the Morrison Formation farther southwest and west. Common chert-rich conglomerate layers in the formation may have been derived from sedimentary rocks of the southern source area.

Subsidence of the Paradox Basin ceased during Burro Canyon time, or at its close and prior to deposition of overlying strata, for erosion almost everywhere beveled the top of the Lower Cretaceous rocks. Even though basin subsidence had come to a standstill, some growth of the salt anticlines continued. Movement of salt was local, however, such as the pronounced flow from beneath a segment of the Disappointment syncline into the large salt cupola underlying the Gypsum Valley anticline. Because only slight tectonic activity occurred in the Colorado Plateau region during the Early Cretaceous, the local development of the salt cupolas presumably was a result of the buoyant flow of salt responding to differential load stresses.

Thin-bedded and evenly bedded argillaceous rocks, limestone, chert, and glauconitic(?) siltstone in the upper part of the Burro Canyon suggest that a marginal or near-shore marine environment of deposition developed late in the Early Cretaceous. A nearly closed basin similar to the Baltic sea may have extended into the area of the Paradox Basin as an arm of a large sea far to the south in the vicinity of Mexico, a sea evidenced by widespread and thick Lower Cretaceous marine strata in that area (Reeside, 1944). Such a basin may have been a precursor of the Late Cretaceous Rocky Mountain geosyncline. Following this marine incursion, however, uplift of the Colorado Plateau region allowed general erosion that swept away most of whatever marine sediments had accumulated, except where local subsidence such as in the Disappointment syncline prevented erosion.

Mild crustal warping that caused slight uplift of the Colorado Plateau and commensurate erosion of the top of Lower Cretaceous strata during the Late Cretaceous also resulted in the development of a broad depression that occupied much of the western interior of the United States. Preceding northward encroachment into this depression by the sea that occupied the present region of Mexico near the end of the Cretaceous, was deposition of a thin layer of terrestrial sediments composed of sand and interlayered mud septa comprising the lower and middle parts of the Dakota Sandstone. The abundance of scour-and-fill structures in sandstone in the lower arenaceous unit of the Dakota indicates that fluvial conditions existed during most of the deposition of the lower part of the formation. The great abundance of carbonized plant material as well as coal in the Dakota Sandstone has been accepted as strong evidence for the deposition of the formation in a dominantly swampy, heavily vegetated environment. In order to preserve the abundant plant debris buried in the sandstone, the sediments must have been mostly submerged in water after they were deposited; otherwise oxidation would have destroyed the carbonaceous material. The area of deposition likely was a low flood plain, a coastal swamp, or a tidal flat bordering a sea, where periodic inundation occurred. Aside from its abundant content of carbonaceous material, much of the mudstone of the Dakota resembles much of the mudstone in the underlying Burro Canyon and Morrison Formations which has been interpreted as being of lacustrine and flood-plain origin.

Much of the evenly bedded carbonaceous shaly mudstone in the upper part of the Dakota appears identical to that in the overlying marine Mancos Shale. Moreover, sandstone in the upper part exhibits foreset bedding of beach deposits and worm borings suggestive of marine and marginal marine deposition. If the upper part of the Dakota were deposited in the sea it must have been in a nearly closed and stagnant basin, that is, in a sapropelic environment, where abundant plant material ensured that the water was continuously deoxygenated. Most likely the change from terrestrial to marine deposition was gradual, with alternations from one to the other during deposition of the middle part of the Dakota. This middle period also saw deposition of most of the Dakota coal, probably in lagoons marginal to a stagnant sea.

Evidence of volcanic material in the Dakota, particularly in the middle and upper parts of the formation, consists of sharply angular flakes of detritus that most likely were airborne to the place of deposition, and gray claystone layers of bentonitic character that probably are dominantly altered ashfall material. Although the amount of volcanic material may not be large, its presence is important to any interpretation of the geologic history of the western interior of the United States. It is pertinent to the present discussion because the volcanic material most reasonably was derived from the same general region that supplied abundant volcanic material to the Morrison Formation, suggesting that land masses (island arcs) still existed farther west, and continued to supply detritus to the depositional region surrounding the Slick Rock district.

The position of the source of material deposited in the Dakota Sandstone is poorly known, but probably it lay west of the present area of Dakota outcrop, in Idaho, Nevada, and southern California. The lower part of the Dakota apparently is locally coarser farther west (L. C. Craig, oral commun., Sept. 1961), and sandstone in the upper part of the Dakota in places apparently tongues out eastward into the overlying Mancos Shale (Young, 1960, p. 179, fig. 17). However, if abundant volcanic rocks were exposed in such an area to the west they presumably did not supply much detritus to the Dakota, inasmuch as the formation consists dominantly of reworked sedimentary material. Perhaps the chief provenance of the Dakota lay farther southwest where extensive land masses blanketed by clastic sedimentary rocks existed during the Late Cretaceous.

Little if any tectonic folding of the salt anticlines occurred during deposition of the Dakota Sandstone, but salt continued to flow locally into salt cupolas, as for example from a segment of the Disappointment syncline into the large evaporite cell in the adjacent Gypsum Valley anticline.

After the Dakota Sandstone was laid down, further subsidence and enlargement of the Late Cretaceous basin led to the deposition of several thousand feet of the marine strata comprising the Mancos Shale. Sedimentation continued without appreciable interruption from Dakota into Mancos time as transgressive layers of mud and sand

and finally almost wholly mud were laid down in stagnant water within a restricted arm of the Mexico sea. Although the sequence of deposition of the transgressive Mancos sediments is described here primarily for the area of the Slick Rock district, it must be understood that specific lithologic units (facies) of the Mancos, and for that matter of the underlying Dakota, were not deposited simultaneously across the entire region. For example, a basal unit of the Mancos Shale in western Colorado has a time equivalent in an uppermost unit of the Dakota Sandstone in eastern Utah. The combination of abundance of carbonaceous material including some petroliferous substances, the abundance of marine fossil invertebrates, and the persistent horizontal bedding in the Mancos Shale attest to the formation's sapropelic marine origin. The formation was deposited in a stagnant continental sea limited on the west by a landmass, probably covered with abundant vegetation and deeply weathered, extending from north to south through Idaho, Nevada, western Arizona, and southern California (Reeside, 1944), from which much of the detritus in the Mancos must have been derived. Large amounts of clay and calcite in the Mancos indicate extensive weathering in the source area. The sea was limited on the east by lowlands in the central Great Plains region which, of course, supplied detritus to eastern parts of the basin. Although the source area of the Mancos Shale was deeply weathered and of low relief, some coarse clastic material was supplied to the depositional basin, inasmuch as silt and sand are locally abundant in the formation. In addition to the detritus and organic debris carried in from land to the west of the Mancos sea, volcanic material in the form of ash falls was supplied in considerable abundance, probably from a region lying to the northwest, as judged from the great abundance of bentonitic shale in equivalent rocks much farther north—for example, Cody Shale in Montana and Wyoming (Knechtel and Patterson, 1956, p. 21-28).

Pyrite probably began to form as an authigenic mineral shortly after deposition of the sediment, as indicated by compaction of beds around pyrite cubes. (See unit 6 of the detailed measured section of the Mancos—Shawe and others, 1968, p. A91.) Pyrite formed as a result of abundant hydrogen sulfide that was associated with decaying organic material reacting with available iron liberated from black opaque minerals in the detritus, as well as from volcanic ash that became devitrified shortly after deposition. According to Marshall (1961), devitrification in the presence of water even at low temperatures is rapid. Sulfur also was present in the volcanic ash in a variety of forms; the action of bacteria formed hydrogen sulfide and ultimately pyrite, or perhaps it formed pyrite directly. Volcanic activity may have changed in character and (or) location at or about the beginning of late Carlile time (when rocks about 300 feet above the base of the Mancos in the Slick Rock district were deposited), as evidenced by the change in chemical character of the diagenetic pyrite associated with bentonitic beds in the Mancos (Shawe, 1968b, fig. 1).

The salt anticlines continued to grow during deposition of the Mancos Shale. During late middle Greenhorn time, at the start of Mancos deposition, flow of salt from beneath the Disappointment syncline into the Gypsum Valley anticline apparently followed the local pattern established during Dakota time, and perhaps the flow was merely a continuation of the tendency for the light salt to rise in a cupola under the pressure of heavier overlying and surrounding rocks. Tectonic deformation of the salt anticlines may not have been important early in the deposition of the Mancos. However, the salt folds showed additional general growth throughout the remainder of Mancos deposition, and this growth was related to renewal of tectonic stresses.

Near the end of the Cretaceous Period and at the beginning of the Tertiary Period in the region of the Colorado Plateau many thousands of feet of largely terrestrial sediments composed of sand, silt, and mud were laid down as the Mesaverde, Wasatch, and Green River Formations or their equivalents. This rapid filling of the erstwhile marine basin occupying a large part of the western interior of the United States resulted partly from rapid rise of land at the western edge of the Colorado Plateau. This sedimentation was also marked by the unroofing of the Idaho batholith, as evidenced by the sudden appearance of monazite in the detritus, and shows a new and large influx of material from a provenance northwest of the Colorado Plateau.

Faulting and jointing occurred during this time in several fault zones in the region. Fractures were oriented generally northwesterly to westerly, as in the Dolores zone of faults, and northeasterly to easterly as in the Glade zone of faults. Fault zones may have formed above deep-lying shears of strike-slip displacement: for example, left-lateral displacement in the northwesterly Dolores zone and right-lateral displacement in the easterly to northeasterly Glade zone (which approximately overlies the Glade subsurface fault zone).

This crustal deformation—rapid uplift of land areas adjacent to the Late Cretaceous geosyncline, and faulting within the geosyncline—was a manifestation of the great Laramide orogeny that dominated the region of the present Rocky Mountains and the eastern part of the present Great Basin (where it has been referred to as the Sevier orogeny) in latest Cretaceous and early Tertiary time.

Accumulation of the great thickness of sediments above the Mancos Shale caused compaction of the clayey Mancos strata, with the result that a very large volume of reducing, uranium- and vanadium-bearing, Mancos pore water—in the order of thousands of cubic miles—was expelled at the end of Cretaceous time and during early Tertiary time.

(The thesis of uranium- and vanadium-bearing pore water in the Mancos is too lengthy for proper elaboration here; the interested reader is referred to Chapter D of this professional paper (Shawe, 1976) for the details.) Much of this water moved into overlying more porous and permeable strata of the Mesaverde, Wasatch, and Green River Formations and their equivalents; the reducing character of the solutions caused wide-scale reduction of the strata. In additon, some pore water of the Mancos was forced into underlying strata where it followed permeable fracture zones and moved laterally from these into permeable beds. Reduction and leaching occurred wherever the reducing solution flowed; iron was leached from much of the altered rocks, for example, by destruction of detrital black opaque minerals and hematitic coloring material. The iron then became concentrated along fracture zones or in bodies in bedded strata, largely near the edges of the zones of solution flow. Some elements were introduced from the pore water into the altered strata. Uranium and uranogenic lead were deposited almost universally in the altered rocks; locally where carbonized plant debris created a favorable chemical environment for precipitation (high humic-acid content), such as in the ore-bearing sandstone of the Salt Wash Member of the Morrison Formation, abundant uranium, uranogenic lead, iron, vanadium, and some other elements were deposited. These deposits are the uranium-vanadium ores whose occurrence and origin will be discussed in detail in Chapter F in this series.

CENOZOIC ROCKS AND EVENTS

Igneous activity occurred at widely scattered centers in and near the Colorado Plateau during the early to middle Tertiary. Laccolithic bodies of porphyry were intruded at a number of centers in the plateau. In the Abajo Mountains west of the Slick Rock district igneous material intruded a graben in the Glade fault zone that probably formed near the end of the Cretaceous or in the early Tertiary (Witkind, 1964, p. 46, 81). The dominant rock type of the plateau laccolithic centers is diorite porphyry that contains about 62 percent SiO_2; in this porphyry phenocrysts were nearly in equilibrium with the magma at the time of intrusion and solidification. The age of diorite porphyry from the La Sal Mountains northwest of the Slick Rock district is about 55 million years (Stern and others, 1965).

Sills and laccolithic, some of considerable size, and minor dikes, all of intermediate composition, were intruded in a broad area along the eastern edge of the Colorado Plateau near the Slick Rock district to the San Juan Mountains farther east. The dominant rock types are granogabbro and granodiorite with SiO_2 content comparable to or slightly lower than that of the dominant rock type of the Plateau laccolithic centers and with relatively more iron oxides, MgO, K_2O, and TiO_2, and less Al_2O_3, CaO, and Na_2O. Phenocrysts in these rocks were not in equilibrium with the enclosing magma at the time of intrusion and solidification as indicated by strong resorption effects. The age of these intrusives is most likely Miocene. Intrusion of some granogabbro sills near the eastern end of Disappointment Valley seems to have been controlled by a fracture zone, and a dike was emplaced along a fault bounding the Glade graben; these faults probably formed near the end of the Cretaceous or in the early part of the Tertiary. Moreover, emplacement of the sills likely occurred following some post-Cretaceous warping of the Disappointment syncline, but prior to the final extensive folding of the syncline during the late Tertiary or the Quaternary.

Intrustion of diorite porphyry probably was nearly simultaneous in all the Colorado Plateau laccolithic centers, most likely in Eocene time, at the time of maximum burial of the red-beds section beneath the Mancos Shale and the early Tertiary strata overlying it. It occurred at the time Mancos Shale pore waters were being expelled as a result of compaction, and therefore the temperature of the pore waters may have been increased and they thereby became more potent chemically to produce increased leaching and other alterations.

Intrusion of granogabbro and granodiorite along the eastern edge of the Colorado Plateau in Miocene time occurred after the Upper Cretaceous and younger strata had been compacted and after the uranium-vanadium ore deposits had been formed. It had no apparent effect on the ores.

After intrusion of the igneous rocks in the middle Tertiary at the eastern margin of the Colorado Plateau, sedimentary rocks were again folded, probably largely in the early Pleistocene. Erosion along the lower reaches of main river systems on the plateau may have started as early as middle Tertiary, but downcutting of the Dolores River canyon in the Slick Rock district did not begin until after deposition of gravels during the early Pleistocene. The final major folding of the Dolores anticline, and possibly other salt anticlines in the region, occurred only after deposition of the gravels. Possibly the erosion of the canyon in the district was instigated by simultaneous regional uplift of the plateau and growth of the Dolores anticline. The basis for this conclusion is the fact that the Dolores River canyon has been incised to a depth of 2,000 feet in the district, whereas the evidence of the gravels indicates probably only about 1,000 feet of growth of the anticline after the canyon cutting was initiated.

Glacial activity was still taking place in the San Juan Mountains after most of the present Dolores River canyon was excavated. Dormant landslides that must have developed under a climate more moist than that of the present occur in places on the slopes of the canyon, and loess deposited probably during the latest Pleistocene glaciation occurs in small patches deep within the present canyon.

The youngest deposits in the district, formed during the Holocene and in fact still being laid down, are alluvium and various types of colluvium. But the configuration of the land surface has changed little since the Pleistocene. On the other hand, the Dolores anticline still may be growing, judged from the gradient of the Dolores River where it crosses the anticline. Downstream from the vicinity of the anticlinal axis, on the northeast limb of the anticline, the river gradient is about 35 feet per mile, whereas upstream from the axis, on the southwest limb of the anticline, the gradient is about 20 feet per mile. The same formations crop out above and below the point where the anticlinal axis crosses the river, so the only reasonable explanation of the difference in gradient seems to be late growth of the anticline.

THE CURRENT SCENE

A look at the south part of the Slick Rock district today shows a gently rolling highlands plain capped largely by Dakota Sandstone. This plain reflects underlying structure. In the north part of the northeast flank of the Dolores anticline that dips into the Disappointment syncline is a Dakota Sandstone-capped surface incised by long straight canyons which extend to Disappointment Valley. The valley lies in the trough of the Disappointment syncline out of which the easily eroded Mancos Shale has been excavated by the Disappointment Creek drainage. The Dolores River canyon is antecedent, cut by the river which had established its course on a level plain and then incised itself with uplift of the plain and rise of the Dolores and adjacent anticlines. Canyons tributary to the Dolores River developed as a corollary to the downcutting of the river.

A few fault-line scarps have formed in the Dolores zone of faults where sandstone beds are at the surface. An elongate topographic depression coincides with the Glade graben.

Residual hills and terraces of glacial till lie on Glade Mountain at the southeast tip of the district. At least five levels of stream gravels are found along the canyon of the Dolores River and its tributary canyons. An old erosion surface lies just under the highest of these gravels situated on the highland plain in the south part of the district.

Hummocky and irregular surfaces of landslides are found along the walls of deeper canyons, especially on Brushy Basin slopes. Many of the landslides have been extensively eroded. Alluvial fans composed of locally derived material are developed in places; some of these have been partly dissected.

Elongate, shallow depressions paralleled by flat, low ridges and oriented about N 25° E. are developed in Pleistocene loess on the Egnar plain. Those were apparently excavated by prevailing strong winds shortly after deposition of the loess.

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☆U.S. GOVERNMENT PRINTING OFFICE: 1976—677-340/82