Geology of the Salt Anticline Region in Southwestern Colorado

By FRED W. CATER

With a section on STRATIGRAPHY

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A study of the stratigraphy, structure, and geomorphology of an area characterized by large salt-cored anticlines, with a discussion of the growth of the salt cores

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GEOLOGY OF THE SALT ANTICLINE REGION IN SOUTHWESTERN COLORADO

By Fred W. Cater

ABSTRACT

This report deals with the general geology of the salt anticline region of southwestern Colorado and covers an area of about 1,057 square miles. The area lies entirely in the Canyon Lands section of the Colorado Plateaus physiographic province.

Crystalline rocks of Precambrian age and sedimentary rocks that range in age from Pennsylvanian to Quaternary are exposed in the area. The crystalline rocks, consisting of gneiss, schist, and quartzite, crop out only on the Uncompahgre Plateau or along its flanks; they have been extensively intruded by a gray medium-grained somewhat gneissic granite and by a younger pink rather coarse grained granite. Cutting all these rocks are dikes of pegmatite, aplite, and lamprophyre. The sedimentary rocks, with a maximum known thickness of 15,000 feet, are largely nonmarine deposits of conglomerate, arkose, sandstone, and shale. Much of the sandstone was wind deposited. Marine deposits consist of evaporites, limestone, shale, and sandstone.

The oldest of the exposed sedimentary formations, the Hermosa of Pennsylvanian age, comprises two members, the Paradox, composed largely of interbedded salt and gypsum, and an overlying unnamed member of gray, fossiliferous limestone with intercalated minor shale, sandstone, and arkose. Salt and gypsum of the Paradox Member are partly intrusive into younger rocks and form the cores of large salt anticlines. The limestone member of the Hermosa is overlain, in places unconformably, by the Rico Formation of Pennsylvanian age, a formation consisting of alternating beds of limestone and red arkosic conglomerate. These beds mark a transition from marine to nonmarine conditions of deposition, for the Rico grades upward into and interfingers laterally with the Cutler Formation of Permian age. The Cutler is a rudely bedded poorly sorted cross-laminated purplish-red and maroon conglomeratic arkose with scattered thin partings of shale and mudstone. This material, as well as the arkosic debris in the Rico Formation, was derived from the crystalline rocks exposed in the ancestral Uncompahgre highland, an element of the ancestral Rocky Mountains.

An unconformity separates the Moenkopi Formation of Early and Middle(?) Triassic age from the underlying Cutler Formation. The Moenkopi is red to chocolate brown and contains a lower member consisting of indistinctly bedded poorly sorted mudstone, a middle member characterized by crossbedded layers of arkosic sandstone and conglomerate, and an upper member consisting largely of thin- and ripple-bedded shale. Unlike most of the younger formations, the Moenkopi and Cutler Formations wedge out to the northeast against the Precambrian rocks. The Triassic Chinle Formation consists mostly of red shale, mudstone, and sandstone, and it rests unconformably on the Moenkopi. Conformably overlying the Chinle Formation is the Glen Canyon Group of Triassic and Jurassic age. This group comprises, in ascending order, the Wingate Sandstone, the Kayenta Formation, and the Navajo Sandstone. The Wingate and Navajo Sandstones are clean fine-grained cross-laminated massive wind-deposited sandstones, whereas the intervening Kayenta Formation consists of fluvial deposits of red shale, mudstone, and sandstone. Both the Kayenta and the Navajo, like the Cutler and Moenkopi, wedge out northeastward near the front of the Uncompahgre Plateau. The San Rafael Group of Late Jurassic age rests disconformably on the Navajo Sandstone. The Entrada Sandstone consists of two members; the Dewey Bridge, the lower member of the formation, is composed of soft red horizontally bedded siltstone, mudstone, and shale, whereas the overlying member, the Slick Rock, is a reddish-orange clean crossbedded sandstone resembling the Wingate. The Summerville Formation, the uppermost formation of the San Rafael Group, is a remarkably evenly bedded sequence of shale and sandstone with a few thin limestone lenses. The Morrison Formation, the youngest of the Jurassic formations, comfortably overlies the Summervile and comprises two members, the Salt Wash and the Brushy Basin. Both members of the Morrison contain shale, mudstone, sandstone, and a little limestone, although the Salt Wash is characterized by thick layers of resistant interfingering sandstone lenses and the Brushy Basin by nonresistant varicolored evenly bedded bentonitic mudstones. The top of the Brushy Basin Member interfingers with the basal part of the Cretaceous Burro Canyon Formation. The Burro Canyon is made up of gray to red thick lenticular layers of crossbedded conglomeratic sandstone and lesser amounts of predominantly light-green mudstone. The top of the formation is an erosion surface of regional extent on which was deposited the Dakota Sandstone of Late Cretaceous age. The Dakota Sandstone is a resistant formation composed of crossbedded sandstone, carbonaceous shale, and impure coal. The Dakota grades upward into the Mancos, a black thinly bedded marine shale, also of Late Cretaceous age. The Mancos is overlain conformably by the Mesaverde Formation consisting of sandstone and some thin shale layers. The Mesaverde is the youngest of the Cretaceous formations.

Tertiary(?) deposits of poorly sorted rudely stratified conglomerate and fanglomerate occupy valleys formed in the collapsed crests of the salt anticlines. Quaternary sediments include widespread wind-deposited and sheet-wash material, lake deposits in Paradox Valley, terrace gravel, alluvium, and talus debris.

Although the rocks are nearly flat lying over large areas, in places they have been warped into northwest-trending folds and cut by steeply dipping faults. The dominant structural element of the region is the broad northwest-trending uplift that underlies the Uncompahgre Plateau which occupies the northeast part of the mapped area. The monoclinal southwest flank of this upwarp is cut by numerous faults; some bound the Ute Creek graben formed along this flank. Lying southwest of and parallel to the Uncompahgre Plateau upwarp are the Sinbad Valley, Paradox Valley, Gypsum Valley, and Dolores anticlines—large folds having intrusive

cores of salt and gypsum derived from the Paradox Member of the Hermosa Formation. These salt anticlines are unlike the salt domes of the gulf coast region, for they are decidedly linear and apparently originated along faults and possibly folds that formed before and during deposition of evaporites. The salt and gypsum cores of all these anticlines except the Dolores are in part piercement structures; the core of the Dolores anticline is not exposed, but it probably consists only of a thickened roll of salt and gypsum. Except for the Dolores anticline, the anticlines are complicated by pinchouts of formations against the salt and gypsum cores, by cupolas produced by the irregular rise of salt and gypsum, and by numerous collapse features occasioned by the removal of the salt through solution and flowage. Collapse of the crests of the salt anticlines occurred in two stages widely separated in time. The first stage probably occurred in the early Tertiary when the crests of the anticlines were downdropped as grabens; the second stage occurred after uplift of the Colorado Plateau, which began in the Miocene when downcutting streams breached the salt cores and exposed them to removal.

The synclines between the anticlines are simple downwarps that have few of the complexities associated with the anticlines, although drilling data indicate that at least some of the formations thicken in the synclines. Faults, other than those parallel and directly related to the salt anticlines, are few and small, but in the vicinity of Sinbad and Paradox Valleys, systems of sizable faults trend northeast transverse to the regional structural trend.

The evolution of the present topography dates largely from the epeirogenic uplift of the Colorado Plateau. At that time long-continued erosion had reduced the region to a surface of low relief; uplands had been planed off and basins filled. Across this surface meandered the ancestral Dolores River as probably did ancestral La Sal Creek, Coyote Wash, and Dry Creek. As uplift of the plateau progressed, these streams maintained their ancient courses and formed deeply entrenched meanders, but other streams wandered from their former channels and began adjusting to the structure of the underlying rocks. Accordingly, the San Miguel River and Disappointment Creek flow in the troughs of synclines because the channels were displaced laterally by slip-off downdip on more resistant layers, whereas other streams carved out and occupy the collapsed and eroded crests of the salt anticlines. When downcutting streams breached the cores of the salt anticlines, final collapse of the crests of the anticlines began, partly through the removal of salt by solution and partly by the flowage of salt from beneath areas still overlain by thick layers of strata.

In the meantime the Gunnison River began carving Unaweep Canyon as the Uncompahgre Plateau rose athwart its course; still later the Gunnison abandoned Unaweep in favor of its present channel. After Unaweep Canyon was abandoned, the Uncompahgre Plateau rose an additional 2,000 feet and Ute Creek graben formed along its northwest flank. By this time the topography had gained nearly its present form except for minor changes brought about by further denudation and stillstands of erosion.

INTRODUCTION

Salt structures, because of their economic significance and their structural peculiarities, have long excited the interest of geologists. Among the largest of these structures are the salt anticlines that lie along the Colorado-Utah boundary, some of which have salt cores measurable in hundreds of cubic miles. Growing as these anticlines did in the rather narrow and deep part of a tectonically active evaporite basin marginal to the steep front of a rising uplift, they differ in both origin and history of growth from the better known salt domes and plugs of the gulf coast region. The structural dislocation between the ancient basin and highland has been reactivated in latest Cenozoic times with uplift of the Uncompahgre Plateau. Sediments planed from this plateau, however—unlike those of its old predecessor—are not coming to rest nearby in an adjacent basin. They, along with those sediments from the surrounding country, are being removed from the region completely and transported hundreds of miles to the Gulf of California, a process now being interrupted until the reservoirs behind various dams on the Colorado River and its tributaries have silted up, a few hundreds years from now.

This report describes the stratigraphy and structural and geomorphic development of that part of the salt anticline region lying in Colorado, although many of the statements and conclusions apply equally well to the remainder of the region which lies in Utah. This account begins with the Precambrian and ends with the present; many chapters, unfortunately, are missing because no record remains of many probable events.

LOCATION, CULTURE, AND ACCESSIBILITY

The part of the salt anticline region of southwestern Colorado described in this report occupies parts of Mesa, Montrose, San Miguel, and Dolores Counties, covers about 1,057 square miles, and includes the principal uranium- and vanadium-producing district of Colorado. The area is bounded on the west by long 109°00′, on the south by lat 37°52′30″ and 38°00′, on the east by long 108°45′ and 108°37½′, and on the north by lat 38°30′ and 38°45′ (fig. 1).

The area is in the eastern part of the Canyon Lands section of the Colorado Plateaus physiographic province (Fenneman, 1931). To the east rise the San Juan Mountains, a part of the Rocky Mountain System; to the south, west, and north the Canyon Lands extends for many miles, its relatively level aspect broken only by the laccolithic Abajo and La Sal Mountains a few miles west of the mapped area.

The area is sparsely populated. Uravan, a mining town with a population of about 750, is the largest community. Gateway, Bedrock, Paradox, and Egnar are much smaller villages centered in small tracts of agricultural land. In recent years an influx of miners, lured by the high price of uranium and vanadium ore, has greatly increased the population of the area. Most of the miners constitute a shifting population that moves from place to place as older deposits are mined out and new ones discovered. A few small sawmills operate in the timbered areas.

The only hard-surfaced roads within the area are State Routes 90 and 141. Although much of the area remains relatively inaccessible, a rapidly expanding system of dry-weather mine roads and truck trails now traverses areas which but a few years ago were accessible only on foot or by horse.

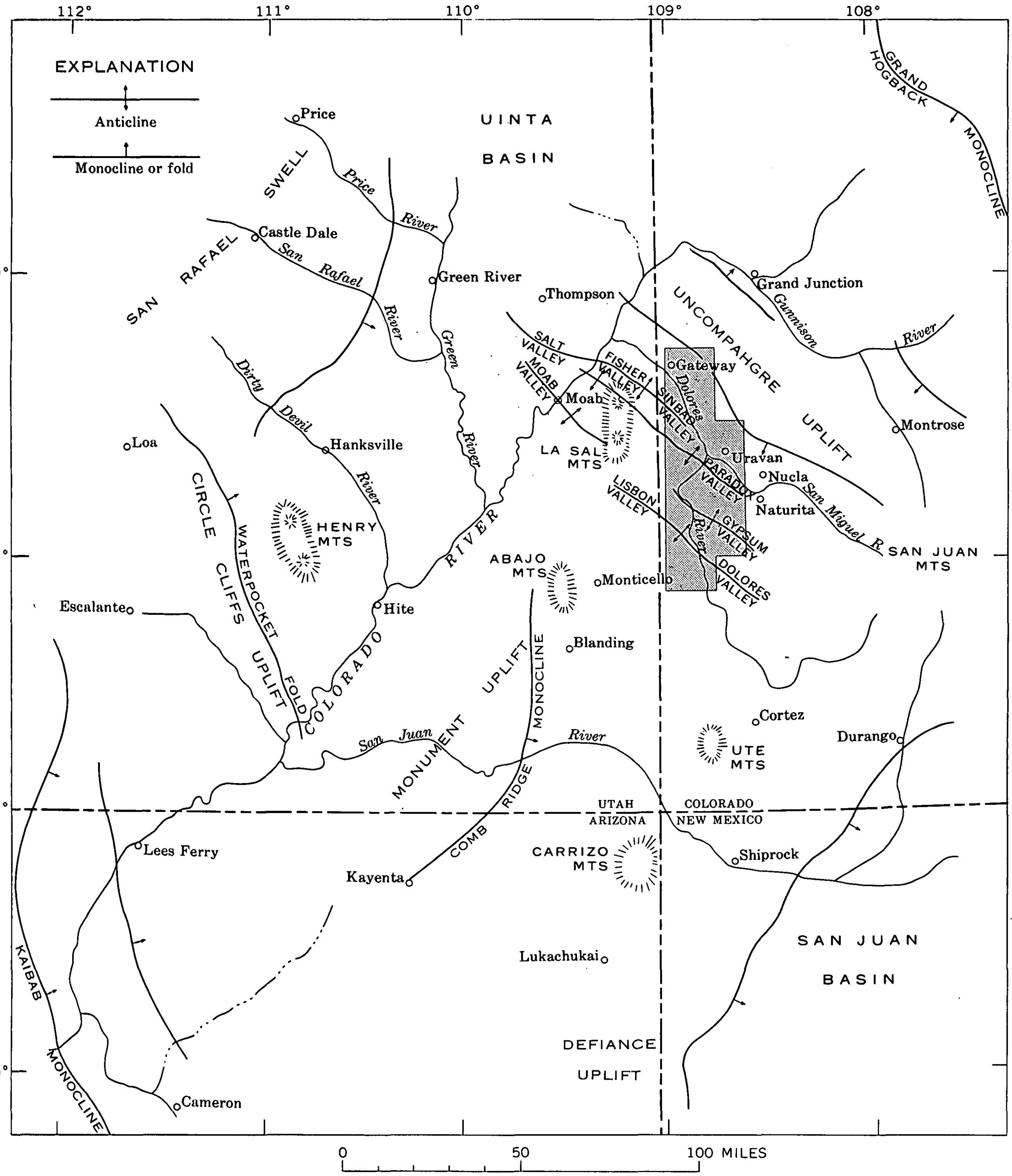


Figure 1.—Tectonic sketch map of part of the Colorado Plateau showing location of report area.

TOPOGRAPHY

Although the Canyon Lands contains many types of topographic features common to the Colorado Plateau as a whole, it is, as the name indicates, preeminently a land riven by countless canyons, many of them so narrow they appear to be mere clefts in the plateau surface. The area described in this report is fairly representative of the Canyon Lands section, although the canyons are not so narrow or so closely spaced as in some other parts of the section. The prevailing grain of the area is northwest, parallel to the structure of the underlying rocks, but this grain is modified greatly over large areas by partly superimposed drainage. The northeast part of the area is dominated by the Uncompahgre Plateau which rises to altitudes of more than 9,000 feet. At the north edge of the area, Unaweep Canyon cuts completely across the plateau and represents an abandoned channel of the Gunnison River. Southwest of the plateau a succession of slightly tilted mesas cut by numerous canyons sweeps down to the San Miguel River and to the brink of the winding Dolores River Canyon, a spectacular gorge that in this part of the area is more than 1,500 feet deep. Southwest of the two rivers the land rises toward the northeast walls of Sinbad and Paradox Valleys. Sinbad Valley is a deep depression completely walled in by nearly vertical cliffs except for one point where the cliffs are breached by Salt Creek Canyon. Separating Sinbad Valley from Paradox Valley is the deep Roc Creek Canyon. Paradox Valley trends northwestward completely across the central part of the area and, like Sinbad Valley, is walled by cliffs and closed at both ends. Near the center of the valley, the Dolores River cuts directly across the valley, entering the valley from one deep canyon and leaving through another. South of Paradox Valley is Dry Creek basin, a broad, shallow nearly featureless synclinal valley that slopes southeast. Northwest of the basin is a precipitous area cut by the Dolores River Canyon and the tributary canyons of Bull and Spring Creeks. Gypsum Valley is somewhat narrower than Paradox Valley, but otherwise resembles it closely. South of Gypsum Valley the Dolores River separates two topographically contrasting areas: to the southeast lies the broad featureless Disappointment Valley; to the west and northwest lies a rugged maze of mesas and canyons. The south end of the mapped area includes part of the generally high and relatively flat Great Sage Plain, into which the Dolores River has carved a canyon more than 2,000 feet deep, the deepest in the mapped area.

The Dolores River Canyon is perhaps the most spectacular topographic feature in a scenically spectacular area. With the exception of where it crosses Gypsum and Paradox Valleys, the Dolores River traverses the area from south to north through a deep canyon. The canyon northward from the southern edge of the area to the mouth of Blue Creek consists of a series of entrenched meanders and is especially sinuous between Gypsum and Paradox Valleys. From the mouth of Blue Creek to where the river leaves the area near Gateway, the course is straight. A number of tributary canyons rival the Dolores River Canyon in depth and grandeur, the largest being those of La Sal and Roc Creeks.

Altitudes in the area range from about 4,540 feet on the Dolores River below Gateway to slightly more than 9,420 feet only 11 miles away on the Uncompahgre Plateau. In many parts of the area, the local relief in a square mile is more than 2,000 feet. Sheer cliffs several hundred feet high wall many of the valleys and canyons and surround many of the buttes and mesas.

Probably more than one-half the surface of the area consists mainly of bare rock; the rest is covered by soil, talus, or landslide material. The topography has a decidedly angular aspect, and breaks in slopes commonly are sharp.

CLIMATE AND VEGETATION

The climate of the area is mostly semiarid but, because of the range in altitudes, annual precipitation varies considerably from place to place. At lower altitudes the precipitation is probably 10–15 inches annually, but above 8,000 feet precipitation is greater and may be as much as 25 inches per year. Accurate precipitation and temperature records of the area are scarce, but July, August, and the winter months are usually wettest. Snow remains on the Uncompahgre Plateau as late as June, but in the canyons and valleys snow rarely remains on the ground more than a few weeks. Rain not uncommonly occurs as violent downpours called "gully washers." The extreme temperature range is from about –20°F to about 105°F, although temperatures below 0°F and above 100°F are infrequent.

The vegetation is of the type common to other parts of the Colorado Plateau and consists at lower altitudes of piñon and juniper on rocky terrain and sagebrush where soils are deep. Cottonwood, willow, and tamarisk border the streams. At higher altitudes scrub oak, serviceberry, and chokecherry are common; above 8,000 feet and locally in favored spots at lower altitudes, ponderosa pine, fir, spruce, and quaking aspen form groves. Several varieties of cactuses and sparse grass are widely distributed.

DRAINAGE AND WATER SUPPLY

The master stream in the area, the Dolores River, heads in the San Juan Mountains, flows south to southwest, and then turns north and traverses the entire length of the area covered by this report. During the summer the river consists of little more than a series of connected pools. The San Miguel River, its principal tributary, flows northwestward across the central part of the areas and empties into the Dolores a few miles below Uravan. The San Miguel River also heads in the San Juan Mountains, and during the summer it normally carries more water than the Dolores.

Most of the tributaries of the Dolores and San Miguel Rivers are small and intermittent. Only four perennial streams enter the Dolores River from the west. These are, from south to north, La Sal Creek, West Paradox Creek, Roc Creek, and Salt Wash; all but Salt Wash deliver fairly large flows of water throughout the year. From the east no permanent streams enter the Dolores River south of the

San Miguel River, but Mesa Creek, Blue Creek, and West Creek enter north of the mouth of the San Miguel; of these streams West Creek is the largest, and water drawn from it is used to irrigate considerable acreage. Tabeguache Creek is a permanent stream that drains a large area along the southwest flank of the Uncompahgre Plateau and is the largest tributary of the San Miguel River. Other permanent streams draining into the San Miguel are Calamity Draw and Dry Creek. The waters of Dry Creek and Salt Wash especially have high mineral content.

Other streams that enter the Dolores and San Miguel Rivers directly are intermittent or flow perennially only in the short stretches immediately downstream from springs. Many, nevertheless, have large drainage basins and for short periods during and following storms become raging torrents of muddy water.

Springs, in general, are few and scattered, but north of the town of Paradox several large springs which furnish considerable irrigation water issue from the northeast wall of Paradox Valley. In several localities dams have been erected across small channels to store runoff for stock. During wet years reservoirs formed by these dams may contain water for long periods.

PREVIOUS WORK

The first report dealing with the geology of the area was that of Peale (1877), which covered the results of his reconnaissance work of 1875–76. During the summer of 1875 he traversed Unaweep Canyon and the country north of Paradox Valley, and the following summer, the country from Paradox Valley to the north edge of the Great Sage Plain. A. C. Spencer visited Paradox and Sinbad Valleys in 1899, and his general observations are included in an article by Cross and Howe (1905). Later, Cross (1907) studied the rocks in Sinbad and Paradox Valleys and along the crest of Uncompahgre Plateau to Unaweep Canyon.

The most comprehensive of the earlier investigations was that of Coffin (1921) who, starting in 1914, spent parts of five summers mapping an area extending from near Gateway southward to McElmo Creek, about 25 miles south of the area included in this report. In addition, reports primarily concerned with the uranium and vanadium deposits have been published; the most comprehensive of these are by Fischer (1937) and Hess (1914, 1933).

FIELDWORK AND ACKNOWLEDGMENTS

In 1941, the systematic geologic mapping on which this report is based was begun in Paradox Valley by A. P. Butler under the general supervision of R. P. Fischer. During parts of 1944 and 1945 the Egnar–Gypsum Valley area was mapped by W. L. Stokes, D. A. Phoenix, R. P. Fischer, and L. E. Smith (Stokes and Phoenix, 1948). The remaining area was mapped during 1947–51 by F. W. Cater, who was ably assisted at different times by E. J. McKay, E. M. Shoemaker, C. M. Withington, and L. R. Stieff. This work was done on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission. In addition to this new mapping, some of the earlier mapping was revised in order to show details permitted by the better base maps that became available after 1947. The results of this work were published as a series of 18 quadrangle maps, with short descriptive texts, at a scale of 1:24,000 (Cater, 1954, 1955a–k; Cater and others 1955; McKay, 1955a, b; Shoemaker, 1955, 1956a; Withington, 1955). From these maps, plate 1 of this report has been compiled at a smaller scale so as to form a single map; certain errors appearing in the original series have been corrected.

Most of the detailed stratigraphic sections in this report were measured by L. C. Craig, C. N. Holmes, and their associates during a stratigraphic investigation of the Colorado Plateau, another phase of the study of carnotite deposits in the plateau region sponsored by the Atomic Energy Commission. R. A. Cadigan furnished information concerning the composition of the sediments in many of the formations.

We are indebted to various other members of the U.S. Geological Survey for geologic information and discussion of problems, especially to R. P. Fischer, whose extensive knowledge of Colorado Plateau geology was a significant aid, to Lloyd Henbest for his help on problems of correlation, and to D. R. Shawe, D. P. Elston, ad E. R. Landis for some revisions in the mapping in the Slick Rock and Paradox Valley areas.

MAPPING AND METHODS OF COMPILATION

The Colorado Plateau is preeminently suited to geologic mapping on aerial photographs. Exposures generally are excellent, and the formations are sufficiently distinctive that they stand out with remarkable clarity on aerial photographs. Therefore nearly all the field mapping was done on contact prints of aerial photographs having a scale of about 1:27,000. The geology was then transferred to the topographic base map with a Wernstedt-Mahan stereoscopic plotter. This method was found to be both fairly accurate and convenient.

STRATIGRAPHY

By Fred W. Cater and Lawrence C. Craig

GENERAL FEATURES

The mapped area consists of crystalline rocks of Precambrian age and sedimentary rocks that range in age from Pennsylvanian to Quaternary. The crystalline rocks crop out in Unaweep Canyon and along the flanks of the Uncomahgre Plateau in the northern and northeastern parts of the area and consist principally of granitic intrusive rocks. Small amount of gneiss, schist, and quartzite occur locally. Dikes are numerous. The rest of the area is underlain by generally flat-lying sedimentary rocks with a known maximum thickness of more than 15,000 feet. Most of these rocks are nonmarine conglomerates, arkoses, sandstones, and shales. A large proportion of the sandstone was wind deposited. Exposed beds of undoubted marine origin were deposited only during the Pennsylvanian Period and the latter part of the Cretaceous Period.

The oldest of the exposed sedimentary rocks are intrusive masses of salt and gypsum of Pennsylvanian age that crop out extensively in the cores of the anticlines that underlie Sinbad, Paradox, and Gypsum Valleys. Unlike most salt structures which begin forming only after deep burial of the salt, some upper surfaces of these cores—for reasons to be explained later in this report—were above levels of sedimentation from the time salt deposition ceased until Morrison time in the Late Jurassic. These cores, therefore, exercised a controlling influence on the thickness and distribution of all intervening formations. Against the flanks of some of these salt cores all the intervening formations wedge out, whereas against the less active cores some formations merely thin. Overlying the salt and gypsum beds along the sides of the valleys are Pennsylvanian marine limestones that grade upward into a thick sequence of continentally deposited conglomerate and arkose of Pennsylvanian and Permian ages. The conglomerate and arkose are widely exposed along the walls of the salt anticline valleys, in the valley of West Creek, and along the flanks of the Uncompahgre Plateau. The arkosic beds wedge out against the Precambrian crystalline rocks on the flanks of the Uncompahgre Plateau.

Lower Triassic shale, sandstone, and arkosic conglomerate unconformably overlie Permian rocks and are exposed in the same general areas as the Permian rocks. These rocks wedge out both along the southwest front of the Uncompahgre Plateau and, because of nondeposition, against the salt and gypsum intrusions whch had reached the surface before Triassic time. Upper Triassic shale and sandstone rest unconformably on the Lower Triassic beds. The Upper Triassic beds are exposed in the valley walls formed in the salt anticlines, along the deeper canyons, and on the flanks of some buttes and mesas.

The Jurassic formations are widely exposed over a large part of the area and crop out as colorful clffs, slopes, and benches. Except for the Morrison Formation they consist largely of sandstone and wedge out at one place or another against the salt and gypsum intrusions. The Morrison contains large quantities of shale and mudstone in addition to sandstone, and it either completely or almost completely blanketed the intrusions.

The Cretaceous formations consist of marine shale and stream-deposited conglomerate, sandstone, and shale. The stream-deposited conglomerate and sandstone form the capping beds on many of the mesas and the floors of the synclinal valleys; the marine shale occurs only in the lower parts of the synclinal valleys or in downdropped fault blocks. Unlike most of the older formations, the Cretaceous rocks were deposited as a blanket of fairly uniform thickness over the entire area.

No rocks of unquestioned Tertiary age now exist within the area, although some conglomerates at the southeast end of Gypsum Valley are probably that old. Quaternary deposits of slightly to thoroughly lithified fanglomerate, partly consolidated shale and sandstone, and terrace gravels are common locally. Deposits of windblown material and sheet wash are widespread on mesas and in some of the valleys.

The southwest front of the Uncompahgre Plateau marks the northeast edge of the uppermost Paleozoic and Lower Triassic formations. These formations wedge out abruptly because of nondeposition or because of erosional truncation against the ancestral Uncompahgre highland, which contributed much of the material making up these formations. The southwestern front of this old highland is followed closely by the front of the present Uncompahgre Plateau. Upper Triassic and Lower Jurassic formations blanket the old highland in the area of this report, but eastward they gradually thin and wedge out. Upper Jurassic and Cretaceous rocks completely blanketed the entire region, including the ancestral Uncompahgre highland.

PRECAMBRIAN ROCKS

The Precambrian rocks are exposed only along the deeply dissected parts of the Uncompahgre Plateau in the drainage of West Creek and in the canyons cut by the headwaters of Ute, Blue, Mesa, and Atkinson Creeks. The most extensive outcrops are in the extreme northeastern part of area in several square miles along the precipitous slopes and canyons bordering the Uncomaphgre Plateau.

Because of time limitations no attempt was made to map the complex of interrelated Precambrian igneous and metamorphic rocks. The oldest rocks of the Precambrian complex are quartzite, hornblende and biotite gneisses, and schist. These occur sparsely in later granites as small isolated masses that have undergone varying degrees of transformation. No masses of these older metamorphic rocks are sufficiently large or continuous to permit working out the probable age relations. They are believed to belong to the series of ancient gneissic rocks in adjacent areas to the northwest described by Dane (1935, p. 20–24) and Case (1966, p. 1425–1433).

Most abundant of the rocks in this Precambrian complex is a medium-grained gray biotite-hornblende granite that in most places has a distinct gneissic texture. In the southernmost parts of the area of Precambrian rocks, the gray gneissic granite far surpasses all other rocks in quantity, but northward later intrusive rocks form an increasingly large proportion of the whole. The granite intrudes the gneisses and quartzites and, within the mapped area, completely engulfs and surrounds all masses of the metamorphic

Sedimentary rock formations exposed in the salt anticline region of southwestern Colorado

System	Series	Stratigraphic unit		Thickness (feet)	Character
Quaternary	Holocene			0–20	Talus, alluvium, and wind-deposited material.
	Pleistocene			0–200	Talus, landslide deposits (in part of Holocene age), fanglomerate, lake beds, and undifferentiated stream deposits.
			Unconformity		
Tertiary (?)	Pliocene (?)			(1)	Gravel composed of pebbles and boulders of porphyritic igneous rock.
			Unconformity		
Cretaceous	Upper		Mesaverde Formation	(2)	Thick-bedded yellowish-gray sandstone and light-gray shale.
			Mancos Shale	2,000±	Dark-gray fissile shale.
			Dakota Sandstone	70–220	Yellow lenticular sandstone and conglomerate; interbedded carbonaceous shale and impure coal.
			Unconformity		
	Lower		Burro Canyon Formation	50–300	White, gray, and red sandstone and conglomerate; interbedded green and reddish-purple shale.
Jurassic	Upper		Morrison Formation	300–750	Brushy Basin Member; variegated bentonitic shale and mudstone; rusty-red and red sandstone and conglomerate; local thin limestone beds.
				240–440	Salt Wash Member; white, gray, buff, and rusty-red sandstone; red, reddish-brown, green, and gray mudstone: scattered thin limestone beds.
			Summerville Formation	0–100	Thin-bedded red, gray, green, and brown sandstone, sandy shale, and mudstone.
		San Rafael Group	Entrada Sandstone	0–225	Slick Rock Member; orange, buff, and white fine-grained massive and crossbedded sandstone.
				0–100	Dewey Bridge Member; red, buff, and orange horizontally bedded mudstone, siltstone, and sandstone.
			Unconformity		
		Glen Canyon Group	Navajo Sandstone	0–500+	Buff and gray crossbedded fine-grained sandstone.
Triassic (?)	Upper		Kayenta Formation	0–300	Irregularly bedded red, buff, gray, and lavender fine- to coarse-grained sandstone, siltstone, and shale. A few lenses of conglomerate.
			Wingate Sandstone	0–500	Fine-grained reddish-brown thick-bedded, massive, and crossbedded cliff-forming sandstone.
Triassic	Upper		Chinle Formation	0–750	Red to orange-red siltstone with interbedded lenses of red sandstone, shale, and limestone-pebble and clay-pellet conglomerate. Lenses of quartz-pebble conglomerate and grit at the base.
			Unconformity		
	Middle (?)		Moenkopi Formation	0–500	Upper member; chocolate-brown ripple-bedded shale; thin lenses of arkosic sandstone.
	Lower			0–290	Middle member; chocolate-brown arkose, arkosic conglomerate, and ripple-bedded shale.
Triassic (?)				0–300	Lower member; reddish- to yellowish-brown indistinctly bedded poorly sorted mudstone. Local gypsum beds near base.
			Unconformity		
Permian			Cutler Formation	0–9,000+	Maroon, red, light-red-mottled, and purple conglomerate, arkose, and arkosic sandstone; thin beds of sandy mudstone.
Pennsylvanian	Upper and Middle		Rico Formation	0–150?	Maroon, red, light-red-mottled, and purple conglomerate, arkose, and arkosic sandstone; interbedded red and gray marine limestone.
			Local unconformity		
	Middle		Hermosa Formation	2,000–2,200	Limestone member; gray fossiliferous limestone and thin beds of shale; minor arkose.
				(2)	Paradox Member; sandstone, arkose, carbonaceous shale, limestone, gypsum, and salt.

[1] Unknown; perhaps several hundred feet.
[2] Unknown.

rocks. The gneissic layering in the rock is exceedingly irregular, and no dominant trend could be determined; on the other hand, dips are consistently either vertical or near vertical.

Cutting the gneissic granite are dikes and irregular masses of pegmatite, aplite, lamprophyre, and coarse-grained pink two-mica–hornblende granite. The granite is the most abundant of these rock types in the northern part of the area, especially in the vicinity of Unaweep Canyon. This granite appears to be the same that Dane (1935, p. 20–24) described as the predominant intrusive rock in nearby areas to the north and northwest. In places it is somewhat porphyritic, with euhedral microcline phenocrysts. The accessory mineral sphene is notable for both its relative abundance and the size of individual crystals, many of which are as much as 2 mm (millimeters) long.

Although no direct field evidence exists for any but a pre-Permian age within the area covered by this report, geologists have been in general agreement that the rocks are Precambrian. Peale (1877, p. 64–69) assigned an Archean age to the metamorphic rocks of the Uncompahgre Plateau; later Cross (1907, p. 676–677) confirmed the possible Archean age of the gneiss and schist but believed the quartzite to be correlative with the quartzites of the San Juan Mountains near Ouray, Colo., which were presumed to be Algonkian. The granitic intrusions were believed to be later Algonkian. Hunter (1925) believed the schists and gneisses of the Gunnison to be of Archean age and the granitic intrusives to be of late Algonkian or early Paleozoic age. A granite from East Creek in Unaweep Canyon a few miles northeast of the mapped area, however, gives ages ranging from 1.05 to 3.18 b.y (billion years), depending on the method used; the potassium-argon age of 1.36 b.y. and the rubidium-strontium age of 1.37 b.y. probably are best (Davis and others, 1956). This rock from East Creek appears to be younger than either of the granites in the mapped area because it is devoid of any effects of regional metamorphism (Shoemaker, 1956b), and therefore the data available point to the probability that the quartzite and the intrusive rocks, at least, are older than formerly believed.

PENNSYLVANIAN SYSTEM—HERMOSA FORMATION

The Hermosa Formation of Pennsylvanian age contains the oldest sedimentary rocks exposed in the mapped area. It consists of two members—a lower, the Paradox, largely evaporites, and an upper unnamed member, largely limestone.

PARADOX MEMBER

The Paradox Member of the Hermosa crops out only in the floors of Sinbad, Paradox, and Gypsum Valleys where it forms the cores of anticlines. It is also exposed in similar valleys in neighboring areas in Utah (Baker and others, 1933). The topography on the Paradox is distinctive and in most places consists of low gently rounded hills, but where cut by gullies it is highly irregular, rough, and complex and forms badlands and cutbanks with nearly vertical fluted walls (fig. 2). All outcrops of the Paradox are so intricately and complexly folded, faulted, and brecciated that it was not possible in the time available to work out even the general stratigraphic sequence of beds or to distinguish with absolute certainty between certain limestone beds in the Paradox and limestone beds of either the upper member of the Hermosa or the Rico Formation. The stratigraphic relations have been disturbed further by the solution and removal of saliferous layers to a depth of several hundred feet. Nowhere is the base of the Paradox exposed, nor, for that matter, has an unquestionably undisturbed upper contact with the overlying limestone member been found.

Surface exposures consist of gypsum, limestone, shale, and sandstone. Gypsum is probably the most abundant material in the Paradox, especially in Gypsum and Paradox Valleys; in Sinbad Valley, gypsum is less abundant than shale. Porous, earthy or sugary, white gypsum is commonest. In some outcrops selenite crystals are very numerous, both as a sort of surface incrustation and mixed with loose powdery gypsum below the surface. In many places porous sugary gypsum gives a hollow sound when walked upon. Thick beds of compact crystalline rock gypsum, banded white and shades of gray and blue, are common and are exposed best where the gypsum has been deeply incised. Mixed with the gypsum are minor quantities of clay and sand. Dark-gray to black thin-bedded highly crumpled shale is the next most abundant rock in surface exposures. Carbonaceous material is abundant, and fresh specimens of the shale commonly have a decided petroliferous odor. Much of the shale is gypsiferous, and some has scattered molds of salt crystals. Beds are generally paper thin, and ripple bedding seems to be nonexistent. Alternating with beds of shale are layers of fine-grained gray and green sandstone as much as 3 inches thick. In some outcrops thicker beds of sandstone not associated with shale occur, and in Sinbad Valley beds of arkosic coarse-grained

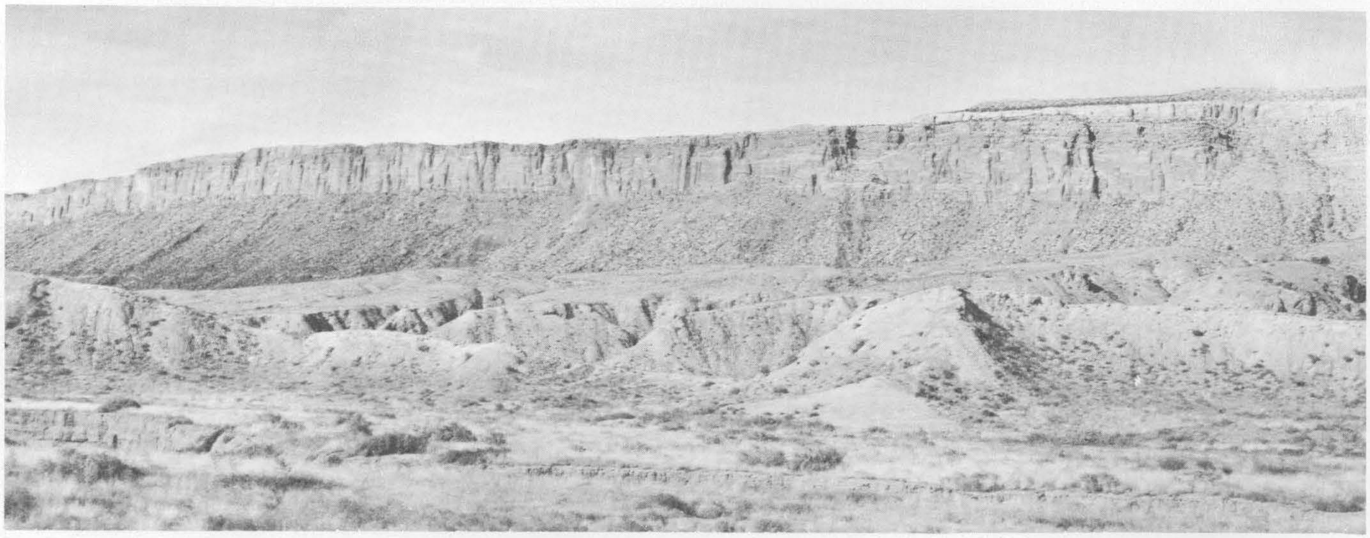


FIGURE 2.—View northward across Paradox Valley. Low hills on valley floor are outcrops of the Paradox Member of the Hermosa Formation; dark cliffs on left skyline are of Wingate Sandstone; light cliffs above on right are of Entrada Sandstone about 100 feet thick.

sandstone crop out. The sandstone consists principally of angular grains of quartz and of lesser quantities of orthoclase, microcline, plagioclase, and dark minerals, the last of which give some of the sandstone a pepper-and-salt appearance. Considerable glauconite is present in most of the sandstone. The cement of both sandstone and arkose consists of calcite and clay. The angularity of the sand grains and the fresh feldspar of the arkosic sandstone in Sinbad Valley indicate that the ancestral Uncompahgre highland to the northeast had already risen to a point where Precambrian crystalline rocks were being eroded, although the abundance of grains having the optical properties of glauconite points to marine conditions of deposition of the sandstone. Extensively exposed in some areas, especially in Paradox Valley, are beds of fine-grained nonfossiliferous limestone. In contrast to the upper limestone member of the Hermosa, the limestone in the Paradox Member is rather thin bedded and flaggy and typically weathers to form flakes 1–2 inches across. Much of the limestone is rather sandy.

In many places where younger formations such as the Rico or Chinle rest with depositional contact on the Paradox, a peculiar breccia in a layer as much as 8 feet thick separates the crumpled Paradox beds from the overlying formation. This breccia seeems to have formed by a mixing, while still unconsolidated, of material similar in composition to that of the overlying beds with fine-grained detritus from the underlying Paradox.

Although no rock salt is exposed, well logs (Shoemaker and others, 1958) shows that the amount of salt in the Paradox Member ranges from about 42 percent in the Sinbad Valley anticline to 82 percent in the Lisbon Valley anticline in Utah but is more than 70 percent in all the salt anticlines of the region except the one underlying Sinbad Valley. According to these logs the Paradox also averages 18 percent shale and siltstone, 4 percent gypsum and anhydrite, 3 percent limestone and dolomite, and 2 percent sandstone and conglomerate. Logs of several wells drilled into the Paradox in Colorado and Utah indicate that salt has been leached out to depths ranging from 600 to 1,000 feet. Active leaching is still continuing as is shown by salt-water springs entering the streams that drain the salt anticline valleys. Late in the summer when the water is low, the Dolores River, below Paradox Valley, is salty, as is the stream in Salt Wash which drains Sinbad Valley.

No undisturbed section of the Paradox Member of the Hermosa is known, and it is doubtful that any entirely undisturbed sections have ever been drilled. Because of these circumstances, estimates of the original thickness are subject to a high degree of error. Of the wells thus far drilled into the cores of the salt anticlines, only one, drilled late in 1958 by the Continental Oil Co. in sec. 8, T. 47 N., R. 18 W., in West Paradox Valley, penetrated the salt core. It entered pre-Paradox rocks at a depth of 14,345 feet. It seems entirely possible that the Paradox may have a comparable thickness under the other similar anticlinal valleys. If it is assumed that the material in the intrusive cores of the anticlines was squeezed from the intervening synclinal areas, material thinning from an overall thickness of about 4,000 feet in the vicinity of Paradox Valley to about 3,000 in the vicinity of Gypsum Valley would be required to account merely for the excess now in the anticlinal cores. Inasmuch as the cores of these anticlines were exposed at the surface from Permian to Late Jurassic time and presumably were subject to extensive solution during this time, it apparently can be assumed that the original undisturbed thickness of the Paradox was considerably more than these figures.

LIMESTONE MEMBER

Although no undisturbed contact between the Paradox Member and the limestone member of the Hermosa Formation has been observed, the limestone member probably was deposited conformably upon the Paradox. The limestone member is exposed mainly along the sides, and locally nearer the central parts, of Sinbad, Paradox, and Gypsum Valleys. The outcrops form steep slopes or cliffs where exposed in the valley walls and low rounded hills where exposed nearer the center of the valleys. Almost without exception the beds exposed in the outcrops are steeply dipping. At no place is a complete section of the limestone member exposed, and in many places the exact stratigraphic position of outcrops is indeterminate. In general only the upper part of the member crops out along the sides of the valleys, but even in some of these locations, as in Little Gypsum Valley, there was an unknown amount of erosion of the upper beds in pre-Late Jurassic time. Consequently the member is overlain unconformably by formations ranging in age from Pennsylvanian to Late Jurassic.

The limestone member of the Hermosa Formation consists predominantly of thick-bedded gray fossiliferous limestone, which is intercalated with thin beds of shale, sandstone, and less commonly arkose. Crinoid stems are abundant in most of the limestone, but other fossils are not abundant within the mapped area except at the southeast end of Gypsum Valley where fossil brachiopods, corals, gastropods, and other invertebrates are abundant. Inasmuch as extensive collections of fossils from the Hermosa Formation have been made (Dane, 1935, p. 35; McKnight, 1940, p. 24–25), collections were not made during the present study.

Thin beds of shale, sandstone, and arkose are interbedded with the limestone. The shale is commonly gray or various tones of light buff and is thin and evenly bedded; no ripple marks were observed. Sandstone is abundant and mostly gray or yellowish gray. It consists of angular grains of quartz with some feldspar and small amounts of dark minerals; the cement is calcite. The arkose is compositionally very similar to the arkose in the overlying Rico and Cutler Formations, but commonly the color is lighter and less strikingly red. It is coarse grained (pebbly in places) and has rock and mineral fragments which can be matched in the Precambrian rocks of the Uncompahgre Plateau. Arkose is more common in the limestone member of the Hermosa in Sinbad Valley than in Paradox or Gypsum Valleys. Dane (1935, p. 34) described a partial section of the Hermosa Formation above the Paradox Member from Fisher Valley, Utah, that is 855 feet thick and consists very largely of sandstone and arkosic sandstone. It is worthy of note that cuttings from wells in the flanks of Paradox Valley which have penetrated the limestone member indicate a considerable quantity of red arkosic material interbedded with the limestone. In view of the fact that nowhere in the valley is there much arkosic material interbedded with the limestone, the well cuttings may have been badly contaminated with debris sloughing from the arkosic Cutler Formation in the upper parts of the drill holes.

The thickness of the limestone member of the Hermosa Formation in this area is not accurately known but is probably about 2,000–2,200 feet. At the southeast end of Gypsum Valley, about 1,000 feet of limestone is exposed without revealing the base of the member; elsewhere the exposed parts of the member are much thinner. The most accurate information concerning the thickness is that from the Chicago Corporation well on the Dolores River south of Bedrock. About 2,250 feet of beds probably belonging to the limestone member was penetrated by this well.

To the northwest in the Moab area of Utah, 1,500–1,800 feet of the limestone member of the Hermosa has been penetrated by wells (Baker, 1933, p. 19), whereas to the southeast in the San Juan and La Plata Mountains the Hermosa Formation, including any beds equivalent to the Paradox Member, ranges in thickness from 1,800 to 2,800 feet (Eckel, 1949, p. 9–13; Cross and Spencer, 1900, p. 48–59). The Hermosa of the San Juan Mountains is marginal to the so-called Paradox Basin where the thick accumulations of evaporites forming the Paradox Member were deposited. In all probability the limestone member was thicker in the Paradox Basin area than corresponding beds in the marginal areas. The limestone member probably correlates with at least a part of the Honaker Trail Formation (Wengerd and Matheny, 1958, p. 2075) of southeastern Utah.

PENNSYLVANIAN AND PERMIAN SYSTEMS— RICO AND CUTLER FORMATIONS

The Rico and Cutler Formations were not generally mapped separately in this area because in many places it is difficult if not impossible to recognize a distinct Rico unit. The Rico Formation has long been a subject of uncertainty and disagreement not only as to what beds should be included but also as to age; moreover, the advisability of recognizing the Rico as a formation has been questioned, and certainly within the area of this report there are only a few localities where such recognition seems justified.

The name Rico Formation was given to a sequence of beds in the San Juan Mountains which are well exposed near the town of Rico (Cross and Spencer, 1900, p. 59–66). These beds are transitional between the Hermosa and Cutler Formations and consist of sandstone, arkose, minor interbedded shale, and fossiliferous limestone. In the area covered by this report, such beds occur only locally; elsewhere no such transitional beds between the Hermosa and Cutler Formations are recognizable, and rocks lithically identical to the Cutler rest directly on the Hermosa.

Rocks lithically similar to those of the Rico Formation are exposed locally in and along the sides of Sinbad, Paradox, and Gypsum Valleys. Some of the best and most extensive outcrops of such rocks are in secs. 22 and 26, T. 48 N., R. 19 W., at the northwest end of Paradox Valley. Rocks having Cutler lithic characteristics are exposed extensively in the sides of the salt anticline valleys, in the canyon of the Dolores River above Gateway and south of Joe Davis Hill, and over large areas in the valley of West Creek and adjacent to the southwest front of the Uncompahgre Plateau.

In general, the Rico and Cutler Formations rest conformably on the Hermosa, but detailed mapping by Elston and Landis (1960) in East Paradox Valley shows that the Rico and Cutler, because of structural complications introduced because of growth of the salt core underlying the valley, rest unconformably on both the limestone member and the Paradox Member of the Hermosa Formation in a few places. In the northeastern part of the area, the Cutler rests on a surface of considerable relief carved on the Precambrian crystalline rocks. The upper contact of the Cutler is an unconformity. The Rico and Cutler consist predominantly of maroon, purple, red, and light-red-mottled arkosic sandstone, arkose, and arkosic conglomerate. Interbedded with the arkosic material are small quantities of reddish-brown sandy mudstone and at the base in some areas thin beds of sandy and muddy limestone. The limestone-bearing parts of this interval, of course, more nearly resemble the Rico in its type locality than they do the Cutler. The arkosic material is poorly sorted, forms rudely crossbedded layers and lenses, and consists of quartz, fresh feldspar, dark minerals, and pebbles, cobbles, and boulders of granite, gneiss, schist, and quartzite—materials derived almost entirely from the Precambrian crystalline rocks. The small amounts of reddish-brown sandy mudstone are distributed through the coarser material as thin irregular seams that serve to delineate the otherwise obscure bedding. Bleached spheres resulting from a change of the red color of the rocks to a light green or greenish gray are very common in many places. These spheres range in size from a fraction of an inch to as much as 1½ inches across and invariably contain a nucleus consisting of a dark grain of an undetermined mineral. In a few localities, notably in Paradox Valley in secs. 15, 22, and 23, T. 47 N., R. 18 W., and in the southeast end of Gypsum Valley, a few thin limestone beds are interlayered with the lowermost red arkosic beds. The limestone is impure and commonly consists of angular fragments

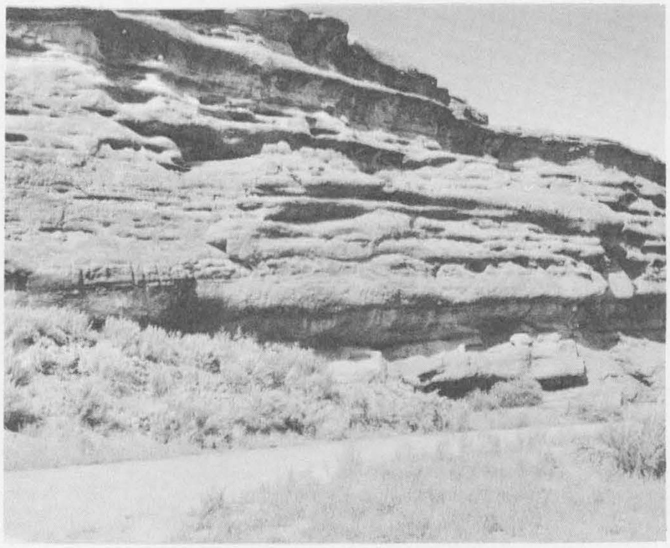


FIGURE 3.—Exposure of the Cutler Formation in the Dolores River Canyon a few miles south of Gateway, Colo.

of limestone cemented in a matrix of the same material. In other localities arkosic debris devoid of limestone interbeds rests directly on Hermosa limestone, so lateral variations in the lowermost beds are marked.

A pronounced regional difference in bedding and grain size exists in the Cutler Formation. In the northeastern part of the area where the formation rests in part upon the Precambrian crystalline complex, the Cutler is bouldery, consists of unweathered granite debris, and has extremely crude bedding (fig. 3). Attitudes of the bedding near the base conform closely to the slopes of the irregular hilly surface on which the debris was deposited. The general lithic characteristics are those of an arkosic fanglomerate. Southwestward the materials become progressively finer grained and the feldspar and dark minerals more decomposed, the clay content increases, and the bedding becomes more clearly defined. Much of the Rico and Cutler in Paradox Valley is not conspicuously conglomeratic; boulders are not abundant. The Cutler exposed in the Dolores River Canyon south of Joe Davis Hill is much finer grained and more evenly bedded than farther north, and it consists mostly of sandstone and arkosic sandstone with interbedded thin layers of mudstone and fissile ripple-bedded shale; however, even the finest grained shale contains abundant mica flakes coating bedding surfaces.

THICKNESS

The Rico and Cutler Formations form a thick asymmetric lens that wedges out abruptly to the northeast and thins gradually to the southwest and southeast. On the southwest flank of the Uncompahgre Plateau, these formations wedge out entirely (fig. 4), but 4–5 miles to the southwest they thicken to several thousand feet. In the Dolores River Canyon a few miles downstream from Gateway, north of the mapped area, a well collared several hundred feet below the top of the Cutler penetrated more than 7,800 feet of arkosic material before reaching the Precambrian basement. Moreover, the upper beds of the Cutler in this area were stripped off by Late Permian or Early Triassic erosion. Therefore, it seems entirely possible that locally the original thickness of these formations may have been as much as 10,000 feet. Farther to the south and southwest in the trough of the Dolores–San Miguel syncline, the thickness probably is about 13,000 feet, although no thickness approaching this is exposed. South and southwest of the Dolores anticline, these formations thin appreciably. In addition to the regional differences in thickness, which consist first of a rapid thickening southwestward from the line of pinchout and then of thinning farther to the southwest, data from wells drilled near Nucla, Colo., indicate that these formations probably thin southeastward along the front of the Uncompahgre Plateau, parallel to the line of pinchout. No detailed sections of the Rico and Cutler were measured because of the uniformity of lithic characteristics from top to bottom.

AGE AND CONDITIONS OF DEPOSITION

The only fossils that have been found in this interval in this area are some fusulinids and pelecypods from Paradox and Gypsum Valleys that probably belong in the Rico. Fossils from rocks having Rico lithic characteristics in Paradox Valley north of the town of Paradox were identified by Lloyd G. Henbest of the Geological Survey as Late Pennsylvanian in age, probably late Virgil, or possibly as old as middle Virgil. Vertebrate fossils from the upper part of the Cutler in the San Miguel River Canyon near Placerville, Colo., have been identified by Lewis and Vaughn (1965, p. C39–C42) as being of Early Permian age. The Cutler Formation, in accordance with Geological Survey age designations, is still classed as Permian. In the area of this report, much of the Rico and possibly all the Cutler are Pennsylvanian.

The sedimentary structures and the coarseness of the material in the Rico and Cutler Formations indicate rapid deposition, and the composition of the material indicates that nearly all of it was derived from the ancestral Uncompahgre highland. The alternation of continental deposits with marine deposits in the Rico Formation in Paradox and Gypsum Valleys represents a transitional stage occurring either as the Hermosa sea was filled or as it retreated. The presence or absence of limestone interbeds in the lower part of the Rico and Cutler may indicate the degree of proximity

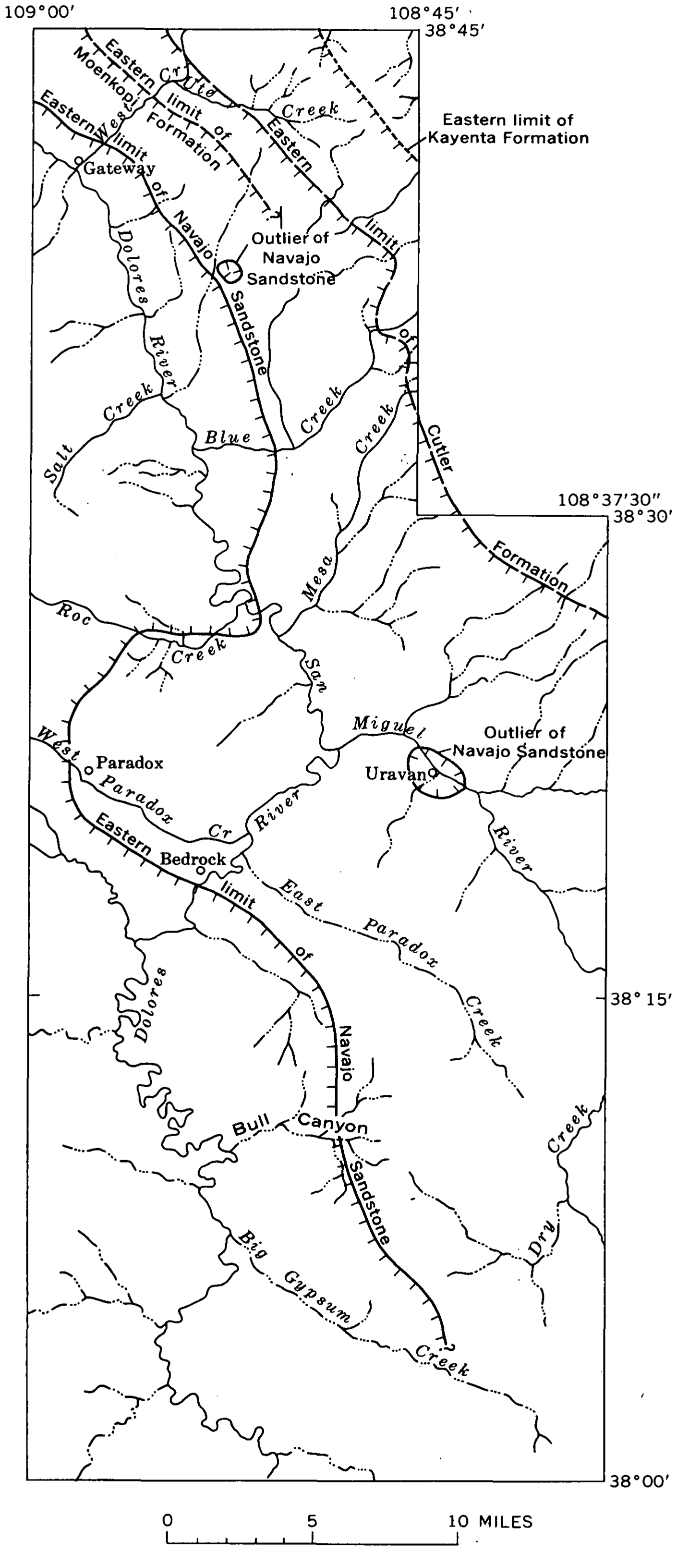


FIGURE 4.—Map of part of area showing eastern limits of formations. Ticks indicate direction of thickening.

of sites of deposition to the mouths of streams draining the old highland, the limestone beds forming in areas between stream mouths. Dumping of material from the rapidly rising ancestral Uncompahgre highland continued after the disappearance of the Hermosa sea. The fanglomeratic texture of the Cutler Formation and the rapid thinning of the formation toward the Uncompahgre indicate that the front of this old landmass was steep and probably was a fault scarp. In all likelihood, uplift was greatest to the northwest in the vicinity of Gateway, and it decreased to the southeast.

TRIASSIC SYSTEM
MOENKOPI FORMATION

The Moenkopi Formation of Triassic(?) and Early and Middle? Triassic age unconformably overlies the Cutler Formation. In the canyon of the Dolores River and in its tributary canyons in the northern part of the mapped area, the unconformity is decidedly angular; the Cutler dips as much as 3°–4° more steeply than the overlying Moenkopi Formation, although part of this difference may be attributed to an original steeper dip in the Cutler. In the vicinity of the salt cores, the Cutler beds in many places are much more steeply upturned than the Moenkopi and younger beds because of pre-Moenkopi folding and upwelling of salt. In many areas of relatively undisturbed rocks, the unconformity is not angular and beds above and below it are virtually parallel. The upper contact is also an unconformity.

The Moenkopi Formation crops out extensively in Paradox and Sinbad Valleys, especially on the north walls, and in the Dolores River Canyon and its tributary canyons below the mouth of Blue Creek. The formation is not exposed south of Paradox Valley.

The Moenkopi Formation commonly forms a slope broken in places, especially in the middle member, by more resistant ledges (fig. 5). The color as seen from a distance is distinctly darker than that of the underlying Cutler Formation or of the overlying Chinle Formation and ranges from deep chocolate brown to red and yellow brown. Within this area the formation comprises three more or less lithologically distinct units in each of which a given rock type predominates. Thus the lower member consists largely of indistinctly bedded mudstone, the middle member of crossbedded arkosic sandstone and conglomerate, and the upper member of thin- and ripple-bedded shale. In each of these members, however, rocks more common in the other members are found in addition to some fairly clean sandstone and locally some gypsum. These members have been mapped separately wherever possible.

Subsequent to the completion of mapping in the area of this report, Shoemaker and Newman (1959) revised the limits of the Moenkopi in the Sinbad Valley area and named four members. The lower member of this report corresponds approximately to the Tenderfoot Member and the middle member to the Ali Baba Member; the upper member corresponds to the Sewemup Member and a part of Pariott Member in Sinbad Valley. As explained later, the upper part of the Pariott Member of Sinbad Valley is included in the base of the Chinle Formation of this report. The formal member names are not used herein because of the disparity between the mapped units of this report and those of the formal member assignments.

The lower few feet of the formation in some areas consists of reworked material from the Cutler Formation, and in Roc Creek Canyon, about 3½ miles above its mouth, the typical red mudstone of the lower member of the Moenkopi is underlain by a zone of breccia fragments of limestone, sandstone, and shale in a matrix of fine-grained detritus, which all is derived from the Paradox Member of the Hermosa Formation. Elsewhere in the area, pebbles in the conglomeratic lenses throughout the formation consist entirely of Precambrian crystalline rocks derived from the ancestral Uncompahgre highland, and the abundance of arkosic layers in the mudstones and of mica flakes in the shale indicates that most if not all the material was derived from the same source.

The mudstone that makes up the bulk of the lower member of the formation is reddish brown to yellowish brown and commonly forms smooth slopes. The rock is distinctive and unlike any of the other rocks in the area. It consists of an evenly but indistinctly bedded homogeneous poorly sorted mass of clay, silt, and sand particles through which are scattered numerous rounded grains of quartz as much as 1 mm in diameter and flakes of mica. In many places the mudstone contains small lenses of sandy arkose 1–12 inches long and ⅛–1 inch thick. Interbedded with the mudstone are beds of reddish-buff coarse-grained dirty arkosic sandstone as much as 10 feet thick and some thin-bedded shale. The arkosic sandstone forms ledges which weather to rounded knobby forms where cut by joints.

The middle member of the Moenkopi Formation is dark chocolate brown and is characterized by abundant arkose and arkosic conglomerate. These beds rather closely resemble those of the underlying Cutler Formation, except that in general they contain a larger fraction of clay and silt and hence have a dirtier appearance than do the Cutler beds. Grains of quartz, fresh feldspar, and dark minerals, and, in the conglomeratic beds, pebbles and cobbles of granite, gneiss, schist, and quartzite—materials derived from the Precambrian rocks of the ancestral Uncompahgre highland —are mixed together in poorly sorted strongly crossbedded lenses. These crossbedded lenses contrast strongly with the even horizontal bedding so characteristic of most of the Moenkopi. Interbedded with the lenses of arkose and arkosic conglomerate is a very fine grained typically ripple-bedded chocolate-colored shale, the individual laminae of which are paper thin and coated with fine-grained mica. Rain-spatter marks and mud cracks are common; the mud cracks generally show up best as casts on the underside of sandstone layers.

The upper member of the Moenkopi Formation consists largely of fine-grained ripple-bedded chocolate-colored shale and consequently crops out as smooth uniform slopes. In Sinbad Valley is a local facies about 200 feet thick that

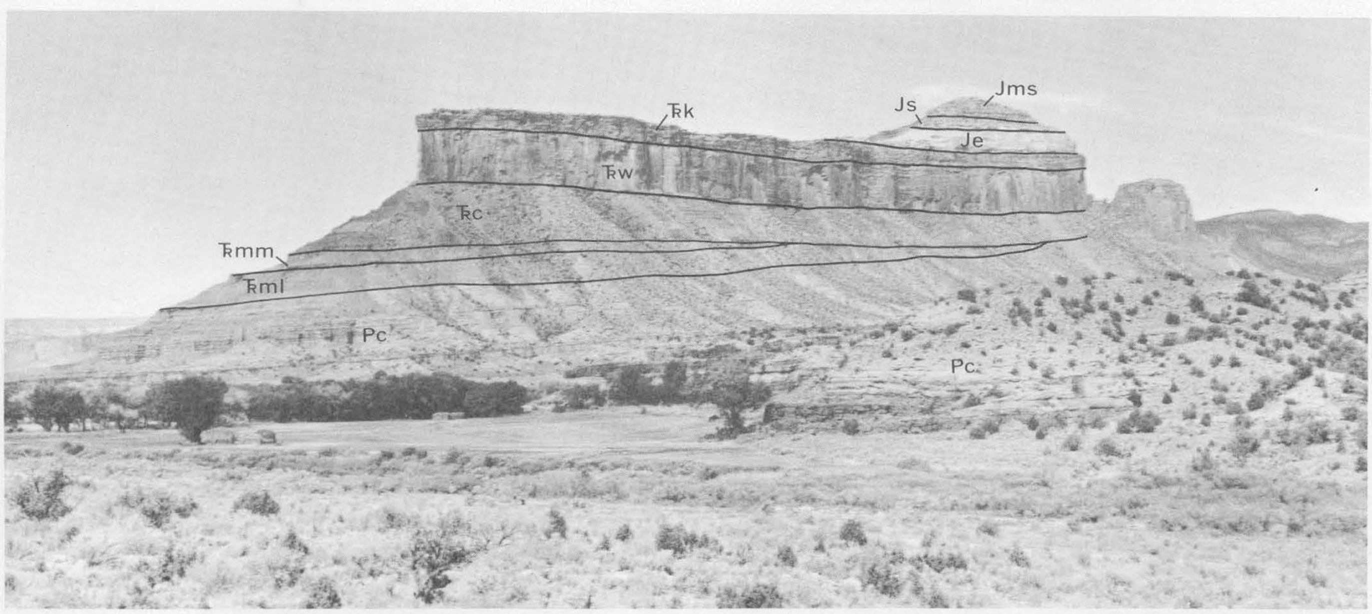


FIGURE 5.—View northward of The Palisade north of Gateway. Pc, Cutler Formation; TRml, lower member of Moenkopi Formation; TRmm, middle member of Moenkopi Formation; TRc, Chinle Formation; TRk, Kayenta Formation; Je, Entrada Sandstone; TRw, Wingate Sandstone; Js, Summerville Formation; Jms, Salt Wash Member of Morrison Formation.

Shoemaker (1955) originally included in the lower part of the Chinle Formation but that he and Newman (Shoemaker and Newman, 1959) later placed in their Pariott Member of the Moenkopi. Their description of these beds in their measured section, however, bears little resemblance to their description of the beds in their type section of the Pariott Member; on the other hand, these beds do not closely resemble the beds usually found in the lower part of the Chinle Formation either. We feel, therefore, a measure of doubt concerning the proper designation of these beds but, because the map was based on their inclusion in the Chinle, we have chosen to follow Shoemaker's original designation and consign them to the Chinle. The stratigraphic section of the Moenkopi Formation in Sinbad Valley given below differs from Shoemaker and Newman's published section only in the exclusion of these enigmatic beds and the inclusion of an unconformity at the top of the section which they eliminated from their published section in a later report. Interlayered with the shale are a few thin beds of dirty arkosic conglomerate and sandstone.

Gypsum is a widespread constituent of the Moenkopi Formation and commonly occurs as thin seams and veins but in places occurs as bedded gypsum near or at the base of the formation. In the Dolores River Canyon south of Gateway, such a bed may be traced for several miles. Although no limestone beds are found in this area, many layers are somewhat calcareous and calcite appears to be a ubiquitous cement.

The following sections are typical of the Moenkopi Formation as exposed in this area:

Section of the Moenkopi Formation in Sinbad Valley, sec. 15, T. 49 N., R. 19 W., Mesa County, Colo.

[Measured by E. M. Shoemaker and W. L. Newman]

	Feet
Chinle Formation.	
Unconformity.	
Moenkopi Formation:	
Contact with overlying Chinle Formation sharp but not noticeably channeled or angular.	
Shale and sandstone interbedded; light brown to chocolate brown. Sandstone is fine grained,[1] ledge forming, ripple bedded and crossbedded. Shale is very thin bedded, ripple bedded. Unit contains scattered beds of granule conglomerate 1–6 in. thick	38.6
Sandstone, light-brown to purplish-brown; forms prominent ledge; consists of alternating massive, crossbedded layers 1–4 ft thick, and thin- and ripple-bedded, somewhat shaly layers 0.1–1.0 ft thick. Scattered lenses and pods of granule conglomerate	21.5
Sandstone and mudstone interbedded. Sandstone is light reddish brown, very fine to fine grained; contains thin lenses of quartz and crystalline rock granules. Mudstone is dark reddish brown, poorly sorted. Unit consists of about equal parts of sandstone and mudstone in beds 0.1–0.3 ft thick	41.2
Mudstone, chocolate-brown, poorly sorted; contains thin interbeds of very fine grained sandstone	57.5
Moenkopi Formation—Continued	
Sandstone, reddish-brown, ledge-forming; crossbedded on small scale; calcareous cement; contains numerous thin stringers of gypsum subparallel to bedding. Mica flakes coat bedding planes	3.4
Shale, chocolate-brown, ripple-bedded; contains interbeds of fine-grained light-brown and reddish-brown sandstone 0.2–1 ft thick. Upper part contains considerable gypsum which occurs as nodules and thin stringers	42.7
Sandstone, light-brown to light-reddish-brown, fine-grained, ripple-bedded. Contains thin beds of chocolate-brown shale and scattered thin lenses of granule conglomerate	20.1
Shale, chocolate-brown, ripple-bedded; lamination paper thin; minor interbeds of very fine grained to fine-grained light-brown sandstone. Ratio of shale to sandstone about 4:1. Some gypsum, which occurs as thin stringers. Beds are locally altered to greenish gray or gray	89.0
Sandstone, light-gray to greenish-gray, very fine grained to fine-grained; some beds are flaggy and shaly, the rest are massive and crossbedded. Light-gray color due to local altered zones that cut across bedding planes	21.8
Mudstone, chocolate-brown, micaceous	1.0
Interval covered	34.6
Sandstone, light-brown, fine-grained; contains thin interbeds of chocolate-brown shale and thin veinlets of gypsum	18.5
Shale, chocolate-brown; beds have average thickness of about 5 ft; thin, ripple-bedded sandstone layers make up about one-fourth of unit. Moderately gypsiferous..	28.5
Sandstone and shale interbedded. Sandstone is light brown, fine to very fine grained, it forms beds 0.1–0.5 ft thick, and makes up about 75 percent of unit. Shale is chocolate brown, micaceous, thin and ripple bedded. Unit also contains scattered beds and lenses of coarse grit containing quartz and feldspar fragments. Gypsum is abundant as disseminations and thin stringers; some veinlets of satin spar	77.9
Mudstone and sandstone interbedded. Mudstone is chocolate brown, Sandstone is reddish brown to purplish brown, medium to coarse grained, argillaceous and poorly sorted, thinly and evenly bedded; some is micaceous, ripple bedded. Unit contains some lumps of gypsum	62.1
Sandstone, light-brown, conglomeratic, arkosic, crossbedded	.5
Shale and sandstone interbedded; poorly exposed	5.2
Sandstone, light-brown, conglomeratic, arkosic	.8
Shale, chocolate-brown, ripple-bedded; contains some interbeds of reddish-brown medium-grained sandstone and coarse-grained conglomeratic standstone....	30.6
Sandstone, yellowish-gray to light-yellowish-brown, medium- to coarse-grained, conglomeratic	4.8

[1] Textural terms used in this report correspond to the Wentworth size scale (Wentworth, 1926) except that two additional size grades were inserted in the sand-sized part of the scale because of the abundance of sand falling in the ranges medium-fine and medium-coarse. The limits of the size grades in the sand sizes are: coarse, 1.0–0.595 mm; medium-coarse, 0.595–0.420 mm; medium, 0.420–0.297 mm; medium-fine, 0.297–0.210 mm; fine 0.210–0.125 mm.

Moenkopi Formation—Continued	Feet
Conglomerate; reddish brown to purple, yellow, and gray at top, ledge forming and caps ridge, very poorly sorted; crossbedded; material ranges in size from clay particles to pebbles 2 in. across. Pebbles consist of granitoid rocks, gneiss, schist, and quartzite	5.4
Shale, chocolate-brown, ripple-bedded	10.8
Conglomerate, light-brown, crossbedded; consists largely of quartz granules	1.4
Sandstone, reddish-brown, micaceous and argillaceous, rather evenly bedded; crossbedding rare; sand grains range from medium to coarse	15.5
Conglomerate, light-brown, crossbedded; consists largely of fairly well rounded quartz ganules	1.3
Sandstone, mudstone, and sandy shale interbedded, light-reddish-brown. Sandstone is medium grained; forms beds generally less than half an inch thick. Unit is evenly bedded and ripple bedded	46.6
Sandstone, reddish-brown and purplish-brown, medium-grained, ledge-forming, evenly bedded	9.4
Shale, reddish-brown, sandy; contains scattered layers of coarse-grained sandstone 0.5–1 in. thick; mudcracks at base of one sandstone layer	21.7
Sandstone and shale interbedded; reddish brown, ledge-forming, thin bedded, ripple bedded; sandstone is medium to coarse grained	5.4
Shale, reddish-brown, evenly bedded and ripple-bedded; contains interbeds of medium-grained to conglomeratic sandstone as much as 4 in. thick	15.8
Sandstone, conglomeratic, crossbedded; contains thin interbeds of reddish-brown shale. Lowermost sandstone bed contorted, and lower surface is marked by ropy ridges due to compression and flowage of subjacent shale	8.0
Mudstone, reddish-brown, sandy, micaceous, ripple-marked	11.8
Sandstone, conglomeratic, purple, strongly crossbedded; unit consists of numerous interfingering lenses. Pebbles consist of quartz, granite, and perthite. Upper part contains scattered thin beds of red shale	26.5
Mudstone, chocolate-brown, micaceous, evenly bedded; beds are 0.1–1 ft thick; some interbeds of sandstone	12.7
Sandstone, muddy, ledge-forming; upper part contains chips of mudstone and sandstone; basal bed of unit contorted	22.1
Mudstone, chocolate-brown, sandy, rather massive; upper part of unit contorted; lower part contains beds of sandstone	22.6
Sandstone, light-brick-red, muddy, very poorly sorted, nearly massive. Consists largely of a muddy matrix through which are scattered grains of sand as much as 2 mm across	227.8
Arkose, purple, medium-grained, soft; appears to be reworked material from Cutler Formation	3.8
Gypsum, white, massive, sugary	3.3
Total Moenkopi Formation	1,072.2

Unconformity.
Cutler Formation.

Section of the Moenkopi Formation, measured on west side of the Dolores River Canyon, sec. 11, T. 50 N., R. 19 W., Montrose County, Colo.

[Measured by F. W. Cater]

Chinle Formation.	Feet
Unconformity.	
Moenkopi Formation:	
Contact with overlying Chinle Formation sharp and unconformable.	
Shale and sandstone interbedded. Sandstone is light reddish brown to brown, fine grained, ripple bedded and crossbedded; some beds arkosic. Shale is brown to chocolate brown, very thin bedded, ripple bedded	76.0
Conglomerate, light-reddish-brown, crossbedded	2.0
Shale, mudstone, and sandstone interbedded. Shale is brown to chocolate brown, very thin bedded, ripple bedded. Mudstone is dark reddish brown, poorly sorted; contains thin interbeds of fine-grained sandstone. Sandstone is light reddish brown to brown, very fine to fine grained; some beds are dirty and arkosic	38.8
Conglomerate, light-red; pebbles consist largely of granitoid rocks and gneiss	5.3
Shale and sandstone interbedded. Shale is chocolate brown, very thin bedded, ripple bedded. Sandstone is reddish brown to chocolate brown, dirty, arkosic; some beds consist largely of crystalline rock granules	45.8
Conglomerate, light-reddish-brown; consists largely of pebbles and small boulders of granitoid rocks and gneiss as much as 7 in. across	12.1
Shale, chocolate-brown, very thin bedded, ripple-bedded; mica flakes coat bedding planes; some silty beds and few thin interbeds of very fine grained sandstone	41.5
Mudstone and grit interbedded. Mudstone is chocolate brown, poorly sorted, micaceous. Grit is reddish brown, arkosic; granules as much as ¼ in. across	5.9
Sandstone, red, fine- to medium-grained, nonarkosic	.9
Sandstone, light-red, coarse-grained, arkosic; contains two or three layers of shale, each ½ in. thick	5.7
Arkose, brown, coarse-grained, massive; contains much clay and silt	11.2
Shale, chocolate-brown, very thin bedded, ripple-bedded	22.0
Shale and sandstone interbedded. Shale is brownish red, evenly bedded and ripple bedded, silty; beds 3–8 ft thick. Sandstone is reddish buff, evenly bedded, fine to medium grained; beds 1–4 ft thick	53.6
Shale, red, poorly exposed	6.2
Sandstone, reddish-buff, coarse-grained, indistinctly bedded, massive, arkosic. Outcrops weather to rounded, mammillary forms	10.3
Mudstone, reddish-buff to brownish-red, thin-bedded, ripple-bedded; bedding planes coated with mica; contains numerous grains of coarse sand and numerous lenses of coarse arkosic sand 1–12 in. long and ⅛–1 in. thick	12.9
Sandstone, reddish-buff, coarse-grained, dirty and poorly sorted, arkosic	4.1
Mudstone, same as 12.9-ft mudstone unit above	29.7
Gypsum, white, massive, sugary, bedding contorted	6.0
Conglomerate and mudstone, probably reworked from underlying Cutler Formation	4.5
Total Moenkopi Formation	394.5

Unconformity.
Cutler Formation.

Section of the Moenkopi Formation in Paradox Valley, north-central part sec. 10, T. 47 N., R. 18 W.

[Measured by R. P. Fischer and A. P. Butler]

	Feet
Chinle Formation.	
Unconformity.	
Moenkopi Formation:	
Shale, reddish-brown to purplish-brown, very thin bedded, ripple-bedded. Unit poorly exposed	10
Sandstone and siltstone interbedded. Sandstone is reddish brown to brown, very fine to fine grained, thin bedded. Siltstone is brownish red, thin bedded, and ripple bedded. Unit forms steep slope	115
Conglomerate, purplish-red; consists of igneous and metamorphic rock pebbles and pebbles of quartz as much as 1½ in. across in a matrix of coarse, arkosic sandstone	3
Sandstone and argillaceous sandstone interbedded. Sandstone is brown, medium to coarse grained; beds 3–6 in. thick. Argillaceous sandstone is brown, fine grained, evenly bedded and ripple bedded; contains considerable clay	10
Sandstone and conglomerate interbedded. Sandstone is reddish brown, fine to medium grained, even and thick bedded. Conglomerate is brown; consists of pebbles of igneous and metamorphic rocks, quartz and shale. Unit forms a cliff	20
Sandstone, reddish-brown to chocolate-brown, fine- to medium-grained, thin- and ripple-bedded; some beds argillaceous and a few beds separated by shaly partings. About 5 ft below top of unit is a massive, crossbedded, shale-pebble conglomerate bed. Unit forms a slope	53
Sandstone and conglomerate interbedded. Sandstone is reddish brown and chocolate brown, fine to coarse grained, slightly arkosic, thin and ripple bedded. Conglomerate is reddish brown; consists dominantly of pebbles of igneous and metamorphic rocks but contains some shale and sandstone pebbles in an arkosic sandstone matrix; crossbedded and lenticular. Unit forms a cliff	35
Siltstone and silty sandstone. Siltstone is brownish red; contains fine grains of amber quartz and flakes of mica; some beds shaly; thin and evenly bedded. Silty sandstone is reddish brown, fine to coarse grained, poorly storted; consists of subangular to well-rounded amber quartz and feldspar grains; thin to thick bedded, sparse ripple-bedded layers. Some silty sandstone occurs as thin lenses in siltstone. Unit forms ledgy slope	75
Silty sandstone to sandy siltstone, brownish-red; grades from siltstone to medium-grained sandstone, which all contains coarse to very coarse grains of sand; poorly sorted; contains clay and abundant mica flakes. Bedding indistinguishable except in upper part where bedding is better defined. Unit poorly exposed	70
Total Moenkopi Formation	391
Unconformity.	
Cutler Formation.	

CONDITION OF DEPOSITION

The source of most of, if not all, the material in the Moenkopi Formation was the ancestral Uncompahgre highland, the same source as that of the underlying Cutler Formation. However, the differences in bedding characteristics and composition between the Moenkopi and the Cutler point to differences not only in the depositional environment but also in the topography of the contributing highland.

The unconformity underlying the Moenkopi Formation indicates a considerable time lapse between the deposition of the Cutler and the deposition of the Moenkopi. The erosion surface represented by this unconformity is flat, with practically no local relief. Dane (1935, p. 52–53) suggested that this surface may have been one of marine planation—a suggestion that seems reasonable because to the west in Utah the Moenkopi contains undoubted marine units and because gypsum beds and calcareous material are present in this area. How far to the east such planation may have extended is not known, for the evidence eastward beyond the edge of the Moenkopi Formation was destroyed by later events.

Regardless of the means by which the unconformity underlying the Moenkopi was formed, one thing seems clear: by the beginning of Moenkopi time the area southwest of the old Uncompahgre highland was largely covered by a body of shallow water, possibly marginal to the sea that existed farther west in Utah during the early part of Moenkopi time (Gilluly and Reeside, 1928, p. 65–66). In the San Rafael Swell of Utah, massive marine limestones were deposited to a thickness of 140 feet, and marine fossils have been found in the Moenkopi as far east as Salt Valley, Utah (Dane, 1935, p. 52). In western Colorado the even bedding in the lower part of the Moenkopi and the general lack of sedimentary structures commonly associated with continental deposits suggest deposition in shallow water. The poor sorting of the mudstones, however, suggests rapid deposition or dumping of material. Nonetheless, the abundant clay in the mudstone suggests that in its provenance on the old Uncompahgre highland, weathering was keeping pace with erosion. Very likely the old highland had been considerably reduced and relief was only moderate, whereas during Cutler time the relief was probably extreme and erosion was so rapid that decomposition of the rocks was relatively inconsequential.

The fluvial arkosic and conglomeratic beds of the middle member of the Moenkopi Formation suggest a period of regional uplift and withdrawal of the body of shallow water from the area of deposition. Streams that drained the rejuvenated Uncompahgre highland cut into unweathered rocks in places and deposited the resulting debris as lenses of arkosic sandstone and conglomerate. The crossbedded and lenticular nature of the coarse-grained material and the mud cracks and rain prints in the finer grained material are characteristic of fluvial deposition.

During the remainder of Moenkopi time the highland to the east was gradually reduced and the material from it was deposited near or at sea level on a terrane of widespread mud flats and local ponds. It is of interest to note that the material composing the ripple-bedded thinly laminated shales of the upper part of the Moenkopi is duplicated exactly in composition and color by the chocolate-brown residual clays derived from the Precambrian rocks on the remarkably flat peneplaned surface of the ancestral Uncompahgre highland beneath the Chinle Formation.

The movement and extrusion of the plastic beds of the Paradox Member of the Hermosa Formation locally disturbed this process of generally placid deposition on a flat, periodically inundated coastal plain. By the beginning of Moenkopi time the great elongate masses of intrusive salt and gypsum had breached the overlying rocks and were reexposed. The movement of salt had decided local effects on the thickness of the Moenkopi formation. Unusually thick Moenkopi is exposed on the northeast wall of Sinbad Valley, where, only 12 miles from the edge of the formation on the flank of the Uncompahgre Plateau, the formation is nearly 1,100 feet thick. Dane (1935, p. 44–45) described beds 855 feet thick along the Colorado River on the north side of the Fisher Valley–Salt Valley anticline, and in general the Moenkopi is unusually thick along a narrow belt lying between the front of the old highland and the salt intrusion underlying Sinbad, Fisher, and Salt Valleys. Southwest of these valleys the formation thins to less than 500 feet, and it maintains about this thickness for considerable distances except in the immediate vicinity of other salt anticlines where the basin of deposition deepened because of the sinking of beds overlying the Paradox Member as the salt and gypsum were squeezed laterally into the salt cores. Salt flowage was manifestly rapid; in places along the north wall of Sinbad Valley, sharp intraformational unconformities formed within the Moenkopi, and, in other places, slump structures developed where the soft, as yet unconsolidated sediments of the formation were tilted upward by the intruding salt and in turn slid down the resulting slope.

THICKNESS

The thickness of the Moenkopi is most variable in the upper member; it is fairly uniform in the lower member and somewhat less uniform in the middle member. On the north wall of Sinbad Valley the upper member attains a thickness of more than 500 feet, and the middle and lower members nearly 300 feet each. Southward in the Paradox Valley area where the formation is about 500 feet thick, the three members are roughly of equal thickness.

CHINLE FORMATION

The Chinle Formation, of Late Triassic age, unconformably overlies the Moenkopi Formation west of the southwest flank of the Uncompahgre Plateau (see fig. 5), but along the flank of the plateau it rests on successively older rocks to the east, first on the Cutler Formation and then on Precambrian rocks. The unconformity is remarkably flat and is of regional extent. Except in the vicinity of the salt anticlines and near the Uncompahgre Plateau, it is not markedly angular, and over most of the Colorado Plateau region it might more properly be termed a disconformity. The upper contact of the Chinle is conformable with overlying beds.

The unconformity on the Precambrian rocks is exceptionally well exposed high along the sides of Unaweep Canyon and at other places where the flanks of the Uncompahgre Plateau have been dissected. In most places where the post-Moenkopi pre-Chinle surface cuts Precambrian rocks, the underlying rocks are fairly fresh and not deeply weathered, but on the North Fork of Mesa Creek in sec. 27, T. 50 N., R. 17 W., the crystalline rocks under the erosion surface were thoroughly decomposed to a reddish-chocolate-colored plastic clay, several feet deep, on which the Chinle was deposited. Although the textures of the preexisting granitic rocks are preserved, all minerals except quartz are altered to clay. Below this zone of clay, the altered rock grades downward through several feet into fresh rock. A line of seeps and small springs marks the unconformity between the Chinle and the zone of impervious residual clay. Very likely the zone of residual clay was much more widespread over the surface of the ancestral Uncompahgre highland in late Moenkopi time and possibly was the source of the material in the ripple-bedded shales in the upper part of that formation. In the area of this report the hiatus represented by this unconformity probably occupied much of, if not all, Middle Triassic time plus some of the Early Triassic because beds equivalent to the Monitor Butte Member and older members of the Chinle are not present (Stewart and others, 1959, p. 503). Stokes (1950) believes that this unconformity developed by a process of large-scale pedimentation. The fact that the erosion surface smoothly truncates both weathered and fresh Precambrian rocks indiscriminately may lend support to his hypothesis, but on the other hand, the products of this pedimentation have not been recognized.

The Chinle Formation is widely exposed in the salt anticline valleys, along the flanks of the Uncompahgre Plateau, and in most of the deeper canyons throughout the area. It crops out almost everywhere as steep slopes broken in places by more resistant ledges (fig. 5). The formation consists of red to orange-red siltstone, with interbedded red fine-grained sandstone, shale, clay-pellet conglomerate containing limestone pebbles, and, at the base, a similar conglomerate that also contains quartz pebbles. A few thin beds of gypsum occur locally at the base. The lithologic units are lenticular and discontinuous. In this area the formation has not been divided into separate members as it has to the southwest (Stewart and others, 1959), but it most nearly resembles the Church Rock Member, although the correlation is not exact. The lowermost beds that contain quartz pebbles probably correlate with the Moss Back Member.

Much of the Chinle Formation consists of the red to orange-red siltstone, an indistinctly bedded rock that weathers into angular prismatic pieces. Evenly bedded shale is sparse. The sandstone varies from massive to conspicuously ripple bedded and is very fine grained and well sorted. It is most abundant in the upper part of the formation, where it forms massive beds as much as 30 feet thick. According to R. A. Cadigan (written commun., 1954), the mean composition of nine samples of sandstone that were collected from this area or from nearby areas is quartz, 63 percent; silicified tuff and chert, 10 percent; quartz overgrowths and silica cement, 2 percent; calcite, 19 percent; potassic and sodic feldspar, 4 percent; muscovite, 2 percent; biotite and heavy minerals, less than 1 percent. The limestone-pebble–clay-pellet conglomerate is highly distinctive and is commoner in the lower part of the formation than in the upper. It forms rudely crossbedded lenses as much as 15 feet thick that tend to stand out as resistant ledges. Structureless gray and reddish limestone pebbles and cobbles, as much as 5 inches across, and clay galls and pellets are the most abundant fragments in the rock; shale and sandstone pebbles are less common. The matrix consists of clay, silt, and sand. According to Schultz (1963, p. C41) the clay fraction of the Chinle in this area is largely illitic. In the basal part of the formation the conglomerate also contains many angular fragments and pebbles, as much as an inch across, of clear quartz. In places these quartz-bearing lenses are relatively clean and consist of scattered pebbles and angular to subrounded fairly well sorted granules with an average diameter of about 2 mm. In the SE¼ sec. 22, T. 48N., R. 19 W., about 2 miles northeast of the town of Paradox, the basal part of the Chinle contains abundant chert as nodules and irregular lenses.

The following sections are representative of sections measured at several localities:

Section of the Chinle Formation on Dry Creek in the Naturita quadrangle, sec. 4, T. 45 N., R. 16 W., Montrose County, Colo.

[Measured by L. C. Craig and L. R. Stieff]

	Feet
Wingate Sandstone:	
Reddish-brown cliff-forming sandstone.	
Chinle Formation:	
Sandstone, pink to light-brownish-red, fine-grained, platy- to slabby-bedded	38.7
Sandstone, dark-red to maroon, friable rubbly weathering; contains two 2-ft beds of pink to greenish very fine grained sandstone	18.5
Sandstone, pink to brick-red, massive-bedded, very fine grained	11.9
Claystone; purple to maroon in lower half, brick red and fine grained sandy in upper half	17.2
Sandstone, pink, red-weathering, very fine grained, ripple-laminated, thick-bedded	17.9
Claystone and sandstone interbedded; claystone is brick red, fissile to rubbly, faintly laminated; sandstone is brick red, very fine grained	75.4
Sandstone, conglomeratic, brown to purplish; contains pebbles of calcareous claystone and siltstone as much as 2 in. in diameter; abundant pelecypods and one low-spired gastropod seen	3.8
Claystone, dark-red to brick-red, variably silty to sandy, rubbly weathering	64.7
Conglomerate, brown to purplish; consists of limestone pebbles as much as 5 in. in diameter, some red clay and maroon siltstone pebbles; numerous bone fragments	13.4
Sandstone, light-gray, gray- to white-weathering, fine grained, highly cross laminated; composed of clear quartz with minor green, pink, and red accessory minerals	11.6
Sandstone, grayish-green and gray to purplish, maroon-weathering, heavy-bedded; clear quartz with sparse green and pink accessory minerals and some mica flakes	40.8
Sandstone, dark-red to maroon, thick- to platy-bedded, calcareous, ripple-laminated to horizontally laminated	38.7
Sandstone and shale interbedded. Lower 10 ft. and upper 14 ft. of massive faintly laminated fine-grained reddish clay to purple calcareous sandstone with thin limestone-pebble conglomerates. Middle 5 ft. is red silty papery shale	29.0
Sandstone, red, very fine grained; massive below, platy to shaly weathering above	17.2
Sandstone, red and gray, red-weathering, very fine grained, slabby bedded, calcareous, structureless to faintly laminated; thin claystone partings	18.3
Claystone, red, silty to sandy, fissile below and platy above; slightly micaceous, ripple laminated	20.1
Sandstone and conglomerate interbedded; red very fine grained, sandstone; channeling; gray to brown conglomerate; contains gray and reddish limestone pebbles as much as 1 in. in diameter	10.5
Sandstone, claystone, and conglomerate interbedded; sandstone and claystone are brick red, rubbly to platy weathering, in part ripple laminated; sandstone is very fine to fine grained; conglomerate is brownish weathering and contains siltstone and limestone pebbles	56.7
Sandstone and siltstone, maroon to grayish-purple and greenish-gray, streaked and mottled; contains disseminated coarse grained to very coarse grained clear to amber quartz; bed of nodular gray to pink chert 6–18 in. thick at top	13.5
Total Chinle Formation	517.9
Disconformity.	
Moenkopi Formation.	

A section measured in the Dolores River Canyon south of Joe Davis Hill differs in color somewhat from other exposures in the area; the colors tend more to shades of green, but these greenish colors seem to be secondary, the result of slight alteration. Here the Moenkopi Formation is absent and the Chinle rests unconformably on the Cutler.

Section of the Chinle Formation on the west side of the Dolores River south of Joe Davis Hill in unsurveyed sect. 12, T. 42 N., R. 18 W., San Miguel County, Colo.

[Measured by F. W. Cater]

	Feet
Wingate Sandstone.	
Chinle Formation:	
Siltstone with thin interbeds of shale and very fine grained sandstone. Siltstone is brick red, indistinctly bedded, weathers to angular; prismatic fragments. Sandstone is light red to brick red, ripple bedded to massive; shale is red to maroon, thin bedded	40
Sandstone, brick-red, very fine grained, massive	8
Shale, red to maroon, sandy	17
Sandstone, pink to brick-red, fine-grained, massive, faintly crossbedded	21
Siltstone, brick-red, sandy; weathers to prismatic fragments; a few massive and ripple-bedded sandstone layers in upper part. Unit weathers to smooth slope	312
Sandstone, brick-red and reddish-brown, thin- and ripple-bedded, very fine grained; shale partings in upper part and layer of limestone-pebble–clay-pellet conglomerate 1 ft. thick in center of unit	31
Sandstone, brick-red, very fine grained, thin-bedded, ledge-forming	25
Sandstone, pink to brick-red, very fine grained, ripple-bedded	22
Conglomerate and sandstone. Conglomerate is dirty green, rudely bedded, and consists of pebbles of limestone, shale, and sandstone. Sandstone is green to red, thick bedded below, thin bedded above	32
Siltstone, light-green, thinly bedded, fissile; rill and ripple marks; some poorly exposed interbeds of shale. Whole unit forms slope	95
Sandstone, light-dirty-green to brick-red, very fine to medium-fine-grained; crossbedded on small scale, massive, cliff forming; contains some conglomeratic lenses with some arkosic material and scattered quartz granules and small pebbles	23
Shale; light green with some chcolate-colored streaks, fissile	3
Sandstone and conglomerate, green to red. Sandstone is medium fine grained, thin bedded; conglomerate forms channel fills in sandstone, contains pebbles of limestone, shale, sandstone, and quartz	6
Conglomerate, green to red, rudely bedded; contains abundant pebbles of limestone and lesser quantities of shale pebbles and clay galls; both angular and subrounded fragments of clear quartz common; scattered chert pebbles	10
Total Chinle Formation	645
Unconformity.	
Cutler Formation.	

The Chinle Formation thins considerably near the front of the Uncompahgre Plateau, apparently by internal thinning. The following section is representative of the formation near and on this plateau:

Section of the Chinle Formation 3 miles east of Gateway in secs. 17 and 20, T. 51 N., R. 18 W., Mesa County, Colo.

[Measured by C. N. Holmes]

	Feet
Wingate Sandstone:	
Reddish-brown, massive cliff-forming sandstone.	
Chinle Formation:	
Siltstone, brick-red; scattered coarse quartz grains and mica flecks; rounded weathering; 2 in. of white very fine grained sandstone to siltstone at top contact; upper contact sharp	10.0
Siltstone, brick-red, thin-bedded; scattered very fine quartz grains, rock fractured, weathers to rubbly slope	60.1
Siltstone, brick-red; scattered very fine quartz grains and mica flecks; ledgy; silty shale partings help form rough-weathering slope	7.8
Siltstone, brick-red; rubbly slope partly covered	29.1
Siltstone, brick-red, very fine grained, shaly; contains mica flecks	29.0
Siltstone; forms brick-red poorly exposed rubble-covered slope	31.9
Conglomerate; contains silty concentrations as much as 1 in. across; shale lenticules; calcite fracture filling 1/16 in. thick	4.1
Siltstone, mottled red and white; scattered coarse grains, mica flecks, and calcite veinlets	26.6
Conglomerate, purpish-red; ranges from coarse sand to round and subangular pebbles of shale and siltstone as much as 2 in. long	2.5
Siltstone, reddish-brown, shaly, partly covered	14.6
Total Chinle Formation	215.7
Unconformity.	
Moenkopi Formation.	

THICKNESS

The Chinle Formation in this area reaches a maximum thickness of about 750 feet on the northeast wall of Sinbad Valley. Along the flanks of the salt cores, it wedges out entirely in many places. Elsewhere the thickness varies considerably from place to place but generally ranges from 450 to 600 feet, except on the Uncompahgre Plateau where the formation is considerably thinner.

AGE AND CONDITIONS OF DEPOSITION

Fossils are uncommon except in a few localities within this area, and they consist only of plant impressions, scattered fragments of bone and petrified wood, and freshwater pelecypods and gastropods, none of which are particularly useful for determining age. Numerous vertebrate fossils from other locations on the Colorado Plateau (Camp, 1928; Baker, 1933, p. 41), however, establish the Chinle as unquestionably of Late Triassic age.

The physical nature of the sediments and the fossil content indicate that the Chinle Formation was deposited under continental conditions. The lenticular beds and the channel-filling sandstones and conglomerates point to fluvial sedimentation. The mode of origin of the limestone-pebble-clay-pellet conglomerate is not clear; although most of the limy pebbles seem to have been transported to their present sites, some of them appear to be concretionary. The clay pellets and pebbles of shale, siltstone, and sandstone that are associated with the concretionary limy pebbles indicate the breakup of preexisting beds and redeposition of the fragmented material. The fragments and pebbles of clear quartz in the lowermost conglomerate beds probably were derived from the deeply weathered Precambrian rocks to the east upon which rest later beds of the Chinle.

TRIASSIC AND JURASSIC SYSTEMS—GLEN CANYON GROUP

The Glen Canyon Group comprises three conformable units in this area which are, in ascending order, the Wingate Sandstone of Late Triassic age, the Kayenta Formation of Late Triassic(?) age, and the Navajo Sandstone of Triassic(?) and Jurassic age. The group is remarkable for its almost unparalleled sequences of clean, massive, cliff-forming sandstones from which are carved some of the most spectacular scenic features of the Colorado Plateau. Dating of the group is based on sparse fossil evidence from outside the mapped area as well as on its stratigraphic position between beds of known Late Triassic age and early Middle Jurassic age.

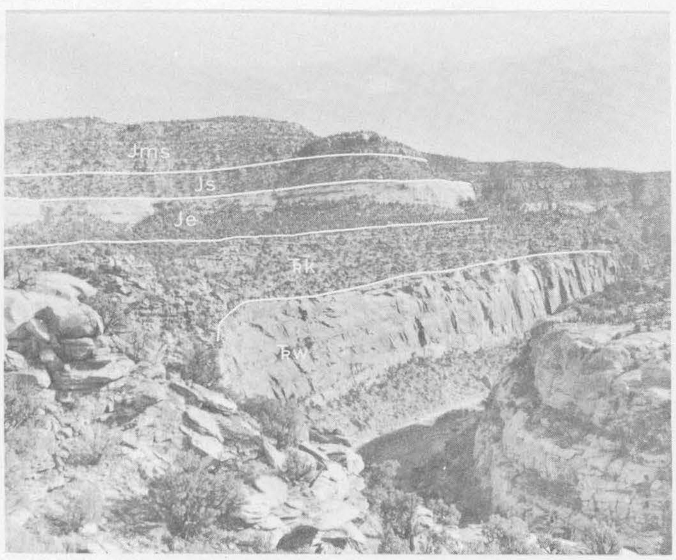


FIGURE 6.—View southeastward of canyon of the Dolores River near confluence with San Miguel River. T̄Rw, Wingate Sandstone; T̄Rk, Kayenta Formation; Je, Entrada Sandstone; Js, Summerville Formation; Jms, Salt Wash Member of the Morrison Formation. Summerville Formation about 100 feet thick.

WINGATE SANDSTONE

The Wingate Sandstone conformably overlies the Chinle Formation and is widely exposed along the walls of the salt anticline valleys, the flanks of the Uncompahgre Plateau, and in the deeper canyons. It typically crops out as a vertical reddish-brown wall, stained and streaked in places with black desert varnish (figs. 5 and 6). Vertical joints cut through the sandstone, and it is largely by spalling of vertically jointed slabs that the cliff recedes. Commonly the spalls occur along huge smoothly curved conchoidal fractures. Three other factors contributing to the cliff-forming characteristic of the sandstone are the massive homogeneous nature of the sandstone, the erosion-resistant character of the basal beds of the overlying Kayenta Formation, and the ease with which the soft beds of the underlying Chinle Formation are eroded. Wherever the Kayenta has been stripped back or where the Chinle is locally more resistant than normally, the Wingate forms a steep slope of rounded benches. In faulted areas it disintegrates rapidly and forms hummocky light-buff outcrops.

The Wingate Sandstone is divided into horizontal layers 2–50 feet thick by bedding planes that may extend for a quarter of a mile or more. Within each horizontal layer the sandstone is crossbedded on a magnificent scale; in places great sweeping tangential crossbeds of eolian type cut across the entire thickness of the horizontal layer. These crossbeds dip predominantly east to southeast and so indicate the sand was deposited by westerly or northwesterly winds. The sandstone is a massive fine-grained rock composed mostly of clean well-sorted sand. According to R. A. Cadigan (written commun. 1954) the mean composition of eight samples of the sandstone obtained from in and near the area is quartz, 70 percent; chert, 2 percent; quartz overgrowths and silica cement, 5 percent; calcite cement, 11 percent; feldspar, 12 percent; muscovite, biotite, and heavy minerals, less than 1 percent. Nearly all the grains in the sandstone range in diameter from 0.05 to 0.15 mm, but in a few scattered localities well-rounded grains having frosted surfaces were found that measured about 0.4 mm in diameter. These large grains occur along laminations in layers one grain thick. Rare horizontal bedding planes are marked by a thin layer of argillaceous sandstone. The lowermost foot or two of the Wingate in places contains partings and thin layers of reddish-brown shale, and the contact is gradational into the underlying Chinle Formation; elsewhere the contact is sharp and Wingate Sandstone rests directly on siltstone and sandstone of the Chinle without an intervening transitional zone. The contact of the Wingate and the Kayenta appears to be gradational everywhere.

In the northeastern part of the area, northeast of Ute Creek from the vicinity of Big Pond to Turner Gulch, the sandstone is highly silicified, brittle, breaks with a conchoidal fracture, and weathers to chips and flakes rather than to loose grains. The silification appears to be related to the zone of faults just northeast of Ute Creek. Original pore spaces in the rock have been almost completely filled with silica.

Because the cliffs are unscalable in most places, detailed stratigraphic sections of the Wingate Sandstone are difficult to measure. The following sections, however, probably are typical:

Section of Wingate Sandstone on Dry Creek in sec. 4, T. 45 N., R. 16 W., Montrose County, Colo.

[Measured by L. C. Craig and L. R. Stieff]

	Feet
Kayenta Formation.	
Wingate Sandstone:	
Sandstone, white to light-yellow; weathers light yellow to buff to pink, fine grained; clear and white quartz sand; cross-laminated beds 5–10 ft. thick; large sand grains extremely rare except in lower 5–20 ft. of formation	242.9
Chinle Formation.	

Section of the Wingate Sandstone 3 miles east of Gateway in secs. 17 and 20, T. 51 N., R. 18 W., Mesa County, Colo.

[Measured by C. N. Holmes]

	Feet
Kayenta Formation.	
Wingate Sandstone:	
Sandstone, reddish-brown, medium-fine-grained, massive; white on fresh surface, slightly crossbedded, rare red clay flecks	17.0
Sandstone, salmon-pink, medium-fine-grained; uniform quartz grains, no visible accessory minerals	13.0
Sandstone, salmon-pink, fine-grained; local black accessory minerals, crossbedded	30.0
Sandstone, salmon-pink, fine-grained	52.0
Sandstone, pink, uniform, fine-grained, fractured	3.0
Sandstone, yellow-brown and pink, medium-fine-grained; scattered black accessory minerals, dense and hard	57.0
Sandstone, salmon-pink, fractured, soft, fine-grained; scattered coarse to medium-coarse grains of amber subangular quartz	17.0
Sandstone, red, soft, crossbedded	38.0
Sandstone, salmon-pink, fine-grained, crossbedded	21.4
Sandstone, pale-brown, fine-grained, slightly crossbedded	16.6
Total Wingate Sandstone	265.0
Chinle Formation.	

Section of the Wingate Sandstone in Summit Canyon, secs. 16 and 17, T. 43 N., R. 19 W., San Miguel County, Colo.

[Measured by L. C. Craig and J. J. Folger]

	Feet
Kayenta Formation.	
Wingate Sandstone:	
Top contact poorly exposed.	
Sandstone, pale-yellow; grain size and composition as below; unit forms capping ledge	4.4
Sandstone, moderate-reddish-orange to light-brown, predominantly very fine grained to fine-grained; composed of subangular clear quartz with sparse white chert and pink and gray accessory minerals. In lower 50 ft. clear to amber medium-fine rounded to well-rounded white chert grains are concentrated along laminae. Predominantly highly crossbedded, thin to thick (as much as 20 ft.) wedging sets; about one-tenth of unit shows horizontal wavy laminations. Even bedding planes at intervals of 15–50 ft.	270.0
Total Wingate Sandstone	274.4
Chinle Formation.	

Section of the Wingate Sandstone at Cashin mine, sec 22, T. 47 N., R. 19 W., Montrose County, Colo.

[Measured by L. C. Craig]

	Feet
Kayenta Formation.	
Wingate Sandstone:	
Sandstone, pale-yellow-brown to light-gray, white- to light-brown–weathering; predominantly fine grained, composed of clear quartz with sparse accessory minerals. Upper 27 ft. is relatively thin bedded, wedging sets of cross-laminae; lowest 100 ft. is thin bedded. Middle part is thick bedded (25–50 ft.) with even bedding planes, highly cross-laminated	351
Total Wingate Sandstone	351
Chinle Formation.	

The colors described in the preceding sections are noticeably lighter than the normal colors of the Wingate as seen in the cliffs. Places where the sandstone can be traversed are exposed to more rapid disintegration, and therefore in these places the surficial staining and desert varnish is rarely so prominent as on the vertical cliffs.

THICKNESS

The thickness of the Wingate Sandstone where unaffected by the movement of salt near the salt anticlines generally ranges from 220 to 500 feet. The latter thickness is extreme and is confined to a local area that coincides with the area near Ute Creek where the sandstone is highly silicified. In a distance of 3 miles in a southwesterly direction from there, the thickness diminishes from nearly 500 feet to less than 300 feet. On the flanks of the salt anticlines the Wingate thins abruptly and in places disappears. Such thinning is strikingly displayed especially in Paradox and Gypsum Valleys. Near Thunderbolt Springs in Paradox Valley a relatively gradual thinning from more than 100 feet to 5 feet occurs within a quarter of a mile. Throughout this distance the tangential crossbedding is constant in attitude, and in places the laminations cut completely across the entire thickness of the sandstone.

CONDITIONS OF DEPOSITION

As is true of other thick crossbedded sandstone formations of the Colorado Plateau, the origin of the Wingate Sandstone is not agreed upon by all geologists who have worked there. The even sorting, the roundness of the sand grains, and the very large-scale crossbedding all point to eolian deposition, yet, unlike the Navajo Sandstone which has frequently been cited as a classical example of a wind-deposited formation, the Wingate is cut at intervals by extensive horizontal bedding planes. Presumably these could have been caused only by water; furthermore, to the west in Utah both Dane (1935, p. 75) and Gilluly (1929) have described thin, discontinuous limestone beds in the Wingate. As Dane stated: "The precise manner of deposition is difficult to visualize, but a combination of eolian and sheet-wash deposition on a surface of very low relief seems to be indicated."

In places the Wingate contains a few bedding units, usually less than 5 feet thick, consisting of faint horizontal, slightly wavy laminae. These sandstone units appear to contain more silt and clay than the crossbedded units. Some geologists have suggested that the widespread horizontal bedding surfaces may represent bevel surfaces formed by the advance of strandlines across sand dune areas, whereas others think the bevel surfaces may represent ground-water levels to which deflation cut. The horizontally laminated units may represent reworked dune material, as well as finer materials, deposited in a body of standing water.

CORRELATION

The Wingate Sandstone is widely distributed over much of the Colorado Plateau country, and, in general, because of its distinctive outcrops it presents no problems of correlation. Nonetheless, the formation originally named the "Wingate sandstone" by Dutton (1885, p. 136–137) is not entirely the Wingate Sandstone now so widely recognized over most of the plateau (Baker and others, 1947). The upper part of Dutton's "Wingate sandstone" correlates with the Entrada Sandstone whereas the lower part of his "Wingate" probably correlates with the Wingate of southwestern Colorado (Harshbarger and others, 1957, p. 8). Fossils that have been found in the Wingate consist of dinosaur tracks (Gilluly and Reeside, 1928, p. 70; Longwell and others, 1923, p. 13) and a Triassic phytosaur, *Machaeroprosopus* (Harshbarger and others, 1957, p. 29). The tracks are of no diagnostic value in age determinations. The phytosaur discovery in Arizona supports the assignment of the Wingate to the Triassic, as do also depositional relations. The Triassic Chinle Formation grades without depositional break into the Wingate Sandstone.

KAYENTA FORMATION

The Kayenta Formation, which conformably overlies the Wingate Sandstone, is widely exposed within the area, especially in the deeper canyons and along the sides of the salt anticline valleys. Eastward and in places along the flanks of the salt anticlines, the formation wedges out; it is absent in the San Juan Mountains and on most of the Uncompahgre Plateau. Within the area covered by this report the edge of the formation coincides rather closely with the southwest front of the Uncompahgre Plateau; thus on Wolf Hill (sec. 15, T. 51 N., R. 17 W.) the Kayenta is missing and the Entrada Sandstone rests directly on the Wingate Sandstone. Similar relations exist through a distance of at least 25 miles southeastward from Ute Creek. To the north, however, the formation crosses the crest of the Uncompahgre Plateau and occurs on the northeast flank near Grand Junction, Colo.

The Kayenta typically crops out in series of benches and ledges and has a wider outcrop than do many of the other formations of comparable thickness in the area (fig. 6). The ledges in many places overhang recesses where softer beds have eroded back. Where the formation is cut by joints, the traces of the joints on the outcrop surface stand out as small ridges as much as an inch across and half an inch high, a characteristic which serves to distinguish the formation in small isolated outcrops from other formations of similar lithology. The lower part of the formation is more firmly cemented and forms especially resistant thick ledges that protect the underlying Wingate Sandstone from erosion.

The Kayenta Formation, in striking contrast to the other formations of the Glen Canyon Group, is notable for its variety of rock types. Sandstone, which is red, buff, gray, and lavender, is the most abundant type, but the formation also contains considerable quantities of red siltstone, thin-bedded shale, and conglomerate. Most of the sandstone is thin bedded, crossbedded in part, and flaggy; some is massive. In the southwest wall of Paradox Valley in sec. 7, T. 46 N., R. 17 W., the sandstone locally is very thick bedded and massive and in general aspect quite unlike the usual sandstone layers and lenses in the formation. Except in this one locality, the sandstone beds are lenticular, discontinuous, and interfinger with shale and, in places, with conglomerate. In general the sandstone is fairly well sorted and the grains are rounded or subrounded, but both sorting and roundness are less perfect than in the Wingate or Navajo Sandstone and the grains are coarser. According to R. A. Cadigan (written commun., 1954) the mean composition of nine samples is quartz, 63 percent; chert, 6 percent; calcite cement, 10 percent; potash and sodic feldspar, 15 percent; muscovite, biotite, and other heavy minerals, less than 1 percent. Mica is much more conspicuous than its low percentage of the composition would indicate. The thick-bedded massive phase in Paradox Valley contains rounded pebbles, largely of quartz but also of black and gray chert, as much as three-quarters of an inch across. Elsewhere such pebbles are very rare if, indeed, they occur at all. Shale occurs in subordinate amounts as well-laminated thin beds and lenses, especially in the uppermost part of the formation; most of it is red but some is chocolate colored. Subordinate amounts of conglomerate closely resembling the limestone-pebble–clay-pellet conglomerates of the

Chinle Formation are common everywhere in the Kayenta. The conglomerate consists of limestone pebbles and irregular-shaped fragments and pebbles of siltstone and shale in a matrix of sand.

The Kayenta Formation was measured at many localities, and the following sections show the lithology of the formation:

Section of the Kayenta Formation half a mile south of Stone Spring, in Paradox Valley, sec. 27, T. 47 N., R. 18 W., Montrose County, Colo.
[Measured by F. W. Cater]

	Feet
Entrada Sandstone.	
Unconformity.	
Kayenta Formation:	
Contact disconformable, surface somewhat irregular and shows some scour channels a foot or so deep.	
Sandstone, red to lavender-red, fine- to medium-fine-grained, thin-bedded and cross-bedded, flaggy; consists predominantly of rounded and subrounded grains of quartz, slightly micaceous; scattered shale partings	37
Sandstone, maroon to purplish-red, lenticular and crossbedded; locally contains boulders of sandy shale as much as 18 in. across	9
Sandstone, pink to purplish-red, thin-bedded and flaggy; lenses of mudstone containing shale pebbles. Unit marks a filled stream channel and laterally grades into more massive ledge-forming sandstone	12
Sandstone, red, bluff-forming, thinly bedded; some crossbedding; consists of rounded to subrounded quartz gains, slightly micaceous	5
Sandstone, red, thin-bedded, slabby, mostly covered	7
Sandstone, red to purplish, thin-bedded and cross-bedded, fine- to medium-fine-grained; slightly micaceous; contains some streaks of green clay	10
Sandstone, red, thinly laminated, flat-bedded	1
Shale, brick-red, sandy, indistinctly bedded; breaks into angular prismatic pieces	4
Sandstone; red with slight purplish or lavender hue, fine grained, thin-bedded and cross-bedded; consists predominantly of rounded to subrounded quartz grains, contains some mica, black chert, and green clay; lower 5 ft. forms a slope, upper 16 ft. forms a bluff	21
Total Kayenta Formation	106
Wingate Sandstone.	

Section of the Kayenta Formation on Dry Creek, sec. 4, T. 45 N., R. 16 W., Montrose County, Colo.
[Measured by L. C. Craig and L. R. Stieff]

	Feet
Entrada Sandstone.	
Unconformity.	
Kayenta Formation:	
Contact lobate to irregular; underlying surface pillowy, suggesting flow or possibly channeling; pebbles of underlying beds worked into base of overlying beds. Contact is probably unconformable, cutting out the top 7.6 ft. of Kayenta west of line of section.	
Sandstone, red to pinkish-buff, fine-grained, well-sorted; consists of subangular clear to amber quartz grains; highly cross laminated	7.6
Kayenta Formation—Continued	
Sandstone, white to light-lavender, fine- to medium-grained; consists of white and colorless subangular quartz grains with small amounts of rose, amber, and lavender quartz; cross laminated	24.6
Sandstone, red and maroon, fine- to medium-grained; consists of subangular clear quartz grains; unit is dark red, ripple laminated, micaceous, and very fine grained in upper part	24.6
Sandstone, maroon to red, massive- to platy-weathering, faintly laminated; consists of subangular clear quartz grains with minor pink and amber accessory mineral grains	42.5
Conglomerate, intraformational, pink to maroon; dark-red clay and silt granules as much as ¼ in. across in a sandstone matrix	4.4
Sandstone, maroon to purple, medium-grained, faintly cross laminated; composed of white, pink, and amber quartz grains with abundant large flakes of muscovite; 3 ft. of intraformational conglomerate near middle of unit	31.2
Conglomerate, red- to brown-weathering; consists of light-red to gray, yellow-brown-weathering pellets of of calcilutite and sparse red claystone pellets	2.8
Sandstone, gray- to purplish-weathering, medium-grained; a few scattered claystone and limestone pebbles in middle part	9.5
Conglomerate and sandstone, irregularly interbedded; red to maroon; contains pebbles of limestone and siltstone	4.1
Sandstone, maroon to purplish-gray, medium-grained; consists of white, pink, and colorless quartz with minor amber accessory grains; platy weathering	20.7
Conglomerate, dark-red; limestone and siltstone pebbles	1.0
Sandstone, maroon to purplish, medium-grained, cross-laminated; consists of white to amber quartz grains with numerous muscovite flakes; unit becomes red to red brown and finer grained upward	21.1
Sandstone, red to brown-red, fine-grained; consists of amber and white quartz; shaly weathering	7.5
Conglomerate, purplish; consists of limestone pebbles in quartz sand matrix	1.0
Sandstone, red-brown, fine-grained, ripple-laminated; rubbly below to massive above	16.4
Total Kayenta Formation	219.0
Wingate Sandstone.	

Section of the Kayenta Formation 3 miles east of Gateway, Colo., secs. 17 and 20, T. 51 N., R. 18 W., Mesa County, Colo.
[Measured by C. N. Holmes]

	Feet
Entrada Sandstone.	
Unconformity.	
Kayenta Formation:	
Sandstone, maroon, micaceous, partly covered; weathers along silty shale partings	19.0
Sandstone, maroon, fine-grained, horizontally bedded, ledgy	1.5
Sandstone, maroon, very micaceous; contains silty shale partings at ⅛-in. intervals; crossbedded, weathers along partings	16.5
Sandstone, white, pale-brown-weathering, medium-fine-grained, porous, calcareous cement, lenticular, subangular grains	15.4

Kayenta Formation—Continued	Feet
Covered	10.6
Sandstone, maroon, medium-fine-grained, lenticular; forms vertical ledge; crossbedded; some dark-red shale and siltstone; mica flakes along partings; blocky and rough weathering	41.8
Sandstone, maroon-purple, fine-grained, partings ⅛ in. thick of micaceous shale in lower 3 ft. of unit; upper 1.5 ft. is hard dense sandstone containing dense gray limestone concretions 4 in. in diameter	4.5
Sandstone, white, rusty-brown-weathering, medium-fine-grained; thin shale partings at intervals of about 3 in.; sparse black accessory minerals	9.5
Shale, dark-maroon, lenticular	6.7
Sandstone, light-maroon, medium-fine-grained; upper 1 ft thin horizontal laminations; lower 1.3 ft contains shale flakes as much as 3/16 in. long and scattered chert grains; some shale partings; unit lenticular	2.3
Covered	5.6
Sandstone, white, reddish-brown-weathering, fine- to medium-grained; sparse pink and black accessory minerals; some red silty shale partings	10.2
Covered	5.4
Sandstone, reddish-gray, fine- to medium-grained; grains subangular; horizontal partings of shale 1/16 in. thick	2.0
Covered	3.0
Sandstone, light-maroon, fine- to medium-grained; lenticular horizontal laminations; grains subangular	3.0
Covered	10.0
Total Kayenta Formation	167.0

Wingate Sandstone.

Section of the Kayenta Formation in Summit Canyon, secs. 16 and 17, T. 43 N., R. 19 W., San Miguel County, Colo.

[Measured by L. C. Craig and J. J. Folger]

Navajo Sandstone.	Feet
Kayenta Formation:	
Contact sharp, marked by color and structure change. Covered on line of section; exposed along outcrop.	
Sandstone and claystone interbedded. Sandstone is dark reddish brown, very fine to fine grained; consists of clear subangular quartz grains with numerous variegated accessory mineral grains, slightly micaceous; ripple laminated to massive and structureless. Claystone is dark-reddish brown and slightly micaceous; it predominates in upper two-thirds of unit	28.2
Sandstone, pale-pink to moderate-reddish-brown, fine- to medium-grained, highly cross laminated; channeling; composition same as that of underlying unit	68.8
Sandstone, pale-pink to pale-yellow, fine- to medium-fine-grained; consists of subangular clear quartz grains with orange and gray accessory mineral grains; highly cross laminated; channeling	33.6
Conglomerate, grayish-brown to dark-reddish-brown; limestone pebbles as much as 3 in. in diameter; poorly sorted matrix of quartz grains	7.2
Sandstone, moderate-reddish-orange; size and composition as below; highly cross laminated; channeling	54.0
Sandstone, dark-reddish-brown, very fine grained to fine-grained; consists of subangular clear quartz grains with numerous colored accessory mineral grains; slabby beds as much as 1 ft. thick	16.8
Total Kayenta Formation	208.6

Wingate Sandstone.

THICKNESS

The Kayenta Formation varies considerably in thickness from locality to locality. In part these variations are due to actual depositional thinning or thickening of the formation, but in areas where the Entrada Sandstone rests directly on the Kayenta the variations are due largely to erosion of the upper beds prior to deposition of Middle Jurassic beds. In other words, in areas where the Navajo Sandstone is absent, the upper contact of the Kayenta is an unconformity. Normally the thickness ranges from about 180 to 220 feet, although locally on Sewemup Mesa the maximum thickness is nearly 300 feet. At the other extreme is the complete wedge out of the formation either by nondeposition or by erosion or by a combination of both along the Uncompahgre Plateau in the northeast part of the area and in places along the flanks of the salt anticlines; for example, on the southwest side of East Paradox Valley the Kayenta is entirely missing for several miles.

CONDITIONS OF DEPOSITION

Irregular bedding, low-angle crossbedding, current lineations, and channel fills, all characteristic of stream deposition, occur throughout the Kayenta Formation. Saurian tracks and species of the fresh-water pelecypod genus *Unio* have been found in the Kayenta in Utah and Arizona (Gregory, 1917, p. 56; Baker, 1933, p. 46). Contrary to what would normally be expected in such beds, ripple marks and mud cracks are uncommon. The conglomerate lenses are similar to those in the Chinle and in all probability have a similar origin.

In general the Kayenta beds mark a sudden change of depositional environment in middle Glen Canyon time. During Wingate time, wind was the dominant depositional agent and the area was probably a scene of utter desolation, a monotonous expanse of shifting sand. The beginning of Kayenta times was marked by more humid conditions which altered the scene entirely; a system of aggrading streams was reestablished which leveled the dunes and blanketed the area with a layer of sediments quite unlike the eolian deposits of the Wingate.

AGE AND CORRELATION

Fossils are sparse in the Kayenta Formation. The dinosaur tracks found by Gregory and the *Unio* shells found by Baker indicate only that the beds can be no older than Late Triassic and could be considerably younger. Two reptile skeletons found by Welles (1954) were identified by him as *Megalosaurus,* a genus found in the European Jurassic; however, Swinton (1955) said of this reptile, "Its relations are certainly with the early carnosaurs, but it is not *Megalosaurus*." The early carnosaurs are mostly of Late Triassic age. Several tritylodont skeletons found near Kayenta, Ariz., were considered by Lewis (1966) to be closely related to species found in the Stomberg series of South Africa and the Lufeng series of Yunnan, China, both of which are in the Upper Triassic. Lewis also wrote (Lewis and others, 1961) that the tritylodonts from the Kayenta were found in association with a fossil crocodilian (*Protosuchus richardsoni*) hitherto known only from the Late Triassic (?) Moenave Formation; this species is closely related to the crocodilian genera *Erythrochampsa* and *Notochampsa* of the Stormberg. Thus it appears that the best fossil evidence indicates a Late Triassic(?) age for the Kayenta.

The Kayenta Formation crops out over wide areas on the Colorado Plateau, and occurring as it does between the highly distinctive Wingate and Navajo Sandstones, it offers few problems of correlation. The beds between the Wingate and the Navajo were originally called "Todilto" by Gregory (1917) because of their supposed correlation with the Todilto Limestone of northwestern New Mexico and adjacent parts of Colorado and Arizona. Baker, Dane, and Reeside (1936, p. 17) in defining these beds as the Kayenta Formation demonstrated that the Todilto Limestone was much younger and did not correlate with the Kayenta.

NAVAJO SANDSTONE

The Navajo Sandstone, the uppermost formation of the Glen Canyon Group, conformably overlies the Kayenta Formation. In most places the contact between the Navajo and Kayenta is sharp, but in the northern part of the area on the west side of Maverick Canyon, the contact is indistinct because the Navajo appears to consist of reworked Kayenta. The transitional beds have a composition apparently identical to the Kayenta but they have the sweeping crossbedding typical of the Navajo, and they grade laterally into beds of typical Navajo aspect. Although the Navajo is one of the most widespread and topographically distinctive formations in the plateau country, in the area covered by this report, its distribution is erratic, and because of its thinness, its topographic forms are relatively subdued.

The east edge of the Navajo Sandstone follows an irregular course through southwestern Colorado and through the part of the area covered by this report (fig. 4). The Navajo crops out in canyon walls, on benches bordering the deeper canyons, and locally both in and along the walls of the salt anticline valleys. It is most widely exposed on benches bordering canyons in the Horse Range Mesa and Anderson Mesa areas. The edge of the sandstone is not exposed south of Gypsum Valley, but from unsurveyed sec. 15, T. 44 N., R. 17 W., on the northeast rim of the valley, the edge of the sandstone trends northwest to the northwest end of Paradox Valley, and from this point it trends irregularly northward and leaves the mapped area west of Gateway. East of the main mass of the Navajo a few thin, isolated masses are exposed; the largest of these centers at Uravan. These isolated masses were probably connected to the main mass of the Navajo prior to the erosion that immediately followed deposition of the Navajo.

The Navajo Sandstone commonly is eroded to hummocky surfaces of rounded knobs where the formation is sufficiently thick and unprotected by overlying formations; where protected by overlying formations it forms vertical cliffs (fig. 8). Locally, where the sandstone is much jointed, it weathers to an exceedingly intricate topography of hoodoos and narrow clefts, as between the mouth of Wild Steer Canyon and Paradox Valley.

The Navajo Sandstone, like the Wingate, consists almost entirely of massive, fine-grained, very well sorted, clean, light-buff, gray, or nearly white sand. The few scattered thin lenses of limestone and sparse shale splits constitute much less than 1 percent of the formation. Here, as elsewhere on the Colorado Plateau, crossbedding on an enormous scale is typical of the Navajo; great sweeping tangential cross-laminae descend at angles of as much as 30° to the true bedding. Unlike the Wingate, the Navajo contains almost no horizontal bedding planes, except in the limestone lenses and near the featheredge of the formation. Conformable sets of cross-laminae form wedges and lenses that truncate one another or lower beds.

According to R. A. Cadigan (written commun., 1954) the mean composition of seven analyzed samples of the Navajo Sandstone is quartz, 78 percent; chert, 3 percent; quartz overgrowths and silica cement, 4 percent; calcite cement, 3 percent; potash and sodic feldspar, 12 percent; and heavy minerals, less than 1 percent. Individual grains are subangular to rounded and range from 0.1 to 0.2 mm in diameter. In a very few places angular granules of white chert are common, particularly in the sandstone enclosing limestones lenses or in sparse localities where the sandstone appears to have been deposited by water. Thin beds of gray to pink limestone crop out in the vicinity of Summit and Bush Canyons, on the lower part of Roc Creek, and on the south end of Sewemup Mesa. The bed on Sewemup Mesa has a maximum thickness of 6 feet. On the south side of the San Miguel River, several hundred feet southeast of Uravan, a 3-foot-thick lens of fissile red shale occurs about 12 feet above the base of the Navajo; this lens wedges out laterally into sandstone. Similar lenses occur at scattered localities elsewhere in the lower part of the sandstone.

Because of the uniform nature of the sandstone, the complexities of the crossbedding, and the lack of true bedding planes, accurate measurement of detailed sections is difficult, but typical character of the Navajo Sandstone in this area is shown in the following sections:

Section of the Navajo Sandstone at the Cashin mine, sec. 22, T. 47 N., R. 19 W., Montrose County, Colo.

[Measured by L. C. Craig]

	Feet
Entrada Sandstone.	
Unconformity.	
Navajo Sandstone:	
Contact poorly exposed, located within 1 ft.	
Sandstone, pale-yellowish-buff to pale-yellow-green, predominantly fine-grained; consists of subangular clear quartz grains and sparse accessory mineral grains; upper 10 ft. massive, structureless; lower 45 ft. wedge bedded with prominent sweeping cross-lamination. Lowest 1.4 ft. horizontally laminated	69.8
Total Navajo Sandstone	69.8
Kayenta Formation.	

Section of the Navajo Sandstone in John Brown Canyon near edge of mapped area

[Measured by L. C. Craig, H. L. Jicha, and others]

	Feet
Entrada Sandstone.	
Unconformity.	
Navajo Sandstone:	
Top contact is undulant and irregular.	
Limestone, light-gray to pink, medium-gray- to buff-weathering, medium-grained to coarsely crystalline; contains disseminated medium-grained quartz; locally contains medium-gray chert nodules	2.6
Sandstone, pink to purplish, fine- to medium-fine-grained; not conspicuously cross laminated. Interval poorly exposed	15.7
Sandstone, pink to buff, fine- to medium-fine-grained; consists of quartz with minor chert; predominantly wedge bedded, torrential cross-lamination	21.6
Sandstone, white to pinkish-buff, medium-fine-grained, thick-bedded, broadly cross laminated; composed of subangular to rounded grains of quartz with minor chert	21.3
Limestone, light-gray to dove, light-gray-weathering, fine-grained	.4
Sandstone, pale-lavender, fine- to medium-grained, poorly sorted, cross-laminated; larger grains are rounded	19.5
Sandstone, white to buff, fine- to medium-grained; consists of rounded to well-rounded clear quartz grains; wedging beds, not highly cross laminated	32.6
Sandstone, red, fine-grained, nonresistant, platy to shaly weathering	1.2
Sandstone; white below grading to pink above, fine to medium grained, evenly bedded; weathers to rounded topographic forms; not conspicuously laminated	20.8
Interval poorly exposed. Shale; dark red below grading to purple above, slightly silty; 6 in. light-green silty to sandy shale at top	12.2
Sandstone, white, fine- to medium-grained, highly cross laminated, irregularly bedded	2.5
Total Navajo Sandstone	150.4
Kayenta Formation.	

THICKNESS

The thickness of the Navajo in the area ranges from a featheredge to a maximum exposed thickness between Silveys Pocket and Wray Mesa of at least 500 feet; the total thickness may be considerably greater. Large variations in thickness occur within short distances, due both to wedging along the flanks of the salt anticlines, which underwent movements during deposition of the sandstone, and to differential erosion at the top of the Navajo.

CONDITIONS OF DEPOSITION

The Navajo Sandstone often has been cited as a classic example of a wind-deposited formation (Huntington and Goldthwait, 1904, p. 214–216; Gregory, 1917, p. 59; Kiersch, 1950). Although a few geologists have questioned this interpretation (Keller, 1945, p. 219; Grater, 1948), the bulk of field evidence favors eolian deposition. The large-scale sweeping cross-lamination, exceptional degree of sorting, the roundness of individual sand grains, and the scarcity of true bedding seem difficult to reconcile with any other mode of deposition. The limestone layers and some of the flatbedded material near the base of the formation were undoubtedly water laid, but these layers constitute a small part of the formation. The limestone layers probably originated in ephemeral ponds of playalike depressions or deflation basins that developed from time to time as deposition progressed. Regardless of the mode of deposition of the Navajo, or for that matter of the other formations in the Glen Canyon Group, one perplexing problem of Colorado Plateau geology still remains—the source of the staggering amounts of clean sand that inundated the region during Glen Canyon time.

AGE AND CORRELATION

Fossil plants, ostracodes, and reptiles have been found in the Navajo, but, unfortunately, these fossils are either of long-ranging species or of species whose ages are too uncertain to permit exact dating. The tritylodonts found in the Kayenta by Lewis (1966) and considered by him to be of Triassic age were 10 feet below the base of the Navajo. *Segissaurus,* one of the dinosaurs that has been found in the Navajo, could be placed in either the Triassic or Jurassic according to Camp (1936, p. 52). An incomplete skeleton of a second dinosaur from the Navajo was stated by Brady (1935) to closely resemble *Ammosaurus* of the Connecticut Triassic, but because of the fragmentary nature of the remains he was not certain of the identification. The upper part of the Navajo is still considered to be Jurassic, but the fossil evidence cited above suggests, at least, that the lower part of the formation could be of Triassic age. The age assignment of the Navajo Sandstone as Triassic(?) and Jurassic has resulted from the recognition of widespread intertonguing between the Navajo and the Kayenta and the Carmel in south-central Utah and north-central Arizona (Averitt and others, 1955, p. 2523–2524; Lewis and others, 1961, p. 1438–1440).

Throughout most of the Colorado Plateau the Navajo Sandstone poses few problems of correlation; the distinctive crossbedding serves to distinguish it from all the formations of fluvial origin, and in most places the sparsity of horizontal bedding planes serves to distinguish it from somewhat similar formations such as the Wingate and Entrada Sandstones. On the other hand, in northern Utah and in Wyoming and Idaho, correlations are less certain, although the Navajo probably correlates with the Nugget Sandstone of those areas. The Nugget has lithic properties that are practically identical to those of the Navajo, and it occupies a similar stratigraphic position.

RELATIONS OF EASTERN EDGES OF FORMATIONS OF THE GLEN CANYON GROUP

Within the area covered by this report the edge of each successively younger formation of the Glen Canyon Group lies successively farther west. The edge of recognizable Wingate Sandstone lies well east of the area mapped; the edge of the Kayenta Formation crosses the northeastern corner of the mapped area (fig. 4), and that of the Navajo Sandstone lies farther west. The wedge-out of these formations reflects pre-Entrada uplift and erosion of an area extending eastward to the Elk Mountains (Vanderwilt, 1937, p. 33–34, 81–82).

JURASSIC SYSTEM

SAN RAFAEL GROUP

In the area covered by this report the San Rafael Group comprises two formations of Late Jurassic age; these are the Entrada Sandstone below and the Summerville Formation above, both of which can be traced almost continuously from the San Rafael Swell into western Colorado. The name San Rafael Group was first applied to a succession of similar beds in the San Rafael Swell by Gilluly and Reeside (1928). In the San Rafael Swell, the Carmel and Curtis Formations were recognized. The Curtis grades eastward into the lower part of the Summerville Formation (Dane, 1935, p. 89; Knight, 1940, p. 99; Baker, 1946, p. 83), and the Carmel Formation grades abruptly into the Dewey Bridge Member of the Entrada Sandstone (Wright and others, 1962). Neither is present in southwestern Colorado.

ENTRADA SANDSTONE

Two members of the Entrada Sandstone were mapped as a single unit in the southwestern Colorado area, partly because they commonly form a narrow outcrop and partly because it is difficult to choose a contact between the two in some places.

Dewey Bridge Member

The Dewey Bridge Member and the overlying Slick Rock Member of the Entrada Sandstone crop out extensively along canyon walls and on the sides of mesas (fig. 7), but in many places the Dewey Bridge is absent, and the overlying Slick Rock Member of the Entrada Sandstone rests directly on pre-Dewey Bridge rocks (fig. 8). The Dewey Bridge was deposited on a slightly irregular erosion surface and failed to bury some of the higher parts of this surface completely. In the vicinity of Uravan such relations are well exposed; the isolated patch of Navajo Sandstone in this area apparently stood as a local topographic high during Dewey Bridge time, and where Navajo is present the Dewey Bridge is either thin or missing. In immediately adjacent areas where the Navajo was removed prior to deposition of the Dewey Bridge, the Dewey Bridge is thicker than is normal for the region. In common with older units the Dewey Bridge was not deposited across the tops of the salt cores in the salt anticlines.

FIGURE 7.—Canyon of the Dolores River south of Mesa Creek. Ꞧk, Kayenta Formation; Jed, Dewey Bridge Member, Jes, Slick Rock Member, both of the Entrada Sandstone; Js, Summerville Formation; Jms, Salt Wash Member of the Morrison Formation. Summerville Formation about 95 feet thick.

The Dewey Bridge Member, largely red to buff or orange-red soft horizontally bedded siltstone, mudstone, and sandstone, commonly crops out as a smooth, somewhat hummocky red to buff slope that forms a narrow platform from which the cliffs of the upper part of the Entrada Sandstone rise. In general the color is distinctly darker than other parts of the Entrada. With the exception of a single locality, nowhere in this area are the Dewey Bridge beds markedly contorted or wavy as they are farther west in Utah (Dane, 1935, p. 90). The exceptional area is on the north side of the San Miguel River about one-half mile below the mouth of Atkinson Creek, where sandy Dewey Bridge fills what appears to be a channel cut in soft shales at the top of the Kayenta and large-scale distortions of the beds of the Dewey Bridge are reflected well up into the locally thickened overlying part of the Entrada Sandstone (fig. 9).

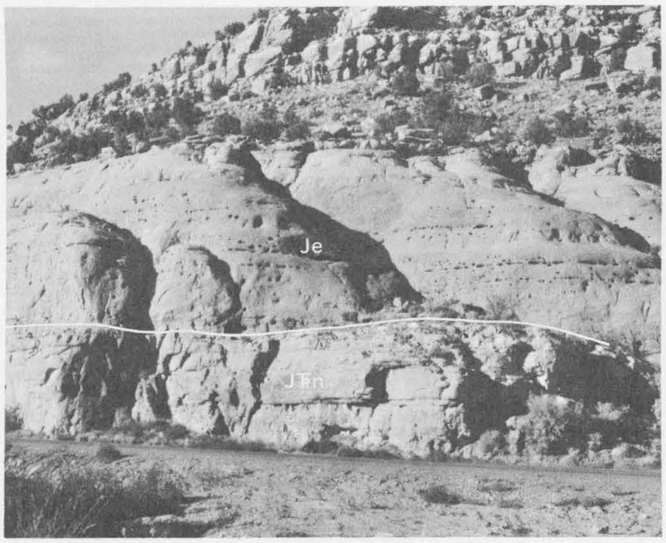


FIGURE 8.—Entrada Sandstone (Je), about 100 feet thick, resting directly on Navajo Sandstone (JŦRn), at Uravan, Colo. Note the relatively flat bedding in the Navajo and rows of pits in the Entrada.

The material in the Dewey Bridge generally is poorly sorted and has an earthy appearance. Shales devoid of sand and sandstones devoid of clay and silt are rare and of local occurrence only. Sand, silt, and clay are mixed together in most beds. Pebbles and angular fragments of white and gray chert, as much as an inch across, are scattered rather abundantly through the lower part and less abundantly through the upper part. Locally, pebbles and fragments are sufficiently abundant to form layers of conglomerate. Included in these layers are scattered greenish-gray, red, and yellow quartzite pebbles and similar boulders as large as 5 by 8 inches. In many places the upper part of the member contains scattered barite nodules as much as an inch across. Over considerable areas the lower part of the member consists almost entirely of reworked Navajo Sandstone, but, strangely enough, where the Dewey Bridge rests directly on the Kayenta Formation, the basal beds contain little reworked Kayenta material.

Localities where detailed complete sections of the Entrada can be measured are relatively uncommon; in most places the Slick Rock Member forms an unscalable cliff, and where it can be traversed the underlying Dewey Bridge Member is poorly exposed. Partly for this reason and partly because at the time the sections were measured the Dewey Bridge Member was thought to be the Carmel Formation, most sections of the two members were measured in different localities, and hence with one exception are presented separately here.

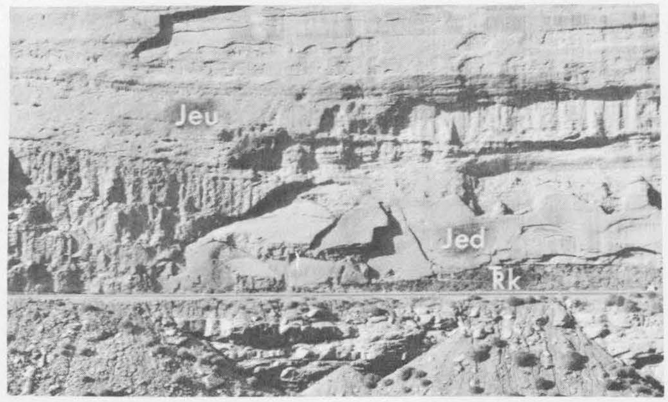


FIGURE 9.—Beds of Dewey Bridge Member (Jed) of Entrada Sandstone filling a channel cut in shale of Kayenta Formation (ŦRk). Overlying beds of Entrada Sandstone (Jeu) show local thickening.

Section of the Entrada Sandstone near the Dolores group of mines in secs. 29 and 30, T. 48 N., R. 17 W., Montrose County, Colo.

[Measured by L. C. Craig, R. A. Cadigan, E. M. Shoemaker, and Carl Setzer]

	Feet
Summerville Formation.	
Entrada Sandstone:	
Slick Rock Member:	
Sandstone, white, fine-grained; composed of predominantly clear quartz with minor pink and black accessory minerals; poorly defined horizontal bedding	7.5
Shale, dark-maroon, papery	.1
Sandstone, white, fine-grained; composed of subangular clear quartz grains with sparse grains of pink and black accessory minerals; massive outcrop with ridging that indicates horizontal bedding and lamination	7.0
Claystone, dark-maroon, papery; contains thin lenses of pink fine-grained sandstone	.2
Sandstone, white to buff, very fine grained to fine-grained; composed of subangular clear quartz grains with minor quantities of pink and black accessory minerals; massive outcrop with faint horizontal bands indicating bedding; thin beds show cross-laminae. Unit appears to bevel underlying beds	12.3
Sandstone, white to buff, very fine to medium-coarse-grained, well-sorted; highly cross laminated; wedge bedded; sparse coarse frosted and well-rounded grains concentrated along laminae. Unit bevels underlying beds	10.8
Sandstone, interbedded, orange-brown and white to buff, very fine grained, contains numerous coarse frosted and well-rounded grains of clear quartz, white chert, and pink grains; interbedded highly cross laminated layers and horizontal irregularly laminated layers. Abundant disseminated coarse grains in lowest 2 ft.	68.2
Total Slick Rock Member	106.1

	Feet
Entrada Sandstone—Continued	
Dewey Bridge Member:	
Sandstone, buff to pale-brown, fine- to medium-coarse-grained, very poorly sorted; massive, structureless; contains large well-rounded and frosted grains and angular chert fragments as much as ½ in. in diameter; interbedded with this sandstone is red-brown fine-grained sandstone containing dark-red, very fine grained clay-bearing laminae showing some distortion	49.3
Sandstone, pale-brown to buff, fine- to medium-coarse-grained, clear quartz with minor pink accessory minerals; massive weathering; long radius cross-lamination. Numerous white angular chert granules. Prominent dark-red clayey sandstone above base	10.7
Total Dewey Bridge Member	60.0
Total Entrada Sandstone	166.1

Unconformity.
Kayenta Formation.

Section of the Dewey Bridge Member near Slick Rock, sec. 25, T. 44 N., R. 19 W., San Miguel County, Colo.

[Measured by L. C. Craig]

	Feet
Entrada Sandstone:	
Slick Rock Member.	
Dewey Bridge Member:	
Sandstone, pale-reddish-brown, grading to pale-yellow buff, fine-grained; contains faint wavy horizontal red clayey laminae in lower half. Probably grades into the Slick Rock Member	1.9
Sandstone, pale-reddish-brown, very fine grained to fine-grained, poorly sorted; contains subangular clear quartz grains and minor accessory minerals, numerous well-rounded frosted-amber quartz grains; weathers to rounded topographic forms; some faint irregular red laminae	13.2
Covered interval probably similar to overlying beds	6.0
Sandstone, moderate-reddish-orange, fine- to medium-fine-grained; composed of subangular to rounded clear quartz grains with minor orange and black accessory mineral grains; structureless	4.1
Sandstone; moderate-reddish-orange, very fine- to medium-fine-grained, poorly sorted; composed of subangular to well-rounded clear quartz grains with faint irregular clayey laminae	4.4
Sandstone, moderate-reddish-orange, very fine grained to medium- fine-grained, very poorly sorted; composed of subangular to well-rounded clear quartz grains with sparse grains of pink and black accessory minerals; faint horizontal wavy laminations; scattered rounded to angular white, gray, and black chert pebbles as much as 3 in. across	2.2
Total Dewey Bridge Member	31.8

Unconformity.
Navajo Sandstone.

Section of Dewey Bridge Member of Entrada Sandstone, north rim of Sinbad Valley about 2 miles west of mapped area, secs. 30 and 31, T. 50 N., R. 19 W., Mesa County, Colo.

[Measured by L. C. Craig, with H. L. Jicha, William Alexander, and James Standard]

	Feet
Entrada Sandstone:	
Slick Rock Member.	
Dewey Bridge Member:	
Sandstone, dark-reddish-orange, fine- to medium-grained, poorly sorted; subangular to well-rounded clear quartz grains; unit is massive, poorly bedded, and contains some dark-red discontinuous clay laminae	37.1
Sandstone, pale-brown, fine- to medium-fine-grained; consists of subangular to rounded clear quartz grains; poorly bedded, poorly laminated unit	4.3
Sandstone, dark-red, medium-fine- to medium-grained; contains irregular discontinuous dark-red clay laminae	1.0
Sandstone, pale-brown to yellow-brown, fine- to medium-fine-grained; contains clear quartz with pink and black accessory minerals; massive, poorly bedded, poorly laminated unit; numerous white chert fragments as much as 1 in. across in lower 5 ft of unit	13.8
Total Dewey Bridge Member	56.2

Unconformity.
Navajo Sandstone.

Thickness.—The Dewey Bridge Member was deposited on a somewhat irregular erosion surface which largely controls the variations in thickness of the member. Variations in thickness of the Dewey Bridge are also caused by irregularities in its contact with the overlying parts of the Entrada, especially irregularities resulting from the contact being gradational and not following one stratigraphic horizon. The Dewey Bridge has a maximum thickness within the area of about 100 feet; such a thickness, however, is exceptional and occurs only in the vicinity of Spring Canyon (T. 46 N., Rs. 18 and 19 W.) and nearby areas. Elsewhere the thickness rarely exceeds 65 feet. Any statement concerning a "normal thickness" would be misleading because, even over small areas, the thickness may range from a featheredge to 50 feet within a distance of a quarter of a mile. A normal range of thickness where the member is continuously present over extensive areas is probably 20 to 50 feet.

Conditions of deposition.—The origin of the Dewey Bridge in Colorado is not readily evident as fossils have not been found, and the lithic characteristics of the member indicate only subaqueous deposition. Probably, however, the member formed in lagoons marginal to a sea.

Slick Rock Member

The Slick Rock Member of the Entrada conformably overlies the Dewey Bridge and, like the Wingate and Navajo Sandstone, is a clean, massive, cliff-forming sandstone. The distribution of outcrops of the Slick Rock is almost identical to that of the Dewey Bridge, although the Slick Rock is more continuous and was deposited over the entire area except along the crests of the salt anticlines. The Slick Rock Member, locally known as the "slick rim" because of its appearance, is perhaps the most strikingly picturesque of all the strata in the plateau region of Colorado (figs. 7–8). The smoothly rounded, in places bulging, cliffs ranging in color from nearly white to pastel shades of orange and buff are a highly distinctive and scenic feature of the region; they contrast strongly in color with the gaudy, flaming hues of underlying formations and the relatively drabber colors of the post-San Rafael formations. Horizontal rows of pits resulting from differential weathering and ranging from a few inches to a foot or more across are also characteristic of these cliffs. The member consists of alternating parallel-bedded units and sweeping eolian-type crossbedded units. The parallel-bedded units are most common in the basal part and in the uppermost lighter colored part of the member, whereas the crossbedded units are commonly dominant in the middle part.

The Slick Rock Member of the Entrada Sandstone differs from the somewhat similar Wingate and Navajo Sandstones in that the sand is sorted into two distinct grain sizes. Subrounded to subangular sand grains mostly less than 0.15 mm in diameter make up the bulk of the sandstone. Contrasting with these small grains are well-rounded grains which have frosted surfaces and which range in diameter from 0.4 to 0.8 mm. Most of the larger grains are distributed in thin layers along bedding and laminations, but at one locality in Paradox Valley a short distance northeast of the Thunderbolt mine (sec. 23, T. 46 N., R. 17 W.), there are a few small lenses a foot or more wide and several inches thick that consist almost entirely of these large rounded grains. According to R. A. Cadigan (written commun., 1954) the mean composition of 15 samples of Entrada Sandstone is quartz, 76 percent; chert, 3 percent; quartz overgrowths and silica cement, 3 percent; calcite, 9 percent; potassic and sodic feldspar, 9 percent; muscovite, biotite, and heavy minerals, less than 1 percent. The large well-rounded grains consist mostly of quartz, but some grains are chert.

Some beds in the upper part of the Entrada Sandstone, north of Sinbad Valley, in the northwestern part of the mapped area can be traced westward into the Moab Tongue of the Entrada Sandstone in Utah (Baker, 1933, p. 49). In the area of this report the contact between beds probably equivalent to the Moab Tongue and those of the main body of the Entrada cannot be traced consistently; prominent parting planes are not continuous. Furthermore, some rocks equivalent to the Moab Tongue grade into the overlying Summerville Formation. Detailed study would allow separation of the Moab Tongue as a distinct member in the mapped area, as Wright, Shawe, and Lohman (1962) have shown, but such a member was not separated when the area was mapped. In general the sandstone in the upper part of the Entrada and those beds probably correlating with the Moab Tongue contain fewer large rounded frosted grains than in the rest of the formation, are much lighter in color, and tend to weather to somewhat ledgy or flaggy outcrops.

Sections of the Entrada Sandstone were measured at numerous locations within the area, and those presented here are typical.

Section of the Slick Rock Member of the Entrada Sandstone, north side of John Brown Canyon, sec. 32, T. 51 N., R. 19 W., Mesa County, Colo.

[Measured by L. C. Craig, H. L. Jicha, and others]

	Feet
Summerville Formation.	
Entrada Sandstone:	
Slick Rock Member:	
Sandstone, white, light-buff-weathering, fine-grained, evenly laminated, evenly bedded; composed of clear subangular quartz grains with minor pink chert	3.9
Sandstone, red and gray-green, banded, fine-grained; contains varying amounts of dark-red and gray matrix. This unit may represent Entrada Sandstone beds grading laterally into Summerville-like beds	7.3
Sandstone, white, brownish-buff-weathering, fine-grained, parallel-bedded and parallel-laminated	27.0
Shale, dark-purplish-red, clayey. This prominent parting may mark the base of beds equivalent to the Moab Tongue of the Entrada	.3
Sandstone, white, fine- and medium-grained, fairly well sorted; wedging bedding	48.6
Sandstone, light-orange-buff to white, fine- to medium-grained, fairly well sorted; composed of clear quartz with large well-rounded and frosted grains nearly confined to laminae; wedging bedding	92.8
Sandstone, light-orange-buff and white, fine-grained; composed of subangular quartz grains with numerous well-rounded, frosted, medium-coarse clear and amber quartz grains, white to gray chert grains, and black grains; prominent horizontal bedding indicated	43.2
Total Slick Rock Member	223.1
Dewey Bridge Member.	

Section of the Slick Rock Member of the Entrada Sandstone, measured in sec. 6, T. 42 N., R. 17 W., San Miguel County, Colo.

	Feet
Summerville Formation.	
Entrada Sandstone:	
Slick Rock Member:	
Sandstone, moderate-reddish-orange (10*R* 6/6)[1], fine- to medium-grained, poorly sorted; composed of subangular to very well rounded clear	

[1] These symbols designate the quality and density of color and are from the National Research Council "Rock-Color Chart" (Goddard and others, 1948). Many of the stratigraphic sections presented in this report were measured before the charts became available and consequently in those sections the symbols are lacking.

	Feet
Entrada Sandstone—Continued	
quartz grains with minor quantities of pink, gray, and black accessory minerals; massive rounded weathering; beds 1–7 ft thick; at base is a wavy reentering parting that separates this unit as a distinct ledge and marks a sharp color	
Slick Rock Member—Continued	
change; faint horizontal wavy lamination	19.4
Sandstone, grayish-yellow, white-weathering; composition as below; structureless	1.4
Sandstone, grayish-yellow, pale-brown-weathering, medium-fine-grained; sparse medium-coarse grains; highly cross laminated	12.0
Sandstone, grayish-orange, white-weathering, fine-grained; numerous medium-coarse grains; horizontal wavy lamination	17.0
Sandstone, grayish-orange, white-weathering, medium-fine grained; numerous medium-coarse grains; wedging cross-lamination	3.4
Sandstone, moderate-reddish-orange, very fine grained to fine-grained; medium-coarse grains common; horizontal wavy lamination	12.9
Sandstone, moderate-reddish-orange, medium-fine-grained; contains a few medium-coarse grains; poorly sorted; highly cross laminated	3.4
Sandstone, mottled pale-yellow; composition and color as below; discontinuous wavy lamination	8.5
Sandstone, moderate reddish-orange (10*R* 6/8), fine-grained to very fine grained; disseminated medium-coarse grains abundant; bedding indistinct, probably consists of horizontal wavy lamination	7.3
Total Slick Rock Member	85.3
Dewey Bridge Member.	

Thickness.—The Slick Rock Member of the Entrada Sandstone maintains a fairly uniform thickness over extensive areas, but in the vicinity of the salt anticlines, it wedges out in places. In general, however, it thickens to the west. It has a maximum thickness of about 225 feet north of Sinbad Valley along the western edge of the area, but elsewhere in the western part of the area it commonly is 130–150 feet thick; in the eastern part of the area, it is as little as 90 feet. Some part of the greater thickness in the vicinity and north of Sinbad Valley is probably due to the presence of beds belonging to the Moab Tongue of the Entrada.

Conditions of deposition.—The bedding characteristics of the Slick Rock Member of the Entrada indicate a combination of agents of deposition. The units made up of sweeping crossbeds evidently were deposited by wind, but the horizontally bedded units were probably water laid, and true horizontal bedding planes cutting the eolian units suggest water action. Gilluly and Reeside (1928, p. 78) considered that the Entrada in the San Rafael Swell of Utah was all water deposited because there the Entrada contains much silt, has an earthy appearance, and devoid of large-scale crossbedding. In that same area the Entrada is both underlain and overlain by marine deposits—by the Carmel and Curtis formations respectively. The overall bedding and lithic characteristics of the Slick Rock Member of the Entrada in western Colorado suggest that the formation was deposited in and marginal to a body of shallow water. The crossbedded units probably are the remains of dunes formed on very broad marginal beaches during times when the water had retreated long distances.

SUMMERVILLE FORMATION

The Summerville Formation conformably overlies the Slick Rock Member of the Entrada and crops out as a rather inconspicuous unit on the lower slopes of most of the high mesas and in many places along the canyon walls of the Dolores and San Miguel Rivers and their tributaries. The formation is also exposed along the sides of Paradox and Gypsum Valleys except where concealed by faulting, or where it pinches out against the flanks of the salt anticlines as in the southeastern end of Gypsum Valley.

The Summerville characteristically forms a red slope above rounded Entrada Sandstone cliffs and below ragged-weathering sandstone ledges of the lower part of the Morrison Formation (figs. 6 and 7). In many places it is covered with talus from the overlying Morrison Formation and generally is rather deeply weathered. Consequently, good exposures are rare and are confined to gullies or to a few localities where the formation is undercut to form a cliff beneath the resistant sandstone of the Morrison Formation. At many places in the upper half of the Summerville, a sandstone ledge forms a low cliff which breaks the regularity of the slope. This sandstone is persistent in the mapped area and has received various field names. At Uravan, for example, Goldman and Spencer (1941, p. 1756–1757) referred to it as the mixed-grain sandstone unit.

The Summerville Formation consists of interbedded claystone and sandstone, and, in the upper part, scattered thin beds of limestone. The claystones are reddish brown and most are silty and sandy. They contain disseminated amber-stained well-rounded small quartz grains that are an aid in identifying the formation in areas of complicated structure or poor exposures. The sandstone ranges from reddish brown, silty and clayey, and very fine grained to light brown or almost white, clean, and fine to medium grained. According to R. A. Cadigan (written commun., 1954), the mean composition of the sandstone, based on 14 samples, is quartz, 67 percent; chert, 5 percent; quartz overgrowths and silica cement, 3 percent; calcite cement, 19 percent; potassic and sodic feldspar, 6 percent; biotite and other heavy minerals, less than 1 percent. Most of the sandstones are well sorted, but the mixed-grain sandstone contains sparse medium to very coarse grains of quartz and gray to black chalcedony. According to Cadigan (written commun., 1954) some of the dark grains of chalcedony contain dolomite. They may be diagnostic of this bed, for they contrast with the dark ilmenite-magnetite and black tourmaline grains of the Morrison sandstones. The thin limestone beds of the Summerville are very fine grained and dark gray to black. At the mouth of Atkinson Creek the limestone contains small gastropod shells, the only fossils known in the Summerville in the mapped area. Thin, parallel, remarkably continuous beds ranging in thickness from 2 inches to

FIGURE 10.—Summerville Formation in roadcut 2 miles southeast of Uravan, Colo.

3 feet are a diagnostic feature of the Summerville Formation (fig. 10). Bedding planes in the claystone and most of the sandstone units are flat and regular; some of the sandstone beds show parallel slightly asymmetrical ripple marks with an average amplitude of 1/4 inch and an average wave length of 1 1/2 inches.

Goldman and Spencer (1941) studied the upper part of the San Rafael Group in detail in parts of southwestern Colorado and recognized a number of distinctive lithic features such as carnelian grains, green chert, barite concretions, and mixed-grain sandstone, which have aided in correlation. However, many of the characteristics which they used for correlations east and south of the Uravan district are not widespread throughout the mapped area or are not detectable because of generally poor exposure. Nevertheless, the mixed-grain sandstone in the upper half of the Summerville Formation is unusually persistent (unit B of the Uravan section of Goldman and Spencer, 1941, p. 1756), and grains of red finely botryoidal chert and similar incrustations on calcareous sandstone fragments are found as float derived from the lower third of the formation in many parts of southwestern Colorado.

Although the basal part of the Summerville is transitional into the underlying Entrada Sandstone through a few feet of thin ledge-forming beds of Entrada-like sandstone that alternate with reddish Summerville-like mudstone, the lower contact is evident enough in most places. Along the Dolores River below the junction of the San Miguel River, careful tracing of beds has shown that the top beds of the Entrada Sandstone grade southward into the Summerville Formation. This gradation of only a few feet of beds takes place through a distance of about 5 miles, and although it has been discerned only at this one place, it is probably characteristic of the Entrada-Summerville contact in western Colorado. These beds lie below and are not the same as the beds listed as Entrada in the measured section in John Brown Canyon (p. 30 and 32) to be described later (p. 34) as transitional into the Moab Tongue of the Entrada Sandstone.

The following sections are representative of the Summerville Formation in the mapped area:

Section of the Summerville Formation, north side of John Brown Canyon, sec. 32, T. 51 N., R. 19 W., Mesa County, Colo.

[Measured by L. C. Craig, H. L. Jicha, and others]

	Feet
Morrison Formation:	
Salt Wash Member (incomplete):	
Sandstone, white, light brown-weathering, medium-fine grained; composed of clear subangular quartz grains with minor quantities of pink and green accessory minerals. Fluviatile channel and fill bedding	6.4
Siltstone and sandy shale, interbedded, dark-red; contains irregular gray-green bands	3.0
Limestone, light-gray to purplish, fine-grained; locally recrystallized to coarse grained	.9
Total incomplete Salt Wash Member	10.3
Summerville Formation:	
Siltstone and sandstone interbedded, pink to brick-red. Sandstone is fine grained, in part clayey; silty clay partings separated thin even sandstone beds	16.2
Sandstone, white, light brown-weathering, fine- to medium grained; poorly sorted, composed of clear quartz with minor accessory minerals including dark-gray to black chert grains	3.2
Siltstone, dark-red; weathers to chippy rubble; contains small amount of disseminated fine quartz grains	14.6
Claystone, dark-red to brown; contains fine grains of disseminated clear to amber-stained quartz; a few hard light-gray siliceously cemented sandstone beds which probably were originally calcareous	16.2
Total Summerville Formation	50.2
Entrada Sandstone (incomplete):[1]	
Sandstone, white light brown-weathering, fine-grained, evenly laminated, evenly bedded; composed of clear	

Entrada Sandstone—Continued — *Feet*

subangular quartz grains with minor pink chert 3.9

Sandstone, red and gray-green, banded, fine-grained; contains varying amounts of dark-red and gray matrix. This unit may represent Entrada Sandstone beds grading laterally into Summerville-like beds 7.3

Sandstone, white, brownish buff-weathering, fine-grained, parallel-bedded and laminated 27.0

Shale, dark-purplish-red, clayey 3

Total incomplete Entrada Sandstone 38.5

Section of the Summerville Formation, northeast side of Dolores River Canyon, sec. 2, T. 48 N., R. 18 W., unsurveyed, Montrose County, Colo.

[Measured by L. C. Craig, H. L. Jicha, William Alexander, and James Standard]

Morrison Formation (incomplete): — *Feet*

Salt Wash Member (basal part only):

Sandstone, white to pale-brown, brown-weathering, medium-fine- to medium-grained; composed of subangular clear quartz grains with common grains of white chert and minor quantities of pink, gray, and black accessory minerals; prominent channeling, wedging sets of cross-laminae. Contains two 2- to 5-ft-thick red shale intervals. One ledge contains granules of red, green, and gray chert as much as ⅛ in. in diameter. This is the lowest prominent channel-fill sandstone ledge of the Salt Wash Member; the base of this unit was used as the base of the Salt Wash in mapping in this area 75.6

Sandstone and sandy calcareous claystone interbedded. Sandstone is fine grained, buff, irregularly lenticular. Claystone is gray green, thin, irregularly bedded 2.5

Claystone, dark-red, shaly weathering 1

Limestone, gray-green; contains irregular reddish patches; argillaceous and slightly sandy 5.4

Limestone, tan, yellow-brown-weathering, fine-grained; platy bed 2

Total incomplete Salt Wash Member of Morrison Formation 83.8

Summerville Formation:

Sandstone and claystone interbedded. Sandstone is white to green, fine grained, platy weathering, ripple laminated and mud cracked. Claystone is dark-red; contains disseminated medium-fine grains of quartz ... 9.4

Sandstone, light-green to buff, fine- to medium-fine-grained; composed of subangular clear quartz grains with minor dark-gray to black and sparse colored accessory minerals; slabby bedded, evenly laminated 3.9

Claystone, dark- to brick-red; contains disseminated amber-stained fine-grained subangular quartz grains; weathers shaly to earthy 15.0

Sandstone, white to pink, fine-grained, composed of subangular clear quartz grains and pink, green, and

[1] The 38.5 ft of beds considered in this section as belonging to the upper part of the Entrada Sandstone was considered by Cater and E. M. Shoemaker, for the purposes of mapping, as belonging to the Summerville. A few miles to the southeast these beds grade into the alternating thin layers of claystone and sandstone of the lower part of the Summerville Formation.

Summerville Formation—Continued — *Feet*

black accessory mineral grains 9

Claystone, dark-purplish-red to brick-red; contains disseminated amber-stained fine- to medium-fine quartz grains; shaly to earthy weathering 11.7

Claystone and sandstone (25 percent) interbedded. Claystone is dark red; contains disseminated fine to medium grains of amber-stained quartz. Sandstone is pink to white, fine to medium fine grained, and is composed of clear quartz with colored accessory minerals; in 1-ft-thick ledges 8.4

Shale, dark-red; contains disseminated amber-stained fine- to medium-fine rounded quartz grains; rubbly to shaly weathering 13.1

Sandstone and claystone (30–50 percent) interbedded. Sandstone is white to pink, predominantly fine grained; composed of subangular grains of clear quartz with pink, green, black, and orange grains of accessory minerals. Claystone is very sandy; contains clear and amber-stained rounded fine to medium grains of quartz in red clay matrix 29.3

Claystone and sandstone interbedded. Sandstone is white, fine to medium fine grained; composed of subangular clear quartz grains with sparse grains of colored accessory minerals. Claystone is dark red; contains disseminated fine to medium fine grains of quartz 1.8

Sandstone, white, fine- to medium-fine-grained; composed of subangular clear quartz grains 7

Claystone, sandy, dark-red; contains amber-stained fine grains of quartz in red clay matrix 1.4

Bottom contact sharp and conformable.

Total Summerville Formation 95.6

Entrada Sandstone (incomplete, only the top unit described):

Sandstone, light-gray to pale-brown, medium-fine- to medium-grained, very poorly sorted; composed of clear quartz with minor red, pink, orange, green, and black grains; not laminated 8.1

Total incomplete Entrada Sandstone 8.1

Section of the Summerville Formation, northeast side of Dolores River Canyon near Slick Rock, sec. 30, T. 44 N., R. 18 W., San Miguel County, Colo.

[Measured by L. C. Craig]

Morrison Formation (incomplete): — *Feet*

Salt Wash Member (basal part only):

Sandstone, grayish-orange-pink (10*R* 8/2) to pale-red (10*R* 6/2), predominantly fine to medium fine grained; composed of subrounded to subangular grains of clear quartz with numerous amber-stained quartz grains and minor amounts of black accessory minerals; red and green clay flecks; highly cross laminated; chanelling........ 18.8

Sandstone, claystone, and limestone interbedded. Sandstone is mottled dark red and gray green, very fine grained to fine grained; composed of clear subangular grains of quartz; structureless wedging and irregular beds as much as 1 ft thick. Claystone is sandy to silty, dark red; in beds as much as 6 in. thick. Limestone is light gray, very fine grained to aphanitic, forms a

	Feet
Morrison Formation—Continued	
Salt Wash Member—Continued	
1- to 3-in. lens at base of unit. Base of Salt Wash arbitrarily placed at base of limestone or base of lowest beds showing appreciable lenticularity where limestone is absent	13.9
Total incomplete Salt Wash Member of Morrison Formation	32.7
Summerville Formation:	
Sandstone and claystone interbedded. Sandstone is pale red, weathering brown, very fine to fine grained; composed of subangular grains of clear quartz; beds finely ripple laminated (amplitude ⅛–¼ in. wave length 1½–2 in.; weathers to form thin ledges. Claystone is sandy to silty, dark red; in beds as much as 6 in. thick	19.0
Sandstone, very pale orange to grayish-yellow, predominantly fine grained; composed of subangular clear quartz grains with numerous grains of colored accessory minerals; poorly sorted in part; structureless to faintly horizontally laminated to cross laminated on a fine scale in thin beds. Forms ledge	13.2
Sandstone, siltstone, and claystone interbedded. Sandstone and siltstone are predominantly dark reddish brown and contain a few light-greenish-gray highly calcareous beds; sandstone composed of subangular grains of clear quartz and forms continuous even beds as much as 3 ft thick. Claystone is dark reddish brown, very sandy to silty, in 6-in.-thick interbeds. Unit forms ledgy slope	34.1
Sandstone, clayey, to sandy claystone, dark-reddish-brown, very fine grained to fine-grained; indistinct bedding, evenly bedded; forms earthy to flake-covered bench or rounded cliff	11.5
Total Summerville Formation	77.8
Entrada Sandstone (incomplete):	
Sandstone and clayey sandstone interbeds. Sandstone is mottled, pale reddish brown and very pale orange, very fine to medium grained; composed of subangular to well-rounded grains of clear quartz with minor amounts of amber, orange, pink, red, and gray to black accessory minerals; poorly sorted; structureless to wavily laminated. Clayey sandstone interbeds are dark red. Forms massive ledges (sandstone) 2 ft thick and reentrants (clayey sandstone) 6 in. thick	30.6
Total incomplete Entrada Sandstone	30.6

Thickness

The Summerville Formation generally ranges in thickness from a featheredge to 100 feet and averages about 75 feet over much of the area, but, in common with older formations, it pinches out at many places along the crests of the salt anticlines. It cannot be determined whether the formation pinched out as a result of depositional convergence against high ground produced by upward movement of salt or whether the formation was upwarped as a result of salt movement and removed locally by erosion during early Morrison time, although both probably occurred.

Correlation and Conditions of Deposition

The Summerville is interpreted as having been deposited dominantly in shallow quiet water, as is indicated by the prevalence of thin regular beds, the parallel ripple marks and horizontal lamination of the sandstone units, and the total absence of scour surfaces. Previous workers have considered the Summerville marine because in eastern Utah it grades laterally into the Curtis Formation which contains a marine fauna. Alternatively some geologists have argued that the red color and nearly complete absence of fossils in the Summerville suggest a continental environment of deposition. If so, currents must have been slow and sediment must have been deposited from broad sheets of water, perhaps on the lower reaches of a delta.

The Summerville that grades into the Curtis Formation is considered to be Late Jurassic on the basis of the marine fauna in the Curtis. Regionally, the stratigraphic interval between the top of the Entrada and the base of the Morrison Formation contains many facies, most of which have separate names. East of the mapped area the Wanakah Formation of the San Juan Mountains region is probably the equivalent of the Summerville. In northwestern Colorado and northeastern Utah the Curtis Formation occupies the entire interval between the Entrada and Morrison, including the entire Summerville Formation, whereas in central Utah the Curtis is gradational into and includes beds equivalent only to the lower part of the formation. To the south the Junction Creek Sandstone of southwestern Colorado and the Bluff Sandstone of southeastern Utah grade and tongue with the upper part of the Summerville. In easternmost Utah and in the northwestern part of the mapped area, part of the Moab Tongue of the Entrada Sandstone grades and tongues into the lower part of the Summerville and in a few places may include all but a few feet of the Summerville. The transition of part of the Moab Tongue into the lower part of the Summerville can be observed clearly in the vicinity of the mouth of Mesa Creek where, northward, the lowermost 25–40 feet of the Summerville grades into clean sandstone rather abruptly. This sandstone forms a ledgy cliff that in places is continuous with the cliff of the underlying Entrada, but because it could be separated from the underlying Entrada Sandstone with no difficulty, it was mapped with the Summerville (see section measured in John Brown Canyon, p. 32). Over most of the mapped area the Moab is probably represented only by thin sandstone beds mapped with the lower part of the Summerville Formation.

MORRISON FORMATION

The Morrison Formation crops out as a prominent unit which forms most of the slopes of the high mesas throughout the area considered in this report. In some places the protective cap of the overlying Burro Canyon Formation has been largely removed by erosion and the Morrison is exposed over broad areas, as in the Carpenter Flats–Carpenter Ridge area north of Paradox Valley and on Tenderfoot Mesa. The Morrison is the oldest formation to have completely or almost completely blanketed the mapped area, including the salt and gypsum cores of the anticlines.

The Morrison Formation of western Colorado is divided into two members of roughly equal thickness: the Salt Wash below and the Brushy Basin above. The Salt Wash Member contains a number of resistant sandstone strata alternating with less resistant mudstones. The sandstone forms clifflike ledges, the mudstone forms steep slopes, and the general physiographic expression of the member is a steep irregular slope broken by low cliffs (fig. 11). The top resistant sandstone ledge of the Salt Wash generally forms a bench from which the Brushy Basin Member has been eroded and which is one-half mile or more wide in many places. The Brushy Basin Member is composed dominantly of nonresistant bentonitic mudstone, and it forms steep slopes capped and protected from erosion by the resistant Burro Canyon Formation (fig. 11). In many places plastic clays of the Brushy Basin have slumped, and the lower part of the Brushy Basin slope may be buried by such slumped material as well as by toreva blocks and talus of the Burro Canyon Formation. The blocks, talus, and slumped clays commonly exhibit the hummocky topography typical of landslides. Large toreva blocks may form small shallow depressions or benches perched high on the Brushy Basin slope, and in places careful examination is required to detect whether the large blocks have slumped.

The Morrison Formation ranges in thickness from about 600 to 800 feet in most of the mapped area, although D. R. Shawe (written commun., 1957) has reported a maximum thickness 1,150 feet from a drill hole in Disappointment Valley (sec. 36, T. 44 N., R. 18 W.). The variations of thickness of the Morrison are in part unsystematic and occur irregularly throughout most of western Colorado, but in the area of the salt anticlines the Morrison generally thickens away from the crests of the major anticlines.

The following stratigraphic sections are representative of the Morrison Formation in the mapped area:

Section of the Morrison Formation at the Dolores group of mines, measured on south face of Atkinson Mesa, secs. 19, 20, 29, and 30, T. 48 N., R. 17 W., Montrose County, Colo.

[Measured by L. C. Craig, R. A. Cadigan, E. M. Shoemaker, and Carl Setzer]

	Feet
Burro Canyon Formation (incomplete):	
Claystone, silty, sandy and conglomeratic, gray-green, nonresistant; contains granules of clear quartz, dark-gray quartz, and sparse red chert	10.8

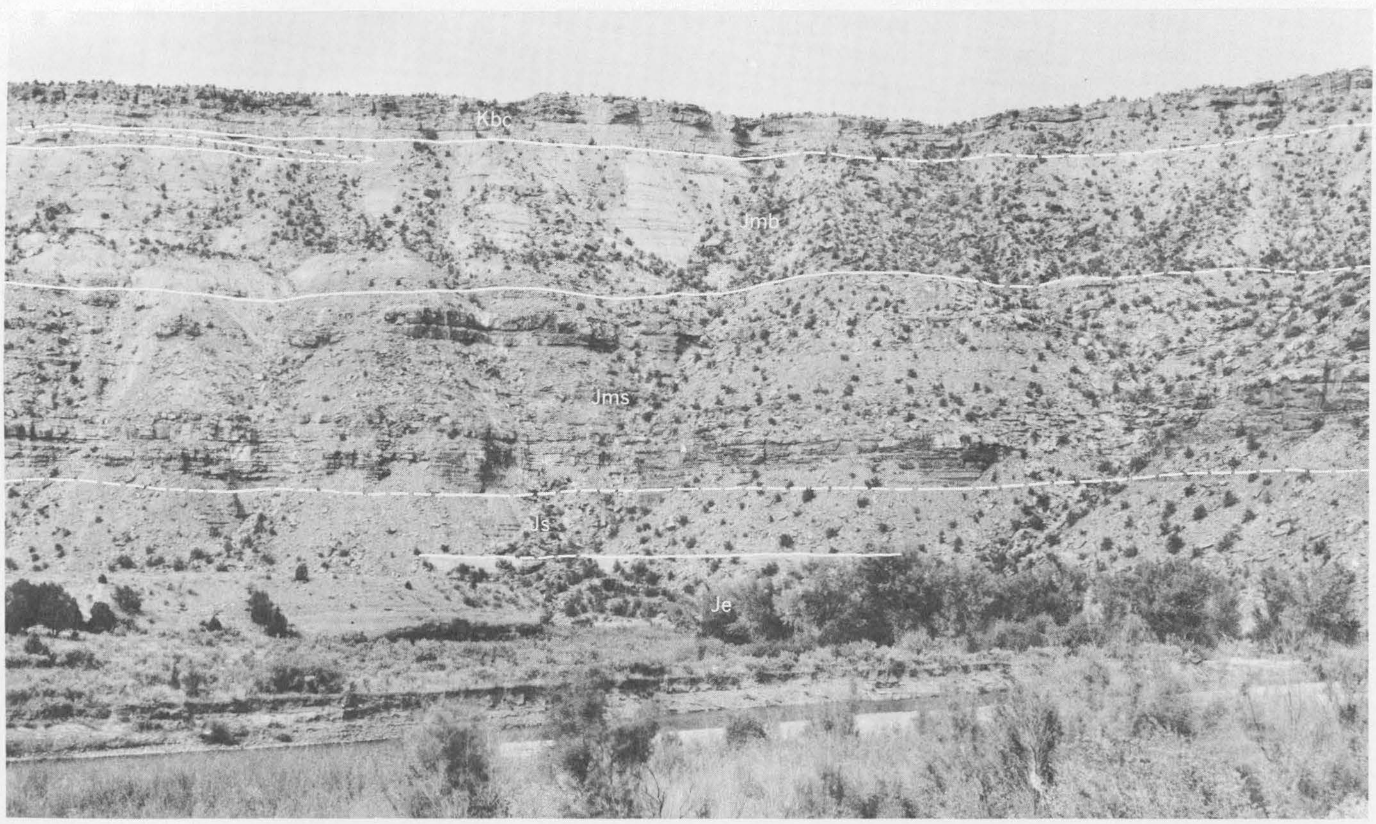


FIGURE 11.—South face of Blue Mesa, showing outcrop of Entrada Sandstone (Je), Summerville Formation (Js), Salt Wash Member of Morrison Formation (Jms), Brushy Basin Member of Morrison Formation (Jmb), and Burro Canyon Formation (Kbc). Note interfingering of Burro Canyon and Brushy Basin at upper left.

Morrison Formation:	Feet
Brushy Basin Member:	
Top contact is an irregular channeled contact.	
Claystone and sandstone. Claystone is dark red, silty. Sandstone is dark red, fine grained, thinly bedded. Scattered exposures	20.9
Sandstone, buff, fine-grained, ledge-forming	2.0
Claystone; as below, but becomes medium gray in upper half	42.7
Claystone, silty, dark-reddish-brown; contains a few irregular greenish-gray streaks. Several ledges of red-brown hackly-fracturing fine-grained sandy siltstone	36.6
Covered	128.7
Claystone, silty, dark-red to maroon, polygonal-fracturing; contains thin lenticular layers of siltstone and very fine grained to fine-grained sandstone	25.2
Claystone, silty, gray-green to green, bentonitic	20.0
Claystone, dark-red to gray, silty, banded; numerous thin light-gray, fine-grained nodular brown-weathering limestone interbeds	20.0
Interval poorly exposed. Lower half gray, yellow, and cream bentonitic silty shale; upper half is green to red silty shale, thin green siltstone, and several thin nodular to platy light-gray fine-grained limestone beds	29.4
Interval poorly exposed. Siltstone, silty claystone, and claystone, dark-red	24.4
Sandstone, conglomeratic, medium-brown-weathering, fine-grained to very coarse grained, very poorly sorted; composed of rounded grains of clear quartz with grains of red and green minor accessory minerals; granules and pebbles of white, tan, gray, red, and green chert	15.9
Total Brushy Basin Member	365.8

Salt Wash Member:	Feet
Covered interval. Probably dark-red silty sandstone and siltstone	12.6
Sandstone, light-brown to brown, fine-grained; composed of clear quartz with green, red, pink and black accessory minerals; ripple laminated to cross laminated	3.6
Interval covered in upper part. Lower part is dark-red sandstone with interbeds of greenish-gray to gray very fine grained sandstone as much as 1 ft thick	25.9
Sandstone, pale-brown-weathering, fine- to medium-grained, poorly sorted; composed of subangular to rounded clear quartz grains with minor grains of accessory minerals and green chert; numerous greenish-gray pebbles; highly channeled cross-laminated thick beds	32.6
Covered. Dark-red silty claystone indicated	9.8
Sandstone, pale- to light-brown, fine- to medium-fine-grained; composed of clear quartz with very minor pink and black accessory minerals, highly cross laminated	6.7
Claystone, light-green, silty to sandy; having beds of greenish-brown to dark-brown very fine grained sandstone as much as 1 ft thick	4.1

Morrison Formation—Continued	Feet
Salt Wash Member—Continued	
Sandstone, brown-weathering, fine grained, ripple-laminated	4.9
Interval very poorly exposed. Claystone and silty claystone, dark-red; contains a few thin very fine grained greenish-brown sandstone beds and thin medium-gray nodular limestone beds	39.8
Sandstone, white, pale-brown-weathering, fine-grained; composed of clear quartz with pink and black accessory minerals; channeled and cross laminated	12.8
Covered. Probably nonresistant	2.1
Sandstone, pale-brown, medium- to dark-brown-weathering, very fine grained; ripple laminated to cross laminated	6.4
Covered. Probably dark-red shale and siltstone and brownish fine-grained horizontally laminated sandstone	6.3
Sandstone, pale-brown, light-brown-weathering, medium-fine- to fine-grained; composed of clear quartz with minor pink and amber quartz and white chert grains; lenticular beds, highly cross laminated, extreme channeling. Unit is uranium bearing lateral to section. Sparse bone fragments noted	15.6
Interval very poorly exposed; dark-red silty friable claystone and interbeds of pink to brown fine-grained, slabby, faintly ripple laminated sandstone indicated	21.0
Sandstone, pale-brown, light-brown-weathering, fine- to medium-fine-grained; composed of clear quartz with minor amounts of white chert, pink and amber quartz, and black accessory minerals; highly cross laminated, channeled	13.3
Interval very poorly exposed. Dark-red silty claystone, dark-red shaly siltstone, and numerous pink to whitish very fine grained sandstone beds indicated	18.0
Sandstone, greenish to brownish, light-brown-weathering, fine- to medium-fine-grained; composed of subangular to rounded grains of clear quartz with angular grains of white chert and minor black and pink to amber accessory minerals; thick bedded, highly cross laminated, channeled	20.0
Interval very poorly exposed in lower part. Slabby interbeds of dark-red claystone, dark-red siltstone, greenish very fine grained sandstone, and pink to pale-brown, medium-grained, poorly to well-sorted sandstone. Fine-grained sandstone and siltstone show worm burrows	21.4
Sandstone, white, light-brown-weathering, predominantly fine grained; composed of clear quartz with numerous grains of amber to pink quartz and black accessory minerals; highly cross laminated	6.8
Sandstone and siltstone interbedded. Sandstone, brown-weathering, very fine grained; contains a few black specks of fossil wood. Siltstone, red to greenish, shaly-weathering	7.0
Sandstone, white, light-brown-weathering, medium-fine- to fine-grained; composed of clear	

	Feet
Morrison Formation—Continued	
Salt Wash Member—Continued	
quartz with very minor quantities of pink and black accessory minerals; thick bedded, highly cross laminated, channeling 5 ft vertically in 100 ft horizontally	7.0
Sandstone, light-yellow to pale-brown, medium-brown-weathering, very fine grained to fine-grained; horizontally bedded, evenly laminated to ripple laminated	19.2
Claystone, shaly, dark-brown, slightly silty. Upper part of interval poorly exposed	9.6
Calcareous sandy claystone and limestone, light-gray, fine-grained; weathers shaly to platy	2.6
Limestone, light-gray, fine-grained; in part slightly sandy	1.2
Sandstone, siltstone, and sandy limestone;[1] yellow brown below, light gray above, platy to slabby; some of limestone shows wavy lamination suggesting algal colonies	4.6
Total Salt Wash Member	334.9
Total Morrison Formation	700.7
Summerville Formation:	
Interval covered	3.6

Section of the Morrison Formation measured on west side of Summit Canyon at Summit Point, secs. 8 and 9, T. 43 N., R. 19 W., San Miguel County, Colo.

[Measured by L. C. Craig and J. J. Folger]

	Feet
Burro Canyon Formation (incomplete):	
Sandstone, conglomeratic, pale-orange, fine- to medium-grained, very poorly sorted; composed of subangular clear quartz grains with quartz overgrowths; contains abundant angular white chert grains, and sparse grains of pink, orange, and gray accessory minerals; highly cross laminated, fills channels; pebbles as much as 2 in. in diameter of light-gray, white, and tan chert; some pebbles fossiliferous	27.0
Morrison Formation:	
Brushy Basin Member:	
Top contact poorly exposed, probably channeled. Covered	30.1
Claystone, predominantly red, some grayish-green, silty to fine-grained sandy; poorly exposed	5.4
Covered	16.2
Claystone; predominantly grayish green with some red, silty; poorly exposed	10.8
Covered	21.6
Claystone, predominantly dark reddish brown, some grayish-green, silty to fine-grained sandy; poorly exposed	42.6
Sandstone, pale-greenish-gray, medium-fine- to medium-grained; composed of clear quartz and red chert in about equal amounts; lenticular unit	6.0
Claystone, dark-reddish- to purplish-brown, silty to fine-grained sandy	14.6

[1] Base of Salt Wash Member arbitrarily placed at base of limestone beds, which mark the most suitable contact regionally, although in this part of western Colorado the base of the lowest channel-fill sandstone ledge (lowermost of the two 7-ft-thick units above) is an appropriate and suitable contact. No significant break in deposition marks the basal Morrison contact.

	Feet
Morrison Formation—Continued	
Brushy Basin Member—Continued	
Sandstone, mottled dark-reddish-brown and greenish-gray, very fine grained to fine-grained; composed of subangular grains of clear quartz with minor red chert	1.0
Surface outcrop covered	.....
Interval covered by windblown material and vegetation on broad bench	159.3
Sandstone, conglomeratic; same as 19.4-ft. unit below; poorly exposed	8.7
Covered; sandstone and some grayish-green and red silty claystone indicated	13.6
Sandstone, conglomeratic, grayish-orange, very fine grained to very coarse grained, very poorly sorted; composed of subangular grains of clear quartz with abundant grains of white chert and sparse colored accessory minerals; pebbles of white, tan, gray, red, and pale-green chert, disseminated and concentrated in lenses; highly cross laminated, channeled	19.4
Total Brushy Basin Member	349.3
Salt Wash Member:	
Contact unexposed, probably channeled, located within 1 ft.	
Claystone and sandstone interbedded. Sandstone is grayish orange, very fine to fine grained; composed of subangular grains of clear quartz with numerous grains of orange-red, green, and black accessory minerals. Claystone is dark reddish brown to maroon to gray, silty to fine grained sandy	36.8
Covered	12.6
Sandstone, very light gray to pale-orange, predominantly fine grained; composed of subangular grains of clear quartz with numerous white angular chert grains and scattered grains of colored accessory minerals; highly cross-laminated, channeled	22.7
Claystone, greenish-gray (5GY 6/1), very fine grained to fine-grained sandy	1.5
Sandstone, grayish-orange (10YR 7/4), very fine grained; composed of angular grains of clear quartz	1.0
Siltstone, grayish-yelow (5Y 8/4), clayey	1.0
Sandstone and claystone interbedded. Sandstone is pale reddish brown to pale red, predominantly fine grained; composed of subangular grains of clear quartz with numerous grains of white chert and orange and black accessory minerals; structureless to ripple laminated in beds as much as 3 ft. thick. Claystone is dark reddish brown, silty to fine grained sandy	46.1
Sandstone, very pale orange to white to pale-pink, medium-fine- to fine-grained; composed of subangular grains of clear quartz with minor quantities of white chert and orange, pink black, and green accessory minerals; highly cross laminated, channeled	25.6
Sandstone and claystone interbedded. Sandstone is pale reddish brown, very fine grained; com-	

Morrison Formation—Continued	*Feet*
Salt Wash Member—Continued	
posed of subangular clear quartz grains with abundant quantities of orange, pink, and black accessory minerals; horizontally laminated to ripple laminated. Claystone is dark reddish brown to chocolate brown, very fine grained, sandy	29.0
Sandstone, very pale orange (10*YR* 8/2) to moderate orange-pink (10*R* 7/4), fine- to medium-fine-grained; composed of subangular to subrounded clear quartz grains with numerous red claystone pebbels at bottom; highly cross laminated, channeled	18.0
Sandstone and shale interbedded. Sandstone is pale reddish-brown, pale pink, pale greenish gray, very fine grained; composed of clear quartz with minor pink and black accessory minerals; structureless to ripple laminated; contains worm burrows. Shale is dark reddish-brown, silt to medium fine grained sandy, slightly micaceous	58.4
Sandstone, pale-brown to light-pink, predominantly fine grained, composed of subangular clear quartz grains with abundant grains of pink and amber accessory quartz; cross laminated, channeled	6.3
Covered; probably nonresistant interbedded shale and sandstone	7.7
Sandstone, pale-brown to white, medium-fine- to fine-grained; composed of subangular grains of clear quartz with numerous subangular to subrounded grains of white to tan chert and minor orange accessory minerals; cross laminated, channeled	13.0
Sandstone and claystone interbedded. Sandstone is pale red, very fine grained; composed of subangular clear quartz grains with grains of colored accessory minerals; forms ripple-laminated ledges. Claystone is dark reddish brown, silty, chloritic	5.4
Sandstone, pale-brown, light-brown- to brick-red-weathering, fine- to medium-fine-grained, poorly sorted; composed of subrounded clear quartz grains with minor amounts of pink, orange, and gray accessory minerals; highly cross laminated, channeled	17.2
Total Salt Wash Member	302.3
Total Morrison Formation	651.6
Summerville Formation (incomplete):	
Top contact is channeled. Contact is marked by color and texture change and is arbitrarily selected at the base of the lowest scoured ledge.	
Sandstone and claystone interbedded. Sandstone is dark reddish brown to pale red with 8 ft. of pale-greenish-gray beds at bottom, very fine grained; composed of subangular clear quartz grains with numerous grains colored accessory minerals; slabby to platy splitting, ripple-laminated to evenly laminated beds. Claystone is dark reddish brown to dark brown, partly silty	31.1

Section of the Morrison Formation in John Brown Canyon, sec. 5, T.50 N., R. 19 W., and secs. 31 and 32, T. 51 N., R. 19 W., Mesa County, Colo.

[Measured by L. C. Craig, H. L. Jicha, and others]

Burro Canyon Formation (incomplete):	*Feet*
Sandstone, conglomeratic, white to pale-brown, medium- to medium-fine-grained; composed of clear quartz with accessory white chert; small pebbles (average diameter ¼ in.) of white to light-brown chert	18.8
Morrison Formation:	
Brushy Basin Member:	
Siltstone and claystone; dark red and maroon in lower third, light green and gray green in upper two-thirds; short lenses of very fine grained sandstone as much as 3 in. thick in upper part	30.5
Siltstone and claystone; dark red and maroon, green and gray green in lower third; poorly exposed	72.8
Claystone, silty; gray green below, red above; upper part poorly exposed	59.0
Sandstone, conglomeratic, pale-brown, medium- to medium-fine-grained; composed of clear rounded quartz grains with numerous grains of pink, green, and gray accessory minerals. Granules and pebbles as much as ½ in. in diameter, both disseminated and concentrated in laminae	15.2
Siltstone; gray green to brown in lower part, bright green with some red in upper part; a few thin lenses of greenish sandstone with hard siliceous cement	47.8
Siltstone, clayey, gray-green; thin cap of brown-weathering, dark-green, fine-grained, quartzitic sandstone at top	12.2
Covered; material deeply weathered along ridge crest. Offset in section	26.9
Claystone and siltstone; green, gray-green, and pinkish-gray; entire unit contains some silt; a few limestone lenses and one very fine grained thin sandstone bed. Unit is capped by 6-in.-thick lens of dark-brown-weathering fine-grained quartzitic sandstone	19.8
Claystone, slightly silty, gray-green; contains yellow silty bentonitic streaks and concretionary lenticles of light-gray fine-grained limestone which locally is replaced by green chert. Limestone nodules are concentrated in zone at top of unit	11.2
Limestone, light-gray, fine-grained, brown-weathering; forms irregular lenticles on top of underlying unit	.4
Sandstone, olive-drab to medium-brown, fine-grained, quartzitic	.8
Claystone, silty, gray-green to pinkish-gray, poorly exposed	8.8
Sandstone, light-gray, pale-brown- to medium-brown-weathering, fine-grained; composed of clear subangular quartz grains with minor amounts of green, black, gray, and red accessory minerals	3.0
Siltstone, clayey, gray-green and dark-red; poorly exposed	10.7
Sandstone, white to light-pink, fine-grained; composed of clear subangular quartz grains with	

Morrison Formation—Continued	Feet
Brushy Basin Member—Continued	
minor quantities of pink accessory minerals; unit composed of 6-in.-thick slabby ledges weathering back from face of ledge formed by underlying unit	2.0
Sandstone, conglomeratic, pale- to medium-brown-weathering, medium-fine- to medium-grained; contains typical Brushy Basin varicolored chert grains and granules in lower part	11.6
Total Brushy Basin Member	332.7
Salt Wash Member:	
Interval poorly exposed. Siltstone, clayey, dark-red; a 3-ft-thick gray-green zone at top	27.9
Sandstone, pale-brown, light-brown- to medium-brown-weathering, fine-grained; composed of clear subangular grains of quartz and abundant grains of amber quartz and green clay with accessory green chert and minor black grains	3.6
Interval poorly exposed. Float indicated siltstone, dark-red, clayey; contains some gray-green streaks	20.0
Sandstone, white gray, fine-grained; composed of clear subangular quartz grains	2.7
Siltstone, dark-red, clayey; contains two beds of red-brown fine-grained sandstone composed of clear quartz and abundant quantities of pink accessory minerals	16.2
Sandstone, pale-brown, light- to medium-brown-weathering, medium-fine- to medium-grained; composed of clear subangular rounded quartz grains with minor amounts of pink and green accessory minerals; contains red-clay laminae and lenses of red-clay granules	35.1
Interval poorly exposed. Dark-red clayey siltstone indicated	29.7
Sandstone and shale interbedded. Sandstone is red brown, fine grained, composed of clear subangular quartz grains. Shale is silty, dark red	15.2
Covered	10.8
Sandstone, pale-brown, light-brown-weathering, medium-fine- to medium-grained; composed of clear subangular grains of quartz with minor amounts of gray, pink, and black accessory minerals	258.
Siltstone, dark-red; gray green at top, clayey	8.4
Sandstone, light-pink, dark-brown-weathering, fine-grained; composed of clear subangular quartz grains with varicolored accessory mineral grains. Siliceous cement	2.4
Claystone, silty; purple and gray green in lower third, dark red brown and gray green in upper part	32.3
Sandstone, pale-brown to pink, reddish-brown-weathering; composed of subangular clear quartz grains with minor amounts of pink and green chert; predominantly fine grained, some medium fine grained	11.8
Siltstone and sandstone interbedded. Siltstone is sandy and clayey, dark-red. Sandstone is gray green to red brown weathering, fine grained, composed of clear quartz; forms several beds 6 in. thick	6.9

Morrison Formation—Continued	Feet
Salt Wash Member—Continued	
Sandstone, red-brown-weathering, fine-grained; composed of clear subangular quartz grains with green, black, and red accessory minerals; siliceous cement	1.0
Siltstone, sandy and clayey, dark-red	16.2
Sandstone, brown-weathering, fine-grained; composed of clear subangular quartz grains with green, black, and red accessory mineral grains; siliceous cement	.9
Siltstone, shaly, dark-red. Contains two fine-grained sandstone beds 6 in. thick	21.6
Sandstone, white, light-brown-weathering, medium-fine-grained, poorly sorted; composed of clear subangular grains of quartz with minor amounts of red and black accessory chert	24.9
Sandstone, pink to white, fine-grained, slabby bedded. Contains thin dark-red silty shale partings	13.1
Sandstone, white, light-brown-weathering, medium-fine-grained; composed of clear subangular grains of quartz with minor amounts of pink and green accessory minerals. Fluviatile channel-and-fill bedding	6.4
Siltstone and sandy shale, interbedded. Dark red with irregular gray-green bands	3.0
Limestone, light-gray to purplish, fine-grained, locally recrystallized to coarse grained	.9
Total Salt Wash Member	336.8
Total Morrison Formation	669.5
Summervile Formation (incomplete):	
Siltstone and sandstone, interbedded, pink to brick-red; sandstone is fine grained, in part clayey; silty clay partings separate thin even sandstone beds	16.2

The Morrison Formation in many places has yielded fossilized remains of dinosaurs, and it generally contains abundant plant fragments and petrified wood and sparse fresh-water mollusks and calcareous algae. The vertebrate and fresh-water invertebrate fossils indicate a Late Jurassic age. However, the uppermost part of the Morrison on the Colorado Plateau interfingers in places with the lowermost beds of the Lower Cretaceous Burro Canyon Formation and thus may be Early Cretaceous. The Morrison Formation is widespread throughout the western interior of the United States and, although the two members mapped in western Colorado are not recognizable outside the Colorado Plateau, some stratigraphic evidence indicates that equivalent beds are present in the undifferentiated Morrison of central and northwestern Colorado (Craig and others, 1955, p. 137, 156).

SALT WASH MEMBER

Throughout the mapped area the Salt Wash Member of the Morrison Formation consists of alternating sandstone and mudstone strata. The sandstone strata are largely very pale orange (10*YR* 8/2) to white (*N*9), fine to medium grained, and yellowish gray, buff, or rusty red weathering. The strata are intricately bedded; each unit is composed of a number of imbricate, highly lenticular beds, each of which may rest with apparent concordance on the subjacent bed or, more commonly, on an irregular surface which cuts into or across the underlying bed. Furthermore, the beds are generally cross laminated, and sets of laminae may truncate other sets. Through most of the sandstone units the cross-lamination is of the festoon or scour-fill type, but near the tops of sandstone units a few feet of beds may show almost horizontal bedding and only gently dipping, horizontal, or wavy lamination. Some flat surfaces exhibit current lineation, and the way laminated beds usually show cuspate current ripples. The bottom contact of each sandstone stratum is marked by a sharp lithologic change, generally along an irregular scour surface. In places these local contacts display channel scours whereas in other places bedding may be concordant and little erosion indicated. The dominantly mudstone strata contain rocks having a variety of lithic characteristics; beds range in composition from claystone to clean sandstone. The dominant rock types are pale-reddish-brown sandy and silty claystone, and pale-reddish silty or clayey very fine grained to fine-grained sandstone. Beds in the mudstone intervals are broadly lenticular, but in places are nearly parallel; they range in thickness from several inches to 5 feet. Cross-lamination is uncommon within beds in the mudstone intervals; beds are either massive and without fine structures or have horizontal, even or wavy lamination; cuspate-current ripples are common in the sandy beds.

Based on 17 samples the mean composition of the sandstones of the Salt Wash in the mapped area (R. A. Cadigan, written commun., 1953) is quartz, 73 percent; silicified tuff and chert, 4 percent; quartz overgrowth and silica cement, 4 percent; calcite cement, 13 percent; potassic and sodic feldspar, 6 percent; gypsum, biotite, and other heavy minerals, less than 1 percent. Cadigan (1967) provided more detail on composition of the Morrison and its members in a report on the regional petrology of the formation. Preliminary studies by A. D. Weeks (written commun., 1953) and subsequent work by Keller (1962, p. 39) showed that the dominant clay minerals in the mudstones of the Salt Wash Member are hydrous micas or illite. The mudstones of the Salt Wash are earthy weathering or weather to hackly fragments, and the clays show little or no tendency to swell. Red mudstones characteristically are altered to green or gray in a zone ranging from a few inches to several feet in thickness immediately beneath some of the sandstone units. The only detectable difference in composition of the mudstones is a greater content of total iron and ferric iron in the red than in the green or gray mudstones (A. D. Weeks and W. D. Keller, written commun., 1953). The smaller amount of ferric iron in the green or gray mudstone apparently is mainly a result of leaching of hematitic pigment from between the particles of clay and silt, inasmuch as ferric iron in the structure of the clay minerals is not appreciably affected by leaching (A. D. Weeks, written commun., 1953).

The contact of the Salt Wash Member of the Morrison with the Summerville Formation is arbitrary; beds with characteristics of the Summerville grade into beds with characteristics of the Morrison within a thickness of about 15 feet or less. For most purposes the base of the lowest cross-laminated sandstone ledge that fills channel scours has been considered the base of the Salt Wash. This contact is readily recognized, is remarkably persistent in southwestern Colorado, and has been used in the mapping of the area covered by this report. In other parts of Colorado and in adjacent areas in Utah, the basal sandstone ledge is not persistent, and the lowest beds with Morrison depositional characteristics are lenticular mudstones, short lenses of sandstone filling small scours, or, characteristically, a few relatively persistent limestone beds which commonly contain fresh-water ostracodes and charophytes. In most places in southwestern Colorado, including the mapped area, such beds may be found below the lowest prominent sandstone ledge of the Morrison in an interval which may be as thick as 35 feet. In many places the gradation from the flat parallel bedding of the Summerville Formation to the lenticular bedding of the Morrison is accompanied by a color change from dark reddish brown below to light greenish gray or grayish red above. Inasmuch as limestone beds are regionally more persistent than the lowest channel-fill sandstone, the base of the limestone has been used as the Salt Wash-Summerville contact in the representative sections in this paper. This lower contact of the Morrison, however, would be difficult to map in southwestern Colorado for the limestone beds are poorly exposed in most places. If it were possible to map this contact conveniently instead of the contact of the base of the cross-laminated sandstone that actually was mapped, the result would be a slight change in position of the basal Morrison contact in only a few places, for the basal Morrison limestone-bearing unit is characteristically thin and forms a steep slope. The Morrison is conformable upon the Summerville Formation, and even where the base of the Morrison is a scour surface the hiatus represented by the surface is probably diastemic in magnitude and local in areal extent.

Thickness

The Salt Wash Member of the Morrison generally ranges in thickness from 240 to 440 feet within the mapped area. Although detailed measured sections are sparsely distributed, less exact control from the geologic quadrangle maps of this area provides enough points of known thickness to show a general northwest elongation of thick and thin parts of the Salt Wash corresponding to the trends of the anticlines, with the thinnest parts on the crests of the anticlines and the thickest parts generally in the intervening basins. Superimposed on this pattern are variations in thickness which seem best explained as irregularities in deposition of materials. These irregularities may be as much as 100 feet or more in less than 3 miles along the outcrop. Section measurements made in connection with lithofacies studies by T. E. Mullens and V. L. Freeman (written commun., 1953) have shown variations of 70 feet in a distance of 200 feet along the outcrop.

Conditions of Deposition

The fluvial origin of the Salt Wash Member is abundantly indicated by the depositional features of the sediments; the crossbedded scour- and channel-fill sandstone was deposited in stream channels, and the nearly parallel bedded mudstone was deposited mainly on flood plains. Lacustrine deposits probably are a minor component of the member, although limestone and possibly some of the mudstone formed in ephemeral lakes on the flood plains. Fresh-water invertebrate and plant fossils and fossils of land-dwelling vertebrates indicate the continental nature of the deposits.

BRUSHY BASIN MEMBER

The Brushy Basin Member of the Morrison consists dominantly of variegated mudstone with lesser amounts of sandstone, conglomeratic sandstone, and limestone. Bedding of the mudstone is difficult to discern and probably is most reliably revealed by a color banding that suggests tabular to somewhat lenticlular beds; lamination is not apparent. Individual beds among the sandstone and conglomeratic sandstone strata range from almost tabular or slightly lenticular, with internal parallel laminations, to markedly lenticular, with complex internal imbrication and cross-lamination. Scour surfaces are common at the base of and within these complex units. The limestone beds are slightly lenticular to tabular and rarely laminated.

The mean composition of the sandstones of the Brushy Basin Member, based on seven samples analyzed by R. A. Cadigan (written commun., 1954), is quartz, 64 percent; silicified tuffaceous material and chert, 9 percent; quartz overgrowth and silica cement, 7 percent; calcite cement, 14 percent; potassic and sodic feldspar, 5 percent; gypsum, 1 percent; heavy minerals, less than 1 percent. A. D. Weeks (written commun., 1953) and Keller (1962, p. 39) have found that the dominant clay in the mudstones of the Brushy Basin is montmorillonite. Most of the mudstones swell in varying degrees when wet and as a result weather to a characteristic hard "frothy" or "popcorn" surface. Shards or relics of shards (Waters and Granger, 1953, p. 6; W. D. Keller, written commun., 1953), analcite (W. D. Keller, written commun., 1953), and books of biotite and euhedral crystals of apatite and zircon (A. D. Weeks, written commun., 1953) attest to the volcanic origin of some parts of the mudstone. The montmorillonite probably was derived from volcanic ash by hydrolysis and devitrification.

The materials of the Brushy Basin are of many grain sizes. The mudstones are composed mainly of clay with varying amounts of silt and fine-grained sand. Sandstones are very fine grained to coarse grained and conglomeratic. In southwestern Colorado most of the pebbles in the conglomeratic parts of the Brushy Basin are less than three-fourths of an inch in diameter, but a few exceed 1 inch.

The Brushy Basin is characterized by a number of rather distinctive materials and beds. The conglomeratic sandstone contains abundant pebbles of red and green chert and of quartzite, commonly much interstitial clay, and in many places, bone fragments and petrified wood. Irregular masses and fragments of highly colored jasper in places litter the weathered surfaces of the member. Pale-green (5*G*, 7/2) to grayish-green (10*GY* 5/2) fine-grained, hard, well-cemented sandstone forms tabular beds one-half inch to 3 feet thick. These greenish sandstones commonly are cemented by silica, in many places sufficiently so to form quartzite. The secondary silica in the cement, as well as that in the silicified wood and bone and the jasper, probably was derived during alteration of the volcanic materials to montmorillonite. Polished and rounded pebbles, so-called gastroliths but actually probably dust polished (Stokes, 1942), occur sparsely on weathered surfaces of the Brushy Basin Member and rarely are found in place. In the Blue Mesa area much of the Brushy Basin in greenish gray to pale green and light blue green. These colors are well displayed along the lower part of Mesa Creek and along the northeast side of the San Miguel River Canyon near the mouth of Mesa Creek; they contrast markedly with the characteristic alternating dark red, light gray, and light greenish gray of Brushy Basin in other parts of the mapped area. The anomalous greenish colors may be the result of alteration, although no compositional difference has been detected.

The basal contact of the Brushy Basin Member is arbitrary, for in many places the Salt Wash Member grades upward into the Brushy Basin. In mapping, the base of the Brushy Basin Member was placed at the base of the lowest conglomeratic sandstone with abundant red and green chert pebbles. According to studies made by J. S. Pomeroy (written commun., 1955) red and green pebbles constitute about 36 percent of the total pebbles in the Brushy Basin but only about 16 percent of the total in the Salt Wash. Sandstones in the Brushy Basin tend to weather to dark brown, and those in the Salt Wash generally weather pale yellow to white.

A change in the mudstones of the Salt Wash and the Brushy Basin is also associated rather closely with the contact between these two members of the Morrison. The mudstones of the Salt Wash are dark reddish brown, silty or sandy, and nonswelling, whereas those of the Brushy Basin commonly are grayish red, slightly purplish, or light gray and contain large quantities of swelling and generally less sandy claystones. The change in the mudstones is not distinct and in most places is several feet below the base of the conglomerate bed selected as the base of the Brushy Basin.

The conglomeratic sandstone at the base of the Brushy Basin is lenticular, but it is present in enough places to allow projection of the basal contact of the member through areas where the marker bed is absent. Although the base of the conglomeratic sandstone is most commonly a scour surface, it is not continuously traceable and is regarded as only of diastemic magnitude. The stratigraphic position of the conglomeratic stratum may vary somewhat from one lens to the neighboring lenses, but it probably varies less than 50 feet throughout the mapped area. This variation of stratigraphic position may account for some of the apparent thickening and thinning of the members of the Morrison but does not account for the larger scale differences of thickness.

Thickness

The Brushy Basin Member in the mapped area generally ranges in thickness from 300 to 750 feet. In general the thinner parts coincide with the axes of anticlines, but data are insufficient to establish precise relations between thickness and the salt structures. About 750 feet of the Brushy Basin was drilled in the northwest part of Disappointment Valley (D. R. Shawe, written commun., 1957).

Conditions of Deposition

The continuation of fluvial deposition through Brushy Basin time is indicated by the cross-stratified sandstones and conglomeratic sandstones which both rest on and contain scour surfaces. The finer grained sedimentary rocks probably were deposited both by sluggish streams and in slack water on flood plains. Thin lenticular limestones probably were formed in local lakes by calcareous algae. Tuffaceous or altered volcanic materials in scattered thin beds may have been deposited directly from the air. Many shards preserved in mudstones have angular forms that also suggest direct deposition from the air or only a short distance of water transport.

CRETACEOUS SYSTEM

BURRO CANYON FORMATION

Coffin (1921, p. 97–100) first divided the sequence of beds earlier called "Dakota" in western Colorado into the "Post-McElmo" and a restricted Dakota. Later, Stokes (1948; 1952, p. 1773–1774) applied the name Burro Canyon Formation to the "Post-Elmo" beds, naming the formation for exposures in Burro Canyon near Slick Rock. The formation is one of the most resistant units in western Colorado and crops out as a series of hogbacks or as broken cliffs along the flanks of the salt anticlines and on the rims and tops of most of the high mesas in the area (fig. 12). The Burro Canyon forms light-colored cliffs and steep slopes above the colorful and relatively unbroken slope of the Brushy Basin Member of the Morrison. In places large toreva blocks of Burro Canyon have slumped as much as 100 feet or more down slopes underlain by the Brushy Basin, and in other places the Burro Canyon has shed large

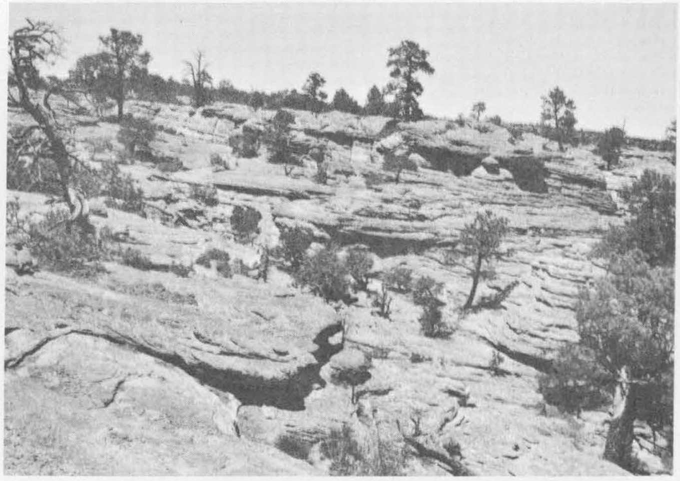


Figure 12.—Outcrop of Burro Canyon Formation near Horsethief Spring northeast of Long Park, sec. 26, T. 47 N., R. 17 W.

blocks which form talus slopes that almost conceal the underlying Brushy Basin.

The Burro Canyon Formation consists of alternating conglomeratic sandstone and mudstone with sparse beds of limestone and chert. The sandstone is grayish yellow to pale yellowish orange, fine to very coarse grained, and is composed dominantly of subrounded to subangular clear quartz grains with minor white and orange accessory minerals. R. A. Cadigan (written commun., 1954) reported that the mean composition of five samples is quartz, 68 percent; chert, 9 percent; quartz overgrowths and silica cement, 11 percent; calcite cement, 10 percent; potash and sodic feldspar, 2 percent; muscovite and other heavy minerals, less than 1 percent. The sandstone strata are crossbedded and consist dominantly of trough sets; the strata commonly rest on surfaces of erosion (fig. 12). The pebbles in the sandstones consist mainly of white and tan chert, light-gray silicified limestone, light-gray to pinkish quartzite, and sparse clear or smoky quartz (P. J. Katich, written commun., 1951). In western Colorado the pebbles have a maximum diameter of about 3 inches and are found either scattered through the sandstone matrix or concentrated in thin beds and lenses, commonly near the bottoms of individual trough sets. The conglomeratic sandstone strata form resistant cliffs and ledges as much as 100 feet high, and these strata are generally the most prominent units in the formation. The mudstones are light greenish gray and very pale green or, more rarely, pale reddish brown. They are variably silty to sandy and weather to earthy or hackly fragments; rarely do they show the fluffy surfaces characteristic of swelling clay. The mudstones have tabular to somewhat lenticular bedding and generally weather to slopes. Limestone, which is sparse, is dense and light gray, and it has a conchoidal fracture. It weathers brownish, either as thin concretionary layers a few inches thick or as resistant ledges as much as several feet thick; in places it is silicified. Both mudstone and limestone are generally more abundant in the upper than in the lower part of the formation; they form relatively thick units only in the upper part.

The basal contact of the Burro Canyon Formation is placed at the scour surface at the base of the lowest conglomeratic sandstone above the variegated mudstone of the Brushy Basin Member of the Morrison Formation. This contact is remarkably persistent, but locally the conglomeratic sandstone of the Burro Canyon is lenticular, and in places the lowest ledge may pinch out or several conglomeratic beds may pinch out. Inasmuch as in places the mudstones of the Burro Canyon and the Brushy Basin cannot be distinguished easily, the mapped contact may not everywhere adhere to the same horizon, but in most places the contact can be projected from the base of one lenticular conglomeratic sandstone stratum through a mudstone sequence to the base of another conglomeratic sandstone stratum occupying virtually the same stratigraphic position. The evident absence of a continuous erosion surface at the base of the Burro Canyon and small-scale examples of intertonguing of Brushy Basin and Burro Canyon indicate that the Burro Canyon and Morrison Formations are conformable. The scour surfaces at the base of the conglomeratic sandstones are regarded as diastems.

The following stratigraphic sections are representative of the Burro Canyon Formation in the mapped area:

Section of the Burro Canyon Formation on south face of Skein Mesa, sec. 9, T. 46 N., R. 18 W., Montrose County, Colo.

[Measured by L. C. Craig, R. A. Cadigan, and E. M. Shoemaker]

	Feet
Dakota Sandstone (incomplete):	
Sandstone, conglomeratic, yellow-brown to light-brown, fine- to medium-fine-grained; composed of clear quartz with abundant white chert grains. Pebbles of chert, predominantly black, tan, and white, are as much as ½ in. across. Cross laminated; scour-and-fill structures	17.4
Unconformity.	
Burro Canyon Formation:	
Upper contact is channeled scour surface	....
Claystone, pale-gray-green, silty; bright green in top 3 ft.	13.4
Sandstone, conglomeratic, pale-gray-green to pale-brown, very fine grained to medium-fine-grained; composed of clear subangular quartz grains, green clay pebbles, and white, tan, gray, red, black, and green chert pebbles as much as 2 in. in diameter; scour-and-fill structures; cross laminated; worm borings in lenses of fine-grained material	32.4
Claystone, pale-greenish-gray; sandy at bottom, silty at top; nonbentonitic	28.8
Sandstone, conglomeratic, pale-greenish-yellow to pale-brown, fine-grained to very coarse grained, poorly sorted; composed of clear subangular quartz grains, green clay pebbles, and white, tan, gray, red, black, and green chert pebbles as much as 2 in. in diameter; scour-and-fill structures; cross laminated	62.9
Claystone, dark-greenish-gray, pale-green-weathering, slightly silty; dark-red-brown silty zone at base; nonbentonitic	8.0
Sandstone, pale-greenish-yellow to pale-brown, very fine grained to medium fine-grained, poorly sorted; composed of clear subangular quartz grains with accessory greey and red chert; siliceous cement; massive, not prominently laminated	8.8
Total Burro Canyon Formation	154.3
Morrison Formation:	
Brushy Basin Member (incomplete):	
Upper contact probably channeled, not well exposed	....
Claystone, pale-brown, pale-green-gray, reddish- to pinkish-brown; slightly silty in lower half, silty to fine grained sandy in upper half; bentonitic	75.6

Section of the Burro Canyon Formation on west side of Dry Creek on north flank of Dry Creek anticline, sec. 33, T. 46 N., R. 16 W., Montrose County, Colo.

[Measured by L. C. Craig and L. R. Stieff]

	Feet
Dakota Sandstone (incomplete):	
Sandstone, conglomeratic, buff- to brown-weathering, fine- to medium-grained; composed of clear quartz grains with abundant impressions of woody fragments and containing light- and dark-gray chert pebbles as much as 2 in. in diameter with accessory pebbles of tan and red chert and white and pink quartz	13.1
Unconformity.	
Burro Canyon Formation:	
Top contact is at base of conglomeratic sandstone with scour-and-fill structures; long offset of section, along contact	....
Interval very poorly exposed. Claystone, light green, hackly to fissile	64.0
Sandstone, conglomeratic, white- to light-buff-weathering, medium- to coarse-grained; composed of subangular to rounded clear quartz grains and pebbles of white, buff, tan, and pink chert as much as 1 in. in diameter; highly cross laminated; scour-and-fill structures	38.7
Sandstone, white- to buff-weathering, fine-to medium-grained; composed of subangular to rounded clear quartz grains; ledgy beds exhibit secondary concretionary silicification	11.8

	Feet
Burro Canyon Formation—Continued	
Shale, clayey, green, fissile	6.8
Shale, clayey, gray to maroon, fissile; contains irregular nodules of pink to light-gray calcilutite	17.6
Sandstone, conglomeratic, light-green, medium- to coarse-grained; composed of well-rounded clear quartz and red and pink accessory grains; contains black, gray, tan, red, and white subangular to rounded chert pebbles as much as 3 in. in diameter	18.6
Total Burro Canyon Formation	157.5
Morrison Formation:	
Brushy Basin Member (incomplete):	
Claystone, light- to bright-green; fissile to blocky weathering; one 3-ft-thick bed weathers brown; fine-grained clear quartz sandstone at 6 ft. above base of unit	39.6

THICKNESS

The thickness of the Burro Canyon generally ranges from 50 to 300 feet, but it averages about 150 feet in the mapped area. The variation in thickness probably is due in part to irregularities in the surface upon which the formation was deposited and in part to movement of salt in the anticlines, but it is due principally to interfingering or gradation with the Brushy Basin Member of the Morrison Formation.

CONDITIONS OF DEPOSITION

The scour-and-fill structures of the conglomeratic sandstone indicate fluvial deposition. Most of the mudstone probably was formed on flood plains or in streams. The limestone and some of the mudstone probably formed in temporary lakes on flood plains.

AGE AND CORRELATION

In contrast to the overlying Dakota Sandstone, the Burro Canyon Formation is almost devoid of fossil plants. Fossil plants from a thin bed of carbonaceous shale about 25 feet below the top of the Burro Canyon Formation near the mouth of Disappointment Creek (sec. 11, T. 43 N., R. 18 W., San Miguel County) are of Early Cretaceous age (Brown, 1950, p. 46, 50). Fresh-water invertebrates collected by G. C. Simmons and D. R. Shawe and identified by J. B. Reeside, Jr. (Simmons, 1957, p. 2526), support the assignment of an Early Cretaceous age. Several of the invertebrate fossils are widespread in the Kootenai and Cloverly faunas of Wyoming and Montana.

The eastern and northern limits of the Burro Canyon Formation are not clearly defined. Lenses of Burro Canyon are recognized in the Placerville area of San Miguel County; in the Ridgeway area, Ouray County, Colo.; as far north as Grand Junction and Loma, Colo.; and as far south as the Four Corners. Beyond these general eastern and southern limits, the formation may be equivalent to some mudstones included in the top of the Brushy Basin Member of the Morrison, or it may not have been deposited, or it may have been removed by pre-Dakota erosion. To the west in eastern Utah, the Cedar Mountain Formation is equivalent to the Burro Canyon (Stokes, 1944, p. 958, 965–67; 1952, p. 1773–1774), a correlation supported by invertebrate fossils (Simmons, 1957).

DAKOTA SANDSTONE

The Upper Cretaceous Dakota Sandstone disconformably overlies the Burro Canyon Formation. Because of its resistance to erosion it crops out extensively as capping beds on broad upland areas, on mesas, and on the long dip slopes flanking the salt anticlines. Like the other formations of post-San Rafael age, the Dakota at one time completely blanketed the area.

The Dakota Sandstone is exposed best on the canyon rims, where it forms a rough flaggy ledge or series of ledges. Although it paves the tops of many mesas, it is generally poorly exposed on these flat surfaces because of a thin cover of Quaternary deposits. In most areas the Dakota comprises three fairly distinct units: a lower unit consisting largely of sandstone and conglomerate, a middle unit of sandstone, carbonaceous shale, and impure coal, and an upper unit of sandstone and conglomerate. The sandstone is flaggy and gray, yellow, and buff; much of it is coarse grained and crossbedded, but some of it is fine grained and thin bedded. R. A. Cadigan reported (written commun., 1954) that of six samples of the sandstone examined, the mean composition is quartz, 68 percent; chert, 12 percent; quartz overgrowths and silica cement, 15 percent; calcite cement, 3 percent; potassic and sodic feldspar, 2 percent; muscovite and heavy minerals, less than 1 percent. Scattered through the sandstone are irregular discontinuous lenses of conglomerate containing chert and quartz pebbles as much as 2 inches across. Thin layers of gray and black carbonaceous shale and seams and beds of impure coal interfinger with sandstone and conglomerate beds and lenses. In places some of the coal reaches a thickness of several feet and has been mined for local use. In a few places shale underlying the coal is nearly white and resembles fire clay. Plant impressions abound in both the shale and the sandstone (Brown, 1950). Certain sandstone and conglomerate beds in the Dakota Sandstone have been highly silicified over extensive areas. The silicified rocks break with conchoidal fractures that cut across sand grains. In fact, the rock is so flinty that it served the Indians for arrowheads and implements.

The contact between the Dakota and Burro Canyon is disconformable but in many places is seen with difficulty because the sandstone and conglomerate are similar in both formations. However, in other places the contact is unmistakable; channels carved several feet into the Burro Canyon have been filled with Dakota sediments, or Dakota Sandstone containing numerous plant impressions rests on characteristic green shale of the Burro Canyon.

The following measured sections present detailed lithic characteristics of the Dakota Sandstone. Only two complete sections were measured because in most places the upper part of the sandstone has been removed by erosion, and where the complete thickness of beds still remains, the exposures are either poor or inaccessible.

Section of Dakota Sandstone near head of Joe Davis Canyon, secs. 27 and 28, T. 44 N., R. 18 W., San Miguel County, Colo.

[Measured by L. C. Craig]

	Feet
Mancos Shale.	
Dakota Sandstone:	
Top of formation taken at top of uppermost sandstone lens.	
Interval poorly exposed. Contains several thin sandstone lenses	4.2
Sandstone, grayish-orange, fine- to medium-fine-grained; consists of subangular clear quartz grains with sparse white angular chert grains; highly cross-laminated; scour-and-fill structures	12.6
Interval poorly exposed. Claystone, medium-gray to black; silty to sandy in part; a few thin (1–3 ft.) olive-green to grayish-orange siltstone and very fine grained sandstone beds composed of clear quartz with sparse accessory grains	45.5
Sandstone, grayish-yellow, predominantly fine to medium-fine-grained; consists of subangular clear quartz grains with numerous clay fragments; highly crass laminated; scour-and-fill structures	10.8
Shale, black, highly carbonaceous, fissile, slightly sandy	4.8
Total Dakota Sandstone	77.9
Disconformity	
Burro Canyon Formation.	

Section of Dakota Sandstone on Skein Mesa, sec. 9, T. 46 N., 18 W., Montrose County, Colo.

[Measured by L. C. Craig, R. A. Cadigan, and E. M. Shoemaker]

	Feet
Dakota Sandstone:	
Top of formation removed by erosion.	
Sandstone, light-yellow-brown, yellow-brown- to reddish-brown-weathering, fine-grained; consists of subangular to subrounded clear quartz with white subangular chert grains and sparse accessory minerals; contains wood fragments; cross laminated; scour-and-fill structures	21.6
Interval poorly exposed. Contains light-brownish-gray sandy claystone, one zone of dark-brown carbonaceous claystone, and a few fine-grained yellow-brown platy sandstone layers	43.2
Sandstone, pale-yellow-brown, fine-grained; consists of clear quartz grains and pebbles of green silty clay; cross laminated; scour-and-fill structures	21.6
Interval poorly exposed. Contains gray-brown silty claystone, a dark-gray carbonaceous silty claystone bed 1–2 ft thick, and one 2-ft-thick bed of gray-brown fine-grained sandstone	18.0
Sandstone, yellow-brown, fine- to medium-fine-grained; composed of clear quartz with accessory white and tan chert; scour-and-fill structures and cross laminated	16.2
Dakota Sandstone—Continued	
Claystone, brownish-gray; contains silt, very fine sand, and carbonaceous flecks	5.4
Sandstone, light-gray, very fine grained; predominantly clear quartz grains with siliceous cement; slabby bedded	1.0
Claystone, pale-gray-brown, light-gray-weathering, silty	11.0
Sandstone, conglomeratic, yellow-brown to light-brown, fine- to medium-fine-grained; consists of clear quartz with abundant white chert grains. Pebbles of predominantly black, tan, and white chert as much as ½ in. across. Cross laminated; scour-and-fill structures	17.4
Total incomplete Dakota Sandstone	155.4
Disconformity.	
Burro Canyon Formation.	

Section of the Dakota Sandstone on Dry Creek, sec. 34, T. 46 N., R. 16 W. Montrose County, Colo.

[Measured by L. C. Craig and L. R. Stieff]

	Feet
Mancos Shale.	
Dakota Sandstone:	
Top contact taken at top of highest sandstone lens.	
Sandstone, white to buff, coarse-grained; consists of clear rounded quartz grains and accessory dark-gray chert	1.2
Interval poorly exposed. Sandstone, dark-brown, medium- to coarse-grained, clayey; contains carbonized plant fragments	2.8
Sandstone, buff to light-yellow, coarse-grained; consists of clear rounded quartz grains with coarse grains and granules of white chert; worm holes	5.3
Sandstone, nonresistant; contains a few partings of medium-gray claystone	1.8
Sandstone, same as second unit above	2.6
Sandstone, yellow-brown to dark-brown, medium-grained, clayey; consists of rounded clear quartz grains and black carbonaceous fragments	8.0
Bentonite, light-yellow; contains irregular crystals of selenite	.3
Sandstone, dark-brown, medium-grained, clayey; contains black carbonaceous fragments	4.8
Sandstone, white, slabby, medium-coarse-grained; consists of rounded clear quartz grains	1.2
Sandstone, dark-brown, medium- to coarse-grained; consists of rounded clear quartz grains with abundant clay and carbonized plant fragments	5.6
Bentonite, light-yellow to white; contains numerous crystals of selenite	.6
Sandstone, dark-brown, fine- to medium-grained, poorly bedded; consists of clear rounded quartz grains with abundant clay and carbonized plant fragments	17.3
Sandstone, buff- to yellowish-brown-weathering, coarse-grained, slabby; composed of rounded clear quartz grains and minor white chert and dark accessory grains	9.2
Siltstone, medium- to light-gray	8.1
Siltstone, light-brown to light-gray, shaly; contains papery carbonaceous partings	1.4
Shale, medium-gray to bright-yellow	1.4
Shale, black, carbonaceous, lignitic	1.2
Claystone, white to pink, hackly; contains abundant	

Dakota Sandstone—Continued	Feet
fossil leaves from deciduous trees and ferns	.6
Shale, black, carbonaceous, lignitic	1.8
Shale, olive-drab to bright-yellow, silty; contains abundant carbonaceous roots	3.6
Shale, medium-gray; contains a few light-yellow bentonitic lenses	19.2
Interval partly covered. Yellow-brown-weathering, fine-grained sandstone indicated in lower part. Dark-gray, carbonaceous shale indicated in upper part	5.3
Shale, dark-gray to black, carbonaceous, papery; contains a few thin carbonaceous sandstone interbeds	15.9
Sandstone, buff- to light-brown-weathering, fine- to medium-grained; consists of subangular clear quartz with accessory grains of chert; ripple laminated to cross laminated; platy to massive in lower part, massive in upper part	19.9
Interval largely covered. Shale; light gray to cream indicated; contains a few black to dark-gray carbonaceous beds	10.6
Sandstone, buff- to yellow-brown-weathering, fine- to medium-grained; platy to slabby, ripple laminated	9.9
Shale and siltstone interbedded; light to dark gray, carbonaceous	21.2
Sandstone, conglomeratic, buff- to brown-weathering, fine- to medium-grained; consists of clear quartz grains with abundant impressions of woody fragments and containing light- and dark-gray chert pebbles as much as 2 in. across with accessory pebbles of tan and red chert and white and pink quartz	13.1
Total Dakota Sandstone	193.9

Disconformity.
Burro Canyon Formation.

THICKNESS

In most places where the Dakota Sandstone is exposed, the uppermost beds have been stripped off by erosion; the maximum thickness of the uneroded Dakota in the mapped area appears to be about 220 feet, and the minimum is probably about 70 feet. Generally, the full thickness ranges from 120 to 200 feet. In the areas where the formation is complete, the variations in thickness appear to be entirely haphazard and to be controlled largely by irregularities of the erosion surface upon which the Dakota was deposited. Inasmuch as the top contact is arbitrarily placed at the top of the highest sandstone beneath Mancos Shale, lensing of the upper sandstone beds may also account for considerable variations in thickness of the formation.

CORRELATION AND CONDITIONS OF DEPOSITION

The Dakota Sandstone is widely distributed over the western interior, and throughout this wide region it is lithically remarkably uniform. The bedding characteristics, the plant fragments, and the coal beds indicate clearly that most of the Dakota is a terrestrial deposit; only the uppermost beds, transitional into the marine Mancos Shale, may be marine. Regionally the basal contact of the Dakota is an unconformity, for it bevels progressively older beds southward in Arizona and New Mexico and westward in southern Utah. In western Colorado no angularity has been recognized between the Dakota and the Burro Canyon. The basal contact of the Dakota in western Colorado is generally a scour surface at the base of a conglomeratic sandstone that in places contains quartzitic boulders and pebbles derived from the Burro Canyon. This indicates a hiatus between the deposition of the two formations at least equivalent to the time required to cement the top sandstone beds of the Burro Canyon (Carter, 1957). In a few places in western Colorado, gray to black carbonaceous shale of the Dakota rests on greenish mudstones of the Burro Canyon, and only the generally sharp contact between the two rocks reveals the disconformable nature of the contact.

It is difficult to visualize how a formation so uniformly thin and of such vast areal extent could have been deposited on a land surface. It may be that the deposit is, as Stokes (1950) suggests, the product of a type of very large scale pedimentation and that the Dakota largely represents material on a surface of transportation. On the other hand, Stokes' theory presupposes a terrain largely devoid of vegetal covering, and it is difficult to reconcile the abundance of plant material in the Dakota with a barren terrain; in fact, much of the Dakota landscape at any given time must have supported lush growths of vegetation. Furthermore, the beds probably were not deposited synchronously everywhere. With these probabilities in mind, we are more inclined to regard the Dakota Sandstone as a deposit that formed on a broad coastal plain in front of the advancing Late Cretaceous sea in which the overlying Mancos Shale was deposited.

MANCOS SHALE

The Mancos Shale, of Late Cretaceous age, conformably overlies the Dakota Sandstone and is gradational into it. Because of erosion, the Mancos is less widely distributed than the underlying formations. It crops out in Gypsum Valley as disconnected fault blocks let down from the collapsed crest of the salt anticline that underlies the valley, in the southeast end of Paradox Valley, and over wide areas in Dry Creek Basin and Disappointment Valley. The Mancos forms monotonous light-gray rolling surfaces and rounded hills. Natural exposures of fresh rock are rare except where gullying has been rapid. Surfaces underlain by the Mancos are notably barren and support only the sparsest vegetation; this apparent infertility probably stems from the thinness and tightness of the soils and the impermeable nature of the underlying shale itself, factors that promote very rapid runoff of precipitation. Furthermore, the shale is relatively rich in salts which rise to the surface during wet weather and form broad white "alkali flats" almost completely devoid of any vegetation.

The Mancos Shale is possibly preserved in its entirety only in the collapsed blocks in Gypsum Valley, and there it is incompletely exposed; elsewhere only the lower part of the formation remains. Throughout, the formation is remarkably uniform in composition. It consists largely of thinly bedded lead-gray to black shale that weathers light gray or yellowish gray. Interbedded with the shale are scattered thin beds of concretionary fine grained light-gray limestone, sandy shale and sandstone, and, at least in the lower part, a few layers of bentonite, 1–8 inches thick. The shale commonly breaks with a hackly fracture, and much of it is calcareous. Also in the shale at irregular intervals along definite horizons are isolated irregular masses of limestone as much as 3 feet thick that may have formed either as concretions or as small local reefs. These masses are more resistant than the surrounding shale and stand out as yellowish-weathering knobs. Sandstone is very sparse and occurs mostly in the upper part of the formation in beds transitional into the Mesaverde Formation. In eastern Utah a thin-bedded sandstone layer about 350 feet above the base of the Mancos has been correlated with the Ferron Sandstone Member in Utah (Lupton, 1916, p. 31), a gas-producing bed in the Clear Creek field of the Wasatch Plateau, but this unit was not recognized within the mapped area.

Fossils of Late Cretaceous age are abundant in some layers of the Mancos Shale; in the lower part, usually 10–50 feet above the base, is a layer containing great numbers of *Gryphaea newberryi* Stanton. Scattered sharks' teeth also are common. Thickness of the Mancos Shale could not be determined but nearby to the east it is at least 2,000 feet.

MESAVERDE FORMATION

The Late Cretaceous Mesaverde Formation consists of interbedded yellowish-gray sandstone and light-gray shale. It conformably overlies and is gradational into the Mancos Shale. It is preserved within the area only in the southeast end of Gypsum Valley and near the mouth of Hamm Canyon. In both places only the lower part of the formation is exposed in downwarped and downdropped blocks of the collapsed crest of the salt anticline that underlies the valley.

TERTIARY(?) SYSTEM

None of the lower Tertiary formations so widespread in the adjoining region to the north and east remain in the mapped area. Later deposits, older than Quaternary alluvium and wind-deposited material, formed in response to local conditions, and probably none of them ever covered more than a few tens of square miles. They do, however, contribute data to the interpretation of geomorphic and late structural history of the area, and for this reason aspects of these deposits relating to this history will be emphasized in the description of these deposits that follows.

Deposits believed to be of Tertiary age consist of gravel beds in the southeast end of Gypsum Valley and fanglomerates in Paradox, Gypsum, and Sinbad Valleys. In earlier reports (Stokes, 1948; Cater, 1955b, 1955f; Shoemaker, 1956a) these deposits were regarded as Quaternary; however, because the fanglomerate in Paradox Valley is unconformably overlain by beds containing volcanic ash tentatively identified by R. E. Wilcox (written commun., 1965) as early Pleistocene, we are now inclined to regard this and the similar fanglomerates in the other valleys as pre-Quaternary and probably of late Pliocene age. The gravel beds in the southeast end of Gypsum Valley could not have been deposited by a stream related to the present drainage pattern, and their relation to the collapse structures of the Gypsum Valley salt anticline strongly suggests that they are older than the fanglomerate and are probably the oldest post-Mesozoic deposits remaining in the area. Pebbles of porphyritic rocks in the fanglomerate of Gypsum Valley that may have been derived from these gravels also lend additional support to their presumed older age.

ANCIENT GRAVELS OF GYPSUM VALLEY

Thick deposits of coarse gravel consisting largely of pebbles and boulders of porphyritic rocks from the San Juan Mountains underlie the high ground at the southeast end of Gypsum Valley, and smaller patches of similar gravel crop out in nearby areas on the floor and along the southwest side of the valley and in Gypsum Gap. Possibly some of the smaller patches are reworked from older gravel. In most places the gravel is poorly stratified, but where bedding is discernible it generally is nearly flat. Locally, particularly along the southwest side of the valley, it dips rather steeply toward the center of the valley. Most of the gravel is only slightly cemented, but locally it is firmly cemented to a conglomerate.

No streams draining areas underlain by rocks compositionally similar to the gravels presently traverse or come close to tranversing this part of Gypsum Valley. The gravel in Gypsum Gap strongly suggests that the southeast part of Gypsum Valley was draining through the gap at the time the gravels were being deposited. The absence of similar gravels down the valley to the northwest indicates that drainage was not down the length of the valley as is the present drainage. The relative antiquity of these gravels is also suggested by their local steep dips, a fault that offsets beds about 50 feet, and the considerable deepening of the valley since they were deposited. The fanglomerates, on the other hand, were deposited when the valleys were at a somewhat deeper level than at present, suggesting thereby that they are younger than the gravel. Although originally regarded as Pleistocene, the gravels in Gypsum Valley are the oldest deposits of probable Tertiary age in the area and are regarded at late Tertiary, possibly Pliocene, in age. Gravel of somewhat similar occurrence in Castle Valley in eastern Utah was considered to be of probable Pliocene age by Hunt (1956, p. 30).

FANGLOMERATES OF PARADOX, GYPSUM, AND SINBAD VALLEYS

Fanglomerates are exposed at numerous localities through the length of Paradox Valley, in the lower part of Big Gypsum Valley, and at scattered localities in Sinbad Valley. These fanglomerates were deposited after the valleys had reached virtually their present form, but at a stage when the valleys were at somewhat deeper level than at present. In most places the fanglomerate is exposed only in washes that have carved through more recent valley fills, and outcrops are not of mappable size; but at several localities in the northwestern part of Paradox Valley it crops out as low hills. Wherever the base of the fanglomerate is seen, it rests directly on Mesozoic or older rocks—not uncommonly on gypsiferous beds of the Paradox Member of the Hermosa Formation.

The fanglomerates consist of a rudely bedded unsorted heterogeneous mass of material that ranges from silt-sized particles to boulders. Pebbles and boulders are angular; those in Paradox Valley and Sinbad Valley consist entirely of material derived from Mesozoic and older formations in the walls of the valley, whereas among those in Gypsum Valley are also some pebbles of porphyritic rocks derived either from old terrace gravels of the Dolores River or from Pliocene(?) gravels of the Gypsum Valley. The material is thoroughly indurated, probably by caliche cement, and where exposed as low hills is very resistant to weathering. The greatest observed thickness of the fanglomerate in Paradox Valley is about 50 feet, but commonly it is only about 5–10 feet thick. The fanglomerates in Gypsum Valley and Sinbad Valley are only 1–4 feet thick. In several places in Paradox Valley the fanglomerate is cut by, and drag folded along, slump faults that result from solution of the salt underlying the valley. The displacement of the fanglomerate along these faults was nowhere seen to exceed 10 feet.

ANCIENT GRAVELS OF THE GUNNISON RIVER

Exposed in roadcuts of State Highway 141 from 1 to about 4 miles northeast of Gateway are gravels resting on arkosic conglomerate of the Cutler Formation and unconformably overlain by fanglomerate believed to be of early Pleistocene age (Cater, 1966). The preponderance of silicic and intermediate volcanic and porphyritic intrusive rock and the scarcity of basalt strongly suggest a Gunnison River rather than a combined Colorado-Gunnison River source. If this inference is true, then the Gunnison rather than the Colorado River carved Unaweep Canyon, a topic discussed in a following section.

The fact that these old gravels were nearly swept from the river channel before the probable lower Pleistocene fanglomerate blanketed the lower valley of West Creek argues that these gravels may well be Pliocene rather than Pleistocene, and in our opinion the Pliocene age is to be preferred.

QUATERNARY SYSTEM

Sediments assigned to the Quaternary System consist of fanglomerates in West Creek; slightly consolidated possibly lacustrine silts and sands; volcanic ash; terrace and bench gravels, talus; alluvial deposits along streams; wind and sheet-wash deposits; and landslides. The higher level terrace gravels are probably of Pliocene age because some of them lie well above levels to which streams had carved by Quaternary time, but they are described here because they are identical to the more abundant terrace gravels of Quaternary age. The relative age of some similar but widely separate deposits cannot be determined with certainty. Some types of Quaternary deposits are mapped separately and are delineated on the geologic map, whereas others are not separated because different types of deposits grade into one another or the boundaries between them are vague and transitional.

FANGLOMERATES IN WEST CREEK VALLEY

Two sequences of fan material, an older, partly indurated fanglomerate and a younger, unconsolidated unit, are widely exposed in the lower valley of West Creek. The older, partly indurated fanglomerate at one time almost completely blanketed the valley as a thick sheet of fan material deposited on an irregular surface that sloped to the center of the valley, but erosion has removed much of it. Generally it crops out as a boulder-covered slope, but in some places where gully erosion has been rapid, it stands in nearly vertical bluffs approaching a height of 100 feet. The fanglomerate is light red or buff and consists of silt, sand, gravel, and angular cobbles and boulders derived almost entirely from Mesozoic formations that rim the valley. Material derived from Precambrian rocks and the Cutler Formation is, strangely, very scarce. The fanglomerate has a maximum thickness of more than 200 feet.

Overlying the older fanglomerate and more widely exposed are fan deposits having the general texture of the older fanglomerate, but the younger fanglomerate differs from the older in that it is unconsolidated and contains a large amount of material derived either from the Precambrian rocks or the Cutler Formation.

These fanglomerates probably correlate with the Pleistocene Harpole Mesa Formation described by Richmond (1962) in the La Sal Mountains of Utah. Richmond divided the formation into three members which he believes correlate with the Nebraskan, Kansas, and Illinoian Glaciations of the Midwestern States. The older fanglomerate probably correlates with the lower member of the Harpole Mesa, and the younger with either or both the middle and upper members of the Harpole Mesa (Cater, 1966).

On Spring Creek Mesa north of Uravan, a slightly indurated fanglomerate consisting largely of debris derived from the Precambrian rocks or the Cutler Formation caps a few low hills. From their character and occurrence we believe them to be approximately contemporaneous with one or the other of the fanglomerates along West Creek.

LAKE(?) DEPOSITS OF PARADOX VALLEY

The northwest end of Paradox Valley is floored by loosely consolidated strata about 50 feet thick that appear to have been deposited in small lakes. The lakes may have formed during the latest stages of collapse of the Paradox Valley salt anticline because of local settling of the valley floor below the temporary base level. The sediments consist of reddish-buff evenly bedded friable silty sandstone in the upper part of which is a layer of volcanic ash a few inches thick and a few thin beds of conglomerate. The conglomerate contains pebbles of Triassic and Jurassic sandstones, and similar small isolated pebbles are scattered through some parts of the lake deposits. Although the material of the lake beds can be crumbled easily in the hand, they are partly cemented and stand up well in vertical bluffs. The beds commonly erode to a "badlands" type of topography.

The volcanic ash layer is of particular significance because it permits a tentative correlation with the lower member of the Harpole Mesa Formation of presumed early Pleistocene age. R. E. Wilcox and G. A. Izett examined samples of this ash and reported (written commun., 1969) as follows:

> The ash of these samples corresponds very closely petrographically and chemically to the lower ash layer of the Harpole Mesa Formation at a locality about 25 miles NW of the Paradox Valley occurrence near the head of Onion Creek in eastern Utah (SE¼NE¼ sec. 26, T. 24 S., R. 24 E., Polar Mesa 15-minute quadrangle). The ash of each occurrence is moderately indurated. The refractive index of the glass shards is predominantly 1.497 to 1.498 with only a few shards above or below this range. Chemical analyses using the electron microprobe give nearly identical results for shards of each occurrence. Phenocrystic minerals (crystals carrying partial or complete mantles of glass) include hornblende, clinopyroxene, orthopyroxene(?), magnetite, ilmenite(?), and rare apatite and allanite. Biotite flakes are common in the ash of each occurrence and are presumed also to be phenocrystic. These characteristics correspond closely with those of the airfall deposits from the catastrophic eruption of the Bishop Tuff in east-central California, and on this basis we regard the ash beds at each occurrence to be correlative. The age of the Bishop Tuff has been determined as about 700,000 K–Ar years by Dalrymple, Cox, and Doell (1965).
>
> It is of interest further that the upper ash at Onion Creek, some 80 feet stratigraphically above the presumed Bishop ash and separated from it by an angular unconformity, has been tentatively correlated by H. A. Powers (*in* Richmond, 1962, p. 35) with the well-known Pearlette Ash Member of the central great plains regarded as late Kansan in age.

The lake beds overlie the hard fanglomerates of Paradox Valley; they are probably disconformable on the fanglomerates, but this relation has not been definitely established. They have been gently folded and locally dip as much as 9°. This folding undoubtedly resulted from slow removal of the underlying salt beds of the Paradox Member of the Hermosa Formation by solution or flowage. In any event, these beds and the underlying fanglomerate indicate that the valleys along the collapsed crests of the salt anticlines had reached virtually their present form and were, in fact, somewhat deeper either by late Pliocene time or certainly by the earliest Pleistocene.

TERRACE GRAVELS

On the south side of West Creek below the mouth of Ute Creek, gravel identical to the ancient gravels of the Gunnison River rests on terraces cut in the fanglomerate. The terraces were probably cut by West Creek and are more than 300 feet above the present bed of the creek. It seems reasonable to suppose that the gravels were derived from the reworking of earlier gravels deposited by the Gunnison River before it deserted Unaweep Canyon.

Elsewhere in the area, terrace gravels are found at various levels along the canyons of both the Dolores and San Miguel Rivers and on the southwest side of Disappointment Valley. Some gravel-covered terraces are several hundred feet above the present beds of the rivers and in all probability are of Pliocene age, although most are much lower and probably of Pleistocene age. The gravel is not clean and consists of sand and well-rounded pebbles and cobbles derived from the more resistant rocks of the San Juan Mountains, such as volcanic and granitoid rocks and quartzite. Regardless of where or at what levels the terrace gravels occur, the pebbles are fresh and virtually unweathered.

ALLUVIUM AND RELATED DEPOSITS

Holocene deposits include windblown material, sheet wash, alluvium, and talus. The windblown material is the most widespread of these deposits. It mantles benches and mesa tops but occurs more sparingly on valley floors. The material consists of indistinctly bedded light-red silt and sand that has been partly reworked by water and mixed with sheet wash. Where rainfall is sufficient, as around Egnar, these deposits are adaptable to agriculture and large acreages are planted to beans; where not cultivated, the deposits support thick growths of sagebrush that contrast strongly with growths of piñon and juniper that flourish in rocky areas. The deposits reach a thickness of 10 feet on some of the mesas.

Alluvial deposits occur most extensively on the broad valley floors as in Sinbad, Paradox, and Gypsum Valleys, Dry Creek Basin, and Disappointment Valley. Stream beds in the canyons ordinarily contain only thin mantles of alluvium and many are rock floored and almost devoid of stream deposits. Much of Paradox Valley northwest of the Dolores River is covered by thick fertile alluvial soils; these are farmed by using irrigation water from West Paradox Creek and various springs. Similar soils in other valleys should be fully as productive, were water available. In general the alluvium consists largely of silt and silty sand, but thin gravel deposits occur along some stream channels. In the larger valleys the alluvium attains a thickness of at least 20 feet.

Talus is abundant throughout the area, on most of the steeper slopes, along the sides of canyons and mesas, and on walls of Paradox, Gypsum, and Sinbad Valleys. Many of the blocks in this debris are 10 feet or more across.

LANDSLIDE DEPOSITS

Landslides have been a decided factor in shaping the topography of many localities within the area. The landslides generally involve only the Brushy Basin Member of the Morrison Formation and overlying formations. The bentonitic shales of the Brushy Basin are particularly susceptible to landslides along the fractured walls of Paradox and Gypsum Valleys where slopes are steep and surface water has penetrated deeply. The water swells the bentonite and produces an unctuous, slimy, lubricating medium that permits the movement of large masses of rock over long distances down rather gentle slopes. Probably the most impressive of these landslides is on the southwest wall of Paradox Valley below the Jo Dandy mine; this landslide mass is more than 2 miles wide and extends down the valley wall for more than 1½ miles. Other slides almost as large are found in the northwestern part of Gypsum Valley and along the upper slopes of the canyon of Roc Creek. The surfaces of the landslides are uneven and hummocky and strewn with large blocks from the conglomerates of the Brushy Basin Member, the Burro Canyon Formation, and the Dakota Sandstone.

STRUCTURAL GEOLOGY

REGIONAL SETTING

The Colorado Plateau is a region distinct both as a physiographic province and as a geologic province, and its duration as a geologic province far exceeds its existence as a physiographic province. The plateau is generally less deformed than surrounding areas, and is characterized by mostly flat-lying sedimentary rocks. Here and there, however, the strata are upwarped, folded, cut by faults, and intruded by igneous rocks and salt plugs. The major structures are the great monoclinal upwarps and intervening basins, but topographically more conspicuous are the domal uplifts surrounding the stocklike centers of the laccolithic mountains. The steep flanks of most of the monoclines on the west side of the plateau dip east whereas those on the east side dip west (fig. 1). The distribution of the laccolithic mountain masses appears to be unrelated to the distribution of the other major structural features of the plateau. Faults are most numerous in the northern part of the region, where most of them trend northwest. Volcanic plugs, calderas, and explosion vents are most common in northeastern Arizona and adjacent parts of New Mexico. The southern and western parts of the plateau are marked by large volcanic fields. Most striking of the structural features are the salt-cored anticlines that lie along the Utah-Colorado boundary near the eastern margin of the plateau in an area between the great east-dipping monoclinal upwarps and the Uncompahgre uplift.

SALT ANTICLINES

GENERAL FEATURES

The salt anticlines of Utah and Colorado are unique in North America both in structure and in mode of development. They comprise a sequence of northwest-trending salt-cored folds that coincide with the deepest part of the Pensylvanian Paradox Basin southwest of the uplift underlying the Uncompahgre Plateau. In Colorado the anticlines and their intervening synclines are (from northeast to southwest) the Nucla syncline, the Sinbad Valley anticline, the Paradox Valley anticline, the Dry Creek basin syncline, and the Dolores anticline (pl. 1). Most of these folds are but enlarged segments or bulges on longer structures that continue northwestward into Utah where other segments have other names—thus the Fisher Valley, Castle Valley, and Lisbon Valley anticlines in Utah are enlarged segments of the same structures from which, respectively, the Sinbad Valley, Paradox Valley, and Dolores anticlines also rise (Williams, 1964). Segmentation of some of these longer structures resulted partly from intrusion of the La Sal Mountains igneous rocks (Hunt, 1958).

The anticlines are structurally far more complex than their seemingly simple forms suggest, but the broad intervening synclines present few complexities. All the anticlines possess cores of salt and gypsum from the Paradox Member of the Hermosa Formation. They are structurally dissimilar to the salt domes of the gulf coast region, notwithstanding the fact that both owe their development largely to intrusion of salt. The salt domes of the gulf coast region are roughly circular or elliptical in plan and show little regularity of distribution or control by basement structures, whereas the salt anticlines of Colorado and Utah are decidedly linear and have a systematic distribution determined by basement structures. Much of the structural complexity of the anticlines is the result of collapse of their crests in Tertiary time because of removal of the underlying salt by flowage and solution.

LOCALIZATION

Structural control of the salt anticlines has long been suspected because of their parallelism to each other and to the edge of the ancestral Uncompahgre uplift, but only in recent years has drilling and geophysical information lent real substance to these suspicions. Structural displacements of pre-Paradox rock where no corresponding displacement of surface rocks exists have been proved in a number of places. More than 5,000 feet of structural relief exists in presalt rocks between the center of Paradox Valley about a mile northwest of the Dolores River and Dry Creek basin syncline 5 miles to the southwest. The base of the salt under the northeast flank of Gypsum Valley is about 2,600 feet lower than under the southwest flank between Gypsum Gap and the Dolores River, and there is about 2,500 feet of local relief in presalt rocks in the Lisbon Valley anticline nearby in Utah. Gravity data (Joesting and Byerly, 1958) indicated the major dislocations in presalt rocks are parallel to and under the southwest flanks of the Paradox Valley and Gypsum Valley anticlines. Furthermore, the gravity gradients are so steep here that it seems highly probable that the gradients are produced by high-angle faults rather than by folds.

Drilling information and geophysical data also suggest that the faulted blocks of presalt rocks are tilted southwest as shown in figure 13. If this is true, then presalt strata are deepest below the salt cores. Most of the salt anticlines are somewhat asymmetrical, the north flanks being the steeper and the synclinal troughs being displaced to the southwest of their geographical centerlines. The southeast parts of all the folds southwest of and including the Paradox Valley anticline are bent and offset to the northeast with respect to the northwest parts of the folds; these offsets or kinks occur along a nearly straight northeast-trending line extending from Sawtooth Ridge (sec. 16, T. 16 W., R. 46 N.) to near the head of Bush Canyon (sec. 25, T. 19 W., R. 43 N.; pl. 1). Magnetic data and to a lesser extent gravity data reflect similar offsets in the basement rocks (Joesting and Byerly, 1958; H. R. Joesting, E. B. Byerly, and Donald Plouff, written commun., 1959); these data suggest that some obscure structure must exist in the basement. Its northeast trend suggests that possibly it may be related to the Precambrian structural elements described by Tweto and Sims (1963), but in any event no displacement along this trend has occurred in the post-Paradox time.

STRATIGRAPHIC MODIFICATIONS

The growing salt cores profoundly affected the thickness and distribution of post-Paradox and pre-Morrison formations and had lesser effects on the thickness of the Morrison and Burro Canyon Formations in the deep part of the Paradox basin. The limestone member of the Hermosa Formation was lifted and beveled, and all later pre-Morrison formations either were intruded or were not deposited along the rising salt cores. On the flanks of the anticlines, successively older formations dip more steeply, and, in general, younger formations are deposited across the upturned and truncated edges of older formations (fig. 13). This process of upturning, erosion, and deposition of overlapping younger formations continued until Morrison time, when salt from beneath the intervening synclines had been largely squeezed out and exhausted.

As the salt was forced from under the synclines, they sank relatively faster than the surrounding region and became traps for sediments. The result was that the involved formations attained a thickness at least 3,000 or 4,000 feet greater than would have been possible were salt nonplastic. The reason for this is that a tapering layer of salt not less than 4,000 feet thick beneath and adjacent to Paradox Valley and 3,000 feet thick beneath and adjacent to Gypsum Valley would be required merely to furnish the salt presently in the cores underlying these valleys if all the salt were squeezed from the bordering synclines. It is not possible to say how much additional salt was extruded and removed by solution during the many millions of years preceding burial by the Morrison Formation when salt cores were growing and exposed at the surface, but it was probably considerable. Thickening of formations as a result of salt mobility was not entirely confined to synclinal areas. In the northwest end of Paradox Valley, the Moenkopi Formation thickens toward the crest of the salt core; in the northwest part of Gypsum Valley, both the Navajo and Morrison Formations locally thicken abruptly, possibly because the underlying salt was subject to more rapid solution in some places while these formations were being laid down.

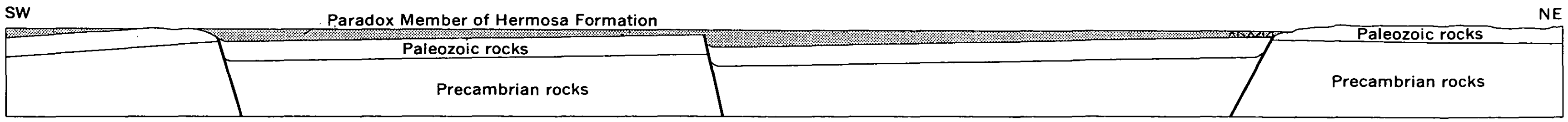
STRUCTURE

ANTICLINES

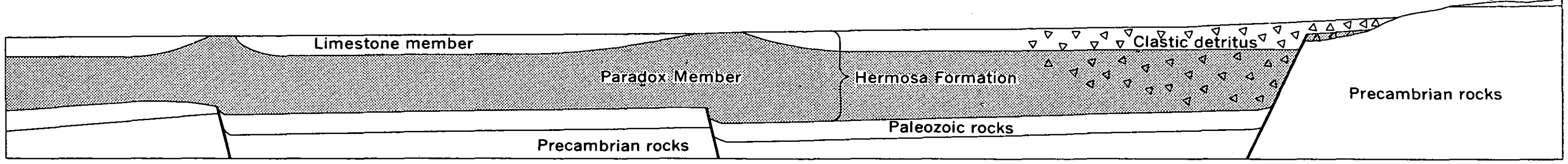
SINBAD VALLEY ANTICLINE

The Sinbad Valley anticline is the northernmost salt anticline in the mapped area. It forms a broad elliptical bulge on the great salt structure from which the Fisher Valley anticline also rises. The flanks of the anticline are marked by hogback ridges of resistant sandstone that rim the precipitous walls of Sinbad Valley. The rolling floor of the valley, in the area of this report, is carved largely from the soft rocks of the Paradox Member of the Hermosa Formation, although large areas are now covered with alluvium and valley fill where the Paradox is not exposed. Beds of the Paradox Member exhibit extreme folding and crumpling.

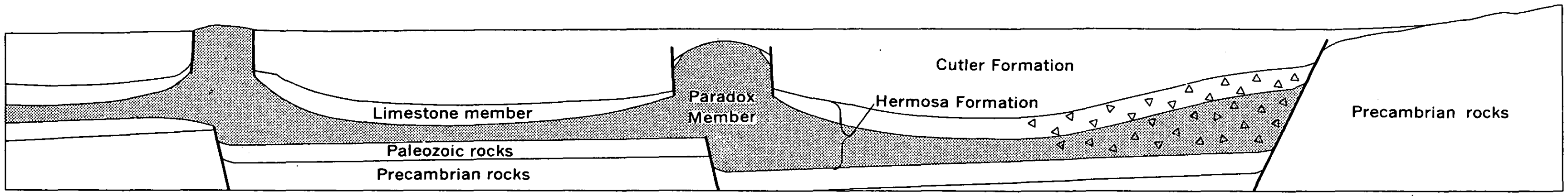
The visible part of the salt-and-gypsum core of Sinbad Valley is a composite of several contiguous cells or cupolas that presumably rise from a central salt-and-gypsum mass. The evidence for the existence of these separate cupolas is not as clear in the southeast part of Sinbad Valley as elsewhere, but the west- to northwest-trending fault near the center of the valley in unsurveyed sec. 27, T. 49 N., R. 19 W. is thought to mark the boundary between two separate cupolas, because along the fault, limestone beds on the north probably belonging to the limestone member of the



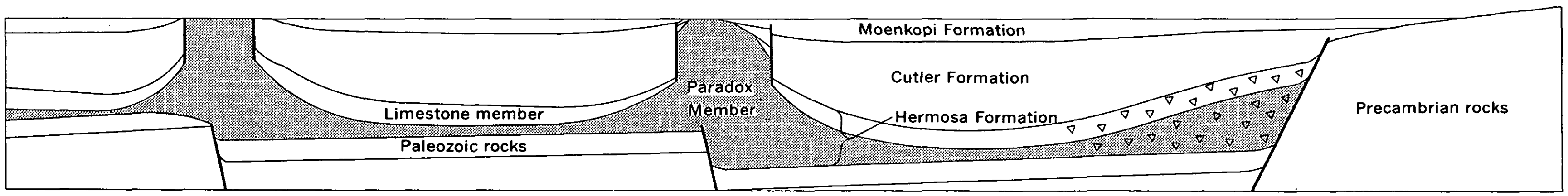
A. Precambrian and Paleozoic rocks during deposition of the Paradox Member (Pennsylvanian) after early downdropping and faulting of deep part of Paradox basin and uplift of ancestral Uncompahgre highland



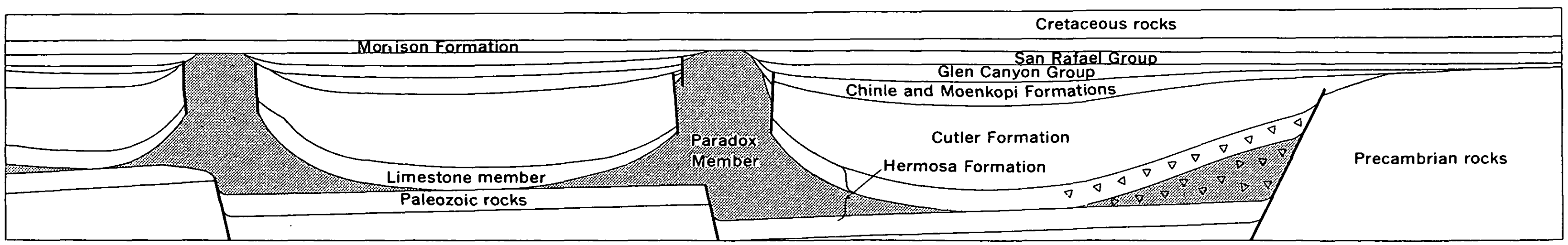
B. Precambrian and Paleozoic rocks at end of deposition of limestone member (Late Pennsylvanian). Downdropping and faulting of basin and uplift of highland continuing



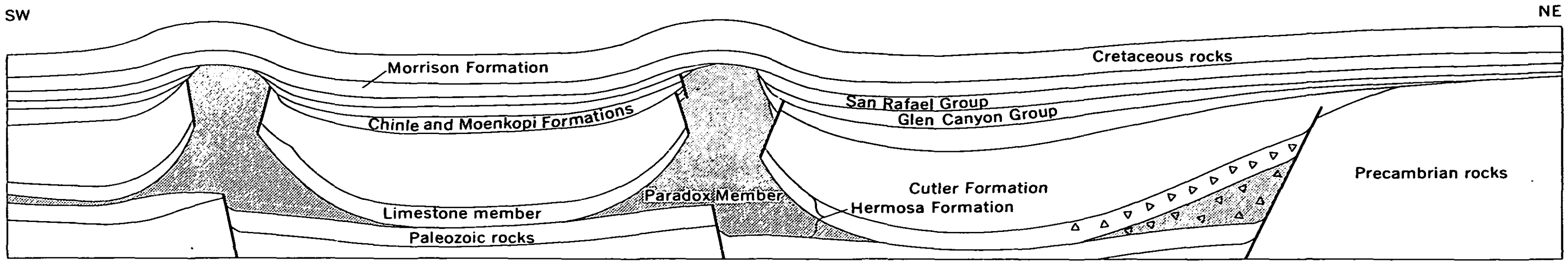
C. Precambrian and Paleozoic rocks near end of Cutler deposition (Permian). Development of salt cores well advanced



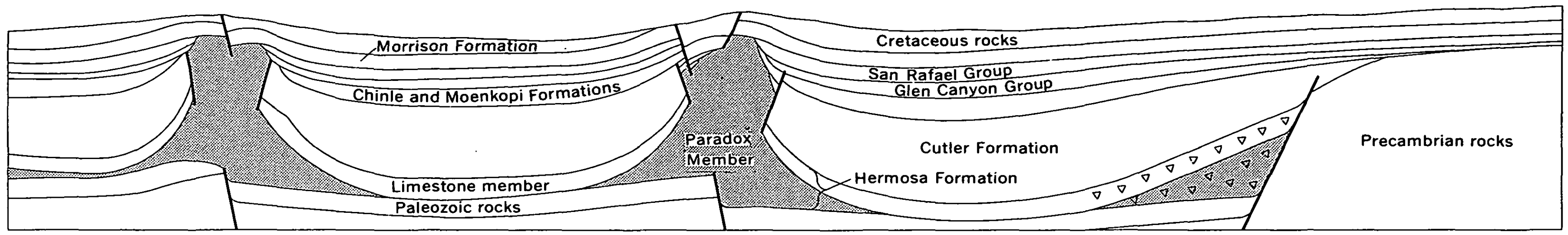
D. Precambrian, Paleozoic, and Mesozoic rocks at end of Moenkopi deposition (Middle? Triassic)



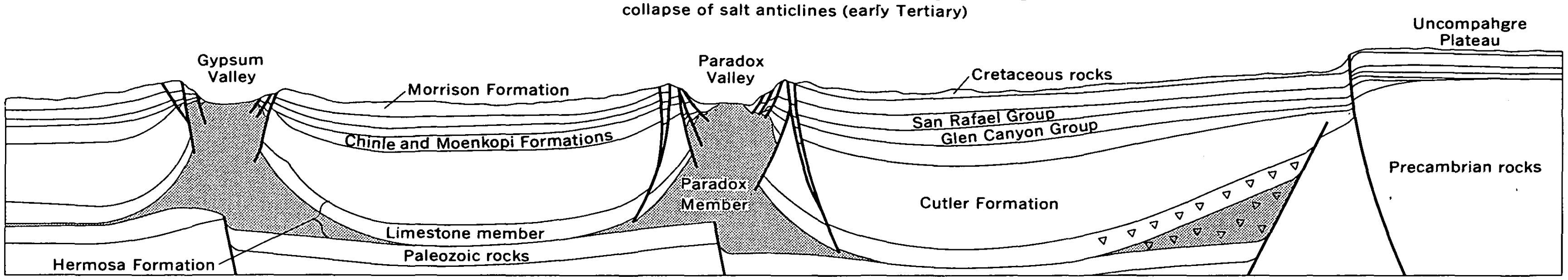
E. Precambrian, Paleozoic, and Mesozoic rocks at end of Cretaceous



F. Precambrian, Paleozoic, and Mesozoic rocks at end of early Tertiary folding



G. Precambrian, Paleozoic, and Mesozoic rocks during first stages of crestal collapse of salt anticlines (early Tertiary)



H. Precambrian, Paleozoic, and Mesozoic rocks since Pleistocene time. Renewed faulting on southwest border of Uncompahgre Plateau during late Tertiary and Pleistocene

FIGURE 13.—Growth and crestal collapse of the Gypsum Valley and Paradox Valley salt anticlines.

Hermosa Formation are set against gypsum beds of the Paradox Member on the south. About 1,500 feet south of the fault, the Chinle Formation rests in depositional contact on Paradox beds, and the limestone member is missing, thereby showing that south of the fault, uplift of the cupola was sufficient for removal of the limestone in pre-Chinle times.

Although stratigraphic effects of the mobile salt in the cores of the anticlines generally can be seen better in some of the other anticlines, some of these effects are readily visible in the Sinbad Valley anticline. For example, on the flanks of the anticline the Cutler dips more steeply than the Moenkopi and younger formations, and the Moenkopi contains intraformational unconformities between units that are normally conformable elsewhere.

The walls of the valley are cut by numerous faults, most of which have their downdropped sides toward the valley. The faults formed as a result of the collapse of the crest of the anticline because the underlying salt was removed by flowage and solution. Some of the faults show no correspondence between stratigraphic and topographic displacement and apparently date back to early Tertiary, the initial period of collapse of the anticline. Others have equivalent stratigraphic and structural displacements—that is, they have been almost untouched by erosion and are of fairly recent origin. Still others are of indeterminate age.

The Sinbad Valley anticline terminates to the southeast at the Roc Creek salt-and-gypsum intrusive plug in unsurveyed sec. 7, T. 48 N., R. 18 W. This plug is nearly circular and is bounded by partly concentric faults which drop the rocks within the plug varying distances. The north rim of the plug has settled most recently, and this part is marked by prominent fault scarps. The intrusive salt-and-gypsum core is exposed at two locations, one on the northwest rim of the plug and the other on the southeast rim. The plug is cut by northwest-trending faults that continue across its borders into Sinbad Valley on one side and Carpenter Flats on the other. From the southeast end of the plug, in Carpenter Flats, faults trend northeastward and die out near the mouth of Roc Creek. The triangular block of rocks that lies between these two systems has dropped with respect to the surrounding strata.

Extending northeastward from Sinbad Valley is a graben, nearly 1½ miles wide and 3½ miles long. It is bounded on the southeast throughout most of its length by a single fault, but at both ends this fault splits into two or more nearly parallel faults. The displacement at the southwest end of the fault is about 700 feet, but to the northeast it diminishes, and the fault dies out at a point about 1¼ miles from the Dolores River. The northwest side of the graben is bounded by a fault zone. The displacement along this fault zone diminishes both to the northeast and to the southwest from a point of maximum displacement of about 400 feet near the center of the zone; to the northeast the zone passes into a single fault that dies out about 1 mile from the Dolores River, and to the southwest it dies out on the northeast rim of Sinbad Valley. The southwest end of the graben is cut by a diagonal fault from which a number of subsidiary faults branch.

PARADOX VALLEY ANTICLINE

The Paradox Valley anticline is the largest single salt-core anticline in the region; the valley trough carved along the crest of the anticline has an average width of about 3 miles and a length of more than 30 miles (pl. 2). The Castle Valley salt anticline, in eastern Utah, is probably a continuation of the same salt-core structure.

The rims of Paradox and Sinbad Valleys are less than 3 miles apart at their closest approach; the intervening area is occupied by a narrow rather shallow syncline that dies out south of the Roc Creek salt plug and merges into the gently dipping northeast flank of the Paradox Valley anticline. In general the rocks forming the cuestalike rims of Paradox Valley dip away from the valley at angles that in few places exceed 9°. Rocks in the valley walls below the rims, however, commonly dip more steeply, and near contacts with the Paradox Member and limestone member of the Hermosa and the Cutler Formations, they in places dip vertically or nearly so. The Paradox Member crops out extensively throughout Paradox Valley northwest of the head of East Paradox Creek, and the beds in it are intricately folded and crumpled in all exposures. Like the core of the Sinbad Valley anticline, the core of the Paradox Valley anticline consists of a number of contiguous cupolas rather than of one simple mass. These various cupolas, however, are in direct contact with one another and, although separated in only a few places by infolded layers of later beds, they are reflected clearly by the wide places or bulges along the length of the anticline.

The Paradox Valley anticline comprises three structurally distinct units characterized by the types of structural feature developed during collapse of the crest of the anticline. These are (1) a unit at the southeast end of the anticline where the crest has downsagged to form a structural basin, (2) a large central unit occupying most of Paradox Valley where the crest has collapsed by downfaulting, and (3) a unit at the northwest end of the valley that collapsed by both downsagging and downfaulting. Mesozoic rocks are preserved in the downsagged crest of the anticline at either end of the valley, but in the central part of the valley, they have been largely removed above the core of the anticline. Each of the three units has structural peculiarities not common to the other two, and for convenience of treatment each unit will be described separately.

The downsagged unit at the southeast end of the anticline overlies a distinct cell or cupola of the underlying salt

FIGURE 14.—View of Dry Creek anticline looking northwest; Paradox Valley in the distance. Php, Paradox Member of Hermosa Formation; TRc, Chinle Formation; TRw, Wingate Sandstone; TRk, Kayenta Formation; Je, Entrada Sandstone; Js, Summerville Formation; Jms, Salt Wash Member of Morrison Formation; Jmb, Brushy Basin Member of Morrison Formation; Kbc, Burro Canyon Formation. Photograph by Hal. G. Stephens.

mass and forms a structural basin that is slightly offset to the northeast from the general trend of the Paradox Valley anticline. The basin is bordered on its northwest end by northeast-trending faults in secs. 20 and 21, T. 46 N., R. 16 W., and a sharp fold in the southern part of sec. 29, T. 46 N., R. 16 W. The basin has no sharply defined southeast end but simply merges into the flat-lying beds of the surrounding plateau.

The northeast and southwest sides of the basin are bordered by anticlines between which a syncline formed because of sagging of the crestal part of the Paradox Valley anticline. The outside flanks of these lateral anticlines are continuous with and indistinguishable from the flanks of the Paradox Valley anticline as a whole. The crests of both the lateral anticlines are cut by faults that drop the rocks in the downsagged central basin.

The more striking of these two lateral folds is the Dry Creek anticline along the southwest side of the basin (fig. 14). This anticline continues southeastward as a distinct fold 7 or 8 miles beyond the edge of the mapped area before merging into the flat-lying rocks of the surrounding plateau and does, in fact, extend farther to the southeast than any other readily visible structure associated with the Paradox Valley anticline. The structural relief from the center of the downsagged central basin to the crest of the Dry Creek anticline, including displacement on the faults along the crest of the Dry Creek anticline, is about 2,600 feet. The rocks in the southwest flank of the Dry Creek anticline dip 5°–9° SW., except that beds a few hundred feet from the crest are sharply upturned and dip 55° SW. This sharp upturning is reverse in direction to the displacement on the faults that cut the crest of the anticline and is not, therefore, drag related to the faults. A possible explanation of this anomalous flexing is presented on page 67 and shown in figure 19. The faults that cut the crest of the Dry Creek anticline produce a series of wedges that narrow downward, and although the overall displacement is down to the northeast, some of the wedges in the northwest part of the fold have been squeezed upward. In the crest of the anticline northwest of Dry Creek, intrusive beds

FIGURE 15.—Intraformational unconformity in the Chinle Formation (R̄c) on the southwest flank of Dry Creek anticline. R̄w, Wingate Sandstone; Qal, Quaternary alluvium; sh, shale; ss, sandstone; ls, limestone; cpc, clay-pellet conglomerate.

belonging to the Paradox Member of the Hermosa Formation are exposed north of the crestline fault. A well drilled in the bottom of Dry Creek Canyon 200–300 feet south of the fault reached a depth of more than 5,000 feet before cutting Paradox beds. This fact provides convincing evidence concerning the steepness of the flank of the intrusive core of the Paradox Valley anticline. Thousands of feet of beds of the Cutler, Rico, and Hermosa Formations were penetrated by the drill, yet a few hundred feet away on the northeast side of the fault, beds of the Moenkopi and Chinle Formations rest directly on Paradox beds with depositional contact and the Cutler Formation is absent. Northeast and immediately southwest of the fault, the Moenkopi is very thin, but southward it thickens rapidly (sec. E–E′, pl. 1). Furthermore, the overlying Chinle Formation thickens southwest of the fault and has intraformational unconformities along which older contorted beds are planed off and overlain by younger uncontorted beds (fig. 15). These relations indicate relatively rapid local upwelling of salt during Chinle time. Beds overlying the Chinle appear to have been unaffected by intrusion of salt in this area. Two miles to the northwest, however, and probably over a different intrusive cupola, the Entrada Sandstone rests directly on the Chinle, and all intervening formations are absent.

The Dry Creek anticline ends to the northwest by bending into the transverse fold that separates the southeastern and central structural units of the Paradox Valley. Only a part of this transverse fold is exposed, but the fold is in part at least an asymmetrical anticline. The west flank dips gently and probably extends only to shallow depths. The east flank dips steeply in its upper parts and gradually flattens out as the bottom of the downsag is approached. The north end of this fold is covered but probably is cut off by extensions of the northeast-striking faults exposed in the valley wall in secs. 20 and 21, T. 46 N., R. 16 W., north of State Highway 90.

The anticline along the northeast border of the southeastern downsagged basin is a fairly simple structure, and most of it lies outside the mapped area. The southwest flank of this anticline is much steeper than the northeast flank which dips toward the Dolores–San Miguel syncline. The crest of the anticline in secs. 21 and 22, T. 46 N., R. 16 W. is cut by a normal fault that dips southwest. Beyond the mapped area to the southeast, the anticline gradually flattens, and both it and the downsagged basin merge into virtually flat-lying rocks. The central part of the downsagged basin is devoid of structural complexities and is unfaulted.

The central structural unit of the Paradox Valley anticline, the largest and most complex of the three units, appears to have a salt core from which a number of cupolas rise. The unit is about 18 miles long and 2½–4½ miles wide. The wider parts of the valley are thought to outline the bulges or cupolas on the partly intrusive core; in the northwest end of the valley about 2 miles northeast of the village of Paradox, an edge of one of these cupolas seems to be delineated by an arcuate layer of nearly vertically dipping Hermosa limestone. In the narrow part of the valley immediately southeast of the Dolores River, older units of the post-Paradox sequence crop out across most of the valley, which indicates that the upper surface of the core was there at a lower general level than in the wider parts of the valley where older post-Paradox rocks overlying the cupolas had been bulged upward and outward.

Numerous closely spaced faults on both sides of the valley cut the rocks into long narrow slivers trending parallel to the length of the valley. Most of these slivers are successively downdropped toward the valley, but a few have been squeezed upward. Southwest of the Dolores River, grabens have formed back from the rims on both sides of the valley. The graben on the northeast side of the valley is complex and is cut by numerous faults and joints (fig. 16), but the graben on the southwest side is longer. Both grabens probably formed as the relatively unfaulted prisms of rock now lying between the grabens and the rims of the Paradox Valley tilted slightly toward the valley and differentially settled into the underlying salt core, thereby pulling away from the rocks farther down the flanks of the anticline. The settling of these blocks is causing the salt to rise and push up hills of gypsum in Paradox Valley between these grabens.

Several northeast-striking transverse faults cut the northwestern part of the central unit. The mineralized zones of the Cashin (sec. 22, T. 47 N., R. 19 W.) and Sunrise (sec. 23, T. 48 N., R. 19 W.) mines have formed along two of the faults; it seems unlikely that these mineralized zones could have formed under the near-surface conditions existent at the time of final collapse of the crest of the anticline, and therefore these faults probably predate final collapse, although movement was renewed on some of

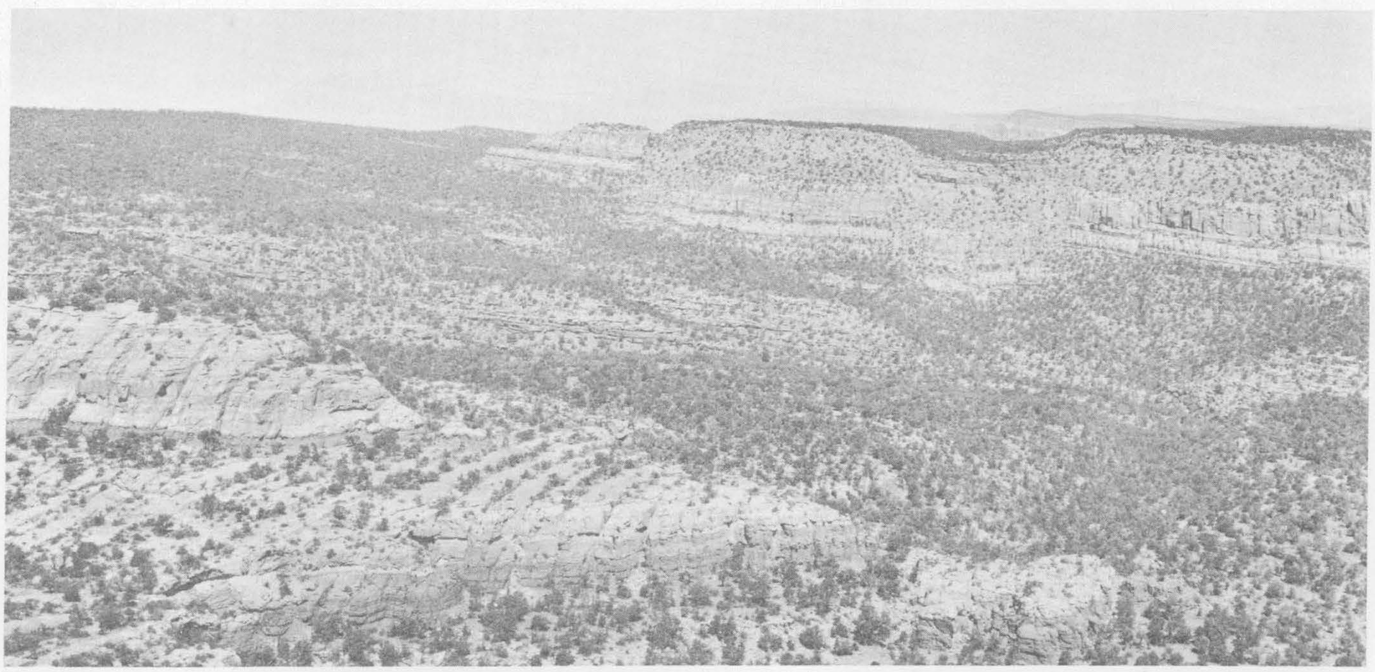


FIGURE 16.—View westward showing graben and joints on northeast flank of Paradox Valley anticline south of Saucer Basin (secs. 11, 12, 13, and 14, T. 47 N., R. 18 W.)

these faults at that time. Groups of slump blocks included between these transverse faults have settled more or less as units. The transverse fault at the Sunrise mine on the northeast side of Paradox Valley also marks the northwest boundary of the central structural unit.

The rocks in the southeast end of a large fault block on the southwest side of the central structural unit, in the vicinity of the Thunderbolt mine in secs. 22, 25, 26, 27, and 36, T. 46 N., R. 17 W., have been warped into a syncline. The syncline is analogous in form and position to the ring synclines that surround some of the Gulf Coast salt domes, although the origin may be different. Similar but sharper synclines are found in Gypsum Valley. These synclines appear to form only above the margins of the salt cores and may be caused by relatively rapid solution and removal of salt and gypsum along the more permeable shattered margins of the cores.

Because the Paradox beds were partly intrusive into the core of the anticline, stratigraphic relations vary considerably in the central structural unit. In places the limestone member of the Hermosa Formation and the Cutler Formation are intruded by the Paradox, whereas in other places both these and younger formations rest with depositional contact on it. All post-Paradox beds to the base of the Morrison Formation either are cut off or wedge out against the salt at one place or another in the central structural unit. Although thinning of the formations can be seen on the northeast wall of Paradox Valley, actual wedgeouts and unconformable contacts between beds not normally in contact are seen best on the southwest wall of the valley southeast of the Dolores River. For example, the Kayenta Formation is more than 100 feet thick below Monogram Mesa in sec. 17, T. 46 N., R. 17 W., but to the southeast near the Thunderbolt mine in sec. 23, T. 46 N., R. 17 W., it is absent, and there the Entrada Sandstone rests on the Wingate Sandstone. In this locality the Wingate thins valleyward from an exposed thickness of more than 100 feet to less than 5 feet within a quarter of a mile. Farther east in sec. 29, T. 46 N., R. 16 W., the Entrada rests on the Chinle Formation. In this general area no post-Paradox beds older than Chinle crop out, and presumably either they are cut off by the underlying intrusive salt and gypsum or their upturned and truncated edges are unconformably overlain by younger formations and lie well back from the foot of the valley wall. The floor of the valley probably is underlain—or before erosion, was underlain—by rocks no older than Summerville. The thinness of the post-Paradox rocks on the valley floor was confirmed by a geophysical traverse (W. E. Davis, oral commun., 1950).

The northwest structural unit of the Paradox Valley anticline consists of downwarped and faulted rocks that dip valleyward; some of these rocks form the steep face in sec. 20, T. 48 N., R. 19 W. at the northwestern end of the valley. The northeast flank of the anticline below Carpenter Ridge is highly faulted, and fault blocks are commonly downdropped toward the valley. Unlike rocks to the southeast, those in the northwest structural unit dip toward the valley rather than away from it. A striking feature in this structural unit are the steeply upturned rocks (dips of as much as 35°) in the southwest part of sec. 17, T. 48 N., R. 19 W., which are bounded on the northeast by a northwest-trending fault that runs up the bottom of a short canyon. The displacement along the fault increases to the northwest and away from the valley. A wedge of the Moenkopi Formation that thins away from the crest of the anticline is exposed at the lower end of the canyon through which the fault runs. The direction of thinning proves that prior to deposition of the Chinle there had been local relative downsagging of the central part of the anticline.

South of this block, in secs. 20 and 29, T. 48 N., R. 19 W. the beds dip, in general, less steeply and to the east into the valley. These valleyward-dipping rocks are cut by a number of faults that strike north, diagonal to the trend of the Paradox Valley anticline. In this vicinity rocks at least as old as the Wingate Sandstone were deposited completely across the top of the salt intrusion, whereas in some other parts of the anticline the Wingate and some younger formations wedge out on the flanks of the intrusion.

A mile south of the confluence of the Dolores and San Miguel Rivers is a circular downfaulted block, the center of which is lowered about 900 feet. The general pattern of the faults in the block consists of concentric arcuate faults and radial faults emanating from about the central part of the block, thus the structure somewhat resembles a spider's web. Most of the radial faults are too small to be shown on the map. The formation of such a structure requires the local removal of a large volume of material from below; the structure probably occupies the roof of a salt dome that collapsed as salt was removed by solution or flowage.

GYPSUM VALLEY ANTICLINE

The Gypsum Valley anticline is about 30 miles long and trends northwesterly almost entirely across the mapped area. Only the extreme southeast end of the anticline lies beyond the limit of the mapped area. Both ends of the anticline die out into flat-lying rocks. The Gypsum Valley anticline, unlike the Paradox Valley and Sinbad Valley anticlines, is a structural feature complete in itself and not a segment of a much longer structure. The axial part of the Gypsum Valley anticline has collapsed, and the resulting valley has a fairly uniform width of about 2 miles except for a slight constriction south of Hamm Canyon. The core of salt and gypsum in the anticline appears to be of fairly uniform shape and generally lacks any of the bulges or cupolas that characterize the Paradox Valley and Sinbad Valley anticlines. Geophysical evidence (Joesting and Byerly, 1958) and recent drilling indicate that pre-Paradox rocks are structurally high beneath the southwest flank of the anticline, although surface rocks show no evidence for such a high. East of Hamm Canyon the southeast part of the anticline is bent to the northeast. This bend is similar to that previously described in the southeast end of the Paradox Valley anticline. The Cretaceous and Upper Jurassic rocks forming the hogback ridges that surround Gypsum Valley are turned up more sharply than are the rocks occupying similar positions around Paradox and Sinbad Valleys.

Many of the relations of the salt core to the overlying rocks are revealed better in the Gypsum Valley anticline than in any other structure in the salt anticline region of Colorado and Utah. At one place or another along the length of Gypsum Valley almost every possible combination of Morrison or pre-Morrison beds resting on older beds may be observed because of the wedging out of intervening formations. Thus, in some places the Morrison rests on the Paradox Member of the Hermosa Formation, and in others on the Chinle or Cutler Formations; the Entrada Sandstone may rest on the Navajo Sandstone or any older formation. Although evaporites of the Paradox were not observed to intrude formations younger than the Cutler, the proximity of gypsum and Mancos Shale in the southeast end of the valley (sec. 3, T. 43 N., R. 16 W.) suggests that the evaporites intruded rocks as high in the stratigraphic column as the Mancos. It seems more likely, however, that the Mancos rocks are remnants of ancient landslide blocks formed during collapse of the crest of the anticlines (Cater, 1964).

Examples of stratigraphic relations resulting from folding

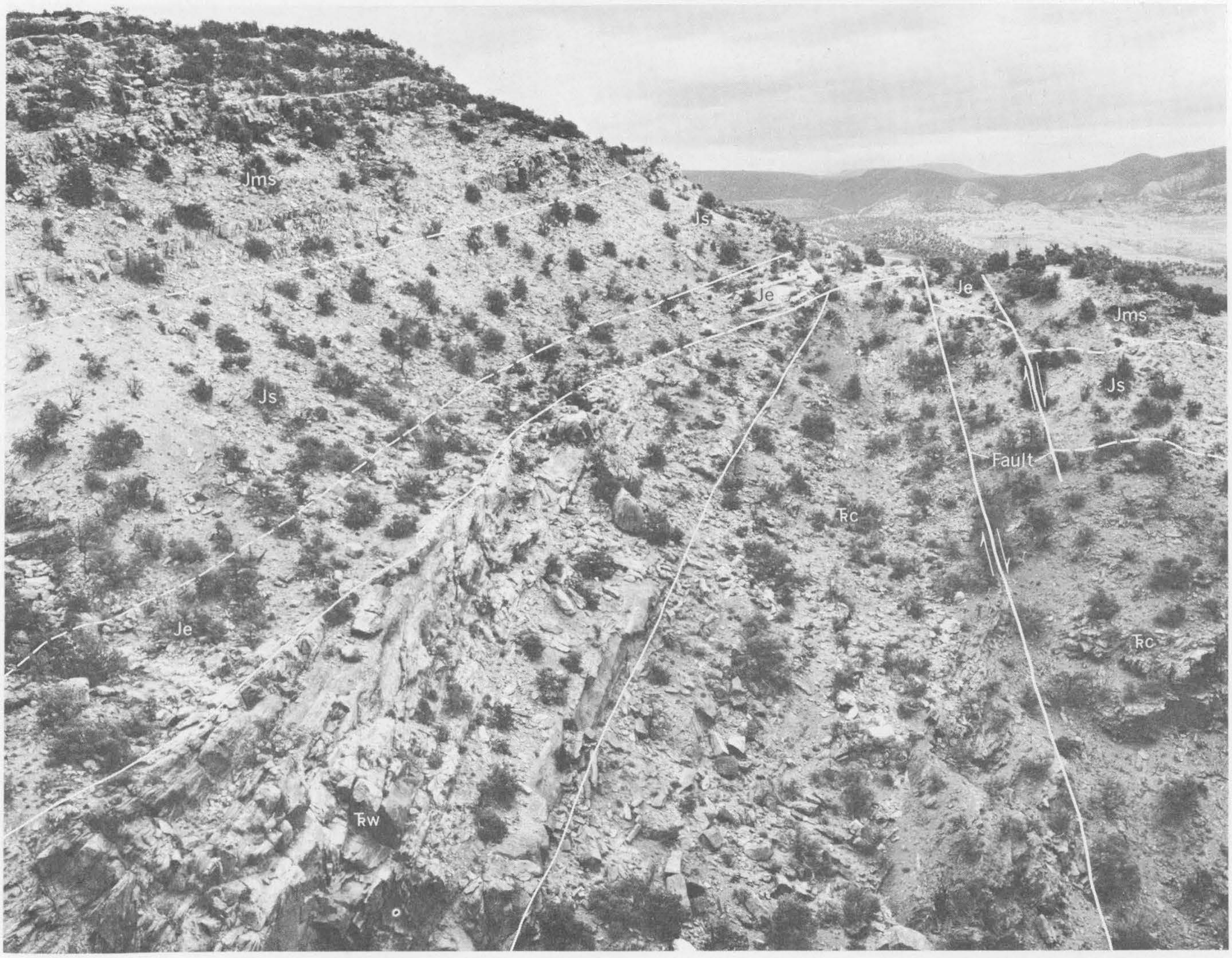


FIGURE 17.—Unconformity between the Entrada Sandstone and formations on the northeast side of Gypsum Valley, 2 miles north-northeast of Gypsum Gap. Ꝇc, Chinle Formation; Ꝇw, Wingate Sandstone; Je, Entrada Sandstone; Js, Summerville Formation; Jms, Salt Wash Member of the Morrison Formation.

FIGURE 18.—Unconformity between the Entrada Sandstone (Je) and formations on the northeast side of Gypsum Valley, about 3 miles northwest of locality shown in figure 17. Js, Summerville Formation; Jms, Salt Wash Member of the Morrison Formation.

and the movement and intrusion of salt are particularly well exposed in the southwest valley wall southeast of Gypsum Gap, in the northeast wall from the Pitchfork mines to a point about 3 miles southeast of Hamm Canyon, and below Anderson Mesa near the north end of the anticline. Southeast of Gypsum Gap the upturned and truncated edges of beds ranging from the Hermosa limestone to the Cutler are overlain unconformably by the Entrada Sandstone and the Summerville Formation; valleyward and to the northwest in secs. 6 and 7, T. 43 N., R. 16 W., and sec. 1, T. 43 N., R. 17 W., the Entrada and Summerville wedge out by nondeposition and erosion and the Salt Wash rests on Paleozoic rocks including the Paradox. On the northeast side of the valley 1 mile northwest of the Pitchfork mines, the Salt Wash rests on the Kayenta Formation in the valley walls and on the Paradox on the valley floor. Near the Bald Eagle mines the Entrada and Kayenta are missing and valleyward the Summerville rests successively on the Wingate Sandstone and the Chinle Formation. One to two miles northwest of the Bald Eagle mines are three short canyons where the wedging out of various formations is displayed to extraordinary advantage. In these canyons, steeply dipping beds of the Hermosa limestone, Cutler Formation, Chinle Formation, and Wingate Sandstone are overlain unconformably by the Entrada and Summerville (fig. 17); toward the valley from these occurrences the Entrada and Summerville wedge out and the Salt Wash lies directly on the Paradox. Northwest of the Long Ridge mines (2½ miles north of Gypsum Gap), the Entrada Sandstone and younger formations dip at angles of less than 20°, whereas older formations dip from 55° to almost vertical (fig. 18).

Along the northeast side of Little Gypsum Valley, unconformable relations between various formations and both members of the Hermosa Formation are also well exposed. Where the Dolores River leaves the valley, the Chinle Formation rests on the upturned beds of the limestone member of the Hermosa Formation. Below Anderson Mesa the Navajo Sandstone and the Kayenta Formation wedge out on the upper part of the valley wall; lower on the wall toward the valley floor, the Wingate Sandstone and the Chinle Formation also wedge out, and the Entrada Sandstone rests on the limestone member of the Hermosa. The same relations also exist on the east side of Silveys Pocket below Buck Mesa in secs. 27 and 34, T. 46 N., R. 19 W. On the opposite side of the valley the stratigraphic relations, at least to the depth the rocks are exposed, are entirely different. No formations below the Navajo are exposed, but the Navajo wedges out valleyward from an exposed thickness of not less than 350 feet below Island Mesa and is absent on the northeast side of the valley. These relations indicate considerable local movement and readjustment of the salt core during Navajo time with possible subsidence on one side of the core and upward movement on the other. Of especial interest is an abrupt thickening of the Salt Wash Member of the Morrison Formation along the northeast side of the valley, which is seen best in the vicinity of The Hat in sec. 34, T. 46 N., R. 19 W., where the exposed part of the member thickens by more than 100 feet in a distance of less than one-half mile. The thickening of the Salt Wash presents almost certain evidence that, at least locally, movement of salt was occurring during Morrison time, notwithstanding the fact that nowhere has the Salt Wash been observed to wedge out along the salt anticlines as do all the older formations.

The collapse structures along the crest of the Gypsum Valley anticline differ somewhat from those on other salt anticlines in the region. The walls of Gypsum Valley are not extensively faulted, and blocks of great thickness have foundered in the salt core. Only in the southeast end of the valley have rocks that formerly occupied the crest of the anticline been removed entirely; throughout much of the rest of the valley varying thicknesses of Mesozoic rocks are still preserved on the valley floor, although these have been greatly deformed by graben faulting and downwarping.

In the southeast part of the anticline the post-Paradox rocks are both faulted and folded. Upper Cretaceous rocks are downfaulted against the Chinle, Rico, and Cutler Formations in the southeast end of Gypsum Valley, and on both sides of the valley the rocks are downfaulted toward the valley. For several miles along both sides of this end of the valley the Salt Wash Member is downwarped into sharp narrow synclines, apparently directly over the line where the Salt Wash crosses on to Paradox beds.

From Gypsum Gap to the vicinity of Hamm Canyon, Mancos Shale crops out in a number of places, thereby indicating that thick blocks have sunk into the salt cores of the anticline. The largest of these blocks occupies the center of the valley south of Hamm Canyon. This block is capped by beds of the Mesaverde Formation, and assuming that it contains the Morrison, the block probably is not less than 3,000 feet thick. The northeast and southwest sides of the block are downfaulted along the edges of the valley, and the ends are almost certainly in contact with the Paradox Member of the Hermosa Formation although the critical areas are covered. The conclusion that this isolated block has foundered in the salt core to a probable depth of 3,000 feet seems inescapable. Between this block and the Dolores River the Salt Wash Member of the Morrison crops out extensively on the valley floor. The Salt Wash is folded irregularly and is faulted along the valley sides, but on the valley floor it is cut only by small, local faults.

In Little Gypsum Valley and Silveys Pocket northwest of the Dolores River, the Gypsum Valley anticline curves northward. Most of the collapse of the crest of the anticline has been accomplished by downfolding rather than by faulting, and beds from the collapsed crest are exposed widely on the valley floor. In places these beds have been downfolded not less than 2,500 feet below the present valley rims, and probably 3,000 feet or considerably more from their precollapse positions in the crest of the anticline. Because the center of the Gypsum Valley anticline has sagged, both rims of the valley are anticlinal, and the crests of the rims coincide closely with the crests of these lateral anticlines. Thus, from the rim of the valley the beds dip in one direction toward the center of the valley and in the other direction away from the valley. The crests of the parts of these anticlines lateral to Little Gypsum Valley are cut by faults that drop the rocks toward the valley center, but northward where the anticlines are lateral to Silveys Pocket, the crestal parts are unfaulted, although the rocks, especially the more brittle sandstone beds, are highly shattered. The north ends of the lateral anticlines flatten out and merge into an extensive area of nearly horizontal beds. These beds are disrupted only by a northward-trending fault, downthrown to the west; this fault is a continuation of the fault system along the collapsed, central part of the Gypsum Valley anticline. The lateral anticline along the west side of Silveys Pocket and the north end of Little Gypsum Valley is cut by several westward-striking faults transverse to the trend of the anticline. The direction of displacement along these differs; two of the blocks between these faults are grabens and one is a horst.

The structure of the collapsed axial part of the anticline on the valley floor of Little Gypsum Valley and Silveys Pocket is highly irregular; the rocks have been broken and shattered first by uplift and later by downdroppings. A system of faults traverses the central part of Little Gypsum Valley and Silveys Pocket. In general, the rocks northeast of the fault system are downwarped farthest, especially near the valley center where the beds dip very steeply toward the faults. Rocks southwest of the fault system are irregularly folded although not so sharply as those on the other side of the system, and a number of small structural basins have formed. West of the Raven mine the faults that transversely cut the rim of the valley extend across the valley floor and join the central fault system.

DOLORES ANTICLINE

The Dolores anticline is a large asymmetrical northwest-trending fold and is the southeast extension of the Lisbon Valley anticline in Utah (fig. 1). Drilling and geophysical data indicate that both anticlines have salt cores, although these cores are nowhere exposed. The crestal part of the Lisbon Valley anticline has been downfaulted, whereas the crestal part of the Dolores anticline, unlike the other salt-core anticlines, has not collapsed. Rocks in the northeast flank of the Dolores anticline dip 5°–7° toward the Disappointment syncline; the southwest flank dips very gently, and over large areas the dip does not exceed 1°. The anticline plunges gently to the northwest. The southeast part of the Dolores anticline is bent slightly to the northeast in the general vicinity of sec. 25, T. 43 N., R. 19 W., along the same line of kinking as that for the folds previously described. The upper part of the northeast flank of the anticline is cut by a large number of faults, but the displacement on only two or three if these faults exceeds 100 feet. From sec. 34, T. 43 N., R. 18 W., to Summit Canyon in sec. 34, T. 44 N., R. 19 W., the faults trend northwest parallel to the trend of the anticline, but northwest of Summit Canyon most of the faults trend east. There is no consistent pattern to the direction of displacement along the faults—the rocks north or northeast of some of them are dropped, whereas along others the reverse is true. The faults may have formed in response either to adjustments of the underlying plastic salt core when the Lisbon Valley anticline collapsed or to tensional stresses developed during folding.

The salt core of the Dolores anticline seems not to have pierced the overlying strata but merely to have bulged them upward. South of Joe Davis Hill the Dolores River Canyon exposes rocks as old as the Cutler Formation. Although several of the formations show no thinning over the Dolores anticline, the Moenkopi Formation is entirely absent, and along the crest of the anticline both the Navajo Sandstone and the Burro Canyon Formation are thinner than normal. It is not known whether the Moenkopi is absent only along the crest of the anticline, thereby indicating Early Triassic growth of the anticline, or whether this part of the anticline is east of the area of deposition of the Moenkopi. Although the contact between the Chinle Formation and the Cutler is an erosion surface, the beds are virtually parallel, suggesting that any possible late Paleozoic or Early Triassic upwarping was mild, regardless of whether or not there is Moenkopi on the flanks of the anticline. The thinning of the Navajo and Burro Canyon Formations probably indicates some slight warping of the anticline. Inasmuch as the upper surfaces of both formations are regional unconformities, however, it is not possible to determine whether this probable warping occurred during deposition or slightly thereafter.

SYNCLINES

The synclines separating the salt-cored anticlines are broad simple folds that lack the complexities of the anticlines. The structure of the Morrison and Cretaceous formations is largely the result of Tertiary deformation, whereas the older formations in addition show the effects of salt flowage. Pre-Morrison formations thicken toward the synclinal troughs because the underlying salt was squeezed out as the sediments accumulated. The synclines, from northeast to southwest, are the Nucla, the Dry Creek Basin, and the Disappointment.

NUCLA SYNCLINE

The Nucla syncline forms a downwarp between the Uncompahgre Plateau uplift on the northeast and the Sinbad Valley and Paradox Valley anticlines on the southwest. The syncline enters the mapped area east of Uravan and trends northwesterly to Mesa Creek, where it turns north around the plunging southeast end of the Sinbad Valley anticline for a few miles before turning northwesterly again and leaving the mapped area west of Gateway. Farther to the northwest in Utah, the Sagers Wash syncline of Dane (1935, p. 129) is probably part of the same fold.

The Nucla syncline locally forms a shallow trough, closed north of Uravan because of slight reversals of plunge directions. A subsidiary downfold trends west to Roc Creek from the junction of the North and South Forks of Mesa Creek. Most of the rocks in the syncline dip less than 5°, and within 1 mile of the synclinal axis dips do not exceed 2°. On the flanks of the Sinbad Valley and Paradox Valley anticlines and the monoclinal front of the Uncompahgre Plateau uplift, however, dips are much steeper.

From Salt Creek Canyon northward, the syncline contains the rather abrupt monoclinal flexure of the Moenkopi Formation mentioned earlier; this flexure runs nearly parallel to the Dolores River and reflects a slight Middle Triassic uplift of the ancestral Uncompahgre highland. South of Cottonwood Canyon in sec. 13, T. 50 N., R. 19W., the angular discordance between the Moenkopi and the Chinle reaches a maximum of about 7°. Thus, although the regional dip of the Chinle and younger formations in this area is northeast, the Moenkopi dips southwest.

DRY CREEK BASIN SYNCLINE

The broad simple northwest-trending Dry Creek basin syncline lies between the Paradox Valley anticline on the northeast and the Gypsum Valley anticline on the southwest. As is true of the Paradox Valley anticline, southeast of a line extending from about sec. 6, T. 45 N., R. 16 W. to about sec. 33, T. 45 N., R. 17 W., the southeast end of this syncline is curved and offset to the northeast with respect to the northwest part of the syncline. The syncline plunges to the southeast; to the northwest it flattens and is scarcely perceptible northwest of the Bull Canyon area.

The structural relief of the syncline at the eastern edge of the mapped area is about 2,300 feet as measured between the trough of the syncline and the southwest rim of Paradox Valley; the structural relief on the southwest flank of the syncline is about 1,400 feet. The syncline is decidedly asymmetrical, the southwest flank being much steeper than the northeast flank. To the southeast the trough of the syncline is crowded against the southwest flank, but to the northwest the trough swings to a central position. Some slight irregularities disturb the northeast flank of the syncline near Dry Creek; these occur along the line where the southeast part of the syncline is bent to the northeast.

DISAPPOINTMENT SYNCLINE

The Disappointment syncline is a broad simple southeast-plunging downwarp that lies between the Gypsum Valley and Dolores anticlines. The northwest part of the syncline is shallow, and the strata generally dip less than 5°; in contrast, the southeast part is deep, and the strata in the flanks attain maximum dips of 20°. This part of the syncline contains the structurally lowest rocks in the mapped area. Southeast of Dugout Wash (secs. 5 and 9, T. 43 N., R. 17 W.), the axial part of the syncline is nearly level. In the vicinity of Nicholas Wash (sec. 35, T. 44 N., R. 18 W), the syncline is somewhat bent along the same line and in the same direction as are the salt anticlines. The syncline is asymmetrical, but the direction of asymmetry changes from southeast to northwest. Southeast of the bend in the trend of the syncline, the northeast flank of the syncline is the steeper, whereas northwest of the offset, the southwest flank is slightly steeper. The maximum structural relief in the Disappointment syncline, as measured on the top of the Entrada Sandstone from the crest of the Dolores anticline to the trough of the syncline, is a little more than 3,600 feet, but relief measured on the base of the Burro Canyon Formation is only about 3,300 feet. A diamond drill hole near the trough of the syncline in sec. 36, T. 44 N., R. 18 W., penetrated 1,093 feet of Morrison beds, which is about 400 feet more than the thickness of the Morrison in the nearest exposures around the rim of Disappointment Valley (D. R. Shawe, written commun., 1958). Inasmuch as the Morrison is conformable to both underlying and overlying beds, this very considerable degree of thickening indicates that the syncline was sinking during the deposition of the Morrison Formation, probably because the deeply buried Paradox beds were still being squeezed out. Southwest of Cape Horn (sec. 8, T. 44 N., R. 18 W) three small normal faults cut the flank of the syncline. These faults trend northeasterly from the bottom of the syncline almost to the rim of Gypsum Valley.

ORIGIN AND DEVELOPMENT OF SALT ANTICLINES

TECTONIC BEHAVIOR OF SALT

Salt structures form because of two independent properties of salt—its ability to flow under moderate pressure and its density deficiency as compared to most common sediments. The second factor is essential in sustaining stress differentials if a salt structure, once started, is to continue growing.

The conditions of temperature and pressure under which salt will flow have been studied in the laboratory by several investigators, including Van Tuyl (1930), Nettleton (1934, 1943), Schmidt (1939), and Stocke and Borchert (1936). Some of these experiments showed that a shear stress as low as 30 kg/cm^2 was sufficient to start plastic deformation of halite. However, as Balk (1949, p. 1820) pointed out: "As every compressive stress can be imagined to generate two equivalent shear stresses, a mass of salt should be under an excess compression of at least 60 kg/cm^2 in one direction, in order that slip along favorably oriented glide planes of its crystals may commence." The figures quoted as the shear stress under which plastic deformation may start are subject to large changes depending on various factors. There is general agreement among investigators that high temperature greatly decreases the strength of salt, that enclosed water increases the strength unless it is sufficient in amount to cause incipient solution, and that unstrained halite crystals are weaker than strained crystals. On the other hand, as temperatures rise, salt recrystallizes rapidly and the increased resistance to stress effected by strain hardening is lost. Evidence of recrystallization is strikingly shown by the fact that aggregates of salt crystals seen in thin sections taken from salt domes are unstrained even though tremendously distorted.

There is much geologic evidence, however, such as the rock salt glaciers of the Near East (Harrison, 1931) and some of the collapse features of the salt anticlines described in this report, that indicates the strength of salt to be much lower than the values cited above. These geologic features formed under conditions where salt was not confined and where water was sufficiently abundant to permit solution, conditions far different from those existing in salt beds at the time most salt structures start forming.

Another factor that may influence the flowage of salt is the presence of beds of other materials; in the Paradox Member the most abundant of these are beds of gypsum. The highly contorted nature of these beds, however, suggests that they neither lent any appreciable strength to the member nor impeded significantly the flowage of salt. In all probability the gypsum was merely carried along passively as a deadhead passenger as were the lesser quantities of anhydrite, shale, sandstone, and limestone.

Parker and McDowell (1955, p. 2391–2392), on the basis of Balk's remarks (1949), stated that a pressure differential equal to 1,000 feet of beds is necessary to start flowage of salt; Stille (1925) believed that a salt bed must be buried to a depth of 2,000 meters before it can begin to flow. Nettleton (1943) stated that experimental evidence and calculations indicated that the ability of rocks to withstand differential stresses decreases greatly as confining pressures rise. The pressure at the base of a layer of rock 2,000 meters thick is much greater than that necessary to cause salt to flow if free to do so, but it seems reasonable to expect that this excess may be necessary to cause flowage where pressure differentials in a mass of confined salt are small. Were this not true it would be difficult indeed to see how many of the world's salt structures could have started forming, for pressure differentials equal to 1000 feet of beds (roughly 60 kg/cm^2) could not have existed during early stages of their development.

In addition to experimental and geologic evidence concerning conditions under which salt will flow, some evidence has accumulated concerning the effects that depth of burial and the thickness of a salt layer may have on the type of salt structure that may eventually form. Parker and McDowell (1955, p. 2425–2426), for example, believed as a result of their experimental work that not only may the thickness of a salt layer be critical in the development of salt domes, but that it may have a direct bearing on the size of domes; Stille (1925) believed as a result of his study of the salt structures in Germany that the thickness of overlying beds controlled, in large measure, the type of salt plug that would form. Under thin cover, salt beds behave like any normal layer of sediment and do not flow; under very thick cover the tendency is for the gulf coast type of salt dome or salt stock to form; under intermediate thicknesses of cover, salt anticlines similar in general characteristics to those of the Colorado Plateau form, although, as explained below, those of the plateau formed in response to deep-seated tectonic disturbances rather than mere loading.

BEGINNING AND GROWTH OF SALT ANTICLINES

Most of the world's salt anticlines appear to have formed only after deep burial of salt beds by later sediments, and until 1958 there was little reason to believe that those of the Colorado Plateau formed differently, although it was recognized that probably they were controlled by deep-seated structures. In 1958, however, Elston and Landis (1960) demonstrated, as a result of detailed mapping in East Paradox Valley, that the underlying salt core started forming no later than the beginning of Rico and Cutler time and hence before deep burial. They found that locally Rico and Cutler beds rest unconformably on the Paradox Member and limestone member of the Hermosa Formation. Some evidence also suggested that the Paradox and the limestone member may be unconformable, but the evidence is not conclusive.

From theoretical considerations discussed above, it seems improbable that the conditions required for salt flowage could have existed before or during early Rico and Cutler time; the approximately 2,000 feet of post-Paradox beds would not have been thick enough to develop the pressure differentials necessary for salt flowage. Therefore, deformation of the Hermosa Formation prior to Rico time probably resulted not because beds of the Paradox Member were intruded above their normal stratigraphic positions, but because of tectonic activity. The beveled folds in the Hermosa beneath the Rico and Cutler beds were probably near-surface manifestations of faults in pre-Paradox rocks. This conclusion finds some additional confirmation from geophysical data and from scattered drill holes which indicate that displacements of pre-Paradox rocks exist where no corresponding displacements of post-Paradox rocks occur.

With the destruction of the confining seal of Hermosa limestone by erosion along lines of tectonic dislocations, the salt was free to escape when Rico and Cutler sediments began flooding the region. Consequently, the salt started rising along the lines of dislocations to form salt cores as it was squeezed from beneath the intervening covered areas. Contrariwise, these intervening areas, in the meantime, were sinking and trapping most of the Cutler sediments precisely because the underlying salt was escaping into the growing cores. For a time the deposition was so rapid that parts of the growing salt cores were buried, but the cores continued to grow, and they intruded the covering of Cutler beds in Cutler time. Only the salt in the core of the Dolores anticline, the most southwesterly of the salt anticlines, seems not to have intruded above its normal stratigraphic position but merely formed a roll of thickened salt. From the end of Cutler time until the beginning of Morrison time late in the Jurassic, the elongate salt intrusive bodies probably stood as topographic highs at one place or another along their lengths. The upwelling of salt balanced or slightly exceeded the accumulation of sediments in the surrounding areas. In a sense, the upper surface of the salt plugs maintained a nearly constant altitude while gradual settling of the surrounding country was intermittently balanced by sedimentation. Salt flowage did not proceed everywhere at a uniform rate. Local surges and comparatively rapid intrusion in many places were countered by relative quiescence at other places. Surges of rapid intrusion may have helped to form the cupolas along the salt cores.

The cupolas commonly acted somewhat as structurally independent units so that of two adjoining cupolas, one might be quiescent while the other was actively upwelling. The rapidity of some of these surges can be gaged from the fact that along the northeast side of Sinbad Valley, uplift was so rapid that unconsolidated beds of the Moenkopi Formation slumped and slid down the slope developed by the upthrust of the salt.

Extrusion of salt continued in most places until salt in the areas adjacent to the salt intrusions was exhausted. If it is assumed that the cores of Paradox Valley and Gypsum Valley anticlines contain salt derived from the adjacent synclines and that virtually all the salt originally in the synclines had been squeezed out, then it would require a tabular mass tapering from a thickness of about 4,000 feet beneath and adjacent to Paradox Valley to a thickness of about 3,000 feet beneath and adjacent to Gypsum Valley merely to supply the salt presently in the two cores. With the exception, possibly, of the northeast flank of the Sinbad Valley salt core and of part of the southwest flank of the Gypsum Valley salt core, it is very unlikely that the salt beds were pinched off until virtually all the salt in the areas between cores had flowed out, for had this occurred, some evidence—such as downfolds or abrupt thickening of beds marginal to the cores such as exists along the northeast flank of the Sinbad Valley anticline—should have been preserved. Salt may have been trapped in the deep part of the Disappointment syncline as post-Paradox beds came to rest against the structurally high pre-Paradox rocks that, according to drilling and geophysical data, probably existed beneath the southwest flank of the Gypsum Valley anticline. Escape of this salt in Tertiary time may account for the unusual depth of the Disappointment syncline. Low gypsum hills in the southeast end of Gypsum Valley indicative of rising salt suggest that this process may still be active. Elsewhere, salt was exhausted in the interanticlinal areas in Late Jurassic time, and active intrusion ceased except for minor readjustments of salt within the cores.

LATER HISTORY AND COLLAPSE OF SALT ANTICLINES

Following deposition of the Mesaverde Formation, anticlines formed along the old salt structures. Although the salt cores undoubtedly exercised some influence on the shape of the folds, they formed not in response to movement of salt but to deep-seated deformation that apparently was controlled in large measure by the Paleozoic basement structures above which the salt rolls and plugs originally had developed. Probably the broad anticline from the crest of which the Uncompahgre Plateau uplift was to rise in late Pliocene and Pleistocene time formed at the same time. If this is true, then folding probably occurred near the end of Cretaceous time, as indicated by the work of R. G. Dickinson (U.S. Geological Survey, 1965, p. A88; Dickinson, oral commun., 1965). He found that thousands of feet of Cretaceous sediments had been eroded from the southeast extension of this anticline in the northern part of the San Juan Mountains before an unnamed Upper Cretaceous unit of volcanic rocks on Cimarron Ridge southeast of Montrose, Colo., was laid down. Furthermore, northeast of the report area, J. R. Donnell (oral commun., 1966) found that the great homocline that separates the Piceance basin from the structurally much higher region to the southwest started forming no later than earliest Tertiary time. This homocline and the northeast flank of the Uncompahgre anticline are one and the same.

Collapse of the crests of the salt anticlines occurred in two stages apparently widely separated in time. The first stage followed perhaps rather closely the Late Cretaceous folding. The second stage followed epeirogenic uplift of the entire Colorado Plateau in the middle and late Tertiary, and this stage is still continuing.

During the earlier stage of collapse, the crests of the anticlines in places were dropped, as grabens, as much as several hundred feet. These grabens may have formed during relaxation of stresses that caused folding. Although the structural details of these early collapse features are rather thoroughly masked by the later collapse, it seems probable that the structures resulting from the early collapse were fairly simple. It appears that at no time during this initial stage of collapse were the salt-gypsum cores of the anticlines exposed; in fact, by the end of Mesaverde time, the upper surfaces of the salt-gypsum cores were buried under nearly 5,000 feet of sediments. With the end of graben faulting the salt anticlines probably were structurally inactive for a long time.

The second period of collapse began after uplift of the Colorado Plateau. This uplift rejuvenated the streams and increased ground-water circulation. Deep canyons eventually breached the crests of the anticlines and exposed the underlying salt to rapid solution and removal. With the abstraction of salt; renewed collapse of the anticlinal crests began. Collapse of the crests of the Gypsum Valley and Paradox Valley anticlines probably started at the points where the Dolores River, which antedates both valleys, cut across the crests. Sinbad Valley is not transected by a throughgoing stream, and it seems likely that the crest of the underlying anticline was not breached, and did not collapse as soon as those in the Gypsum and Paradox Valleys. Collapse of the anticlinal crests probably progressed in both directions away from the points where the salt cores of the anticlines were first exposed. Streams working headward along the crests removed both the material in the cores and the overlying beds.

In Gypsum Valley a number of sinkholes underlain by gypsum indicate that much of the collapse was due directly to removal of salt by solution; nevertheless, it seems unlikely that all the collapse can be attributed to this process, as was believed by earlier workers in the area. Rather, much of the collapse apparently was caused by flowage of salt from parts of the anticlines still overlain by thick layers of sediments to parts from which the overlying sediments had been removed. Such flowage probably became operative as soon as erosion had breached the anticlines and thereby removed the confining seal of sediments that restricted the free movement of salt. The basinlike downwarp at the southeast end of the Paradox Valley anticline appears to be almost if not entirely due to this process of salt removal by flowage. Elsewhere much of the faulting along the flanks of the anticlines appears to be due to this same process. The relatively plastic salt offered little support for the beds in the flanks of the anticlines; consequently these largely unsupported beds slumped, probably along fractures and joints formed during earlier flexuring. The probability that much collapse is the result of removal of salt by flowage rather than by solution is supported by data obtained from various boreholes in Paradox Valley and similar valleys in the region. Rock salt commonly is found in these boreholes at depths of 1,000 feet or less, indicating that solution and removal of salt by circulating ground waters has been ineffective below this depth. Rocks in areas of collapse, however, have sunk to far greater depths; for example, in Big Gypsum Valley, south of the mouth of Hamm Canyon, the block of rocks capped by the Mesaverde Formation foundered in the salt core to a depth of probably 3,000 feet, and beds not less than 1,500 feet thick at the southeast end of Paradox Valley anticline have downsagged in the salt core so that the surface at the center of this downwarp is about 200 feet lower than outcroppings of the Paradox Member northwest of the downsag. The differences in elevation may be due to partial isostatic balance between the salt-and-gypsum core and heavier downsagged rocks suspended in the core.

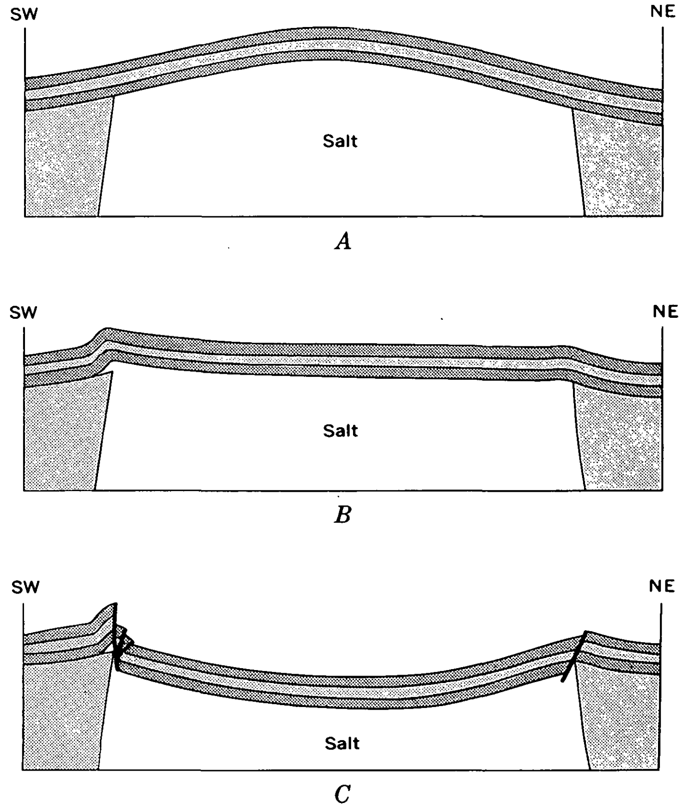


FIGURE 19.—Successive stages in the development of the downsag and the faulted marginal anticline at the southeast end of Paradox Valley.

The type of collapse dominant in any part of a salt anticline seems to be governed in part by the radius of arching of the anticline. This relation between degree of arching and type of collapse structure probably is shown best in Paradox Valley; downsag occurred where originally the anticline was gently arched and faulting without downsagging where the anticline was most strongly arched. Thus, the highly faulted central structural unit of the Paradox Valley anticline was strongly arched, as deduced from the dip of the beds in the downdropped blocks and in the flanks of the anticline, prior to collapse, whereas the downsagged unit at the southeast end of the anticline was only gently arched. When support was removed from beneath the arched rocks—that is, when the incompetent salt was no longer confined and hence was free to move under differential pressures—the upwarped rocks settled under their own weight and had a tendency to push aside the rocks in the flanks of the anticline. Where the arching was pronounced, this tendency was small, and the arch failed by fracture and downfaulting rather than by gradually flattening and thrusting apart the buttressing rocks in the flanks of the anticline. Where the arching was gentle, however, the arch tended to fail because the buttresses were pushed aside. These relationships suggest a possible mode of origin for the peculiar sharp upturning of beds along the fault in the crest of the Dry Creek anticline (fig. 19).

As the beds in the crest of the Paradox Valley anticline where crossed by Dry Creek subsided and flattened, the underlying salt was squeezed out to the northwest, and the buttressing rocks in the flanks of the anticline were forced apart and flexed sharply upward (stage B, fig. 19). Later, as sagging continued and more salt was forced from beneath the Paradox Valley anticline, dips in the crestal rocks reversed, and the block subsided along marginal faults. The stage was eventually reached where the sharply upturned beds southwest of the marginal fault attained the appearance of drag folds in reverse.

OTHER STRUCTURAL FEATURES

UNCOMPAHGRE UPLIFT

The Uncompahgre uplift is a great northwest-trending asymmetric upwarp about 30 miles wide and 100 miles long that rises from the crestal part of an older even larger broad, open anticline (Cater, 1966) To the southeast its identity as a structural unit is largely lost in the complex volcanic structures of the San Juan Mountains, and to the northwest in Utah it plunges and disappears into the Uinta Basin. The axis of the uplift and the summit of the Uncompahgre Plateau coincide either along or near the plateau's southwest rim. The southwestern flank of the uplift and part of the northeast flank in the vicinity of Grand Junction (Lohman, 1965) are sharp locally faulted monoclines, but elsewhere the northeast flank dips gently and uniformly. The monocline marking the southwest flank enters the mapped area in the upper reaches of Atkinson Creek and leaves the northern edge of the area 4 or 5 miles northeast of Gateway. Where the monocline crosses the North Fork of Mesa Creek, it swings north for about 4 miles before resuming its general northwesterly trend. The total structural relief of the uplift in the mapped area as measured on the top of the Entrada Sandstone from the trough of the Nucla syncline is more than 4,000 feet.

The southwest-flanking monocline of the Uncompahgre uplift is cut locally by faults throughout much of its lentgh, and probably it passes into a fault at depth everywhere. The faults are most conspicuous, however, in the northern part of the area where they bound the Ute Creek graben which downdrops a part of the monocline. Most of the visible faults are normal, but where the strata in the monocline are vertical or nearly so, faults underlying the vertical beds must have a reverse throw, for it is difficult to see otherwise how the overlying beds could be vertical. Beds warped into a monocline above even a vertical normal fault probably would not be draped into perfect parallelism with the fault plane and therefore would not have vertical dips, and beds draped over normal faults of less than vertical dips would have correspondingly lower dips. The normal faults in the folded strata probably result from local tension inherent in the development of any fold.

The Uncompahgre uplift is one of the youngest large structural features in the region (Cater, 1966), but it had a predecessor in the ancestral Uncompahgre uplift, a far larger structure that dominated the late Paleozoic and early Mesozoic landscape. The faulted monocline fronting the southwest edge of the modern uplift parallels and is only a short distance northeast of the edge of the ancestral uplift, but the ancestral uplift extended much farther east. A large fault probably bordered the southwest edge of the old uplift, for the front, as indicated by the abrupt wedge out of the thick Cutler Formation, was remarkably steep. The 7,800 feet of Cutler beds drilled northwest of Gateway (see p. 11) rest on granite rather than on older Paleozoic strata. This fact indicates that the block penetrated by the drill was upthrown, not downthrown. Otherwise the older Paleozoic strata could not have been stripped off, for the downthrown or basin block was receiving sediments rather than undergoing erosion. Therefore, barring the possibility of extensive faulting between the site of the drill hole and where the Cutler wedges out against granite 4 miles to the northeast, the indications are that the old uplift still towered more than 8,000 feet above the adjoining Paradox basin and perhaps a good deal more by the time the onlapping sediments encroaching on the lower slopes of the upthrown block reached the site of the drill hole. The drilled block, perhaps, may have been a sliver elevated only high enough for the Paleozoic beds to have been eroded, and the main block may have continued to rise only a little faster than erosion was cutting it down so that the uplift was never greatly higher than the surrounding country. This possibility, however, seems unlikely, for at least during later Cutler time, no movement occurred along the dislocation wherever it may have been. The visible Cutler beds are more than 1,000 feet thick and are neither cut by old faults nor appreciably warped between the Cutler pinchout and the salt anticlines to the southwest. Furthermore, the rate of thickening of the Cutler overlying visible Precambrian rocks, if projected from the edge of the formation to the drillhole near Gateway, indicates the thickness of beds cut in that drillhole is not excessive.

The location of the edge of the ancient highland is not known precisely but can be placed within a zone having a width not greater than 5 miles. The front of the ancient highland obviously lay southwest of the present front because the Cutler Formation here wedges out abruptly against Precambrian rocks which were exposed at the beginning of Cutler time and must have been within the borders of the ancient highland. The southwest front of the old highland probably was northeast of where the Salt Creek graben dies out in unsurveyed sec. 26, T. 50 N., R. 19 W., because the graben presumably is a shallow structure bottoming in the salt and gypsum of the Paradox Member of the Hermosa Formation, which was deposited in the Paradox Basin southwest of the old highland. At this same locality on the Salt Creek graben, a monoclinal flexure in the Moenkopi but not in the Chinle indicates a slight Middle Triassic uplift, further indicating the location of the southwest border of the old highland. Small faults in secs. 11 and 14, T. 50 N., R. 18 W., on Calamity Creek, and in sec. 30, T. 50 N., R. 17 W., on Blue Creek, may possibly represent upward extensions of ancient faults bordering the old highland, developed in response to some slight Tertiary movement.

UTE CREEK GRABEN

In the northern part of the mapped area, the southwest flank of the Uncompahgre uplift is cut by two roughly parallel northwest-trending faults. The block between these faults has dropped to form a graben 1–2½ miles wide that enters the mapped area near Unaweep Canyon and extends southeastward to the vicinity of Cow Creek, where the northeastern fault turns southward and dies out and the graben ends. The southwest fault, however, continues southeastward and leaves the mapped area near Pine Hill in sec. 10, T. 50 N., R. 17 W. Displacement on the southwest fault increases from about 100 feet at the north edge of the mapped area to about 850 feet near Pine Mountain; it then decreases southeastward to about 300 feet at the east edge of the mapped area. Displacement on the northeast fault is about 600 feet at the north edge of the mapped area, increases to about 1,300 feet near Ute Creek in sec. 33, T. 15 S., R. 10 W., and then decreases southeastward and dies out near Cow Creek.

Structure within the graben is not uniform. Sedimentary rocks in the northwest part of the graben, north of the east-trending fault east of Pine Mountain, are gently warped and tilted southward; whereas in the southeast part of the graben south of the east-trending fault, the rocks are cut by many faults, most of which trend northwest at a small angle to the main southwest graben-border fault, from which they may branch. The relatively complex structure of this part of the graben probably is related to the abrupt change in trend of the Uncompahgre front at this general latitude. The faulted monoclinal front trends almost due north to this latitude and then in the area between Indian and Ute Creek it turns northwest.

The graben is youthful and, in fact, may still be dropping. The stratigraphic displacement nearly equals topographic displacement, and the graben is little eroded. Consequently, it is believed to have formed during late stages of uplift of the Uncompahgre Plateau, which has been elevated perhaps 1,800 feet since the Gunnison River abandoned Unaweep Canyon; most of this uplift was concentrated along the faulted monocline.

STRUCTURAL HISTORY

The earliest record of the geologic structural development of the area is preserved in the Precambrian rocks of the Uncompahgre Plateau where highly folded and contorted metamorphic rocks have been repeatedly subjected to igneous intrusions. The visible Precambrian structures, however, seem to have exerted little control on later structures; furthermore, the extent of the Precambrian rocks in the mapped area is too small to permit unraveling of any large structural patterns.

The record of structural events causing significant deformation of sedimentary rocks in the area dates from Middle Pennsylvanian time when the region was gently warped and faulted. These dislocations gave rise to the Paradox Basin in which the Paradox Member of the Hermosa Formation was deposited; to the ancestral Uncompahgre highland, an element of the ancestral Rocky Mountains; and to the structural features ultimately responsible for location of the salt anticlines. Uplift of the highland inundated the Paradox Basin under a flood of Cutler arkosic debris. Uplift was probably greatest in the Gateway area and was sufficient to expose Precambrian rocks to erosion earlier in this area than elsewhere along the front of the old highland. This conclusion rests on the great known thickness of the Cutler Formation in the Gateway area, the more domelike shape of the Sinbad Valley salt core which suggests origin at greater depth, and the fact that only in Sinbad Valley has arkosic debris been found in beds as old as the Paradox Member of the Hermosa Formation. After the highland attained its maximum height and while the Cutler was being deposited, the highland began sinking—at least along its southwest flank. This part of the highland and the adjacent part of the Paradox Basin subsided as a unit, and by the beginning of Moenkopi time the lowermost Cutler beds resting on the flanks of the highland were not less than 8,000 feet below sea level. Possibly, during this subsidence, the structural crest of the old highland migrated eastward.

Concurrent with rapid rising of the ancestral Uncompahrge highland in early Cutler time, the basement faults that controlled the salt anticlines were rejuvenated, thereby setting the stage for the further development of the anticlines as shown in figure 13.

The tectonic activity that marked the end of the Paleozoic was followed by slow subsidence through most of the Mesozoic Era, although it was interrupted at the ends of Moenkopi, Glen Canyon, and Burro Canyon times by brief regional uplifts. Uplift at the end of Moenkopi time was accompanied by some gentle warping along the front of the old Uncompahgre highland, but aside from this, warping seems to have been restricted entirely to that caused by slow movement of salt from the synclines into the salt cores.

The second major deformation of the sedimentary rocks of the area probably occurred near the end of Cretaceous time. A series of broad folds, guided and localized by the preexisting salt-cored anticlines, were formed. Although salt flowage was renewed, it consisted—with the notable exception, perhaps, of addition of salt from Disappointment syncline into the Gypsum Valley salt anticline (see p. 65)—largely of readjustments of salt already in the cores.

Epeirogenic uplift of the Colorado Plateau probably began in the Miocene (Hunt, 1956, p. 77). With uplift, the streams started downcutting rapidly and eventually breached the cores of the salt anticline, whereupon final collapse of anticlines began partly through removal of the by solution and partly by flowage of salt from beneath areas still overlain by heavy burdens of strata. The last episode in the structural history of the area, the rise of the Uncompahgre uplift and downdropping of the Ute Creek graben, probably began in Pliocene time and may still be continuing.

GEOMORPHOLOGY

The geomorphic history of the area as disclosed by its topographic forms is largely a record of late Tertiary events, although, insofar as these forms are controlled by the structure of the underlying rocks, the evolution of the present topography depends upon the geologic history of the area. It is rather generally conceded that epeirogenic uplift of the Colorado Plateau began during the Miocene (Hunt, 1956, p. 77), and, inasmuch as the evolution of the present topography dates largely from the beginning of this uplift, it seems justifiable to begin a discussion of the geomorphic history with a description of probable conditions in the Miocene immediately preceding uplift.

MIOCENE SURFACE

Prior to epeirogenic uplift of the Colorado Plateau, longconitnued erosion had reduced most of the area to a surface of low relief; uplands had been planed off and basins filled, both in the area of this report and elsewhere. Probably rising above this surface, however, were the domed La Sal, Abajo, and other laccolithic mountain masses. Across the area meandered slow-moving streams, including the ancestral Dolores River, and probably ancestral La Sal Creek, Coyote Wash, and Dry Creek. The Dolores River and probably other streams whose courses are not now preserved headed to the east in the San Juan Mountains where large thicknesses of volcanic rocks were piling up. To the west small streams probably headed in the Abajo and La Sal Mountains (fig. 1). It seems likely that over most of the area rocks no older than the Mancos Shale were exposed, and it is even possible that much of the area was underlain by lower Tertiary deposits which have been long since completely stripped away. The anticlinal ridges that had formed along the old intrusive salt cores in Late Cretaceous time had been planed off, thereby exposing rocks in their crests that may have been as old as the Morrison Formation but more likely were no older than Cretaceous. Early graben faulting of the anticlinal crests had occurred, but the anticlines had not yet collapsed. The Uncompahgre Plateau had not started to rise, although there is not much doubt that the Gunnison River was flowing in the position now occupied by Unaweep Canyon.

EFFECTS OF UPLIFT

The onset of epeirogenic uplift signaled a radical change in the regimen of the streams draining the area. The streams began downcutting, and the rate of erosion in general was greatly accelerated. As uplift progressed, some streams adjusted their courses to the structure of the underlying rocks, whereas others maintained their ancient channels. In the meantime, softer formations were being stripped back rapidly, and broad benches were carved on the upper surfaces of the more resistant beds in a manner similar to that occurring at the present time, although, of course, at much higher stratigraphic levels. Eventually all lower Tertiary beds, which presumably covered all the area except, perhaps, for the salt anticlines, were completely removed.

DEVELOPMENT OF DRAINAGE

The record of the development of the present drainage system is not complete; nevertheless enough of the record still remains in the form of drainage pattern, stream deposits, and terraces so that the broad outline of the development can be traced with reasonable assurance. Some of the streams, including the master stream of the area—the Dolores River—are superposed throughout most of their courses and show little or no relation to the structure of the underlying rocks, whereas other streams, such as the San Miguel River and East Paradox Creek, show varying degrees of adjustment to the structure. One of the most remarkable canyons in the area, Unaweep Canyon, may be antecedent rather than superposed.

The Dolores River traverses the area from south to north in a deep canyon that is uninterrupted only where the river crosses Gypsum and Paradox Valleys. Throughout most of its length within and northwest of the mapped area, the canyon is markedly sinuous, and with little doubt the sinuousities are entrenched meanders inherited from the stream that flowed on the flat Miocene surface. Hunt (1956, p. 82) thought that doming of the La Sal Mountains may have shifted the course of the Dolores River eastward during the Miocene before epeirogenic uplift of the plateau began. Sufficient time elapsed, however, if such a shift was made, for the river to establish or reestablish a meandering course. That part of the Dolores River from north of the mouth of Blue Creek to the Utah State line is rather straight, but from the State line to its confluence with the Colorado River, the canyon again consists of a series of entrenched meanders, although these are less pronounced than those south of the mouth of Blue Creek. From the mouth of Blue Creek northwestward to the Colorado River, the Dolores River follows the trough of the Nucla and Sagers Wash synclines rather closely, suggesting a certain degree of adjustment to the structure. On the other hand, the entrenched meanders in the lower part of the Dolores River's course suggest that such adjustment to the structure occurred before epeirogenic uplift began. Thus a sufficient length of time had elapsed after adjustment of the stream to the syncline for the development of a wide valley across which the stream was beginning to meander. With the start of uplift, the river began downcutting so rapidly that throughout most of its course it had no chance to straighten its channel, and thus the ancient meanders have been preserved. Terraces at various levels in the canyon record periods during which lateral cutting locally predominated over downcutting. Some of these terraces are several hundred feet above the present streambed.

Aside from the Dolores River, only three other streams in the area definitely seem to flow in their ancient preuplift courses; these are La Sal Creek, Coyote Wash, and Dry Creek. Although the evidence is less impressive and convincing, McIntyre, Summit, and Bush Canyons may also be superposed inasmuch as sizable sections of their canyons appear to be entrenched meanders. Both La Sal Creek and Coyote Wash flow in deeply entrenched meanders. The meanders of La Sal Creek are notably small, indicating that the preuplift stream that made them was small. None of these three streams is adjusted to the structure; La Sal Creek flows more or less parallel to the regional strike of the rocks, but it follows the flank of a fold rather than the axis. Coyote Wash cuts across the plunging north end of the Gypsum Valley anticline, and Dry Creek cuts across the southeast end of the Paradox Valley anticline. Dry Creek, unlike the Dolores River, La Sal Creek, and Coyote Wash, does not flow through a series of entrenched meanders, yet there can be little doubt that it is superposed. Possibly, before uplift started, the stream did not meander as did those farther west; on the other hand, the stream may have had an opportunity to straighten its course or destroy any meanders that did exist before they became deeply incised and permanent. Possibly during downsagging of the southeast end of the Paradox Valley anticline that part of the stream within the downsag was ponded temporarily.

Many more streams are adjusted to the structure than are superposed. Most prominent of these are the San Miguel and Disappointment Creek (except its last few miles) which flow down synclines and East and West Paradox Creeks and Gypsum and Little Gypsum Creeks which occupy the collapsed crests of anticlines. The courses of the San Miguel River and Disappointment Creek probably resulted from the gradual slip-off of the streams downdip on more resistant layers. For many miles east of the mapped area, Disappointment Creek flows along or near the southwest side of Disappointment Valley, about 1½ miles southwest of and 400 feet above the structural bottom of Disappointment syncline. This side of Disappointment Valley is practically a dip slope on the Dakota Sandstone and the Burro Canyon Formation. Further evidence that Disappointment Creek has migrated downdip on the southwest flank of the syncline is found in the numerous remnants of sheets of stream gravel on the dip slope southwest of the creek and the absence of such gravels northeast of the creek. The remnants of gravel extend more than 1½ miles from the present channel of Disappointment Creek and 250 feet above it. These relations strongly suggest that Disappointment Creek is in the process of migrating downdip on the resistant Cretaceous sandstone, although the process is relatively inactive at present because the base level formed by the Dolores River is being lowered very slowly. In time the streams draining Dry Creek Basin will very likely become better adjusted to the structure, and the streams near the trough of the syncline will grow at the expense of those farther from the trough.

As large areas of dip slope were formed on resistant layers, many tributaries developed directly down or nearly down these slopes. Red and Hieroglyphic Canyons draining the northeast flank of the Paradox Valley anticline, many of the streams draining the southwest flank of the Uncompahgre Plateau, and streams draining the northeast flank of the Dolores anticline—especially in the neighborhood of Joe Davis Hill—are examples of such streams. Gravel containing pebbles of Precambrian rocks on the two low hills on the mesa top south of Hog Park Wash (sec. 17 and 18, T. 48 N., R. 16 W.) probably is not a stream gravel such as that of Disappointment Creek but a remnant of broad alluvial fans that accumulated along the front of the Uncompahgre Plateau during some stillstand of erosion.

Probably the streams most perfectly adjusted to structure are those draining Paradox and Gypsum Valleys. The development of these streams was very largely dependent on the collapse of the anticlines that underlie the valleys, and consequently will be discussed in connection with the topographic development of the salt anticline valleys.

Two other streams obviously related to structure are Salt Wash, which drains Sinbad Valley through a graben, and Ute Creek, which drains part of Ute Creek graben. The origin of Salt Wash is not certain; it may have been a dip-slope stream occupying virtually its present course prior to downfaulting of the graben, or it may have formed only as a consequence of graben faulting. Ute Creek may have existed before the Ute Creek graben was formed; nevertheless, it is clear that the upper part of the stream formed after graben faulting, during headward erosion which has greatly lengthened the stream and increased its drainage basin. Furthermore, Ute Creek appears to have captured two sizable drainages that, before the graben dropped, may have been the headwaters of Maverick Canyon; in time, the upper reaches of both Calamity and Cow Creeks will also become victims of piracy by Ute Creek.

Aside from the probability that they await decapitation, Calamity and Cow Creeks, along with Indian Creek, are of geomorphic interest because of their antecedent relations to Ute Creek graben. As the graben was lowered, the southwest rim became a barrier through which these streams cut as rapidly as the graben sank. Very likely these creeks were prevented from deserting their channels when the graben formed because any given displacement along the faults was less than the depth of the little canyons that contained the streams.

One of the most extraordinary physiographic features in western Colorado is Unaweep Canyon, which cuts completely across the Uncompahgre Plateau from northeast to southwest, but only the westernmost part of the canyon lies within the mapped area. The size of the canyon through much of its length, nearly 1 mile wide and 3,000 feet deep, is out of all proportion to the size of the two puny streams presently draining it; furthermore, no readily perceptible divide separates West Creek, which drains the western end of the canyon, from East Creek, which drains the eastern end—they both head in the flat bottom of the canyon. All field evidence points to the probability that the canyon was formerly occupied by a far larger stream. Peale (1877, p. 64–69) believed Unaweep Canyon to be the former channel of the Gunnison River, but later authors (Stokes, 1948; Shoemaker, 1954; Cater, 1955a; Lohman, 1961, 1965) believed that the canyon more likely was the channel of the Colorado River. The old river gravels recently uncovered in roadcuts along State Highway 141, northeast of Gateway, and other evidence indicate, however, that Peale was right in believing the canyon was carved by the Gunnison River. The history of Unaweep Canyon and uplift of the Uncompahgre have been covered in a recent paper (Cater, 1966).

There are, of course, many streams whose positions appear to be neither adjusted to structure nor inherited from earlier erosion cycles. Most of the smaller streams and some of the larger ones, including Bull Canyon, fall in this category. The relation of Roc Creek to Sinbad and Paradox Valleys is one of considerable geomorphic interest. Either valley would seem to offer a far more likely passage for Roc Creek than the canyon which it occupies. This canyon is carved into a narrow ridge or mesa separating the two valleys. The probable reason for this seemingly anomalous drainage pattern lies in the likelihood that Roc Creek is older than either valley and has been unable as yet to establish a new channel in either valley, although in time it may do so. Although Roc Creek may be older than either Sinbad or Paradox Valleys, it is doubtful that it is as old as the superposed streams, inasmuch as its channel is straight and rather near the trough of the shallow syncline between the two valleys. Probably the channel formed after epeirogenic uplift had started and after Roc Creek had adjusted itself to the structure with some success.

TOPOGRAPHIC DEVELOPMENT OF THE SALT ANTICLINAL VALLEYS

The salt anticlinal valleys owe their origin primarily to the collapse of the crests of the underlying anticlines, although the shapes of the valleys are largely the result of erosion subsequent to collapse.

In response to the epeirogenic uplift of the Colorado Plateau, the Dolores River cut down rapidly and eventually reached the salt cores of both the Gypsum Valley and Paradox Valley anticlines. The upper surfaces of both these salt cores then probably stood at least 3,000 feet higher than the present valley floors. Slumping of the anticlinal crests progressed rapidly once the salt cores were exposed and valleys were eroded in them. The salt core underlying Sinbad Valley probably was exposed later than the cores of either the Paradox Valley or the Gypsum Valley anticlines, for the present landforms on the floor of Sinbad Valley are considerably more youthful than those of either Paradox or Gypsum Valleys. Collapse of the crests of both the Paradox Valley and Gypsum Valley anticlines progressed rapidly following exposure of their salt cores; probably no appreciable thickness of beds had been removed from the general region, however, between the time the Dolores River cut through the Morrison Formation and reached the salt core, and the time of most of the collapse. At any rate, the Mancos Shale had not been stripped from the southeast end of the Paradox Valley anticline by the time the crest of the anticline downsagged.

Although the crest of the Paradox Valley anticline probably slumped progressively both northwestward and southeastward away from the Dolores River, it seems improbable that collapse of the crest of the Gypsum Valley anticline followed the same systematic pattern. This conclusion is based on the drainage history of Gypsum Valley as deduced from the distribution of the Pliocene(?) gravels in the southeast end of Gypsum Valley. The distribution of the gravels indicates that the drainage pattern of the area has changed radically since the major part of collapse was accomplished. The igneous rocks from which the gravels were derived lay to the east on the west flank of the San

Juan Mountains. No stream presently draining any area of igneous rocks flows through Gypsum Valley, except the Dolores River, which has not changed its course since the beginning of epeirogenic uplift of the Colorado Plateau. The gravels in Gypsum Valley indicate that the stream that deposited them left the valley through Gypsum Gap and drained into the Dolores River at some point south of Gypsum Valley. Such a drainage pattern suggests that part of the Gypsum Valley anticline between Gypsum Gap and the Dolores River either had not collapsed or had not been sufficiently eroded following collapse to permit drainage down the length of the valley directly into the Dolores River.

Erosion and continued minor slumping continued to enlarge the salt-anticlinal valleys. Most of the streams draining the flanks of the anticlines undoubtedly became established after erosion of the nearly featureless preuplift topography and the development of extensive dip slopes on the more resistant beds. Red Canyon, which heads about 3 miles northwest of where the Dolores River leaves Paradox Valley, rather obviously has been beheaded because the upper part of its drainage area has slumped into Paradox Valley—that is, at one time the canyon headed nearer the crest of the anticline than at present. Grabens, such as the one on Davis Mesa along the southwest rim of Paradox Valley, attest to slumping even later than beheading of Red Canyon. While Paradox Valley was being formed, large masses of rock from the crest of the Gypsum Valley anticline that had not been eroded were slowly foundering in the salt core.

After the valleys had attained approximately their present form, a stillstand allowed accumulation on the valley floors of coarse detritus derived largely from the valley walls. This detritus was calichified and forms the hard, resistant fanglomerate in Paradox, Sinbad, and Gypsum Valleys. The partly indurated, flat-bedded silt and sand overlying the fanglomerate in the northwest part of Paradox Valley indicate that local ponding followed deposition of the fanglomerate. Faulting of the fanglomerate and gentle warping of the pond deposits show that minor readjustments of the salt core were continuing. Deposition of the pond material was followed by erosion before deposition of the unconsolidated material that now covers wide areas on the floors of all the valleys.

MINOR FEATURES

Landslides have altered the topography considerably in some places, particularly in the neighborhood of the salt anticline valleys. Landsliding probably began soon after the crests of the anticlines collapsed and thereby produced steep gradients. The bentonitic shales of the Brushy Basin Member of the Morrison Formation, or rocks resting immediately on them, are especially susceptible to sliding when wet. The surfaces of the landslides are highly irregular and commonly are covered by large blocks of sandstone and conglomerate from the Brushy Basin Member or overlying formations.

One natural bridge, Juanita Arch, is in Maverick Canyon (unsurveyed sec. 29, T. 50 N., R. 18 W.). It formed where the stream cut through the neck of a tight curve that may be an entrenched meander. Elsewhere in the area, alcoves, caves, niches, and holes have been carved or have been formed in the face of cliffs by weathering. The rows of pits that line the cliffs of Entrada Sandstone are the most numerous of these features; these have formed by differential weathering of certain layers. The regular shape of these pits and their fairly regular spacing are indicative of controls that are not haphazard, although what these controls are is not known. Alcoves and shallow caves formed by overhanging cliffs are most common in the Entrada Sandstone although some have formed in other massive sandstone units. Alcoves and caves form by the weathering of soft beds overlain by resistant beds or, in massive sandstones, they form where percolating water has removed the cement thereby permitting the removal of the sand grains by water, wind, or gravity. Some of the largest caves occur under intermittent waterfalls in the Wingate Sandstone at the heads of short box canyons. The back ends of some caves are moist or are coated with salts that were deposited as seepage water evaporated. Contrary to popular opinion, wind or sand blasts seem to have had little effect in producing any of the sculptured forms that decorate the cliffs, for these forms show little polishing or blast effects normally associated with wind erosion.

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