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GEOLOGY OF THE SALT VALLEY ANTICLINE AND ADJACENT AREAS GRAND COUNTY, UTAH

BY

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GEOLOGY OF THE SALT VALLEY ANTICLINE AND ADJACENT AREAS, GRAND COUNTY, UTAH

By C. H. DANE

ABSTRACT

The area described in this report includes about 800 square miles of semiarid, rugged country in Grand County, Utah, adjacent to the Utah-Colorado State line. Its northern part is crossed by the main line of the Denver & Rio Grande Western Railroad from Denver to Salt Lake City. The area lies near the northern and eastern margins of the Canyon Lands subdivision of the Colorado Plateau.

The oldest exposed rocks, which are of pre-Cambrian age and crop out only in the Uncompahgre Plateau, in the northeastern part of the area, are hornblende and biotite gneisses and schists, intruded by a coarse-grained granite. On the peneplaned surface of the pre-Cambrian rocks lie red beds of Permian and Triassic age. The pre-Cambrian rocks, however, represent part of the southwestern margin of a land mass which shed erosional debris southwestward to produce a series of sedimentary formations of Pennsylvanian, Permian, and Triassic age. All these formations thin northeastward toward the site of the old land mass, of which a portion occupied the present site of the Uncompahgre Plateau.

The oldest exposed sedimentary formation is an unnamed conglomerate of Pennsylvanian (?) age, which crops out at two localities in Salt Valley. Apparently succeeding this conglomerate is the Paradox formation, also of Pennsylvanian age, consisting of black shale, fine-grained sandstone, limestone, gypsum, and salt, and containing marine fossils. The thickness of the Paradox is unknown but exceeds 1,000 feet. The next overlying formation, consisting of greenish-gray sandstone, red shale, arkosic conglomerate, and marine fossiliferous limestone, is the Hermosa formation, of Pennsylvanian age, in places more than 800 feet thick. Above the Hermosa are the continental red beds of the Cutler formation, in places more than 1,700 feet thick, consisting of maroon sandy shales and arkosic conglomerate that contains boulders of granitic and metamorphic rocks. The Moenkopi formation, of lower Triassic age, consists of ripple-bedded reddish-brown sandstones, chocolate-red shales, and arkosic conglomerates, more than 800 feet thick in places but thinning out northeastward toward the Uncompahgre Plateau. The red clay, buff sandstone, and limestone conglomerate of the Upper Triassic Chinle formation have a maximum thickness of more than 400 feet, but the Chinle also thins northeastward, though it is the oldest formation to continue northeastward across the summit of the Uncompahgre Plateau.

The overlying Glen Canyon group, of Jurassic (?) age, includes three sandstone formations—the reddish-buff Wingate sandstone at the base, about 300 feet thick; the purplish-gray Kayenta formation, which contains some red shale and limestone conglomerate and ranges from 150 to 320 feet in thickness; and the

buff Navajo sandstone at the top, present only in the southwestern part of the area, where it attains a thickness of 300 feet. The Wingate and Navajo are believed to be largely of eolian origin, and the Kayenta is largely of fluviatile origin. Fresh-water pelecypods have been found in the Kayenta formation. The next overlying San Rafael group has at the base a thin formation of red earthy sandstone, the Carmel. Above it is the orange-buff Entrada sandstone, with a white sandstone member at the top called the Moab sandstone, the formation unit having a thickness of 227 to 300 feet. The uppermost formation of the San Rafael group is the Summerville, consisting of red ripple-bedded sandstones and shales, for the most part less than 50 feet thick. Though no fossils have been found in this area in the beds of the San Rafael group, the formations have been traced from localities farther west in which beds in the group contain marine Upper Jurassic fossils. The continental Morrison formation, of Jurassic age, consists of gray and variegated shales and marls, with lenticular channel sandstones and conglomerates of chert pebbles. A variable unit with thicker and more numerous white sandstone beds lies at the base of the formation and is called the Salt Wash sandstone member. The Morrison is 700 to 900 feet thick.

The basal formation of the Upper Cretaceous series is the Dakota (?) sandstone, comprising brown and buff sandstone and conglomerate, as much as 100 feet thick. Over it lies the gray marine Upper Cretaceous Mancos shale.

The rocks were folded during several periods, most conspicuously at the end of the Upper Cretaceous epoch. At this time the large northwestward-trending anticlinal arch of the Uncompahgre Plateau, lying mainly in Colorado, was formed, and beds with northwestward dip in the eastern part of the area here described form part of the northwestern flank of this major fold. The rocks of the western part of the area here described dip generally northward, away from the La Sal Mountains and toward the Uinta Basin. There are many normal faults, some of which have throws of more than a thousand feet. The most prominent fold, the northwestward-trending Salt Valley anticline, is broken by many faults, and its crest is in part dropped by a complicated fault system into a structural trough. Other folds of the area are also affected by trough-fault systems. During the folding the salt and gypsum beds of the Paradox formation yielded plastically and were forced upward through the overlying beds in several places, transgressing their normal stratigraphic position. Large areas of the Paradox formation are exposed in the core of the Salt Valley and Onion Creek anticlines.

Several wells have been drilled for oil and gas within the area, and oil has been found in the Dakota (?) sandstone and the Paradox formation. No commercial production has been obtained, but the beds in the Paradox formation have not yet been thoroughly tested. Soluble potassium salts have been found in the squeezed and crushed masses of the Paradox formation, but the complexity of structure within the formation will render commercial production of them difficult in most if not all of the area. Disseminated deposits of uranium and vanadium ores are irregularly distributed in the Salt Wash sandstone member of the Morrison formation and have been mined in the past but can probably not be profitably exploited except under favorable economic conditions.

INTRODUCTION

PURPOSE AND SCOPE OF THE WORK

The area described in this report includes more than 800 square miles in Grand County, Utah, adjacent to the Utah-Colorado State line. It forms part of a rugged, arid, and sparsely populated region of which a large portion still remains public land. The location and extent of the area are shown on figure 1. As a result of showings of oil obtained in early wells drilled in this and adjoining regions many applications were made for permits to prospect for oil and gas on different tracts of these Government-administered lands. The

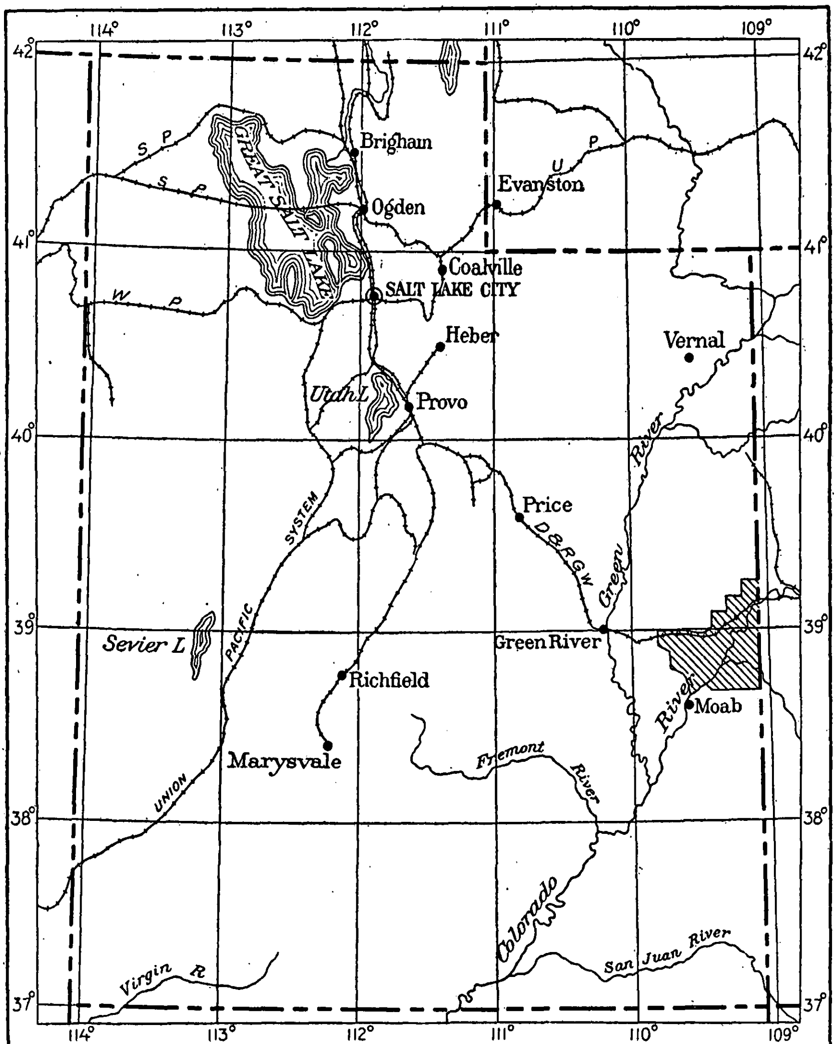


FIGURE 1.—Index map of Utah showing location of area mapped on plates 1 and 2 (ruled area).

study of this area was undertaken by the United States Geological Survey primarily to obtain the information necessary for appropriate action on these applications. This report makes available to the public the results of the study. It describes the sections of rocks encountered and their variations within the area, discusses the deformation of the originally horizontal strata by folding and faulting and its relation to the geologic structure of the surrounding region, and considers the possibilities for oil and gas production.

FIELD WORK

The western part of the area was mapped in May, June, and July 1927 by a party in charge of E. T. McKnight. The mapping at that time was a continuation eastward of the mapping done the previous year by Mr. McKnight between the Green and Colorado Rivers. The writer joined the party early in June 1927 and after the departure of Mr. McKnight was in charge of the work until its termination early in November. J. D. Sears, John Vanderwilt, O. R. Murphy, and C. E. Erdmann assisted in the mapping during this season. J. M. Turnbow, M. O. McKnight, and Jack Christensen served as camp hands. In May, June, and July 1929 the writer, assisted by C. B. Hunt and H. O. DeBeck, completed the mapping eastward to the Utah-Colorado State line. The late J. W. Steele and Marshall Cowsert served as camp hands during this season. A small area south of the Colorado River and west of Castle Creek, mapped in 1926 by A. A. Baker, is included in this report in order to show the geology on both sides of the river.

The only topographic maps covering this area are the old reconnaissance 1° maps on a scale of 1:250,000 or about 4 miles to the inch. Although these show the major features of the land surface they are inadequate as a base for detailed mapping. Most of the area mapped lies within the northeast quarter of the La Sal quadrangle, but a small area in the northeastern part lies in the southeast corner of the East Tavaputs quadrangle.

In the absence of a base map of satisfactory quality, base lines were measured as required, and control points were established by careful triangulation, in which a plane table and a geologist's alidade were used. Positions of other points were determined from these by three-point locations, and the mapping was carried on by intersection and sketching. In addition some mapping by stadia traverse was necessary. Most of the work was done independently, though under the general supervision of the party chief. The exigencies of the work were such that the resulting map is a composite of interlocking irregular areas mapped by eight different individuals. It is impracticable to attempt to indicate the portions of the map for which each individual is responsible.

A previously published map of the Colorado River [1] was with only minor modifications incorporated into the mapping by locating distinctive topographic and cultural features along the river on the

[1] Profile surveys in the Colorado River Basin in Wyoming, Utah, Colorado, and New Mexico: U. S. Geol. Survey Water Supply Paper 396, 1917.

field sheets. The map of the river shows topography in narrow belts on each side, and this was utilized in drawing formation boundaries along the river.

Land corners of the township surveys of the United States General Land Office were searched for in the field and where possible were located on the triangulation sheets. As the land surveys do not completely cover the area, the base map was compiled from the field triangulation and the separately constructed land net was superimposed on it, the corners located in the field being used as tie points. It was found that relatively little adjustment was required in combining the triangulation and land nets, and therefore it is thought that the mapped position of points in the area with respect to land lines is as accurate as could be expected and within the limits of accuracy of the survey of the land lines.

ACKNOWLEDGMENTS

The writer acknowledges gratefully the cooperation of Mr. E. T. McKnight and Mr. J. D. Sears, of the United States Geological Survey, during the early part of the field work and the capable aid given by those who assisted him in the field. The members of the field parties are indebted to many residents of the area for numerous kindnesses.

During the preparation of the report the writer had the aid of criticism and suggestions from several members of the staff of the Geological Survey, and he is under special obligation to Messrs. H. D. Miser, J. B. Reeside, Jr., and A. A. Baker, all of whom read and criticized the manuscript. The writer wishes to express his appreciation to the Director of the Geological Survey for permission to submit this report to Yale University, in essentially its present form, as a dissertation in partial fulfillment of the requirements for the degree of doctor of philosophy. He also acknowledges with thanks the helpful criticism of Prof. C. R. Longwell and Prof. C. O. Dunbar, of the department of geology at Yale University.

TOPOGRAPHY, DRAINAGE, AND WATER SUPPLY

The area here described lies near the northern boundary of the Canyon Lands subdivision of the Colorado Plateau.[2] In the Canyon Lands the plateau surface is for the most part gently rolling, and much of it has only moderate relief, but it is deeply trenched by numerous canyons. Also, scattered groups of mountains rise high above the general level of the plateau, and in and near these moun-

[2] Fenneman, N. M., Physical divisions of the United States: U. S. Geol. Survey special map.

tain masses are many areas of high country. The total relief of the area is thus measured in thousands of feet.

North of the area rises the sinuous southeastward-facing escarpment of the Book Cliffs and beyond these lies the Uinta Basin. South of the Book Cliffs is a strip 10 miles or more in width of barren gently rolling land, diversified only by low gray hills, some of which are capped by gravelly benches sloping southward from the cliffs. The drainage courses wind southward and southeastward across this monotonous gray belt in broad, shallow trenches. This type of land surface extends into the area as a southeastward-pointing wedge, the apex of which is at McGraw Bottom, on the Colorado River. The south border of the wedge extends a little north of west from this apex, and the east border extends a little east of north. From the east border the land surface gradually rises toward Pinyon Mesa, the northwest end of the Uncompahgre Plateau, just east of the area mapped. This plateau extends N. 35° W. from the north end of the San Juan Mountains, in southwestern Colorado, for more than 80 miles and attains an altitude of 8,500 to 9,000 feet. About 20 miles from the northwest end the gorge of Unaweep Canyon cuts across the crest. The portion of the elevated tract north of this canyon is known as Pinyon Mesa, but geologically and topographically it forms a part of the Uncompahgre Plateau. Renegade Point of Pinyon Mesa, which was used as a triangulation point during the present investigation and lies about 1 mile east of the Utah-Colorado State line north of Ryan Creek, stands at an altitude of over 8,200 feet, but within the area mapped the highest altitudes in this vicinity are but little more than 7,500 feet.

From the south border of the wedge of gray rolling country the land surface rises irregularly southward toward the La Sal Mountains (pl. 4, *A*). Nine miles south of the south edge of the mapped area Mount Waas of that mountain group reaches an altitude of more than 12,000 feet, and the culminating peak of the group, Mount Peale is more than 13,000 feet above sea level. Among the places that reach altitudes of about 7,500 feet along the southern margin of the area are the east and west walls of Fisher Valley and the southern part of Polar Mesa. All the area outside the gray rolling country has the typical topography of the canyon lands.

The Colorado River, the master stream of the canyon lands, enters the area near the northeast corner and flows across it in a winding course that maintains a general trend of S. 60° W. The altitude of the river surface where it enters the area is 4,325 feet; where it leaves at the south edge, its altitude is less than 3,960 feet, the lowest level within the area and about 3,500 feet lower than the highest parts.

On plate 1 a few altitudes are given. Some of these have been placed on distinctive topographic features that can be easily recognized in the field. Others are located only with the intention of giving the reader of the map a general idea of the topographic relief. These altitudes are given to the nearest 10 feet. Spirit-level lines [3] have been run along the Denver & Rio Grande Western Railroad by the United States Geological Survey, and five bench-mark altitudes along the railroad are given on the areal map to the nearest foot.

The sparsity or absence of soil cover impresses on the topography of the canyon lands a vivid individuality. Bare rock surfaces appear everywhere—as sheer cliffs, as smoothly rounded knolls, as intricately dissected "slick rock" slopes or benches. Even the softer formations where exposed on steep slopes are covered only by a thin layer of mechanically disintegrated debris through which ledges of the harder beds project. The exposed rock surfaces are wind-swept, and the sand derived from them has been piled into dunes or distributed widely as a thin mantle. Only in the alluvial bottoms of the larger streams and on a few protected flat or gently sloping alluvial surfaces at higher levels is there an approximation to sod or grass cover.

There is a striking and intimate relation between the topography and the nature and consequent resistance to erosion of the several formations that crop out. The harder and more resistant beds crop out in vertical or steep cliffs; softer beds are weathered down into slopes of varying inclination and may be stripped off for miles back from the outcropping edge of underlying harder strata. Where this stripping has occurred the topographic slope of the land may partly or wholly correspond with the dip of the exposed harder stratum. From such dip slopes or from broad level stripped surfaces, isolated flat-topped buttes or mesas of more resistant beds may rise with steep or vertical walls. The details of topography are so closely related to the kind and attitude of the underlying bedrock that it seems impossible to describe them adequately without a discussion of the geology. Accordingly such details are omitted here, and the topographic response of the several formations is discussed in the sections on those formations.

Although many features of the topography are controlled largely by the disposition of the types of bedrock, the positions of the larger drainage courses are not so controlled and have therefore been an independent factor in the development of the present configuration of the surface. Thus the general direction and local windings of

[3] Results of spirit leveling in Utah, 1897 to 1914, inclusive: U. S. Geol. Survey Bull. 566, 1915.

the Colorado River are not controlled by the bedrock, but as the river crosses rocks of different attitude and resistance to erosion there are great variations in the topography. At the Colorado-Utah line the river emerges from Ruby Canyon, with its cliff walls of red sandstone, into a stretch of more open country about 5 miles in length, southeast of which lies a canyon-dissected surface sloping upward away from the river. It then breaks through a narrow gap in a long northeastward-facing sandstone cliff into Westwater Canyon, where it flows in an inner gorge trenched in dark metamorphic rocks, above which rise sandstone cliffs more than 500 feet high. The northwest wall of the canyon is broken only by the rincons known as "Big Hole" and "Little Hole", but the southeast wall is cut by the lower parts of the canyon of the Little Dolores River and of Star and Marble Canyons, the ramifying upper parts of which intricately dissect a high tableland sloping upward to the northwest. The superior resistance of the metamorphic rocks across which the river flows in Westwater Canyon is shown by the fact that although the level of the river falls 140 feet in the 12 miles of the river's course through the canyon it falls only 190 feet from the lower end of the canyon to the southwestern edge of the area, a distance of nearly 45 miles.

The river emerges from the 12-mile stretch of Westwater Canyon into more open country and some miles to the southwest, at McGraw Bottom, cuts across the tip of the wedge of low gray rolling country, thence flowing through gradually rising country in a canyon of increasing depth (pl. 4, *B*) from which it emerges into the great open sweep of Richardson Amphitheater. The river flows near the northwest wall of the amphitheater, which bounds on the southwest the highest part of the Dome Plateau, more than 1,500 feet above the river level. The eastern wall of the amphitheater rises to still greater heights but swings eastward, away from the amphitheater, and becomes a southward-facing cliff overlooking the rugged surface through which the canyon of Onion Creek is cut and serving also as the rim of a great dip slope, dissected by canyons that drain northward into the Dolores River.

Leaving Richardson Amphitheater the Colorado runs into another deep canyon, in which it continues to the south edge of the mapped area—indeed, except for a short open stretch across Moab Valley (not shown on the map but only a short distance to the west), it continues in this canyon to the Green River and beyond.

The most striking topographic feature of the western part of the area is the narrow trench of Salt Valley and its eastern continuation, Cache Valley, which combined have a length of nearly 25 miles. The width of this trough varies from several miles to a fraction of a mile and it is walled on both sides by only briefly interrupted cliffs from a few hundred to over 1,000 feet high. For about a third of its length it is floored by the same gray-shale formation that crops out as the wide strip of gently rolling country south of the Book Cliffs. Indeed, the gray shale extends from this wide strip for some miles into the north end of the valley (pl. 5). Elsewhere the valley is floored with other formations of relatively low resistance to erosion. The valley owes its origin to the disposition by structural features of several softer formations into a long, narrow belt, with more resistant sandstones on each side which now stand up as nearly continuous walls above the valley floor. The southeast end of this structural valley is separated by only a narrow divide from the northwest corner of Richardson Amphitheater, and its position is clearly marked by a gap in the line of cliffs that form the northwest wall of the amphitheater.

The Colorado River has its source far to the east in the Rocky Mountains and receives in its headwaters a supply of water sufficient to insure a perennial flow across the less humid plateau region. Much of the supply is derived from the spring melting of snow in the mountains, and the discharge of the river thus reaches a maximum in late May or early June and diminishes to a minimum in the winter. The variations in discharge of the river and its headwaters have been exhaustively discussed by Follansbee.[4] The largest tributary of the Colorado within the area is the Dolores River, which has its source far to the southeast, in the San Juan Mountains of southwestern Colorado. The Dolores River enters the area about 6 miles north of the southeast corner and flows generally northwestward in a very irregular course, joining the Colorado River near Dewey. Like the Colorado, the Dolores receives in its headwaters a supply of water sufficient to insure a perennial flow, but this flow is greatly reduced in late summer, fall, and winter.

The triangular area northeast of the Dolores and southeast of the Colorado is drained in part by a number of intermittent streams that head on top of Pinyon Mesa. For months in the spring and early summer these streams flow continuously, supplied by the melting of the accumulation of winter snow on top of the Mesa. The largest of these streams is the Little Dolores River, which flows into the Colorado near the north end of Westwater Canyon. Coach Creek drains into the Colorado River south of the Sand Flat and receives the flow of Spring Creek, Renegade Creek, and Ryan Creek, all of which head on Pinyon Mesa. Granite Creek is another stream of this type which drains into the Dolores River above Utah Bottoms. The other streams in this part of the area are intermittent,

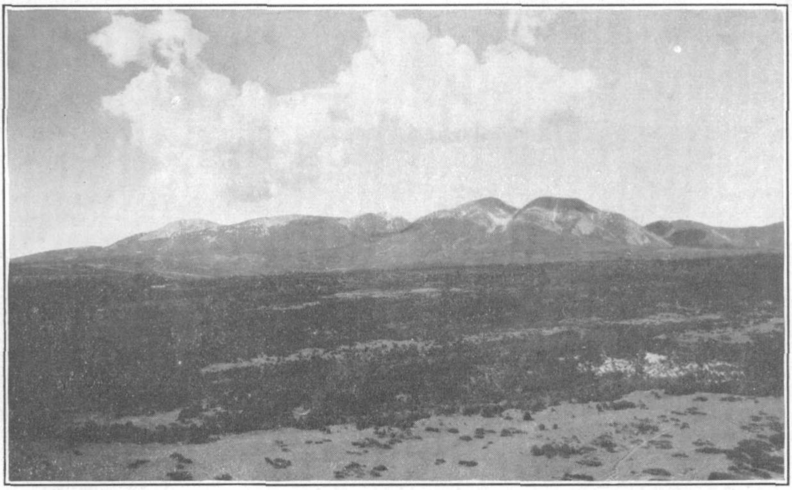
[4] Follansbee, Robert, Upper Colorado River and its utilization: U. S. Geol. Survey Water-Supply Paper 617, 1929.

although some may carry trickles of water for weeks at a time, particularly in the lower parts of their courses and after storms.

In the tract southwest of the Dolores and southeast of the Colorado the largest stream is Beaver Creek, which heads in the eastern slopes of the La Sal Mountains and flows northward into the Dolores River. The melting of the winter snow on the mountains furnishes a sufficient supply to insure a continuous flow throughout the summer and well into the fall. Beaver Creek is mapped as a permanent stream, but it is possible that the flow may cease at times of lowest temperature during the winter. Part of the headwaters of Beaver Creek are diverted by a rock-cut channel to flow as a cascade into Fisher Valley for use in irrigation. This water eventually contributes to the small nearly continuous flow in Cottonwood Canyon, which also drains into the Dolores. Onion Creek heads as a spreading group of dry gullies on the high flats of Fisher Valley but receives the flow of several springs lower down in its course. It then runs northwest into the Colorado as a very small but permanent stream unless frozen during midwinter. The great dip slope to the northeast between Onion Creek and Cottonwood Canyon is drained into the Dolores River by a number of short temporary or intermittent streams in some of which small trickles of water run for short distances, disappearing under the stream bed, perhaps to subsequently reappear on the surface for a short distance. Rock Creek flows into the Colorado about 2 miles west of the mouth of Onion Creek. It heads to the south in the lower slopes of the La Sal Mountains and flows during the spring and early summer. Castle Creek, which empties into the Colorado just southwest of the area mapped, heads far enough up in the La Sal Mountains to maintain a small flow even in the late fall.

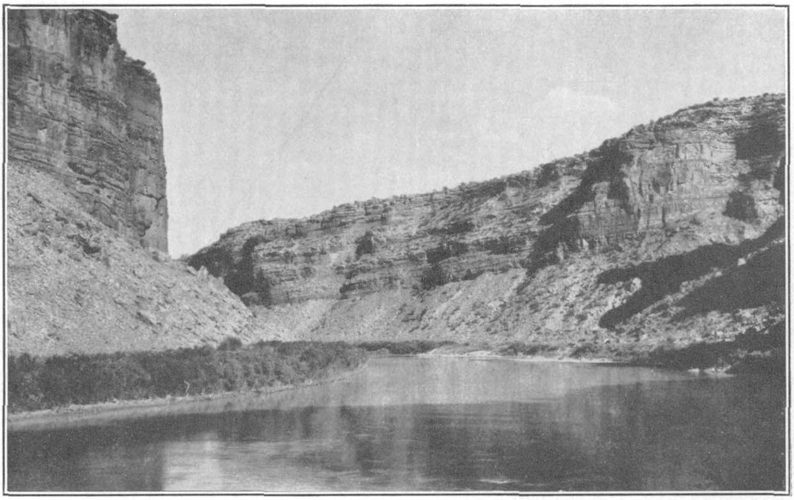
No truly permanent streams empty into the Colorado from the north in this area. Bitter Creek, Westwater Creek, Cottonwood Wash, Cisco Wash, and Sagers Wash and its large tributary, Nash Wash, all head in or north of the Book Cliffs and drain into the Colorado River east of the mouth of the Dolores. Some of them emerge from the Book Cliffs as small permanent streams, but the flow of all is occasionally dissipated by evaporation before they reach the Colorado. Thompson Wash and Crescent Wash, which flow across the northwest corner of the area, are intermittent streams of the same type.

Most of the western part of the area is drained by Salt Wash and its numerous tributary drainage courses. Salt Wash is a dry stream bed except during or immediately after rainfall. About 3 miles above its mouth Salt Wash receives the flow of several large springs of strongly saline water and runs as a small permanent stream to its junction with the Colorado.



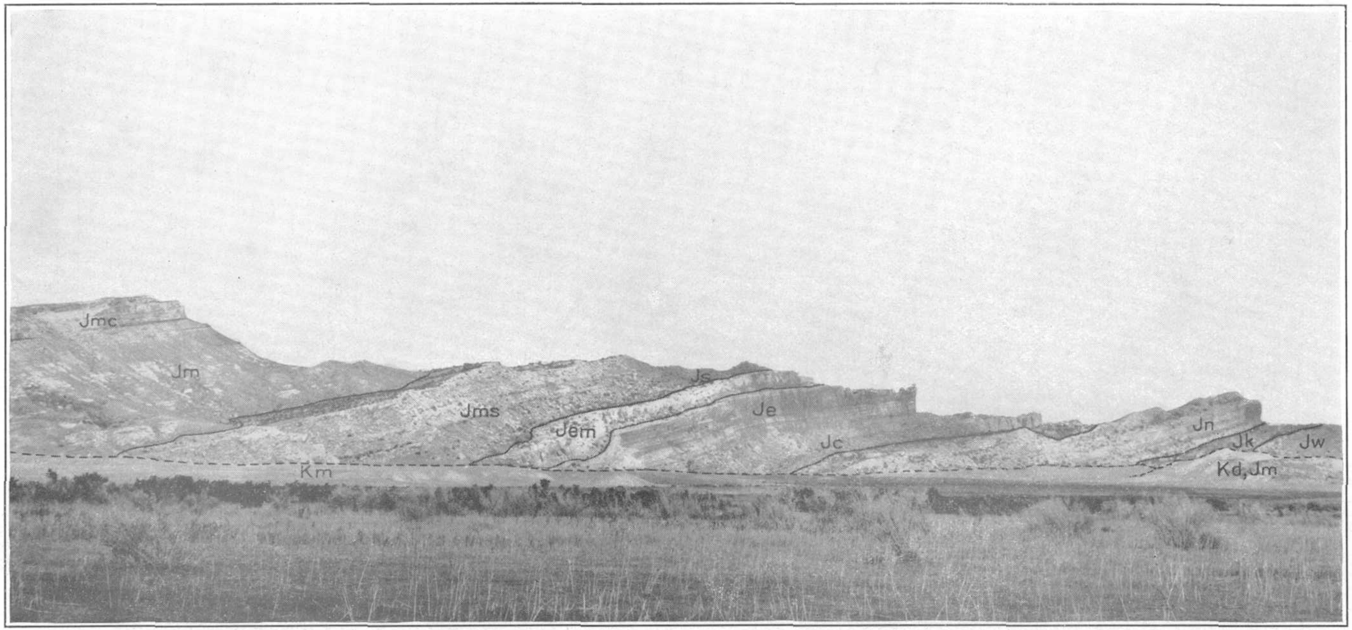
A. LA SAL MOUNTAINS, FROM SOUTH END OF POLAR MESA.

Tree-covered slopes of Navajo sandstone dipping toward the camera. Road to Castleton in lower right corner.



B. VIEW UP THE CANYON OF THE COLORADO RIVER ABOUT 3 MILES BELOW DEWEY.

Ledges of bedded Kayenta formation resting on more massive Wingate sandstone; softer Chinle formation below largely concealed by talus.



EAST WALL OF NORTH END OF SALT VALLEY.

The valley flat in the foreground is largely underlain by the Upper Cretaceous Mancos shale, dropped against the Jurassic formations of the valley wall by a large fault. **Km**, Mancos shale; **Kd**, Dakota (?) sandstone; **Jm**, Morrison formation; **Jmc**, conglomerate bed near top of Morrison; **Jms**, Salt Wash sandstone member of Morrison; **Js**, Summerville formation; **Je**, Entrada sandstone; **Jem**, Moab sandstone member of Entrada; **Jc**, Carmel formation; **Jn**, Navajo sandstone; **Jk**, Kayenta formation; **Jw**, Wingate sandstone. *Photograph by W. T. Lee.*

All the streams except the Colorado and Dolores Rivers are subject to sudden and violent floods. The combination of great surfaces of bare rock without soil cover and local sudden very heavy rains favors maximum run-off, and although there may have been little or no indication of rain in the immediate vicinity, a practically dry stream channel may be transformed in a few moments into a raging torrent several feet deep. The only warning may be the roar of the approaching water, which may be audible from a distance of a mile or more.

In a region of such sparse rainfall, where the water of running streams cannot be relied on as a source of supply, springs are of great importance. Permanent springs are shown on the areal map and, with the exception of the strongly saline springs along Onion Creek and Salt Wash, provide potable water unless fouled by stock, although the water of some is unpleasantly alkaline. The water from the Stinking Springs, along Onion Creek, is regarded as dangerous for stock. The running water in the streams that flow southward to the Colorado across the great shale flat is too alkaline to be satisfactory for stock but can be used, particularly for short periods after floods. The water of the Colorado and Dolores is of course excellent for stock, and shallow wells drilled some distance from the streams are used for human consumption, although the river water is exposed to pollution from towns higher up their courses.

The water draining from the melting winter snow of Pinyon Mesa and the La Sal Mountains is potable, but Coach Creek and the Little Dolores River are exposed to slight pollution from ranches east of the area, and their water should probably be treated before drinking.

The running water of the Dolores River, the Colorado River, Coach Creek, Rock Creek, and Beaver Creek is used for irrigation in a few favorable localities. Pumping stations on the Colorado River supply water to the Denver & Rio Grande Western Railroad. Temporary supplies of water are furnished by natural rock tanks, which fill with water after rains and, in situations protected from direct exposure to the sun, may retain water for weeks or months.

The springs of the area provide the most satisfactory source of drinking water.

CLIMATE

The region has a semiarid climate, with a mean annual rainfall of 10 inches or less. Cisco and Thompson have or have had Weather Bureau records, but as the rainfall increases with altitude the precipitation records of four other nearby Weather Bureau stations have been included in the following table, kindly prepared for the writer by the United States Weather Bureau.

118763—35——2

Monthly and annual mean precipitation, in inches, at 6 stations in Utah and Colorado

	Length of record (years)	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Cisco, Utah	13	0.67	0.94	0.48	0.39	0.64	0.10	0.28	0.52	0.90	0.67	0.37	0.54	6.50
Thompson, Utah	15	.36	.44	.81	.49	.47	.37	.76	.82	.91	.90	.81	.67	7.81
Moab, Utah	30	.91	.69	.91	.64	.74	.33	.85	.66	1.01	.91	.66	.93	9.24
La Sal, Utah	14	.97	1.04	.78	.76	.80	.61	1.25	1.22	1.19	.95	.78	.80	11.15
Near Fruita, Colo	21	.95	.85	1.08	.79	.90	.41	.88	1.13	1.07	1.16	.73	.78	10.73
Grand Junction, Colo	50	.60	.58	.76	.83	.81	.40	.61	1.17	.92	.95	.57	.63	8.83

The largest mean annual rainfall is recorded at La Sal, the station of highest altitude, situated on the south slopes of the La Sal Mountains. The smallest annual means are recorded at Cisco and Thompson, at low altitudes, situated where the westerly storm winds have swept for some distance over a low arid semi-desert. The somewhat higher rainfall at Moab results from its proximity to the La Sal Mountains and the more rugged topography of the area in which it is situated; and the higher rainfall at Fruita and Grand Junction is explicable as due to their geographic position just east of the higher Pinyon Mesa country. The monthly means, even over periods ranging from 13 to 50 years of record, show a lack of concordance, which is attributable to the fact that the rainfall for the most part accompanies thunderstorms and, although often exceedingly heavy, may fall only over a small area. To emphasize this the following has been prepared:

Monthly and annual precipitation, in inches, at stations in or near Grand County, Utah, with departure from normal

[Summarized from Climatological data for the United States, by sections, U. S. Weather Bureau]

	January		February		March		April		May		June		July	
	Precipitation	Departure	Precipitation	Departure	Precipitation	Departure	Precipitation	Departure	Precipitation	Departure	Precipitation	Departure	Precipitation	Departure
1927														
La Sal, Utah	0.50	−0.37	3.20	+2.31	2.00	+1.31	0.30	−0.47	0.30	−0.51	3.06	+2.46	0.70	−0.62
Near Fruita, Colo	2.07	+1.12	1.63	+.78	1.33	+.25	.10	−.69	.25	−.65	2.03	+1.62	.38	−.50
1929														
Moab, Utah	.74	−.07	1.09	+.41	1.09	+.17	1.14	+.47	1.85	+1.08	.10	−.27	.78	−.11
Thompson, Utah	.99	+.63	.90	+.46	.32	−.49	.42	−.07	.30	−.17	.10	−.27	1.55	+.79
Grand Junction, Colo	.95	+.35	.79	+.21	1.02	+.26	.49	−.34	.45	−.36	.08	−.32	2.72	+2.11

Monthly and annual precipitation, in inches, at stations in or near Grand County, Utah, with departure from normal—Continued

	August		September		October		November		December		Annual	
	Precipitation	Departure	Precipitation	Departure	Precipitation	Departure	Precipitation	Departure	Precipitation	Departure	Precipitation	Departure
1927												
La Sal, Utah	2.60	+1.27	4.64	+3.54	2.50	+1.48	0.31	−0.48	No data		Incomplete	
Near Fruita, Colo	1.02	−.11	2.92	+1.85	1.09	−.07	.66	−.07	0.67	−0.11	14.15	+3.43
1929												
Moab, Utah	.83	+.10	1.73	+.43	.14	−.83	.73	+.60	.08	−.90	10.30	+.54
Thompson, Utah	1.27	+.45	2.15	+1.24	.35	−.55	.40	−.41	.08	−.59	8.83	+1.02
Grand Junction, Colo	.99	−.18	2.16	+1.24	.41	−.54	.74	+.17	.10	−.53	10.90	+2.07

There is no well-defined rainy season, but there is a tendency for rainfall to be heavier from perhaps the middle of July through early fall.

The following table showing average monthly and annual snowfall was compiled for the writer by the United States Weather Bureau.

Average monthly and annual snowfall, in inches, at 6 stations in Utah and Colorado

[None in June, July, and August]

	Length of record (years)	January	February	March	April	May	September	October	November	December	Annual
Cisco, Utah	11	3.8	6.7	1.1	0.2	0.2	0	0	1.7	3.6	17.3
Thompson, Utah	5	4.1	3.3	1.0	.2	0	0	Trace	2.4	4.5	15.5
Moab, Utah	24	5.4	3.3	1.6	Trace	.1	0	.2	.9	5.6	17.1
La Sal, Utah	9	10.0	8.7	3.6	1.4	1.0	0	.8	5.5	9.1	40.1
Near Fruita, Colo	20	6.7	5.5	1.8	.5	Trace	Trace	.3	2.1	5.8	22.5
Grand Junction, Colo	24	5.8	4.7	2.1	.9	.1	Trace	.4	2.2	5.3	21.5

There is a wide daily and annual variation in temperature. During the summer the days are frequently very hot, but the nights may be cool except in sheltered canyons whose heated walls radiate the day's accumulation of heat. The temperature rises abruptly at sunrise and falls off with almost equal rapidity at sunset. During the winter there is a similar wide daily range in temperature, but at a lower range, and temperatures much below zero are common. July is the hottest month of the year, but August is nearly as hot. The temperature falls off rather abruptly from its July and August maximum and decreases to the low temperatures of December and the slightly lower temperatures of January, after which it rises more slowly to the July maximum. The United States Weather Bureau has furnished the tables of temperature which follow.

Mean monthly and annual temperatures (°F.) at 6 stations in Utah and Colorado

	Length of record (years)	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Cisco, Utah	13	23.2	29.7	42.0	53.1	62.0	72.0	79.3	77.3	67.2	52.2	39.3	25.6	51.9
Thompson, Utah	15	23.2	33.5	42.6	50.4	62.0	70.8	77.7	75.7	64.8	53.1	41.0	26.7	51.8
Moab, Utah	28	28.8	36.2	43.4	55.2	63.6	72.1	77.7	75.3	66.3	53.6	41.4	30.3	53.7
La Sal, Utah	14	24.7	28.4	35.7	44.2	51.3	61.4	67.1	66.1	57.3	46.5	36.9	24.8	45.4
Near Fruita, Colo	21	21.4	30.3	42.6	50.0	58.4	68.1	74.2	72.8	63.5	51.1	37.8	25.0	49.6
Grand Junction, Colo	46	24.0	32.9	43.6	52.4	61.1	71.4	77.7	75.4	66.2	52.8	39.3	27.5	52.0

Highest and lowest monthly and annual temperatures (°F.) recorded at 6 stations in Utah and Colorado

	Length of record (years)	January		February		March		April		May		June		July	
		Highest	Lowest	Highest	Lowest	Highest	Lowest	Highest	Lowest	Highest	Lowest	Highest	Lowest	Highest	Lowest
Cisco, Utah	13	66	−26	71	−23	90	8	88	12	100	27	109	32	108	45
Thompson, Utah	5	56	−1	62	−10	76	20	85	22	96	30	107	38	108	48
Moab, Utah	30	65	−18	78	−13	88	8	97	16	102	27	107	36	109	43
La Sal, Utah	16	56	−22	64	−15	70	−3	76	5	85	19	94	25	94	34
Near Fruita, Colo	20	59	−34	69	−29	78	0	88	2	96	24	101	30	104	38
Grand Junction, Colo	24	62	−19	70	−15	81	7	85	14	94	29	104	35	105	47

	Length of record (years)	August		September		October		November		December		Annual	
		Highest	Lowest	Highest	Lowest	Highest	Lowest	Highest	Lowest	Highest	Lowest	Highest	Lowest
Cisco, Utah	13	107	45	100	29	88	16	77	5	64	−18	109	−26
Thompson, Utah	5	103	49	94	37	85	22	80	10	62	−3	108	−10
Moab, Utah	30	107	41	101	29	90	18	82	9	68	−10	109	−18
La Sal, Utah	16	93	37	86	19	89	0	81	−1	76	−11	94	−22
Near Fruita, Colo	20	101	39	94	22	88	9	73	−2	62	−28	104	−34
Grand Junction, Colo	24	103	48	98	28	86	16	74	4	66	−21	105	−21

The influence of altitude on the temperature is seen in the lower temperatures recorded at the La Sal station, which is the highest of the stations tabulated.

VEGETATION

Most of the area falls within the province of northern desert-shrub vegetation.[5] The characteristic shrub is the sagebrush, but rabbitbrush, shadscale, salt sage, and other shrubs are associated with it. Piñon and juniper are scattered over the rockier tracts and at higher altitudes become the most prominent type of vegetation. Cottonwoods grow in favorable localities, chiefly along the alluvial bottoms of the larger streams. Greasewood is abundant on the allu-

[5] Shantz, H. L., and Zon, Raphael, Atlas of American agriculture, pt. 1, section E, Natural vegetation, U. S. Dept., Agr., 1924.

vial flats of both the large streams and the dry washes. Pricklypear is abundant locally, and a few other types of cactus are not uncommon. At the highest altitudes, notably on Polar Mesa, there are scattered stands of western yellow pine and thickets of oak brush. At the higher levels grasses are abundant but not abundant enough to make sod, and at lower levels only a dispersed growth of the more resistant grasses is maintained.

FUEL

The development of power for drilling wells in the district is expensive, partly because favorable drilling sites may necessitate long hauls of coal by truck over poor roads. The nearest source of coal is the mines at Sego, north of Thompson, but coal is also mined at many places in Utah and Colorado along the Denver & Rio Grande Western Railroad. Up to the present time there has been no production of petroleum in or near the district sufficient to permit the use of locally produced crude oil in further drilling. Gasoline is shipped into the district by railroad from refineries in Salt Lake City or Denver. Natural gas produced on the Cisco dome, northwest of Cisco, has been utilized in the manufacture of carbon black, and gas has been found in considerable amounts at other nearby localities in Colorado and Utah, but its use as a fuel in exploratory drilling is obviously impracticable. Wood is unsatisfactory as a fuel and at many localities could not be obtained in sufficient quantity without prohibitive hauling cost.

POPULATION, ACCESSIBILITY, ROUTES OF TRAVEL

The main line of the Denver & Rio Grande Western Railroad runs across the northern part of the area and is the chief artery of the economic life of the region. Coming from the east through the gorge of Ruby Canyon, it runs generally southwestward for 15 miles through broken country, emerges onto the gray shale flats and runs thence nearly westward. Three stations on the railroad—Westwater, Cisco, and Thompson—are the principal settlements of the area mapped. At Westwater there are several small ranches that use the water of the Colorado River for irrigation. Cisco and Thompson are supply points for the contiguous region and also stock shipping points. From Thompson a branch line of the railroad runs a few miles north to the small coal-mining town of Sego. United States Highway No. 50 enters the area near the northeast corner and runs generally southwestward near the southeast edge of the gray-shale plain to Cisco, where it crosses the railroad and turns westward, paralleling the railroad through Thompson, from which it continues westward toward Green River, Utah. From Thompson

United States Highway No. 450 runs 9 miles southwestward to the place called Valley City, from which it runs a little east of south toward Moab, the largest town and county seat of Grand County. Thompson is not only the railroad point for Moab but also for almost all of the region south of Moab and east of the Colorado River in Utah. Motor-stage service is maintained from Thompson to Moab and points south. There are no other graveled roads in the area, but a county road from Cisco southwestward to Castleton is maintained in fair condition, and there is stage service on it three times weekly in each direction. This road crosses the Colorado River over a steel bridge at Dewey, the only automobile crossing of the Colorado within the area. This road serves the ranch at Dewey, several ranches in Richardson Amphitheater, and the ranches in Castle Valley, to the southwest. Near the southwest corner of Richardson Amphitheater the road forks, the south fork turning up into Castle Valley and the west fork continuing along the south side of the Colorado River to Moab. South of the railroad and northwest of the Colorado the only permanent inhabitants are a few people near the road junction called Valley City. A road runs southeastward from the highway north of Valley City for 14 miles through the Salt Valley trench, and in dry weather a car can be driven 5 or 6 miles farther southeast down the bed of a dry wash to Turnbow's cabin, on Salt Wash.

The permanent inhabitants in the eastern part of the area are located where a semipermanent or permanent water supply makes irrigation possible. Larsen's ranch, in Fisher Valley just south of the mapped area, uses water diverted from the head of Beaver Creek. This ranch is not accessible by automobile. The nearest road is that from Castleton to Polar Mesa, which runs close to the high south rim of the valley. Scharf's ranch, on the Dolores River, is accessible by a rough road from Dewey. A cable bridge across the Dolores, just above the ranch, provides a somewhat hazardous crossing of the river for stock at times of high water. A few ranches along the Dolores in the southeast corner of the area are accessible by automobile from Gateway, Colo., and a cable bridge across the river can be used by light cars. Wood's ranch, on Granite Creek, is not accessible by car. Gordon's ranch, also called "Picture Gallery ranch", on Coach Creek, is reached by car from Grand Junction, Colo., and a rough road down Dry Gulch to the Sand Flat can be traversed by car. If the water of Coach Creek is low enough to permit crossing, this road can be followed south from the Sand Flat to the footbridge across the Dolores near Scharf's ranch. Ranches on the Colorado River east of Cisco are accessible by automobile. A cable bridge across the river about 5 miles southeast of

Cisco provides a crossing for stock and is used for bringing sheep from Pinyon Mesa to Cisco for shipment.

A road from Cisco to the Denver & Rio Grande Western Railroad pumping station on the Colorado River continues northeast to Westwater and thence northeast to join United States Highway No. 50, a few miles east of the Colorado State line. A road down the Little Dolores River Valley in Colorado continues west into the area mapped; and if the water is not too high in the Little Dolores at the crossing just west of the State line, the road may be traversed by car west almost to the Colorado. A few other roads are shown on the map, but like most of those already mentioned, they should be attempted only by an experienced driver, equipped for emergencies and prepared to do road work. Much of the area is accessible only on horseback or foot, and accordingly the more important trails have been shown on the areal map. Many of these trails may be traveled on horseback only as a result of trail building done by stockmen or prospectors.

The population statistics of Grand County are presented by precincts in the census for 1930. None of these precincts fall wholly within the area mapped, but the figures afford a general idea of the distribution of the population.

Population of precincts lying partly within the area mapped

No.	Name	Population	No.	Name	Population
2	Richardson	55	5	Westwater	44
3	Thompson	93	6	Dolores	14
4	Cisco	193			

A considerable proportion of the population of the Cisco precinct live north of the mapped area and were or had been associated with the production of carbon black and drilling operations on the Cisco dome.

PREVIOUS PUBLICATIONS

The first description of the geology of the area is the report of A. C. Peale on the Grand River district, which included the area limited on the north and south by parallels 37°52′ and 39°15′, on the west by meridian 109°30′, and on the east by the Gunnison and Uncompahgre Rivers. This report was based on a 6 weeks' reconnaissance during the summer of 1875.[6] Further reconnaissance by Peale in the summer of 1876 on an area between the Dolores and San Miguel Rivers in Colorado and a larger area north of the La Sal

[6] Peale, A. C., Geological report on the Grand River district: U. S. Geol. and Geog. Survey Terr. 9th Ann. Rept., pp. 31–101, 1877.

Mountains in Colorado and Utah led to a second report on the same district.[7]

Late in the winter of 1904 Boutwell[8] made a hasty study of the vanadium and uranium deposits in the vicinity of Richardson, and in the summer of 1905 Cross[9] made a stratigraphic reconnaissance across the area. In 1911 Hill[10] made reconnaissance observations on the northern La Sal Mountains, and his report includes some data on the area mapped by the writer.

Most of the geologic literature on the region is, however, of comparatively recent date, and although no detailed geologic report on the area has heretofore been published, several papers discussing the oil possibilities, stratigraphy, or peculiar types of structure have been published.[11]

The list of publications cited is intended to include only those which specifically and directly refer in whole or in part to the geologic features of the area mapped. Many other publications that deal with stratigraphy and structure of adjoining regions in the Colorado Plateau province are cited at appropriate places in the subsequent pages of the report.

STRATIGRAPHY

The rocks exposed within the area range in age from pre-Cambrian to Upper Cretaceous. The pre-Cambrian basement complex is composed of granite and various types of metamorphic rocks, and the

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[7] Peale, A. C., Geological report on the Grand River district: U. S. Geol. and Geog. Survey Terr. 10th Ann. Rept., pp. 161–185, 1878.

[8] Boutwell, J. M., Vanadium and uranium in southeastern Utah: U. S. Geol. Survey Bull. 260, pp. 203–207, 1905.

[9] Cross, Whitman, Stratigraphic results of a reconnaissance in western Colorado and eastern Utah: Jour. Geology, vol. 15, no. 7, pp. 634–679, 1907.

[10] Hill, J. M., Notes on the northern La Sal Mountains, Grand County, Utah: U. S. Geol. Survey Bull. 530, pp. 99–118, 1913.

[11] Prommel, H. W. C., Geology and structure of portions of Grand and San Juan Counties, Utah: Am. Assoc. Petroleum Geologists Bull., vol. 7, no. 4, 384–399, 1923. Prommel, H. W. C., and Crum, H. E., Salt domes of Permian and Pennsylvanian age in southeastern Utah and their influence on oil accumulation: Idem, vol. 11, no. 4, pp. 373–393; Structural history of parts of southeastern Utah from interpretations of geologic sections: Idem, vol. 11, no. 8, pp. 809–820, 1927; Oil Weekly, vol. 146, no. 7, pp. 31–34, 1927. Harrison, T. S., Colorado-Utah salt domes: Am. Assoc. Petroleum Geologists Bull., vol. 11, no. 2, pp. 111–133, 1927. Taber, Stephen, Fault troughs: Jour. Geology, vol. 35, pp. 577–606, 1927. Gould, L. M., The geology of La Sal Mountains of Utah: Michigan Acad. Sci. Papers, vol. 7, pp. 55–106, 1927. Gilluly, James, and Reeside, J. B., Jr., Sedimentary rocks of the San Rafael Swell and some adjacent areas in eastern Utah: U. S. Geol. Survey Prof. Paper 150, pp. 61–110, 1928. Lee, W. T., Boyer, W. W., and Gilluly, James, Possibility of finding oil in southeastern Utah: U. S. Dept. Interior Press Mem. 6064, 1926. Baker, A. A., Dobbin, C. E., McKnight, E. T., and Reeside, J. B., Jr., Notes on the stratigraphy of the Moab region, Utah: Am. Assoc. Petroleum Geologists Bull., vol. 11, no. 8, pp. 785–808, 1927. Baker, A. A., and Reeside, J. B., Jr., Correlation of the Permian of southern Utah, northern Arizona, northwestern New Mexico, and southwestern Colorado: Idem, vol. 13, no. 11, pp. 1413–1448, 1929. Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., Correlation of the Jurassic formations of portions of Utah, Arizona, New Mexico, and Colorado: U. S. Geol. Survey Prof. Paper 183 (in press). Lang, W. B., Potash investigations in 1924: U. S. Geol. Survey Bull. 785, pp. 29–43, 1926.

overlying succession of Paleozoic and Mesozoic formations includes all the common kinds of sedimentary rocks and some unusual varieties. The lithologic characteristics, succession, and relation of the formations exposed and their variations in thickness are summarized in the following table:

General section of rock formations in Salt Valley area

System	Series	Group	Formation	Thickness (feet)	Character of rocks
Cretaceous.	Upper Cretaceous.		Mancos shale.	410+	Lead-gray marine shale.
					Buff thin-bedded sandstone and sandy shale (Ferron sandstone member), 60 feet thick.
					Lead-gray marine fossiliferous shale, 350 feet thick.
			Dakota (?) sandstone.	20–110	Buff and gray conglomeratic sandstone, with pebbles of black and gray chert; gray shale, carbonaceous shale, and coal.
			-Unconformity-		
Jurassic.	Upper Jurassic.	San Rafael.	Morrison formation.	682–900	Variegated shale, conglomeratic sandstone, conglomerate with pebbles of quartzite and varicolored chert, with silicified wood and vertebrate bones.
					Salt Wash sandstone member (white and gray conglomeratic sandstone, cross-bedded, locally carnotite-bearing, interbedded with red and gray sandy mudstone).
			-Unconformity-		
			Summerville formation.	37–58	Thin-bedded red sandstone and shale, much ripple-marked; some gray limestone locally studded with large chert concretions.
			Entrada sandstone.	227–300	White cross-bedded fine-grained quartz sandstone, massive or in thick beds, with a few red-shale partings (Moab sandstone member).
					Cross-bedded buff, orange-red, and white sandstone, with quartz grains sorted in two sizes.
			Carmel formation.	0–150	Red muddy sandstone and sandy mudstone, with contorted bedding.
			-Unconformity (?)-		
Jurassic (?).		Glen Canyon.	Navajo sandstone.	0–300	Massive cross-bedded buff, gray, and white fine-grained sandstone, with local beds of dense gray limestone.
			Kayenta formation.	150–320	Irregularly bedded lavender, gray, and white micaceous quartz sandstone, red sandy shale, limestone and shale-pebble conglomerates; contains scattered fresh-water invertebrates.
			Wingate sandstone.	250–373	Massive, horizontally thick-bedded and cross-bedded reddish-buff fine-grained quartz sandstone.
Triassic.	Upper Triassic.		Chinle formation.	107–408	Irregularly bedded buff to red sandstone, red mudstone, limestone, and mud-pellet conglomerates, locally with a soft quartz grit and conglomerate at the base; contains scattered fresh-water invertebrates, silicified wood, and vertebrate bones.
			-Unconformity-		
	Lower Triassic.		Moenkopi formation.	0–855	Thin-bedded brown micaceous shale, ripple-marked gray and brown sandstone, arkosic grit, and conglomerate of pebbles of metamorphic rocks, locally with gypsum bed at or near base.
			-Unconformity-		

General section of rock formations in Salt Valley area—Continued

System	Series	Group	Formation	Thickness (feet)	Character of rocks
Carboniferous.	Permian.		Cutler formation.	0–1,730	Chocolate-brown and red sandy shale, maroon and pinkish-gray arkose and conglomerate of pebbles of metamorphic and igneous rocks, and orange-red sandstone. Lower part of these red beds is probably equivalent in age to Rico formation of parts of southwestern Colorado and southeastern Utah.
	Pennsylvanian.		Hermosa formation.	0–855+	Gray marine fossiliferous sandy limestone, gray and greenish-gray sandstone and sandy shale, and red sandy shale.
			Paradox formation.	0–1,000+	Gray sandy shale and sandstone, dense gray limestone, black shale, and gypsum. Wells drilled into the formation disclose large quantities of rock salt.
	Pennsylvanian (?).		Unnamed conglomerate.		Exposed at two localities in Salt Valley, of unknown thickness; yellow sandstone with boulders of limestone and chert containing Mississippian fossils.
			Unconformity		
Pre-Cambrian.					Granite, porphyritic granite, pegmatite-granite gneiss, and biotite and hornblende schists.

PRE-CAMBRIAN COMPLEX

East of the Dolores River and from Westwater Canyon southward, on the northwest slope down from Pinyon Mesa, the Mesozoic and Permian sediments rest on a metamorphic complex of granite and gneiss with subordinate biotite and hornblende schists. Although the direct field relations prove only the pre-Permian age of this complex, all writers have agreed that there is no reason to doubt that it belongs to the pre-Cambrian complex exposed in many areas in western Colorado. In the San Juan Mountains a great succession of metamorphosed sediments, including quartzite, slate, and conglomerate, unconformably underlies the oldest Paleozoic rocks of the region, the Cambrian Ignacio quartzite and the Devonian Elbert formation. This great succession of metamorphic rocks, the Needle Mountains group, is referred to the Algonkian system.[12] Of this succession only the Uncompahgre quartzite is exposed in the Ouray area. In the Silverton and Needle Mountain areas schists and gneisses definitely older than the Needle Mountains group are referred to the Archean system, but in the Needle Mountains there are also more massive granites which are later than the quartzites of the Uncompahgre formation.

[12] Cross, Whitman, Howe, Ernest, and Irving, J. D., U. S. Geol. Survey Geol. Atlas, Ouray folio (no. 153), pp. 2, 3, 1907. Cross, Whitman, Howe, Ernest, and Ransome, F. L., idem, Silverton folio (no. 120), p. 3, 1905. Cross, Whitman, and others, idem, Needle Mountains folio (no. 131), p. 3, 1905.

The metamorphic rocks of the Uncompahgre Plateau were called "Archean" by Peale,[13] but Cross[14] suggested that the granite portion of the complex was younger than the Algonkian quartzites of the Ouray district. Some direct evidence supporting this view was subsequently obtained when quartzites similar to the Uncompahgre quartzite were discovered near West Creek, Colo., apparently surrounded by granite in which small fragments of quartzite were observed. But in the same article[15] Cross also states that "there are many very dark hornblendic schists and others containing both hornblende and biotite. Such gneisses and schists are probably the oldest rocks of the district and are naturally referable to the Archean."

The pre-Cambrian rocks of the nearby Gunnison River region have been subdivided into late Algonkian or early Paleozoic granitic intrusives and Archean schists and gneisses.[16]

In the area mapped there are two types of pre-Cambrian rocks exposed. From Coach Creek southward across Spring and Renegade Creeks to the exposures along Ryan Creek, the pre-Cambrian outcrops consist predominantly, if not entirely, of a coarsely crystalline biotite granite and associated pegmatitic phases. The parent rock contains large phenocrysts of pink and light-gray to white feldspar and some phenocrysts of quartz and weathers to a dark gray. It is cut by thin stringers, dikes, and larger irregular masses of very light gray fine-grained granite, which consists mostly of quartz and feldspar with some biotite and muscovite (pl. 6, *A*). In places there is a gradational transition between this fine-grained granite and the more abundant coarser-grained and somewhat porphyritic granite. The fine-grained granite has a pegmatitic phase, seen as center streaks in the light-gray granite dikes and also here and there as bordering streaks to them. This phase also occurs as dikes without the fine-grained granite. The pegmatite consists mostly of chunks of pink feldspar, which may have a longest dimension as much as 4 inches, and a smaller proportion of masses of quartz almost as large. Platy crystal aggregates of muscovite are common, and there are some small garnets and black crystals of tourmaline. The extensive exposures of granite and pegmatite show little if any megascopic evidence of metamorphism by movement and pressure.

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[13] Peale, A. C., Geological report on the Grand River district: U. S. Geol. Survey Terr. Ann. Rept., pp. 64–69, 1877.

[14] Cross, Whitman, and others, U. S. Geol. Survey Geol. Atlas, Ouray folio (no. 153), p. 1, 1907.

[15] Cross, Whitman, Stratigraphic results of a reconnaissance in western Colorado and eastern Utah: Jour. Geology, vol. 15, no. 7, pp. 676, 677, 1907.

[16] Hunter, J. F., Pre-Cambrian rocks of Gunnison River, Colorado: U. S. Geol. Survey Bull. 777, 1925.

In fact, the distribution of fine-grained granite and pegmatite in dikes exhibits a linearity in systems which suggests their segregation or intrusion into a poorly defined joint system developed during consolidation of the darker parent granite and quite incompatible with the existence of compressive metamorphic stresses during or immediately after the solidification of the magma.

The two thin sections of the granite examined show no plagioclase feldspar but abundant microcline, part of which is altered to clay minerals and part of which is quite clear. The quartz is subordinate in amount and shows some strain shadowing. A little of the feldspar shows crystal form and boundaries, but most of it is irregular and crystallized at the same time as the quartz. Biotite, chlorite, and muscovite are common but are estimated to make up less than 10 percent of the rock. Of these minerals biotite is the most abundant. Accessory minerals are magnetite, apatite, and zircon.

Along Dry Gulch and Coach Creek and in Westwater Canyon, Star Canyon, Marble Canyon, and the lower canyon of the Little Dolores River the pre-Cambrian exposures consist of strongly foliated biotite gneisses and hornblende and biotite schists (pl. 6, *B*), intricately injected with quartz veins and stringers and pegmatite dikes. The foliation strikes generally east but ranges through northeast to N. 30° E. and locally is exceedingly variable and contorted. The foliation has a prevailingly steep or vertical dip, but in many places it dips toward the south at an angle as low as 45°. It is interesting to note that the foliation of the Archean schists and gneisses in the Needle Mountain region in Colorado also trends prevailingly east, with variations to a few degrees east of north, and that the dip of the foliation is there nearly vertical.[17]

Along Dry Gulch a fine-grained biotite gneiss with small garnet porphyroblasts in some layers alternates with a hornblende quartz schist in layers parallel to the foliation and ranging from a few inches to tens of feet in thickness. Porphyroblastic needles and prisms of hornblende are rare in the gneiss. Both gneiss and schist are cut by stringers and masses of quartz and of pegmatite, the latter with crystals as much as half an inch in length, and there are locally large masses of extremely hard silicified rock, the silicification apparently having cut across the foliation. The impression is gained that the gneiss was originally igneous and intrusive into the schist, although in only one place was it observed to cut off a layer of the schist across the direction of foliation. The gneiss appears to grade into the pegmatitic rock in places, and the pegmatite is definitely intrusive into the schist.

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[17] Cross, Whitman, and others, U. S. Geol. Survey Geol. Atlas, Needle Mountains folio (no. 131), p. 2, 1905.

Along the canyon of the Little Dolores River and in Westwater Canyon the exposures consist mostly of garnetiferous biotite-hornblende gneiss abundantly injected with quartz and pegmatite, the pegmatites locally with large amounts of black tourmaline. The gneiss is everywhere strongly foliated, and where the quartzose injection is abundant the foliation is contorted and sigmoidal.

A thin section of the gneiss from the Big Hole of Westwater Canyon contains much biotite and hornblende, with marked bluish-green to yellow-green pleochroism. Quartz is somewhat greater in amount than the plagioclase, which is an andesine. No orthoclase or microcline was observed. Garnet, apatite, and magnetite are accessory minerals, and the zircon in the biotite exhibits large pleochroic halos.

The exposures at the head of the canyon of Coach Creek, a little over a mile southwest of Gordon's ranch, are mostly biotite granite gneiss, which is clearly a metamorphosed coarse-grained granite. Lenses of crushed feldspar may represent original feldspar phenocrysts in the igneous rock, and in extreme types of gneiss these have been so drawn out that coalescence has developed a gneiss consisting of alternating bands of feldspar and biotite. Pegmatitic and quartz veinlets are not common, but those seen transgress the foliation and may be later than most of the foliating process. Less than half a mile south of this place are exposures consisting largely of apparently unmetamorphosed coarse-grained biotite granite and subordinately of a biotite gneiss. This gneiss appears to have been developed from a schist by such abundant injection with granitic and feldspathic material that the original schist is represented only by biotite layers now complexly and sigmoidally folded. Half a mile farther south the very coarse-grained unmetamorphosed granite is exposed, and only rock of this type is exposed still farther south.

The observations recorded above seem to support the view that the pre-Cambrian rocks of the area may be separated into an older gneiss and schist series and a younger granitic intrusive. The coarse-grained and porphyritic granite appears to have been intruded after the period of metamorphic compression, because it does not show metamorphism within the granite mass and also because it appears to have been intruded along its northern margin into an already foliated schistose rock. Furthermore, the regional metamorphism of the gneiss and schist area does not show any obvious relation to the area of granitic intrusion. For these reasons and partly also because of the accordance in direction in foliation with that of the Archean rocks in the Needle Mountains, it seems probable that the gneisses and schists in the northern part of the pre-Cambrian area here mapped are of Archean age and that the unmetamorphosed granite is of late Algonkian age.

As the area examined is rather small, as field observations were more or less casually made in connection with the studies of the other rocks, and as the various rocks have not been adequately studied microscopically, the writer feels that the crystalline complex should be referred to pre-Cambrian time without attempting a more definite age assignment.

CARBONIFEROUS SYSTEM

PENNSYLVANIAN (?) SERIES

UNNAMED CONGLOMERATE

A conglomerate containing boulders of limestone and chert as much as 15 inches in diameter embedded in an indurated yellow sandstone matrix is exposed in two isolated areas in Salt Valley—one in sec. 15 and the other in secs. 9 and 10, T. 23 S., R. 20 E. The stratigraphic relations of the conglomerate have not been ascertained, owing to complicated structure and poor exposures. The boulders of the conglomerate contain fossils, all of which are regarded by G. H. Girty as either Mississippian or longer-ranging species that could be Mississippian. The list of forms identified from the first collections is given in another paper[18] but is summarized here for completeness.

Triplophyllum, one or more species.
Fenestella, several species
Schuchertella aff. S. chemungensis
Schuchertella sp.
Productella aff. P. concentrica
Productus ovatus
Productus aff. P. fernglenensis
Rhipidomella aff. R. pulchella
Schizophoria sedaliensis?
Schizophoria sp.
Camarophoria bisinuata?
Camarotoechia aff. C. metallica
Camarotoechia sp.
Spiriferina solidirostris
Spiriferina sp.
Delthyris novamexicana?
Spirifer centronatus
Spirifer aff. S. centronatus
Spirifer sp.
Pseudosyrinx aff. P. keokuk
Cliothyridina? sp.
Composita humilis?
Composita? sp.

A collection made subsequently by E. T. McKnight contains the following species:

Triplophyllum sp.
Fenestella, several species
Schuchertella? sp.
Chonetes loganensis
Productus aff. P. burlingtonensis
Camarotoechia metallica
Aviculipecten sp.
Naticopsis sp.
Phillipsia sp.
Bairdia? sp.

These identifications were made by G. H. Girty, who says:

> This collection, like the collections made at the same locality last year, is rather certainly of Mississippian age, probably Madison.

[18] Baker, A. A., Dobbin, C. E., McKnight, E. T., and Reeside, J. B., Jr., Notes on the stratigraphy of the Moab region, Utah: Am. Assoc. Petroleum Geologists Bull., vol. 11, no. 8, pp. 789–790, 1927.

The occurrence in the boulders of the conglomerate of fossils of Mississippian age proves only the post-Mississippian age of the rock, but the abundance of fossil-bearing boulders, the absence of boulders definitely identifiable as belonging to later rocks, and the fact that no comparable conglomerate has been discovered elsewhere in any formation cropping out in the region point together to an early age for the conglomerate. As Pennsylvanian rocks are abundantly exposed in the region, the conglomerate is presumably of early Pennsylvanian age, a conclusion a priori probable from its physical constitution and somewhat reinforced by the existence of the thin Molas formation in the San Juan Mountain region of Colorado.[19] The Molas contains conglomerate beds, the boulders of which carry Mississippian fossils, and a scanty invertebrate fauna has been found in it that indicates its Pennsylvanian age and has some points of similarity with the more abundant fauna found in the overlying Hermosa formation. The Molas rests upon an erosional unconformity cut on the underlying Leadville limestone, which is of lower Mississippian age and correlated with the Madison limestone. The outcrops in the San Juan Mountains are the nearest present-day outcrops from which the lower Mississippian boulders in the conglomerate in Salt Valley could have been derived, but the probability appears strong that the lower Mississippian limestone underlies a much wider area than its existing exposures would indicate and that the boulders were derived from some source exposed nearby at the time of deposition. As the Molas formation is only 40 to 50 feet thick, and there seems no reason to suppose a great thickness for a basal Pennsylvanian conglomerate, it appears possible that Mississippian limestone may exist at no great depth beneath the surface exposure of the conglomerate. However, the structural relations in the vicinity of the exposures are so complex that this must be regarded only as a possibility. This possibility, however, might appropriately be investigated by core drilling by any company interested in exploiting the possible oil resources of the region, the drilling to be regarded only as an attempt to obtain information on the lower part of the stratigraphic succession—information which might be of practical value in subsequent deep drilling elsewhere and would surely be of scientific interest.

PENNSYLVANIAN SERIES

PARADOX FORMATION

Definition and distribution.—The Paradox formation is defined in this report as the thick series of beds of shale, sandstone, limestone, and gypsum of Pennsylvanian age which is exposed along the crest

[19] Cross, Whitman, and others, U. S. Geol. Survey Geol. Atlas, Silverton folio (no. 120), p. 4, 1905.

of the Salt Valley anticline, in two very small areas in the southeast end of Cache Valley, and along Onion Creek. Elsewhere its surface exposures are confined to small scattered areas along the crests of anticlinal folds or at the apex of domal intrusions in Grand and San Juan Counties, Utah, and west of the Uncompahgre Plateau in Colorado, but rocks of equivalent age and similar lithology are believed to crop out over wide areas in central Colorado. All outcrops of the formation have been so complexly folded, faulted, and brecciated that no complete section is exposed and no partial sections of more than a few hundred feet in thickness. The base of the formation is nowhere exposed, unless possibly in the vicinity of the outcrops of unnamed conglomerate in Salt Valley, believed to be probably the next underlying formation or the basal part of the Paradox formation. The confused structural relations and inadequate exposures around these outcrops inhibit observation of stratigraphic relations. The type locality for which the formation is named—Paradox Valley, Montrose County, Colo.—is not distinguished by particularly striking or complete exposures of the formation, although outcrops are numerous in the vicinity of the town of Paradox and along the floor of the valley. The name is applied rather because of its availability and the accessibility of the locality and outcrops as compared with most of the other exposures of the formation.

Age and stratigraphic relations.—The beds now called "Paradox formation" were briefly described by Peale [20] from their exposures on the floor of Sinbad Valley, in western Colorado. He regarded them as Permian or †Permo-Carboniferous [21] in age, because he believed that they conformably overlay eastward-dipping *Productus*-bearing limestone on the west side of the valley and dipped eastward conformably beneath the conglomeratic red beds exposed on the east side of the valley.

Later Cross saw on the way to the northern slopes of the La Sal Mountains a considerable thickness of gypsiferous beds "in the valley of Fisher Creek", obviously the Onion Creek area, and recognized their probable equivalence with the Sinbad Valley gypsiferous beds but remarked that there, as in Sinbad Valley, a zone of faulting and folding hindered an accurate determination of relationship.[22]

The exposures of the Paradox formation in Sinbad, Paradox, and Gypsum Valleys in western Colorado were described by Coffin.[23]

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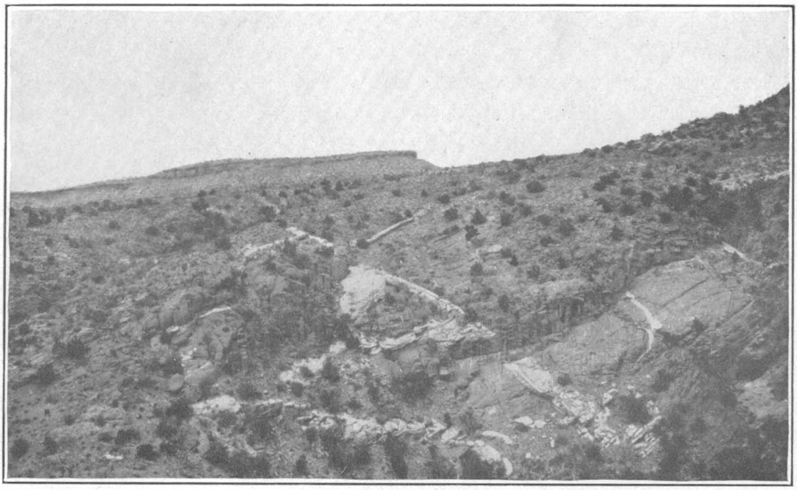
[20] Peale, A. C., Geological report on the Grand River district: U. S. Geol. and Geog. Survey Terr. 9th Ann. Rept., pp. 71–77, 1875.

[21] A dagger (†) preceding a geologic name indicates that the name has been abandoned or rejected for use in classification in publications of the U. S. Geological Survey. Quotation marks, formerly used to indicate abandoned or rejected names, are now used only in the ordinary sense.

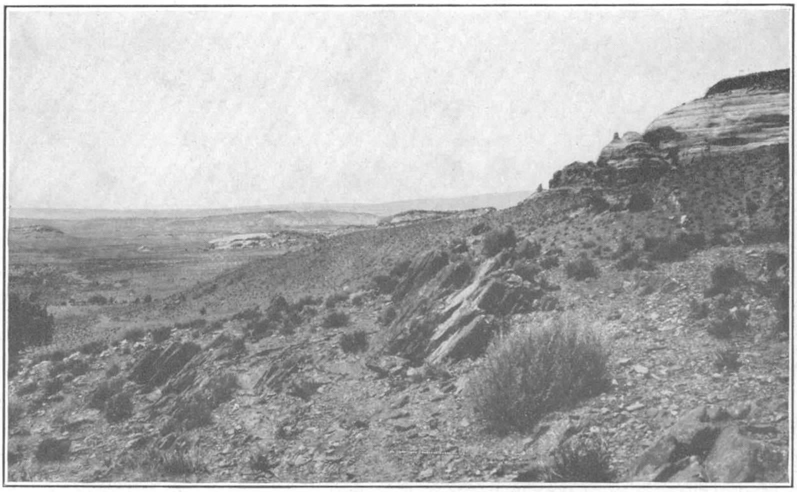
[22] Cross, Whitman, Stratigraphic results of a reconnaissance in western Colorado and eastern Utah: Jour. Geology, vol. 15, p. 666, 1907.

[23] Coffin, R. C., Radium, uranium, and vanadium deposits of southwestern Colorado: Colorado Geol. Survey Bull. 16, pp. 36–45, 1921.



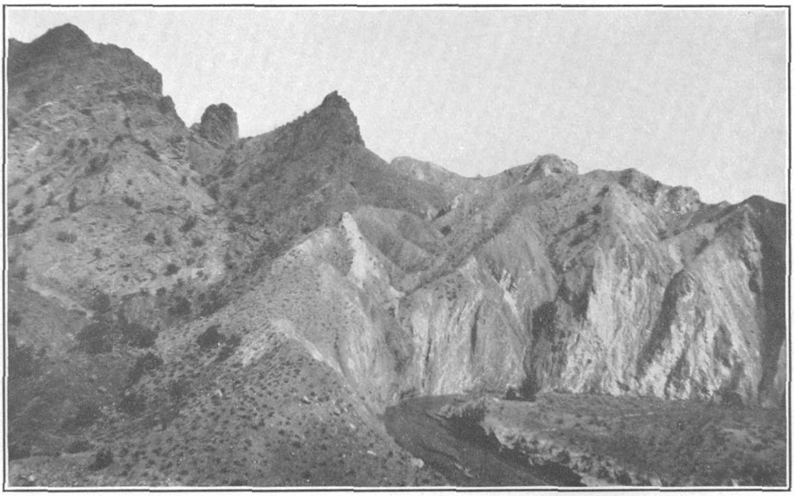
A. PRE-CAMBRIAN GRANITE NORTH OF RYAN CREEK.

View north from a point about 2½ miles west of Utah-Colorado line. The lighter-colored masses and dikes in the foreground are pegmatite. Chinle shale and the lower part of the Wingate sandstone make the sky-line ridge at the left.



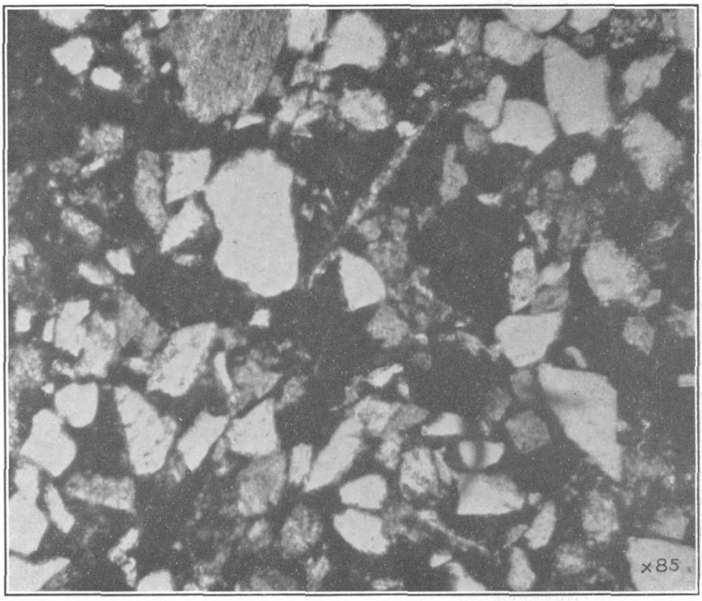
B. PRE-CAMBRIAN GNEISS AND SCHIST NORTH OF DRY GULCH.

View west from sec. 33, T. 21 S., R. 25 E. Wingate sandstone cliff at right. White patch at middle left is Entrada sandstone dropped by the Dry Gulch fault against Wingate and Kayenta formations at right. In the distance are hills of the Morrison across the Colorado River.



A. PARADOX FORMATION AT WEST END OF ONION CREEK MASS, SHOWING INTRUSIVE CONTACT WITH CUTLER FORMATION.

View up Onion Creek. Cutler formation at left; small patch of Moenkopi at right.



B. PHOTOMICROGRAPH OF FINE-GRAINED SANDSTONE OF PARADOX FORMATION.

Angular grains of quartz and feldspar and flakes of biotite in carbonate matrix.

He came to no definite conclusion on the age and stratigraphic relations of the "gypsum series", now called "Paradox formation", partly because he accepted Peale's early belief that the gypsum beds of Sinbad Valley conformably overlay the "*Productus*-bearing limestones" of the west side, which are quite surely part of the overlying Hermosa formation. Cross,[24] however, recognized that "the fault zone parallel to the axis of the valley is more complex than Peale supposed, and it seems probable that the fossil-bearing strata form a narrow and vertically upturned block * * * and that no continuous section exists in the valley by which the position of these fossiliferous beds in the whole section can be established."

With the recognition of the intrusive nature of the gypsum series[25] it is clear that the series is stratigraphically older than all formations with which it is in contact on the crests of the anticlinal folds and in all probability is the next formation in the stratigraphic succession below the Hermosa, of Pennsylvanian age, the oldest formation into which it has anywhere been thrust. There is the additional possibility that the "gypsum series" actually is the lower part of the Hermosa formation, a possibility supported by the occurrence of rock gypsum in the Rico Mountains in the lower part of the Hermosa.[26]

In 1927 the writer collected some indistinct and imperfect impressions of fossils in fragile carbonaceous shale of the Paradox formation in the Onion Creek area. These were tentatively identified as upper Mississippian by G. H. Girty.

In September 1929, however, H. D. Miser, J. B. Reeside, Jr., and the writer collected an invertebrate fauna from black shale of the Paradox formation at a locality about 1 mile west of the point where Salt Wash leaves Sinbad Valley, Mesa County, Colo. The following fossils were identified by Mr. Girty.

Conularia crustula	Deltopecten aff. D. arkansanus
Orbiculoidea sp.	Euchondria neglecta?
Chonetes sp.	Clinopistha radiata var. levis?
Ambocoelia planiconvexa	Phanerotrema aff. P. grayvillense
Nucula sp.	Trepospira sphaerulata?
Leda aff. L. arata	Pleourto maria? sp.
Schizodus sp.	

The fossils occur in a soft shale and have been more or less crushed. In consequence of their poor preservation few definite identifications could be

[24] Cross, Whitman, op. cit., p. 671.

[25] Powers, Sidney, Effect of salt and gypsum on the formation of Paradox and other valleys of southwestern Colorado: Geol. Soc. America Bull., vol. 37, no. 1, p. 168, 1926. Prommel, H. W. C., and Crum, H. E., Salt domes of Permian and Pennsylvanian age in southeastern Utah and their influence on oil accumulation: Am. Assoc. Petroleum Geologists Bull., vol. 11, no. 4, pp. 378–386, 1927.

[26] Cross, Whitman, and Ransome, F. L., U. S. Geol. Survey Geol. Atlas, Rico folio (no. 130), p. 3, 1905.

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made, some of the generic relations even being problematic. A small collection from the same horizon previously submitted to me was, I believe, tentatively identified as upper Mississippian, but on the evidence of this larger collection I am satisfied that the age of these beds is Pennsylvanian. The fauna probably represents some horizon in the Hermosa formation, though nothing closely resembling it is as yet known from the typical Hermosa. It might represent some pre-Hermosa formation that has not yet been distinguished, though it is unlike the very scanty fauna of the Molas formation at present known.

Messrs. Miser, Reeside, and the writer collected also some fragmentary plant fossils from gray sandy shales of the Paradox formation cropping out just south of the place where Salt Wash leaves Sinbad Valley. This material was submitted to the late David White for examination, and he reported in part as follows:

The plant fragments consist of fragments of stems and fern pinnules. The stems appear to belong to ferns—one may be a part of a slender calamarian branch—and are of no correlation value. The fernlike material embraces portions of pinnules only, no complete pinnule is present, and therefore specific identifications are impossible. The genera *Neuropteris* and *Pecopteris* appear to be represented. Two species of *Neuropteris* are present. One specimen showing the extreme tip of a pinnule appears by the characters of its distinct nervation to be very close, if it does not belong, to the group represented by *Neuropteris rarinervis*. The thinness of the nerves suggests a horizon either in the lower part of the McAlester shale or near the top of the Pottsville. In fact, on the strength of this single fragment, I am inclined to think that the plant horizon is somewhere near the top of the Pottsville, and more probably a little above it, though it may fall a short distance below it.

The specimen sent under separate cover probably is a tip of a pinnule of *Pecopteris*. One specimen contains one leaf that may belong either to *Asterophyllites* or *Lepidodendron* of a type more common in the late Pottsville and lower Allegheny.

I hope that the determination of the material as Pennsylvanian, and as rather likely early Pennsylvanian—that is, near to the Pottsville-Allegheny boundary—will be of assistance as well as of interest to you.

An additional collection of plant fragments made by the writer from the same locality was examined later by Mr. White, who reported as follows:

It contains a fragment of an *Asterophyllites* belonging to the *Asterophyllites gracilis* group; also a minute ovate seed, resembling a scale, that might belong to a *Cordaianthus*.

Among the fragments of indeterminate stems with carbonaceous residues there is a single short segment, which on the basis of the ribbing may have belonged to a *Sphenophyllum*. That this is probably the case is indicated by a very obscure fragment of a foliate branchlet bearing what apparently are *Sphenophyllum* leaves, but these are so badly preserved as to leave open the generic identity of the fossil, notwithstanding a suggestion of *Sphenophyllum cuneifolium*.

The small fragments representing portions only of two fernlike pinnules are perhaps both referable to the genus *Neuropteris*. One of them may, however, belong to *Sphenopteris*. The *Neuropteris*, if such it is, appears to represent a form included in the *N. schlehani* group. I think that is the species represented, though it is possible that the pinnule belongs to a form of *Phacopteris* found in the upper Mississippian.

A small seed, probably referable to *Trigonocarpon* but too badly preserved to admit reliable generic determination, also is found.

With reference to the age of the fossils I am by no means confident, for the fragments are so few and so extremely small that there is very little to go on. Not a single pinnule is complete, not to mention the complete lack of pinnae. Therefore I may be wrong in viewing these fragments as belonging to Pennsylvanian species, which they certainly resemble, rather than to Mississippian types, of which our knowledge is at the present moment relatively meager. Therefore, while I am inclined to regard these beds as of Pottsville age (they can hardly be younger) it is nevertheless to be admitted that plants which might furnish similar particles of pinnules might have lived in the upper Mississippian in western America. Were there no evidence to the contrary, I should be more strongly inclined, withal, to hold the fossils as basal Pennsylvanian.

Additional evidence on the age of the Paradox formation is furnished by a conodont fauna obtained from cuttings from a depth of 3,250 to 3,350 feet in the Midwest Refinings Co.'s well no. 1, in the SW¼ sec. 31, T. 26 S., R. 21 E., on the Cane Creek anticline, about 9 miles southwest of the town of Moab. According to P. V. Roundy, of the United States Geological Survey, who examined the cuttings, the conodont evidence indicates that the shale from 3,250 to 3,340 feet in the well is a single unit and that it probably belongs in the lower half of the Pennsylvanian.[27] Mr. Girty's remarks suggest that the fauna of the Paradox formation, although distinct from that of the Hermosa and also from that of the Molas formation, which underlies the Hermosa in the San Juan Mountain region, contains nothing to indicate that it necessarily is definitely older than the Hermosa.

Lithology and thickness.—In all known outcrops of the Paradox formation the beds have been so complexly folded, faulted, and brecciated that no section can be measured, and no idea of any original rough sequence of types of beds or of the original approximate thickness of the formation can be gained. In addition, the exposures have been intruded and veined with gypsum, in greatly varying amounts, soluble salts to unknown amount have been removed from the outcrops by solution, and it is impossible to obtain more than a general notion of the percentages of various rock types that were present in an undeformed section.

The exposures along Onion Creek (pl. 7, *A*) give the best idea of the lithologic types present in the formation. Probably the most abundant rock type in these exposures is black shale, thin-bedded or even paper-bedded. This may occur in layers several feet thick or may alternate with gray sandstone, beds of both sandstone and

[27] Baker, A. A., Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, p. 18, 1933.

shale ranging from a quarter of an inch to 2 or 3 inches in thickness. The sandstone is gray and very fine grained, and there are some gray sandy shales. The sandstone and gray shale locally contain macerated lignitic fragments and may be very carbonaceous. Some of the sandstone is richly spattered with mica flakes. The bedding is thin and regular, with flat surfaces. No ripple bedding was observed. Dense gray and yellow-gray limestone and sandy limestone are common. No fossils have been found in the limestone, although it was naturally searched first. The invertebrate fossils found in the Onion Creek area were in a shale so richly resinous that thin sections were submitted to W. H. Bradley for examination. He comments in part as follows:

As seen in the thin section parallel to the bedding, the greater part of the shale consists of somewhat cloudy brownish-yellow organic matter comparable to the organic matter in the Miocene oil shale from Elko, Nev., but of somewhat darker color. In thicker parts of the section it is dark reddish brown or even opaque, and this deep color suggests that the material is perhaps more strongly carbonized than that in the early Tertiary oil shales. The organic matter appears to be made up of minute flattened and irregular lumps that have been more or less welded together into a compact mass along with the mineral matter. The greater part of the mineral matter is concentrated in thin laminae or irregular flattened lenses. Organic matter is intimately mixed with the mineral grains of these laminae, and this suggests that a part of the organic matter was nearly or quite fluid at the time of deposition. The lumps that make up the greater part of the organic matter appear to have been gelatinous enough to retain some individuality. It is barely possible that these flattened lumps represent individual algal colonies similar to those that make up a large part of certain boghead coals, but as they show no trace of internal structure their true character is, of course, unknown. All the organic matter contains an abundance of minute organic granules that are spheroidal or rod-like, or somewhat irregular. They range from about 1 micron to 6 or 7 microns in maximum dimensions and suggest very strongly the coccoid of Renault, that is, fossil bacteria. However, I am not at all convinced that these really are bacteria; they show no corrosion pits and they seem to be withal somewhat too irregular.

The rock also contains many very minute drops of free oil, which has a rather strong reddish-brown color in transmitted light.

The thin section cut transverse to the bedding of this shale shows laminae of organic matter and mineral matter alternating in a fairly regular manner, though many irregular lenses of mineral matter occur to obscure this regularity. The average thickness of a couplet of laminae is about 0.06 millimeter (0.025 inch), the organic laminae being 2 to 9 times as thick as the mineral laminae.

The mineralogy was not studied, but quartz, feldspar, chalcedony, bleached mica, and glauconite were noted incidentally.

The scarcity of pyrite in this shale is remarkable. Most organic shales and oil shales contain an abundance of it.

Thin sections of the fine-grained sandstone of the Paradox formation were examined and reveal extraordinary angularity of the grains (pl. 7, *B*). Grains of quartz, sodic plagioclase, and microcline are scattered through a matrix of carbonate and clay minerals. The grains of feldspar are unusually fresh and unaltered. The largest grains are as much as 0.25 millimeter (0.01 inch) in longest dimension but are mostly about 0.1 millimeter (0.004 inch). There are some rounded grains, but most of them are sharply angular. Abundant flakes of biotite and some flakes of chlorite are arranged in parallel fashion through the rock, producing the appearance of flat regular bedding. The biotite flakes are deflected by and bend around the quartz and feldspar grains. The excessive angularity of the grains and the abundance of biotite suggest at first that the rock is of tuffaceous origin, but the abundance of microcline and the absence of crystals or glass show that the rock is derived from the erosion of plutonic rocks. The distance of transportation was certainly very short, and it may be that most of this distance was under water and that the grains were partly protected from abrasion by the calcareous mud that forms the matrix of the rock. The thin sections show stringers of opaque carbonaceous material that parallel the biotite flakes. Bright-green grains of glauconite are abundant in most of the sections. In the matrix there are several organic structures, not definitely referable to any class of organisms but suggesting sponge tissue or echinoid fragments. A thin section of a rock identified in the field as sandy limestone is closely analogous to the others examined, containing finer grains of quartz and feldspar, which are as strikingly angular as the grains in calcareous fine-grained sandstones. It is interesting that no organic structures were observed in this more calcareous rock, and this lack agrees with the absence of macroscopic fossils in the limestone.

Much of the shale and sandy shale is somewhat gypsiferous and salty. Rock gypsum in thick beds is abundant and is typically dark blue, gray, crystalline, and banded in lighter and darker gray. Much of it is, however, white, porous, and sugar-textured or powdery. The weathered outcrops of the formation are so abundantly coated and strewn with the white gypsum powder or with selenite crystals that they appear to be largely gypsum. In Salt Valley this is perhaps true of the surface exposures, but in the Onion Creek area probably not more than a third of the exposed rock is gypsum, and in the exposures of Sinbad Valley, southeast of the mapped area, a still smaller percentage of gypsum is present.

Bedded sodium and potash salts form part of the Paradox formation, and the wells drilled deeply into the formation report great thicknesses of pure salt and of salt alternating with anhydrite.[28]

[28] Lang, W. B., Potash investigations in 1924; U. S. Geol. Survey Bull. 785, pp. 38, 39, 1926. (The salts were at that time tentatively believed to be in the †McElmo formation.) Prommel, H. W. C., and Crum, H. E., Structural history of parts of southeastern Utah from interpretations of geologic sections: Am. Assoc. Petroleum Geologists Bull., vol. 11, no. 8, pp. 816–820, 1927.

No bedded salt has been observed by the writer in this area, but cubical salt crystals in sandstone were noted in Sinbad Valley, and the content of soluble salt in the formation is indicated by the excessively saline waters of the Stinking Springs, in the bed of Onion Creek, which flow from exposures of the Paradox formation. An analysis of this water made by Margaret D. Foster follows.

Analysis of water from Stinking Springs, Grand County, Utah

[Parts per million]

Calcium (Ca)	965
Magnesium (Mg)	132
Sodium and potassium (NaK) (calculated)	4, 489
Carbonate radicle (CO_2)	0
Bicarbonate radicle (HCO_2)	490
Sulphate radicle (SO_4)	2, 347
Chloride radicle (Cl)	6, 994
Total dissolved solids at 180° C	15, 825
Total hardness as $CaCO_3$ (calculated)	2, 954
Hydrogen sulphide (H_2S)	72

Weight in air of 1 cubic centimeter at 24° C., 1.0081 grams.

The determination of hydrogen sulphide is probably low, for it was not precipitated at the time of collection of the sample and some loss probably occurred before analysis.

It is apparent from the exposure in the Onion Creek area that the total thickness of the Paradox formation may be more than 1,000 feet, but no close estimate can be made from the evidence given by outcrops. Wells have been drilled for more than 3,000 feet in the Paradox formation, but these are on anticlines where the thickness has been increased perhaps manyfold by squeezing.

Correlation.—It seems likely that the Paradox formation is at least in part equivalent to the Pennsylvanian †Weber shales of central Colorado,[29] although the two represent deposits which may not have been continuous. The †Weber shales are lithologically similar to those of the Paradox formation, and the exposures in the vicinity of Glenwod Springs and along the Colorado and Eagle Rivers above Glenwood Springs are lithologically identical with those of the Paradox formation west of the Uncompahgre Plateau,[30] including thick beds of contorted gypsum.

The †Weber shales rest on Mississippian limestone and are succeeded upward by the †Weber grits, in places by gradation but in others with a sharp separation between the two lithologic types.[31] The two constitute the Weber (?) formation of central Colorado. The †Weber grits consist of interbedded micaceous gray grits and

[29] Emmons, S. F., Geology and mining industry of Leadville, Colo.: U. S. Geol. Survey Mon. 12, pp. 67–70, 1886.

[30] Reeside, J. B., Jr., personal communication.

[31] Lovering, T. S., Geologic history of the Front Range, Colo.: Colorado Sci. Soc. Proc., vol. 12, no. 4, p. 81, 1929.

conglomerates and gray and black shales. They are not sharply separable from the overlying Maroon formation, of Permian and Pennsylvanian (?) age.

The correlation of the Weber (?) and Maroon sequence of central Colorado with the Hermosa, Rico, and Cutler sequence of the San Juan Mountains is probably indeterminate, because of the intervening highland, which provided sediments for both sequences. A priori it seems probable that the combined †Weber grits and Maroon formation should be equivalent to the Hermosa, Rico, and Cutler sequence. If so, the equivalence of the †Weber shales and the Paradox formation would imply that neither is represented in the San Juan Mountains. However, beds of Paradox lithology are recorded below limestones of Hermosa type in a deep well in sec. 30, T. 41 N., R. 16 W., in Dolores County, Colo., only about 30 miles from the gypsiferous Hermosa beds in the Rico district. On the other hand, the eastern limit of the Paradox formation farther north has a linear trend toward the southeast, which might well separate the two occurrences of gypsiferous beds. The evidence seems to the writer to lead to the conclusion that the Paradox formation antedates most of the Hermosa, although perhaps not the Molas of the San Juan Mountains. Nevertheless, the physical evidence is inconclusive, and the relations will be definitely established only by the widespread collection of more abundant faunas accurately located in the various stratigraphic sections.

HERMOSA FORMATION

Definition.—The Hermosa formation was named and defined by Spencer in 1900, from its exposures along Hermosa Creek in the San Juan Mountain region. It includes chiefly limestone, shale, and sandstone,[32] and the sandstone is arkosic and in some beds conglomeratic. The abundant invertebrate fauna identified the formation as of Pennsylvanian age. In the same report an overlying formation of sandstone and conglomerate with intercalated shale and sandy fossiliferous limestone was distinguished and called the Rico formation. Although the Rico is conformable upon the Hermosa, it has a different faunal aspect, which led to its original assignment to the †Permo-Carboniferous, although some fossils are common to both formations. The upper limit of the Rico was arbitrarily placed at the highest known occurrence of Rico fossils, as the formation was observed to be transitional into the overlying nonfossiliferous red beds.

Both the Hermosa and Rico formations are recognized in the Moab district, west and southwest of the area described in this

[32] Cross, Whitman, and Spencer, A. C., Geology of the Rico Mountains, Colo.: U. S. Geol. Survey 21st Ann. Rept., pt. 2, p. 48, 1900.

report. The relations between the Hermosa and Rico [33] and between the Rico and the overlying beds are analogous to the relations in the San Juan Mountains. The Rico formation appears to be everywhere conformable on the Hermosa, and in places there is a lithologic transition between the gray and greenish-gray sandstone and shales and gray limestones of the Hermosa and the predominantly red sandstones and shales of the Rico. The boundary between the faunas is, however, apparently sharp, the Hermosa in general containing numerous brachiopod species and relatively few pelecypod species, and the Rico, on the other hand, containing a relatively great number of pelecypod species. The Hermosa fauna is regarded as Pennsylvanian and that of the Rico as Permian. The upper limit of the Rico formation in the Moab region, as in the San Juan region, has been arbitrarily placed at the highest known occurrence of Rico fossils, with the recognition that the upper limit as thus determined occurs at different stratigraphic horizons from place to place.

Distribution, lithology, and fossils.—The Hermosa formation crops out in only one locality in the area mapped. This is the steeply dipping exposure on the west side of Fisher Valley in unsurveyed sec. 34, T. 24 S., R. 24 E. Figure 2 shows a cross section of this exposure. The stratigraphic section given below was measured by stadia traverse.

Section of Hermosa formation on west side of Fisher Valley

Cutler formation.	
Hermosa formation:	*Feet*
Limestone, gray, poorly bedded, fossiliferous, with a zone 5 feet thick of black chert masses from a few inches to 1 foot across, the top of the zone 4 feet below the top of the unit	45
Sandstone, in part shaly, dominantly gray but streaked with red and white, cross-bedded, with streaks of conglomerate consisting principally of white and light pink feldspar	230
Sandstone and conglomerate, in thick beds, gray, the conglomerate consisting principally of angular fragments of white and light-pink feldspar as much as three-fourths of an inch in maximum dimension, but with a subordinate amount of pebbles of quartz, schist, and granite	20
Sandstone, light buff, fine- to medium-grained, thick-bedded	30
Limestone, gray, dense, with a few fossils	10

[33] Baker, A. A., Dobbin, C. E., McKnight, E. T., and Reeside, J. B., Jr., Notes on the stratigraphy of the Moab region, Utah: Am. Assoc. Petroleum Geologists Bull., vol. 11, no. 8, pp. 790–795, 1927. Baker, A. A., Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, pp. 18–29, 1933.

	Feet
Hermosa formation—Continued.	
Sandstone, light buff, fine- to medium-grained, thick-bedded. The upper half of this unit is shaly, and in places more than half of it is red shaly sandstone	240
(At this place in the section is a band of about equal proportions of excessively contorted and brecciated gypsum and gray and black shale. As shown in figure 2, this is believed to be a part of the Paradox formation which has been squeezed into the lower part of the section of the Hermosa formation, and the beds stratigraphically below this layer of gypsum are believed to be part of the Hermosa underlying the section given above, although the relations are obviously indeterminate. The gypsum and shale band is 230 feet thick.)	
Conglomerate, composed of angular fragments of pink feldspar, half an inch in maximum dimension, with much mica, calcareous cement	20
Sandstone, gray, fine- to medium-grained, thick-bedded, micaceous, calcareous, with gray shale beds in the upper half of the unit	260
Paradox formation.	
	855

From the fossiliferous limestone at the top of the section given above, a collection was made from which Mr. Girty identified the species listed below. He regards this fauna as distinctly of Hermosa aspect.

Fusulina secalica
Echinocrinus sp.
Rhombopora lepidodendroides
Derbya sp.
Chonetes granulifer
Productus cora
Productus hermosanus
Productus n. sp.?
Productus pertenuis?
Pustula nebraskensis
Spirifer triplicatus
Ambocoelia planiconvexa
Composita subtilita
Solenomya trapezoides
Edmondia aspinwallensis?
Edmondia gibbosa?
Parallelodon sp.
Schizodus sp.
Deltopecten occidentalis
Aviculipecten herzeri
Myalina perniformis?
Myalina swallowi?
Pinna peracuta
Pseudomonotis hawni
Cypricardinia carbonaria?
Dentalium sp.
Bellerophon crassus
Bucanopsis sp.
Euphemus carbonarius
Naticopsis sp.
Sphaerodoma primigenia
Schizostoma catilloides?
Euomphalus n. sp. aff. E. luxus
Griffithides.

As no fossiliferous limestones were observed higher in this section there is no portion of the overlying section that can be definitely assigned to the Rico formation, although it is possible and even likely that the lower part of the section of red beds overlying the Hermosa of this section and herein identified as Cutler formation is equivalent to beds that elsewhere can be definitely assigned to the Rico.

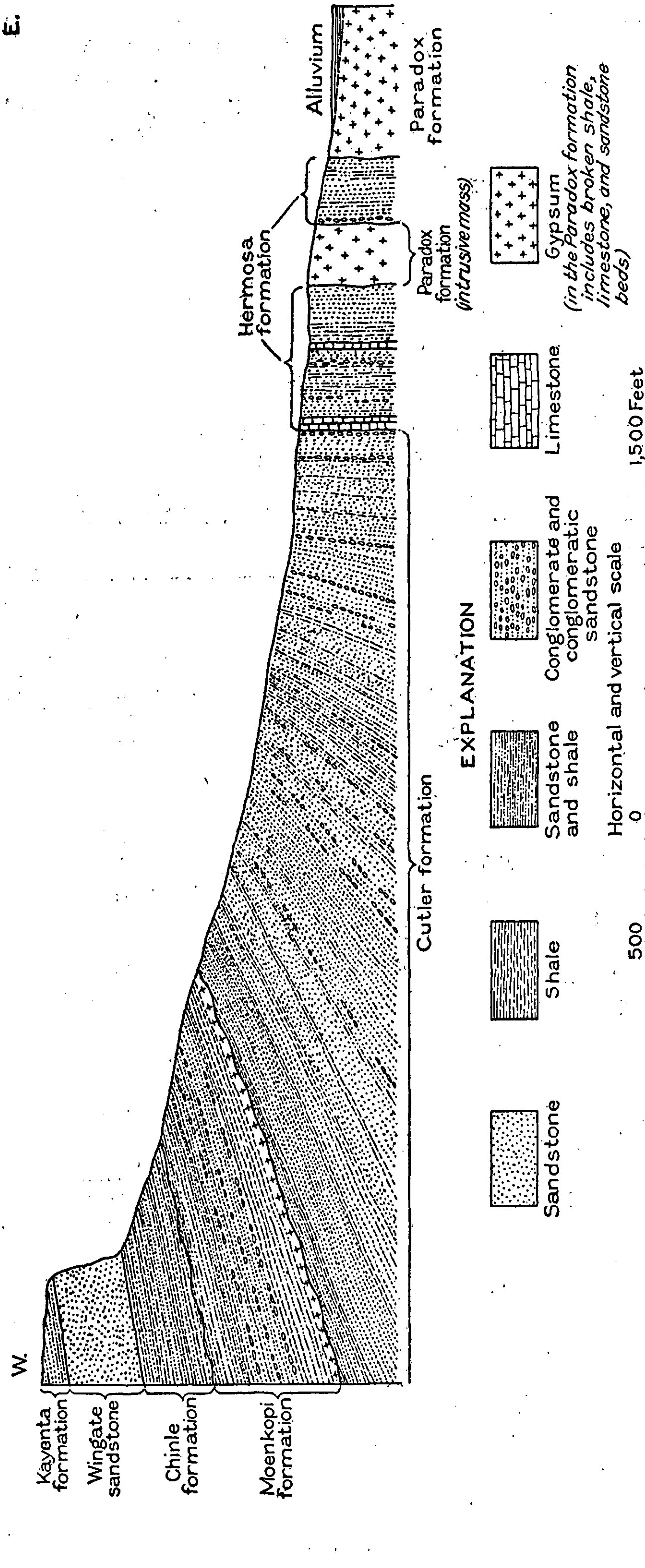

FIGURE 2.—Cross section of southwest side of Fisher Valley in theoretical secs. 32 and 33, in partly surveyed T. 24 S., R. 24 E., showing dips diminishing away from the intrusion of Paradox formation. Line of section N. 60° E. (based on stadia traverse to base of Moenkopi formation and above on widths of outcrop, dip of the Kayenta formation, and estimated formation thicknesses).

Thickness and origin.—Obviously there is little information on the probable thickness of the Hermosa in this area, and its underground thickness as shown on the cross sections is based largely on inference. The King No. 1 well of the Utah Southern Oil Co., in the SE¼ NE¼SE¼ sec. 13, T. 23 S., R. 20 E., was drilled through limestones from 1,020 to 1,570 feet. Their stratigraphic position and the drillers' description indicate that these limestones represent the Hermosa formation. Government Potash core test 24, less than half a mile south of the King No. 1 well apparently did not pass through limestones of Hermosa type before reaching the Paradox formation. Although thus locally absent, the Hermosa probably underlies most of the western half of the area mapped. Its probable subsurface distribution is indicated in several of the structural cross sections (pl. 3). The total thickness of the Hermosa penetrated by wells in the Moab district is from 1,500 to 1,800 feet.[34] The eastern limit of extension of the Hermosa is fairly well marked by its absence between the pre-Cambrian and the Permian in Granite Creek and its absence in the Utah Southern State No. 1 well, in sec. 26, T. 21 S., R. 23 E. The meager evidence available suggests that the clastic part of the Hermosa was derived by erosion from a land mass the western margin of which corresponded roughly with the present western margin of the Uncompahgre Plateau, and that the fresh feldspar, schist, gneiss, and granite pebbles found in the Hermosa conglomerates had their source in the erosion of pre-Cambrian rocks like those now exposed in the core of the plateau. The Permian and Triassic formations, which are more certainly thus derived, show gradual thinning toward the plateau, the thinning in large part occurring within the formations rather than as a result of angular truncation by overlying formations. It seems likely that the Hermosa also thins toward the plateau and is overlapped by the Cutler formation.

On the structural cross sections (pl. 3) the Hermosa formation is shown as extending farther northeast than the underlying Paradox formation. This is wholly hypothetical, for the only known Hermosa outcrops are geographically and structurally associated with outcrops of the Paradox formation. The assumption that the Hermosa conglomerates were derived from a land mass to the northeast raises the question whether the underlying Paradox formation was derived from the same source or whether it was originally a continuous deposit but was in part removed by erosion during or after the elevation of the land mass. The absence of coarse clastic material from the Paradox formation and the abundance of chemical sediment and black shales, at first thought, would imply the absence

[34] Baker, A. A., Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, p. 19, 1933.

of nearby land to the northeast. On the other hand, the local abundance of carbonaceous material and the local preservation of plant material, some of it of delicate nature, would imply that land was not far distant.

Nor could the highly angular shapes of the clastic grains in the Paradox formation have been preserved if they had been transported very far. It seems likely, therefore, that the Paradox formation also was derived from the area of the present Uncompahgre Plateau and somewhat farther east in Colorado. The clastic grains of the Paradox are apparently derived from the erosion of plutonic rocks. It seems probable, however, that the wide-spread limestones of Mississippian and Devonian age (the Leadville and Ouray limestones of the San Juan Mountain region and the Madison limestone of northern Utah) were deposited continuously across the area, which was later uplifted and eroded. Possibly older Paleozoic sediments were also deposited in this same area. These Mississippian and older sediments would have been eroded when the land mass was uplifted before or during early Pennsylvanian time, and probably they contributed much of the finest-grained material to the sediments of the Paradox formation. As elevation and erosion proceeded, more of the pre-Cambrian plutonic rocks would be exposed and the coarser sediments of the Hermosa would be deposited. On this theory the Paradox might be expected to be in some places transitional into the Hermosa, and possibly in others a sharp contact might be expected at the base of the coarser Hermosa beds. Evidence from well logs is unsatisfactory, but the record of the King well, in Salt Valley, shows an alternation of salt and limestone at the base of the limestone beds that represent the Hermosa, and similar evidence of transition is reported by Baker from wells in the Moab district.[35] The local transitional relations between the †Weber shales and †Weber grits in central Colorado appear to accord with the theory. If transitional relations exist, an overlap of the Hermosa over the Paradox toward the northeast as shown in the structural cross sections is almost certain. On the other hand, if there is an angular unconformity between the two formations, the Hermosa may or may not extend farther northeast than the underlying Paradox.

PERMIAN SERIES

CUTLER FORMATION

Definition.—The Cutler was first differentiated as a formation by Cross[36] in the Silverton quadrangle, Colorado, in the San Juan Mountains. It was separated from the overlying Triassic red beds on the convincing evidence provided by an intervening notable

[35] Baker, A. A., op. cit., p. 20.

[36] Cross, Whitman, and others, U. S. Geol. Survey Geol. Atlas, Silverton folio (no. 120), p. 5, 1905.

angular unconformity, and it was provisionally referred to the Permian because of its conformity with and transition into the underlying Rico formation. In spite of the lack of paleontologic evidence and the discontinuity of outcrops, the name "Cutler" has been justifiably applied to the formation in the Moab region because of its lithologic similarity to the outcrop in the type locality in the San Juan Mountains and because of its identical relations in both areas to the conformably underlying partly marine and fossiliferous Permian, although it is probable that the lower part of these red beds in this area is equivalent in time to the Rico formation of southwestern Colorado.

The regional correlation of the Cutler formation of this area with the Permian in adjoining States has recently been thoroughly discussed.[37]

Distribution, lithology, and thickness.—In this area the Cutler formation is a series of red and maroon cross-bedded sandstones and conglomerates with subordinate sandy shales. It crops out widely over the floor of Richardson Amphitheater, in the valley of Onion Creek and the lower part of the walls of Fisher Valley, in the eastern part of the canyon of the Dolores River, and in a narrow strip along part of Granite Creek. Red beds probably in part representing the Cutler were encountered in the King No. 1 well in Salt Valley, and the formation probably underlies nearly all the western portion of the area mapped.

The color of the mass of the Cutler is a striking and distinctive hue which has been variously described as "light pinkish purple", "claret colored", "red to maroon", and "gray pink or purplish." This purple-gray or maroon color is normally that of the arkosic portion of the formation and not that of the muddier or siltier portion, which is for the most part reddish brown in various shades.

The coarser-grained sandstones and grits of the formation are typically arkosic, with abundant fragments of feldspar, some of which are recognizable as only slightly worn crystals. Partly euhedral flakes of muscovite, biotite, and chlorite are abundant; grains of other ferro-magnesian minerals are less common. The sandstones and grits carry scattered pebbles and boulders of igneous or metamorphic rocks, the types of which can be duplicated in the exposures of the pre-Cambrian farther northeast. The pebbles where more abundant occur in irregular stringers and beds, so that there are all transitional types between coarse sandstone and conglomerate with a relatively small amount of coarse sandstone or grit matrix. The average size of the boulders and the percentage of conglomerate in the formation increase toward the northeast. In

[37] Baker, A. A., and Reeside, J. B., Jr., Correlation of the Permian of southern Utah, northern Arizona, northwestern New Mexico, and southwestern Colorado: Am. Assoc. Petroleum Geologists Bull., vol. 13, no. 11, pp. 1413–1448, November 1929.

Richardson Amphitheater the Cutler is fully half sandstone and brown minutely micaceous shale, but in the exposures along Granite Creek and east of Gateway, Colo. (east of the mapped area), it is largely conglomerate.

Along the west side of Castle Valley just southwest of the mapped area the top of the Cutler is a massively bedded orange-buff sandstone (pl. 8, *A*), which merges with the thinner-bedded brown and purplish phase of the Cutler toward the southeast along the wall of the valley and toward the northeast across the valley. This is the easternmost appearance of massive and thick-bedded lighter-colored sandstones in the Cutler, but farther west bright orange-red and buff sandstones make up an increasing portion of the formation. Gray dense unfossiliferous limestones are also present in the Cutler farther west [38] but have not been observed by the writer in this area, although a sedimentary breccia with limestone fragments is present at the base of the exposures of Cutler southwest of Round Mountain, in Castle Valley just southwest of the mapped area.

The complete thickness of the Cutler is exposed on the west side of Fisher Valley, along the south border of the area mapped, where the following section was measured by stadia traverse:

Section of Cutler formation on west side of Fisher Valley

	Feet
Moenkopi formation.	
Cutler formation:	
Arkose, medium- to coarse-grained, deep red, poorly bedded, weakly cemented	250
Arkose, massive, light red, with pebbles of schist, gneiss, and granite as much as 3 inches in diameter; grades upward into darker-red and finer-grained material	1, 100
Sandstone, micaceous, fine-grained, thin-bedded, gray streaked with red; and shale, sandy, red, micaceous	250
Conglomerate, dominantly red, with angular fragments of feldspar and quartz as much as half an inch in size, and angular pieces of limestone and red sandstone as much as 2 by 3 inches in size, with a few crinoid-stem fragments. Bed not continuous	5
Sandstone, micaceous, fine-grained, thin-bedded, gray streaked with red	120
Conglomerate, arkosic	5
Hermosa formation.	
	1,730

As shown in figure 2, the beds in the lower part of the Cutler stand vertical or dip so steeply that it seems likely that they have been squeezed and thinned, and probably the thicknesses given are too small.

Along Granite Creek the Cutler rests on the pre-Cambrian rocks. The exact thickness of the Cutler here is uncertain because of the

[38] Baker, A. A., op. cit. (Bull. 841), p. 30.

deep weathering and slump of the only partly consolidated conglomerates down over the underlying pre-Cambrian. It is probably less than 250 feet thick, although more than 150 feet. Boulders as much as 3 feet in diameter occur in the lower part of the Cutler at this locality, but the average size is much less than this, and the boulders decrease in size toward the top. A short distance farther northeast, in the gorge of Ryan Creek, no Cutler is present in the section, nor is any recorded in the log of the Utah Southern State No. 1 well, in sec. 26, T. 21 S., R. 23 E. The inferred thickness and distribution of the Cutler formation are shown on the cross sections (pl. 3).

In spite of the lack of paleontologic evidence and discontinuity of outcrops, the name "Cutler" has been justifiably applied to the formation in the Moab region [39] because of its lithologic similarity to the outcrop in the type locality in the San Juan Mountains and because of its indentical relations to the conformably underlying partly marine and fossiliferous Permian of the Rico formation.[40] The Rico formation is not recognized in the area covered by this report, as no fossiliferous limestones carrying the distinguishing Permian fauna have been found in the red-bed sequence overlying the highest fossiliferous limestones carrying the Hermosa fauna.

In the places where the Rico formation has been recognized, the assignment of the contact with the overlying Cutler formation is arbitrary, being based on the highest known occurrence of Rico fossils. The fossiliferous limestones that alone distinguish the Rico from the Cutler in the Moab region drop out of the section toward the northeast, with closer approach to the old highland, the southwest edge of which paralleled the Uncompahgre Plateau. It then becomes impossible to separate the continental red beds equivalent to the recognizable Rico from the overlying red beds, and it is necessary to refer the whole thickness to the Cutler formation, which is the procedure adopted in the paper.

Analogous relations apparently exist in the San Juan Mountains, for the Rico formation is not recognized in the vicinity of Ouray,[41] which is much closer to the margin of the old Uncompahgre highland than the vicinity of Rico, 30 miles southwest of Ouray, where the Rico formation is recognized.

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[39] Baker, A. A., and others, Notes on the stratigraphy of the Moab region, Utah: Am. Assoc. Petroleum Geologists Bull., vol. 11, no. 8, p. 795, 1927. Baker, A. A., and Reeside, J. B., Jr., Correlation of the Permian of southern Utah, northern Arizona, northwestern New Mexico, and southwestern Colorado: Idem, vol. 13, no. 11, p. 1425, 1929.

[40] Cross, Whitman, and Spencer, A. C., Geology of the Rico Mountains, Colo.; U. S. Geol. Survey 21st Ann. Rept., pt. 2, p. 61, 1900. Cross, Whitman, and Ransome, F. L., U. S. Geol. Survey Geol. Atlas, Rico folio (no. 130), pp. 3–4, 1905. Baker, A. A., and others, op. cit., p. 792.

[41] Cross, Whitman, U. S. Geol. Survey Geol. Atlas, Ouray folio (no. 153), pp. 4–5, 1907. Burbank, W. S., Revision of geologic structure and stratigraphy in the Ouray district of Colorado and its bearing on ore deposition: Colorado Sci. Soc. Proc., vol. 12, no. 6, pp. 165–166, 1930.

TRIASSIC SYSTEM

LOWER TRIASSIC SERIES

MOENKOPI FORMATION

Definition.—The term "Moenkopi formation" was applied by Ward [42] to the lowest portion of the Mesozoic beds exposed near the mouth of Moenkopi Wash,[43] in northeastern Arizona. The term was extended throughout the Navajo country by Gregory,[44] but, as recently shown by Baker and Reeside,[45] he included a considerable thickness of Permian red beds in his Moenkopi of the Defiance Plateau and the San Juan Valley. He regarded the Moenkopi as probably of Permian age, basing this assignment in part on the identification as Permian of fossil plants collected from beds that Baker and Reeside now exclude from the Moenkopi.

The Lower Triassic age of the Moenkopi was established by the paleontologic studies of G. H. Girty and the stratigraphic studies of several workers.[46] Subsequent investigations have increased the known geographic distribution of the formation, more rigorously defined the stratigraphic relations to overlying and underlying formations, and confirmed its lower Triassic age.[47]

Distribution and fossils.—In the area mapped the Moenkopi crops out most extensively in the lower part of the walls of Richardson Amphitheater, Fisher Valley, Beaver Canyon, Cottonwood Canyon, and the adjoining portion of the Dolores River Canyon. It also crops out in two small areas in the east end of Cache Valley and in scattered small areas in the lower part of Salt Valley. The correlation of the Moenkopi of this area with that of areas farther east and south is based on lithologic similarity and corresponding stratigraphic relations to overlying and underlying formations. Although

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[42] Ward, L. F., Status of the Mesozoic floras of the United States: U. S. Geol. Survey Mon. 48, pt. 1, pp. 18–19, 1905.

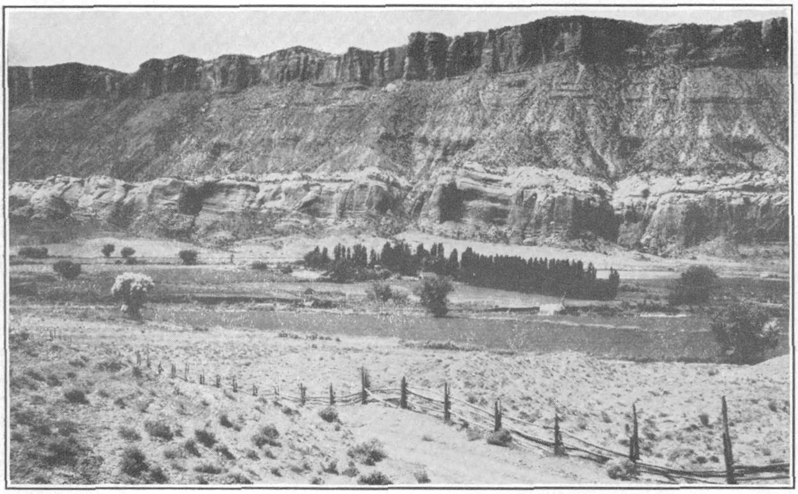
[43] The spelling "Moenkopi" has been adopted by the United States Geographic Board in place of the original "Moencopie."

[44] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, pp. 23–31, 1917.

[45] Baker, A. A., and Reeside, J. B., Jr., Correlation of the Permian of southern Utah, northern Arizona, northwestern New Mexico, and southwestern Colorado: Am. Assoc. Petroleum Geologists Bull., vol. 13, no. 11, pp. 1423–1425, 1929.

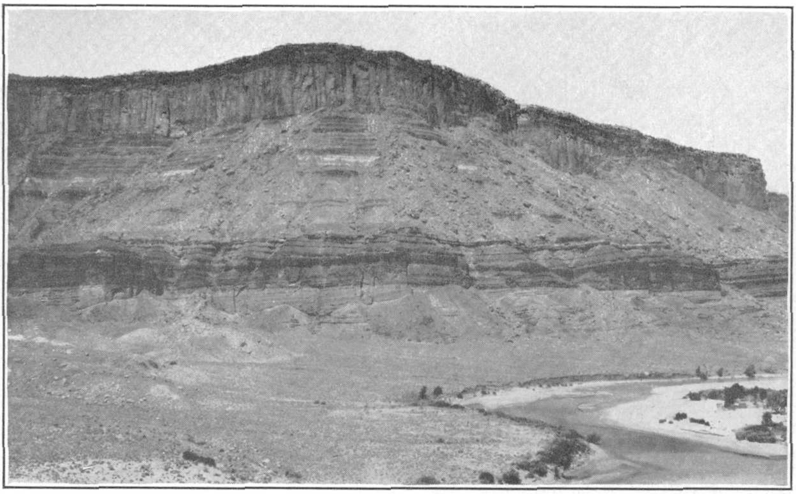
[46] Shimer, H. W., The Permo-Triassic of northwestern Arizona: Geol. Soc. America Bull., vol. 30, pp. 492–497, 1919. Longwell, C. R., Geology of the Muddy Mountains, Nev., with a section to the Grand Wash Cliffs, in western Arizona: Am. Jour. Sci., 5th ser., vol. 1, p. 49, 1921. Reeside, J. B., Jr., and Bassler, Harvey, Stratigraphic sections in southwestern Utah and northwestern Arizona: U. S. Geol. Survey Prof. Paper 129, pp. 59–62, 1922. Longwell, C. R., and others, Rock formations in the Colorado Plateau of southwestern Utah and northern Arizona: U. S. Geol. Survey Prof. Paper 132, pp. 9–11, 1925.

[47] Gilluly, James, and Reeside, J. B., Jr., Sedimentary rocks of the San Rafael Swell and some adjacent areas in eastern Utah: U. S. Geol. Survey Prof. Paper 150, pp. 65–66, 1928. Baker, A. A., Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, pp. 34–37, 1933. Baker, A. A., Geology and oil possibilities of the Monument Valley-Navajo Mountain district, Utah: U. S. Geol. Survey Bull 865 (in press).



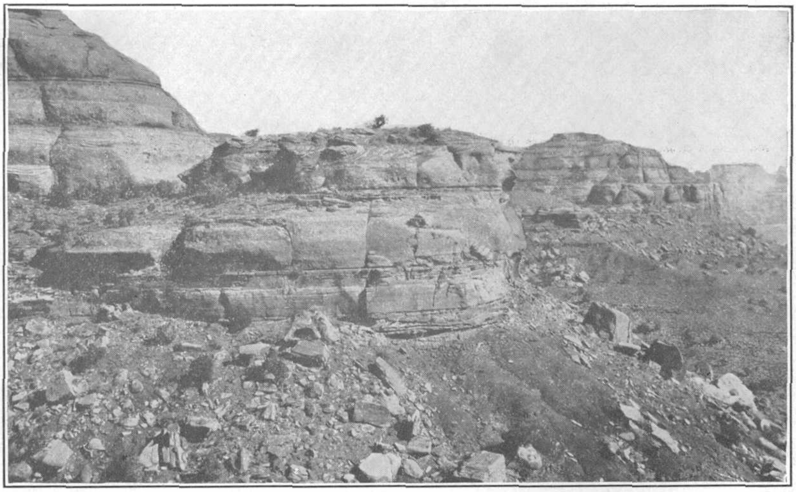
A. ANGULAR UNCONFORMITY TRUNCATING CUTLER SANDSTONE IN LOWER CASTLE VALLEY.

View southwest across the valley. The steep slope above includes the Moenkopi and Chinle formations; the cliff at the top is the Wingate sandstone with a thin capping of basal Kayenta.



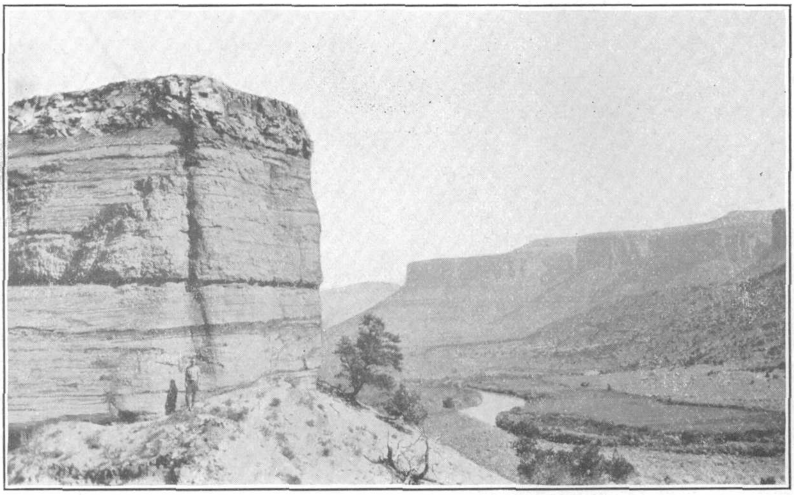
B. CLIFF NORTH OF THE COLORADO RIVER, FROM NE¼ SEC. 20, T. 24 S., R. 23 E.

The skyline cliff is Wingate sandstone capped by the Kayenta formation; the white streak is the basa grit bed of the Chinle formation; the dark ledge below is the basal part of the Moenkopi formation which rests with angular discordance on the underlying Cutler.



A. CHINLE SHALE AND OVERLYING WINGATE SANDSTONE AT BIG HOLE, WESTWATER CANYON, COLORADO RIVER.

Photograph by C. E. Erdmann.



B. VIEW DOWN THE DOLORES RIVER FROM A POINT A FEW MILES ABOVE GATEWAY, COLO.

At the left the basal beds of the Moenkopi formation rest on the Cutler formation, the contact marked by the deeply shadowed recession. At the top is a bed of gypsum. The prominent cliff across the river is made by the Wingate sandstone. Photograph by H. D. Miser.

outcrops are not continuously connected, they are interrupted for such short distances that the formation has virtually been traced over most of southeastern Utah. In the San Rafael Swell the Moenkopi contains a marine limestone member [48] from which a definitely Lower Triassic fauna has been determined. This limestone member with its contained marine fauna forms part of the Moenkopi as far east as the head of Stillwater Canyon on the Green River.[49] From sandy shales in Salt Valley, however, McKnight collected a scanty fauna, which is described as follows by G. H. Girty:

> This lot contains trails, plant fragments, and enigmatic objects of several sorts. Aside from these I find only one fossil type of any significance—concentrically coiled shells that occur in considerable abundance. Although none of the specimens collected shows sutures or other diagnostic structures, it seems highly probable not only that these are cephalopods but that they are ammonoids rather than nautiloids. Smooth ammonoids of the same general appearance are rather characteristic of the Lower Triassic of this region. This fact, together with the absence of any Paleozoic types of fossils and other attendant circumstances leads me to believe that the horizon is Lower Triassic.

Stratigraphic relations.—In this area the Moenkopi rests upon an angular unconformity which truncates the underlying Cutler beds. This angular discordance is well shown at several localities in Richardson Amphitheater (pl. 8, *B*) and in Castle Valley just southwest of the mapped area (pl. 8, *A*). In the area of Richardson Amphitheater this unconformity systematically cuts down through the Cutler beds and, as can be seen east of the mapped area in the canyon of West Creek, east of Gateway, Colo., reduces the Cutler to a very small thickness.

Despite the definite angular unconformity separating the Moenkopi from the Cutler, it is at many places difficult to locate the precise contact between the two formations, because of similar lithology and evident reworking of the immediately underlying Cutler into the basal layer of the Moenkopi. At one locality rounded boulders of soft Cutler arkose are included in the basal Moenkopi, and at others the basal Moenkopi layer contains so large a percentage of finer material reworked from the Cutler that there is actually transition of lithology across the contact. Where observed the contact shows only slight local irregularity.

Lithology.—The basal beds of the Moenkopi, except for the thin zone of reworked material, are nearly everywhere fine-grained and where they are sandstone have a muddy or silty matrix that serves to differentiate them from the cleaner sands of the Cutler immediately below. More commonly the basal beds are brown mudstone or siltstone with poorly defined but regular horizontal bedding.

[48] Gilluly, James, and Reeside, J. B., Jr., op. cit., p. 65.

[49] McKnight, E. T., unpublished data.

The basal portion of the Moenkopi in the southern part of its exposed area contains a bed of gypsum which is only locally interrupted. It crops out southwest and southeast of Pariott Mesa, just off the area shown on plate 1, and on the west wall of Fisher Valley, and local thin beds of gypsum are present near the base of the Moenkopi along the south side of the Dolores River east of Beaver Creek. West of the mapped area the gypsum occurs at the base of the Moenkopi along the west wall of Castle Valley, and east of the mapped area it has been observed on the west end of Palisade Butte, north of Gateway, Colo., along the southwest side of the Dolores River west of Gateway, and along the southwest wall of the Dolores River as far south as Sinbad Valley (pl. 9, *B*). The thickness of the bed in few places exceeds 6 feet. The gypsum may be at the base of the formation but in most places succeeds 5 to 20 feet of brown mudstone or siltstone. Its distribution does not accord with any specific thickness of the formation, nor does its approximate northern and eastern edge conform in direction to the line of disappearance of the Moenkopi from the section. Whether it is a contemporaneous deposit or homotaxially equivalent, its occurrence has a significance which accords with the generally finer-grained material deposited in the lower part of the formation, as contrasted with the coarsely conglomeratic material higher in the formation over part of its area of outcrop.

Typically the Moenkopi exposed in Cache Valley and the western part of Richardson Amphitheater is an evenly bedded series of alternating chocolate-brown to reddish brown sandy shales and micaceous silty sandstones, weathering to steep slopes covered by soft fine debris. The bedding surfaces of the sandstones are strikingly marked with current ripples. In Cache Valley and in the westernmost exposures north of the Colorado River there are a few beds of arkosic conglomerate with pebbles and small boulders of metamorphic and igneous rocks. Such beds are few, however, and the section given below may be regarded as typical of the Moenkopi of this locality.

Section of Moenkopi formation on north side of Colorado River northwest of Richardson

[Measured by J. W. Vanderwilt and O. R. Murphy]

Chinle formation (contact irregular).	
Moenkopi formation:	*Feet*
Sandstone, red, medium-grained, micaceous, light purplish gray on weathered surface	6
Siltstone, red, sandy in places	18
Sandstone, light purplish red, friable, medium-grained, mostly quartz grains but with some feldspar and much biotite mica in streaks 1 to 1½ inches thick	8
Shale, sandy, brownish red, with much mica	24

	Feet
Moenkopi formation—Continued.	
Sandstone, red, fine-grained; much mica along bedding planes	3
Shale, light brownish red	22
Sandstone, red, fine-grained, with included fragments of red shale; lower 18 feet massive; upper 15 feet in beds 2 to 4 feet thick and cross-bedded	33
Shale, thin-bedded, yellowish brown, penetrated by thin veinlets of gypsum	214
Sandstone, brownish red, fine-grained, thin-bedded	6
Sandstone, light gray, medium-grained, friable; lower part massive; upper part thin-bedded and shaly	14
Shale, yellowish brown, thin-bedded, penetrated by thin veinlets of gypsum	155
Shale, sandy, light brownish red, ripple-marked, containing appreciable amounts of biotite and muscovite along bedding planes, with interbedded sandstone layers making about 10 percent of the total thickness	89
Sandstone, thin-bedded, brownish red, fine-grained, shaly in places; weathers to a massive ledge	16
Shale, sandy, very thin-bedded, dark brownish red, interbedded with sandstone in layers less than 6 inches thick; the more sandy beds abundantly ripple-marked; sandstone and shale in about equal parts; a few discontinuous beds of limy sandstone 2 to 4 inches thick	88
Sandstone, shaly, light brownish red, uniformly very fine-grained	66
Sandstone, shaly, dark brownish red, uniformly very fine-grained; bedding indistinct on weathered surface but very regular when examined in detail; commonly weathers to a vertical cliff	85
Sandstone, dark brownish red, argillaceous, fine- to medium-grained, bedding regular; thin streaks of grit with grains as much as one-eighth of an inch in diameter, principally of quartz but in part of feldspar and mica, in the lower 1 foot contains reworked material from the underlying Cutler, including rounded pebbles and boulders 6 inches or less in diameter	8
	855

Unconformity, irregular surface and angular discordance.
Cutler formation: Red and purplish coarse arkose and conglomerate.

The lower portion of the Moenkopi in Richardson Amphitheater and as recorded in the above section is distinctly darker in color and weathers to a nearly vertical cliff. This lower dark band is clearly shown in plate 8, *B*.

Eastward in Richardson Amphitheater the Moenkopi contains an increasingly large percentage of grit and conglomerate, and the boulders in the conglomerate reach larger sizes. In the same direction the formation diminishes to less than half of the thickness exposed on the west side of the amphitheater and in lower Castle Valley. Along the northwest wall of the amphitheater the formation is continuously exposed, although somewhat obscured by talus and slide rock from the cliffs above. The exposures are sufficiently clear to show that the northeastward thinning of the Moenkopi takes place largely within the formation by thinning and disappearance of individual beds, rather than by truncation of the formation as a whole by unconformity at the base of the overlying formation, although such angular truncation is a minor factor in reducing the thickness of the Moenkopi eastward. The section at the northeast end of Richardson Amphitheater, given below, illustrates the more coarsely conglomeratic nature of the formation in this direction.

Section of Moenkopi formation northeast of Hittel's ranch, on the southeast side of the Colorado River

	Feet
Chinle formation (contact obscure but apparently sharp).	
Moenkopi formation:	
Shale, slightly micaceous, dark brick-red	2
Shale, minutely micaceous, thin-bedded, principally chocolate-red, with some red-brown sandstone	20
Shale, minutely micaceous, chocolate-red, and sandstone, brick-buff, cross-bedded, ripple-bedded	11
Sandstone, banded purple and reddish buff, slightly calcareous; makes a ledge	6
Shale, minutely micaceous, chocolate-brown and dark red; sandy shale; sandstone, buff, ripple-bedded, thin-bedded, in layers 1 foot thick; and a few ledges of brick-buff sandstone 2 feet thick	83
Sandstone, fine-grained, reddish-buff, calcareous	3
Shale, minutely micaceous, chocolate-red, nearly pure	4
Sandstone, fine-grained, reddish buff, and sandy shale, with a few light-green thin-bedded partings of shaly sandstone	6
Sandstone, micaceous, the mica flakes outlining contorted bedding structures in the lower foot, apparently owing to subaqueous flowage; these structures truncated by overlying lenticular poorly ripple-bedded sandstone; similar structure appears above in two other beds in the unit	2
Sandstone, fine-grained, light green, and sandy shale, red	1
Sandstone, shaly, buff, hard	6
Sandstone, shaly, buff, poorly ripple-bedded, and shale, dark red-brown; alternating in beds a quarter of an inch to 2 inches thick; thinner beds lenticular and discontinuous within a few feet; thicker beds traceable for 50 feet along the exposure; sandstone beds carry flakes of red shale	6

	Feet
Moenkopi formation—Continued.	
Sandstone, brick-red, fine-grained, ripple-bedded; arkose, medium-grained; shale, sandy, very chloritic; arkose, coarse, with pebbles of feldspar three-eighths of an inch in maximum dimension; buff sandstone; and thin-bedded dark-red sandy shale. These materials alternate in beds from 2 to 6 inches thick; individual beds vary in thickness but are essentially continuous and horizontal	25
Arkose, coarse, cross-bedded, subangular pebbles of feldspar and granite a quarter of an inch in maximum dimension	2
Sandstone, shaly, light brick-red, ripple-bedded; interbedded with shale, minutely micaceous, dark red-brown	14
Sandstone, fine-grained, brick-red, cross bedded, with irregular layers of coarse arkose containing granite and feldspar pebbles; at the top ripple-bedded and cross-bedded	13
Sandstone, fine-grained, brick-red, ripple-bedded	2
Arkose, soft, calcareous	2
Sandstone, fine- and medium-grained, light brick-red, hard, poorly ripple-bedded; contains some flakes and pellets of red shale	4
Sandstone, fine-grained, brick-red, ripple-bedded; shale, pure, dark red; shale, sandy, red-brown; and arkose, coarse, with subangular pebbles of feldspar half an inch in maximum dimension. These types alternate in beds 2 to 12 inches thick. The thickest arkose bed is 6 inches thick and is traceable at least 200 feet along the exposure. There are some thin beds of light-green shale and hard micaceous light-green sandstone	15
Sandstone, fine-grained, brick-red, ripple-bedded	2
Sandstone, shaly, light brick-red, and shale, sandy, dark red	6
Sandstone, arkosic, coarse-grained, purple, cross-bedded, and sandstone, brick-red, fine-grained. Some of the arkosic beds an inch thick contain about 25 percent of muscovite and chlorite flakes	7
Shale, sandy, dark-red, thin-bedded, and sandstone, shaly, light brick-red	4
Sandstone, brick-red, fine-grained, ripple-bedded, and sandstone, purple-red, medium-grained, ripple-bedded, with much bedding-plane chlorite and some muscovite	2
Grit, arkosic, purplish red, cross-bedded; sandstone, brick-red; and shale, sandy, brick-red. Alternating in beds 2 inches to 6 inches thick	9
Arkose, conglomeratic, with pebbles half an inch in maximum dimension but averaging less than a quarter of an inch; calcareous cement	3

Moenkopi formation—Continued.	Feet
Sandstone, shaly, brick-red, thin-bedded; some beds with grit lenses and abundant bedding-plane muscovite and chlorite; some beds without these features and with pronounced ripple bedding	8
Arkose, conglomeratic, with calcareous cement, cross-bedded, alternating with brick-red sandstone	9
Sandstone and arkose, brick-red, with calcareous cement; the lower 2 feet is coarse conglomeratic arkose, which grades upward into hard cross-bedded fine-grained sandstone; the arkose diminishes to disappearance laterally in a few hundred feet	5
Shale, sandy, red, thin-bedded	2
Conglomerate, arkosic, with calcareous cement, and sandstone, reddish gray. The largest pebbles in the conglomerate are 1 inch in maximum dimension. Pebbles of quartz, quartzite, granite, biotite gneiss, and feldspar are abundant. This bed dies out within 50 feet in each direction along the exposure	½
Shale, sandy, red-brown; sandstone, shaly, fine-grained, and some shale, pure, dark red, thin-bedded. Mostly hard and slightly calcareous, occasionally mottled green. The shaly beds are micaceous; some bedding planes are almost continuously sheeted with fine flakes of chlorite and muscovite. The sandstone is composed principally of subrounded to perfectly rounded quartz grains with subangular grains of feldspar as an accessory constituent. The unit is in regular continuous beds 2 to 4 feet thick, separated by softer more shaly partings 2 inches to 1 foot thick. The harder beds stand out but weather into rounded surfaces separated by subvertical joints. Within these beds the bedding is irregular, stringers of coarser material not paralleling the general bedding and dying out in less than a foot laterally. Some thin layers are grits with rounded, coarse grains of pink, salmon-colored, transparent, and dark quartz. The sandy beds predominate in the unit, and quartz pebbles a quarter of an inch in diameter are common. Toward the top the color of the unit gradually becomes lighter and in the upper half is a light yellow-brown. Scattered throughout the sandy beds are flakes and pellets of red shale	106
Shale, sandy, red-brown, calcareous, with much biotite and muscovite and scattered quartz grains; sandstone, shaly, red-brown, calcareous, with much biotite and muscovite, chiefly quartz, but with some feldspar grains; and sandstone, light green, of the same grain composition	8
Sandstone, brown, medium-grained, calcareous, principally containing subrounded quartz grains, in discontinuous beds and small lenses, alternating with shale, dark red, pure, thin-bedded, and some shale, sandy, light green	2

	Feet
Moenkopi formation—Continued.	
Sandstone, brown, coarse-grained, with subangular and subrounded quartz, some biotite, chlorite, and muscovite, and a little feldspar. Within this sandstone there are lenses 3 to 4 inches long of fine-grained light-green sandstone, of subrounded quartz and very small flakes of mica. This unit is apparently reworked Cutler at the base of the Moenkopi, and in this section the actual sharp contact is not recognizable	1
Total Moenkopi formation	401½

Angular unconformity.

Cutler formation: Sandstone or arkose, slightly argillaceous, light purple, grain size variable from fine to medium coarse, with scattered grit grains. Grain content is angular quartz, partly euhedral feldspar, flakes of muscovite, partly euhedral flakes of biotite and chlorite, and a decomposed ferromagnesian mineral, possibly pyroxene.

A section measured about 7 miles southeast of the preceding one, in the lower part of the cliff north of the north line of sec. 24, T. 24 S., R. 24 E., shows that the Moenkopi is 370 feet thick at this place. As this is only a little less than the thickness of 401½ feet measured near Hittel's ranch, it is clear that the thinning of the Moenkopi occurs in a northeasterly direction at right angles to the line between the two sections and almost parallel with the line of cliffs northwest of Richardson Amphitheater.

The nature of the Moenkopi formation in its easternmost exposures within the area mapped is indicated by the following section:

Section of Moenkopi formation on south wall of Dolores River Canyon just east of Beaver Creek

[Measured by C. H. Dane, J. B. Reeside, Jr., and H. D. Miser]

	Ft.	in.
Chinle formation (contact poorly exposed but undoubtedly an irregular surface).		
Moenkopi formation:		
Sandstone, red-brown, fine-grained, platy, with a few layers of coarse sandstone. Indications of ripple bedding	10	
Conglomerate, purplish gray; maximum pebble diameter 3 inches	4	6
Sandstone, buff, fine-grained, laminated		6
Grit, arkosic, purplish gray, coarser-grained toward the top	5	6
Conglomerate, with coarse sandstone layers near the base; contains pebbles of igneous rock 6 to 9 inches in diameter	8	
Mudstone, red-brown, with a zone 5 feet thick of slightly ripple-bedded sandstone and thin sandy shale, near the middle	12	

Moenkopi formation—Continued.	Ft.	in.
Sandstone, buff, fine-grained, thinly laminated; perfect horizontal bedding at the top, with low-angle cross-bedding below; makes a ledge	9	
Conglomerate of general purple-gray hue but at close observation shows red, brown, gray, and white as well as purple. Pebbles of schist, pegmatite, gneiss, graphic granite, feldspar, and vein quartz. Some pebbles decayed; others fresh. The maximum coarseness is near the top, where cobbles from 12 to 18 inches in diameter were observed. Some thin sandstones are interbedded with the conglomerate	81	
Gypsum, white, sugar-textured, contorted and irregular	1	
Grit, coarse sandstone, and conglomerate, with pebbles like those in the next overlying conglomerate but rarely exceeding half an inch in diameter	13	
Sandstone, salmon-brown, very fine grained; bedding thin and so curved as to suggest ripple bedding throughout	3	
Sandstone, white, coarse-grained, with grit lenses, ripple bedding	4	
Sandstone, red-brown with green streaks, muddy, coarse subrounded and subangular polished quartz grains, grains of green mica and some feldspar scattered in a muddy matrix; weathers to a soft slope, which probably conceals some shale layers	15	
Mudstone, red-brown, and fine-grained calcareous sandstone, with some nearly pure red clays. Good ripple bedding	19	
Sandstone, muddy, red-brown, poorly sorted, with coarse grains scattered throughout; considerable mica, a large part of which is biotite	40	
Sandstone, muddy, with some layers of grit, mud-pellet conglomerates, and richly micaceous layers	23	
Grit and sandstone, poorly sorted, grains of feldspar, quartz, and mica 0.15 inch in maximum size; bed is of irregular thickness	2	
Sandstone, red-brown with green-gray streaks, muddy, with layers of fine grit, composed chiefly of subrounded and some angular grains of quartz, subordinately of feldspar and green mica; weathers to a soft slope, which probably conceals some shale layers	35	
Gypsum, white, finely sugar-textured, cut by veinlets of selenitic gypsum. Thickness variable; probably thins out in places. Bed is visible only at the place where the section was measured; if present elsewhere it is washed over	1	
	286	6

Contact irregular, obscured by secondary gypsum veining.
Cutler formation: Arkosic conglomerate, grit, and sandstone.

No Moenkopi has been identified between the Cutler and the overlying Upper Triassic in the exposures along Granite Creek, 5 miles north of the section given above, so the disappearance of the Moenkopi from the section takes place under cover in the area mapped. It is, however, well exposed in the canyon of West Creek east of Gateway, Colo., a short distance southeast of this area.

The thickest section of Moenkopi yet measured in this general region crops out in Sinbad Valley, Colo., about 10 miles south of Gateway. Although 1,120 feet thick, it contains an abundance of conglomeratic and gritty material, indicating a distance from the source of supply comparable with that indicated by the thinner sections exposed in the eastern part of Richardson Amphitheater and in Fisher Valley.

The Moenkopi is not present in the stratigraphic section exposed northeast of the Dolores River, nor in the Utah Southern State No. 1 well, in sec. 26, T. 21 S., R. 23 E.

The sections of the Moenkopi given above bring out clearly the northeastward thinning toward the present Uncompahgre Plateau, which is also shown on the structural cross sections (pl. 3). Although this northeastward thinning is systematic in the east half of the area mapped, there are less uniform variations in the thickness of the Moenkopi in the west half of the area. The Moenkopi is exposed at only one locality along the Colorado River west of Castle Valley, and there incompletely, and in scattered small areas in the structurally complex southern part of Salt Valley. The Moenkopi is exposed along the southwest wall of Castle Valley southwest of the area mapped (pl. 8, *A*). Toward the east and south along this wall internal thinning is clearly visible in the Moenkopi, most pronounced in the lower part of the formation.

The Moenkopi is also exposed along the west wall of Moab Valley and is there cut out southward by an angular unconformity.[50] It is, moreover, greatly thinned northward along the northern continuation of the valley wall north of the Colorado River by an unconformity at the base of the overlying Upper Triassic.[51]

The King No. 1 well of the Utah Southern Oil Co., in sec. 13, T. 23 S., R. 20 E., passes through only 510 feet of red beds between the base of the Jurassic (?) sandstones and the limestones supposed to be the Hermosa formation. Of this thickness 50 feet has more or less arbitrarily been assigned to the Moenkopi. For reasons discussed in the section on structure (p. 152), the thinness of the Moen-

[50] Baker, A. A., and others, Notes on the stratigraphy of the Moab region, Utah: Am. Assoc. Petroleum Geologists Bull., vol. 11, no. 8, p. 793, 1927.

[51] McKnight, E. T., Geology of an area between the Green and Colorado Rivers, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. (in preparation).

kopi at this place is attributed to regional northward truncation of the formation, and this interpretation is shown on the structural cross sections.

Conditions of deposition.—It is obvious that the source of the Moenkopi sediments of this area and probably of a much larger area to the southwest lay in the direction of the Uncompahgre Plateau and probably not far northeast of the present vanishing edge of the formation. The vast quantities of coarse conglomerate, in which the boulders are of lithologic types present in the complex of metamorphic and igneous rocks exposed along the crest of the plateau, point surely to a nearby source. To judge from the size of the boulders, the percentage of conglomerate as compared with finer-grained sediments, and the places at which the formations thin out, both the Cutler and the Moenkopi formations were derived from an eroding area in about the same geographic position. Nevertheless, the two formations present some striking lithologic differences, which imply a somewhat different mode of accumulation. The bedding of the Moenkopi is strikingly regular and horizontal. This is true to an extreme degree in the finer-grained silty and shaly beds, but regular bedding is maintained to a surprising extent, even in the more gritty and conglomeratic beds, which are interbedded with thin even layers of shale and siltstone. In the Cutler, on the other hand, lenticularity, channeling, and cross-bedding are in many places conspicuous. Nevertheless, regular horizontal bedding is predominant in places in the Cutler beds, and cross-bedding of minor degree is common in the Moenkopi. The Moenkopi beds are strikingly ripple-marked from top to bottom, not only in this area but almost everywhere the formation is exposed. The ripples are of the current-formed type, although oscillation ripples have been observed. Mud cracks are less conspicuous, but are widespread and fairly common. In connection with the lithologic features of the Moenkopi in this area, it is necessary to keep in mind the definite marine limestones farther west in Utah and the marine fossils found in the Moenkopi as far east as Salt Valley. It seems certain that part of the Moenkopi even within this area was deposited in the marginal portion of an extensive sea.

The angular discordance at the base of the Moenkopi and the truncation of the underlying Cutler indicate that a considerable time elapsed between the periods of deposition of the two formations and also that the older beds were tilted by structural movements away from the axis of uplift to the northeast. It is known also that more local and irregular deformation occurred before the deposition of the Moenkopi. The smooth contact between the two formations seems to indicate marine planation rather than subaerial channeling. Unfortunately, the Moenkopi nowhere rests on the pre-Cambrian directly, as the overlying Upper Triassic transgresses the Moenkopi before that formation truncates the underlying Cutler. It is therefore impossible to say whether the remarkable peneplaned surface of pre-Cambrian rocks on which the Upper Triassic rests would be equally smooth beneath the Moenkopi formation. The smoothness of the surface seems to accord with an origin by marine planation, or by coastal-plain peneplanation during the Lower Triassic transgression, acting on a surface that probably was already reduced to moderate relief as a result of the prolonged late Pennsylvanian and Permian erosion. Incidentally, it is almost certain that the smooth surface was not developed during Permian time, for observations in the canyon of West Creek east of Gateway, Colo.,[52] indicate that the surface of the pre-Cambrian beneath the Cutler is more irregular, knolls of rock more resistant to erosion rising above the general level of the pre-Cambrian surface and being encircled by basal Cutler beds.

It may perhaps be doubted whether the coarsely arkosic lithology of the Moenkopi accords with such complete planation as the peneplaned surface exhibits. If the smoothness of the surface should be explicable, however, as due to marine planation, the lithologic constitution of the formation would not show the elimination of less resistant pebbles that would result from prolonged subaerial erosion. Actually the lithologic variation of the Moenkopi from bottom to top does not show the basal conglomerate and finer overlying material that would be expected in a formation deposited during transgression, and to assume that it was deposited during regression seems impossible if the level sub-Moenkopi surface was formed during transgression, for no adequate supply of coarse debris would be left. This quandary might be resolved by assuming the source of supply to be farther east than the peneplaned surface extends.

The nature of the pre-Triassic unconformity farther west has been discussed by Longwell,[53] who points out that there is little evidence of beveling from west to east by marine planation, and that although the pre-Moenkopi surface is channeled and eroded into a hill and valley topography there is little indication of clastic offshore deposition in the basal Moenkopi beds, which are limestone and normally thin conglomerate beds with obviously locally derived chert pebbles from the underlying Kaibab, at the top of the Permian. His conclusion that the evidence indicates widespread rapid flooding of a subaerially developed old erosion surface at a generally low altitude seems to accord with such evidence as is available within this area. This evidence as interpreted by the writer indicates a rapid marine transgression of the Lower Triassic sea extending to or be-

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[52] Cross, Whitman, Stratigraphic results of a reconnaissance in eastern Utah and western Colorado: Jour. Geology, vol. 15, no. 7, p. 677, 1907.

[53] Longwell, C. R., The pre-Triassic unconformity in southern Nevada: Am. Jour. Sci., 5th ser., vol. 10, no. 56, pp. 93–106, August 1925.

yond the limit of present outcrop of the Moenkopi. During this rapid transgression the Permian sandstones and shales were beveled, and part of the material was incorporated into the basal Moenkopi. The shallow marginal area of the sea received little sediment at first but was probably gradually reclaimed from the sea by the deposition of fine-grained sediments from the northeast. The extensive gypsum bed near the base may be conceived to have formed in a lagoon bordered by an offshore bar. It seems plausible to believe that the widespread marine invasion may have initiated a climatic change, with a higher rainfall and accelerating erosion on the land mass to the northeast. The surface of this land had been already reduced to moderate relief, but with accelerated erosive activity coarse material was carried away from it and deposited as the sediments that now form the upper part of the Moenkopi.

UPPER TRIASSIC SERIES

CHINLE FORMATION

Definition and age.—The name " Chinle formation " was proposed by Gregory [54] from exposures in Chinle Valley, northern Arizona, and the name " Shinarump " [55] was restricted by the same writer to the conglomerate unit which now bears that name. The history of the earlier usage of the name " Shinarump " is given in the papers by Gregory above cited.

The Chinle has been assigned definitely to the Upper Triassic on the basis of rather scanty invertebrate fossils and the fairly satisfactory evidence of scattered occurrences of vertebrate fossils. The evidence for the Upper Triassic age of the Chinle was summarized by Gregory,[56] and reasons for assigning the Shinarump to Upper (?) Triassic were given by him and later by Gilluly and Reeside.[57]

Lithology.—The Chinle formation of this area consists largely of red siltstone, with which is interbedded a variable but normally smaller proportion of brick-red to buff sandstone in discontinuous beds. Conglomerate beds in which the pebbles are mostly structureless limestone form a subordinate but highly distinctive part of the formation. At the base in the southern part of the area is a thin normally unconsolidated sand or conglomerate, the well-rounded pebbles of which are mostly quartz (pl. 8, *B*). The formation almost everywhere crops out as a steep slope beneath the sandstone cliffs

[54] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, p. 42, 1917.

[55] Idem, pp. 37–38. Gregory, H. E., The Shinarump conglomerate: Am. Jour. Sci., 4th ser., vol. 35, pp. 424–438, 1913.

[56] Gregory, H. E., op. cit. (Prof. Paper 93), p. 48.

[57] Gilluly, James, and Reeside, J. B., Jr., Sedimentary rocks of the San Rafael Swell and some adjacent areas in eastern Utah: U. S. Geol. Survey Prof. Paper 150, p. 67, 1928.

of the overlying formations. In general aspect the Chinle differs little from the underlying Moenkopi, but there is a color distinction between them, the Chinle having a distinctly brighter-red tone, verging on a cherry-red, as contrasted with the less brilliant yellower and browner reds of the Moenkopi. In addition, the discontinuity and irregular bedding of the Chinle, which is particularly apparent in the appearance and disappearance of sandstone beds along the strike, contrasts with the regular and distinct bedding of the Moenkopi. Close examination discloses other individualities. Much of the finer-grained material of the Chinle is siltstone or clay which breaks into angular fragments, or chunks, and in which definite bedding is not apparent. Distinctly bedded shale is rare in the Chinle and almost universal in the Moenkopi. The ripple bedding that is so exceedingly common in the Moenkopi formation has not been observed in the Chinle except in the uppermost part. Limestone conglomerates such as are common in the Chinle are not found in the Moenkopi, and conversely arkosic beds, which are so abundant in the Moenkopi of the eastern part of the area, are not found in the Chinle. Nevertheless, the precise position of the contact is in places difficult to determine, particularly where the basal Chinle quartz conglomerate is not present, because of similar lithology in the uppermost Moenkopi and basal Chinle.

Farther west in Utah and in northern Arizona, and southern Nevada the Upper Triassic series probably includes two formations, the Shinarump conglomerate occurring below the Chinle formation, although the Upper Triassic age of the Shinarump has not been proved. The Shinarump is described [58] as " an interfingering series of lenticular gritty sandstones, conglomerates, clean sandstones, variegated mudstones, and even shales " cut by numerous channel unconformities, containing silicified and carbonized wood, and ranging from 30 feet to nearly 200 feet in thickness. The Shinarump rests unconformably upon the underlying Moenkopi. The overlying Chinle is apparently conformable upon the Shinarump.

Basal grit.—Eastward from the San Rafael Swell the Shinarump conglomerate thins irregularly, and in the northern part of the Moab district its horizon is marked by a thin and discontinuous gray zone composed of poorly cemented quartz sandstone and grit.[59] In the area mapped the thin zone of conglomerate and grit which crops out at the base of the Chinle has not been mapped as Shinarump conglomerate because of the geographic discontinuity between it and the Shinarump, because of some lithologic peculiarities that distinguish it from typical Shinarump, and because of its thinness

[58] Gilluly, James, and Reeside, J. B., Jr., op. cit. (Prof. Paper 150), p. 67.
[59] Baker, A. A., Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, p. 37, 1933.

and local discontinuity within the area. Nevertheless, it is clear that the basal conglomerate of the Chinle in this area has much the same stratigraphic significance as the Shinarump conglomerate and may be regarded as the eastern equivalent of the Shinarump.

The lithologic description of this basal grit is given in several sections of the Chinle formation on the following pages. It has been found at only one locality northeast of the Dolores River within the area mapped but occurs at the base of the Chinle east of Gateway, Colo., and in Sinbad Valley, Colo., and a similar thin grit bed is found at the base of the Upper Triassic at wide-spread localities in central Colorado.[60]

The thin grit at the base of the Chinle in Richardson Amphitheater is continuous with the remarkable cross-bedded grit and conglomerate along the Colorado River west of Castle Creek. This cross-bedded conglomerate also crops out along the Colorado River at the mouth of Salt Wash but is not exposed at the same horizon in eastern Cache Valley, below the big bend of the Colorado River, or in the southern part of Castle Valley, although it attains a thickness of probably 200 feet near Salt Wash. The bedding is a combination of topset and foreset bedding with slopes of as much as 12°, the aggregate simulating angular unconformity, for which it was mistaken during a reconnaissance examination.[61] The foreset beds west of Salt Wash dip upstream toward the north, as exposed on the wall of the canyon. The exposures on the north wall of the canyon west of Castle Creek show a westward dip. These dips may both accord with a prevailing northwestward direction of foreset bedding.

Lithologically the largest proportion of this material seems to be a coarse sandstone or arkose, in which the distinguishable grains are subangular to subrounded and predominantly quartz. These grains are embedded in a gray matrix, which seems to be decomposed feldspar and in which only a few crystal or grain outlines can be discerned. This type merges into a rock composed almost exclusively of the gray structureless matrix material, which where weathered is traversed by innumerable joints streaked with a dark-purplish stain. Locally this gray rock has the appearance of a mass of subparallel but twining cylindrical columns from 1 to 3 inches in diameter. Some of the coarser-grained beds contain rounded pebbles of quartz 1 or 2 inches in diameter, and a few pebbles of metamorphic and igneous rocks were found.

Sections.—Sections of the Chinle formation were measured at several localities, and some of them are given below.

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[60] Reeside, J. B., Jr., personal communication.

[61] Cross, Whitman, Stratigraphic results of a reconnaissance in eastern Utah and western Colorado: Jour. Geology, vol. 15, no. 7, pp. 654–655, 1907.

Section of Chinle formation on north side of Colorado River northwest of Richardson

[Measured by John Vanderwilt and O. R. Murphy]

	Feet
Wingate sandstone: Massive cliff-forming buff sandstone.	
Contact sharp but varying in stratigraphic position from place to place with the appearance or disappearance of sandstone beds and shale partings in the zone between the formations.	
Chinle formation:	
Sandstone, red, thin-bedded, cross-bedded, with streaks of red shale	15
Sandstone, brownish red, in massive beds 3 to 8 feet thick, and red structureless siltstones, the sandstone making about two-thirds of the total	87
Shale, sandy, brownish red, with some beds of brownish-red argillaceous sandstone 2 to 6 feet thick	30
Sandstone, brownish red, fine-grained, lower 10 feet thin-bedded, upper part massive	27
Sandstone, argillaceous, red, and red sandy shale in about equal proportions	122
Shale, sandy, red	13
Sandstone, argillaceous, calcareous	2
Shale, sandy, light brownish red	28
Conglomerate; pebbles as much as three-fourths of an inch in diameter of fine-grained red sandstone; changes along outcrop to argillaceous sandstone	6
Siltstone, red, with some sandy beds	48
Sandstone, light gray to white, medium- to coarse-grained, calcareous cement, friable, irregularly blotched yellow, deep red, and black	28
Sandstone, white, calcareous cement, coarse-grained, mostly quartz grains less than one-eighth inch in diameter but ranging up to pebbles half an inch in diameter	2
	408
Moenkopi formation (contact irregular).	

Section of Chinle formation northeast of Hittel's ranch, on southeast side of Colorado River

[Measured by C. H. Dane]

	Feet
Wingate sandstone:	
Buff sandstone making vertical cliff.	
Chinle formation:	
Parting of red shale.	
Sandstone, buff, like overlying bed, in channels 6 feet thick and from 6 to 15 feet wide in cross section, with irregularly subcircular bases. These channels are separated by triangular upward extensions of the underlying red-shale bed that reach the parting of red shale.	
Shale, dark red and purple	2

Chinle formation—Continued.	*Feet*
Sandstone, buff, with a few red-shale streaks, probably ripple marks and mud-cracks	8
Shale, red, thin-bedded	1
Sandstone, buff, with some included shale pellets	1
Shale, red, thin-bedded, poorly bedded, and some beds of brick-buff sandstone 1 to 2 feet thick	19
Sandstone, buff	3
Clay, red, structureless	6
Sandstone, brick-buff, fine-grained, massive to poorly bedded, with scattered red-shale pellets; some layers 2 inches thick chiefly composed of red-shale pellets	10
Clay, red, structureless, with a few sandstone layers	16
Chiefly sandstone, brick-buff, fine-grained, regularly bedded, with many red-shale pellets; some red shale	11
Clay, bright brick-red, structureless, with a few calcareous nodular concretionary layers 1 foot thick and a few layers of buff sandstone 1 foot thick	43
Sandstone, brick-buff, and conglomerate of red and green shale pebbles and red-shale flakes	2
Clay, dark red, structureless, streaked and mottled with light green	20
Sandstone, fine-grained, brick-buff, and clay, structureless, dark red, alternating in beds 1 to 2 feet thick	38
Clay, structureless, dark red	4
Sandstone, argillaceous, bright brick-red, poorly bedded	10
Sandstone, argillaceous, brick-buff, notably lenticular and discontinuous, and shale, sandy, red; bedding in both lithologic types indistinct; scattered lenses of limestone conglomerate as much as 1 foot thick and 20 feet long	17
Conglomerate, hard, with dense calcareous cement; pebbles irregularly rounded and as much as 1 inch in diameter, of gray and violet dense limestone and red shale; streaked with lenticular beds of calcareous red shale and gray limestone	12
Clay, brick-buff, nearly structureless, mottled with light green near the top	13
Conglomerate, light green-gray, pebbles and concretionary lumps of dense gray and violet limestone and pellets of red and purple shale cemented by a dense light green-gray calcareous matrix. The top foot is harder than the underlying conglomerate and forms a ledge	14
Shale, mottled and streaked, purple, dark red, violet, and green	2
Shale, slightly sandy, mottled, light red-brown, dark cherry-red, and light waxy green	6
	264

Moenkopi formation (contact obscure but apparently sharp).

Section of Chinle formation in lower part of cliff north of north line of sec. 24, T. 24 S., R. 24 E.

[Measured by C. H. Dane]

	Feet
Wingate sandstone: Buff sandstone, which makes a vertical cliff; a discontinuous red-shale parting about 20 feet above the base of the cliff.	
Chinle formation:	
Sandstone, buff, like that of the overlying Wingate, in beds 1 to 6 feet thick, showing channel irregularities where the sandstone beds rest on thinner-bedded sandstone and red sandy shale. Possible dinosaur footprints in the thicker sandstone beds. Large mud cracks (2 or 3 inches deep and separated by a foot or more) in the thinner-bedded sandstone and shale are filled with sand from the overlying beds. This unit is variable in lithology and by lateral lensing out of the sandstone beds merges with the underlying Chinle	20
Sandstone, brick-buff, and shale, red	16
Clay, red, without perceptible bedding	28
Sandstone, medium-grained, lenticular, in beds 1 to 6 feet thick, and shale, red, in about equal parts	125
Principally clay, red, without perceptible bedding	33
Conglomerate, light purple, chiefly of chunks and pebbles of red shale, but with pebbles of quartz 2 inches in maximum dimension, of feldspar half an inch in maximum dimension, and a few pebbles of gray and violet dense limestone. A few small pebbles of granitic metamorphic rocks were observed. The conglomerate is interbedded with about an equal amount of brick-buff sandstone and some red shale	8
Clay, red, without perceptible bedding, with some beds of brick-buff sandstone	5
Conglomerate like that in the next overlying bed, but with a somewhat larger number of pebbles of igneous metamorphic rocks	4
Poorly exposed; apparently mostly soft fine-grained argillaceous sandstone	8
Shale, pure, mottled green and purple	3
	250

Section of Chinle formation on south wall of Dolores River Canyon just east of Beaver Creek

[Measured by C. H. Dane and C. B. Hunt]

	Feet
Wingate sandstone.	
Chinle formation:	
Red clay and silty sandstone	237
Grit, coarse, and conglomerate, whitish gray, with purple streaks and splotches. The pebbles are chiefly quartz,	

	Feet
Chinle formation—Continued.	
some of which reach a diameter of 1 inch. There are chunks of red and gray clay which reach a greater size. Red siliceous chunks, some of which are replaced wood and vegetable matter, are sparingly distributed. The unit is coarsest in the lowest foot	4
	241
Moenkopi formation (contact poorly exposed but undoubtedly an irregular surface).	

The quartz grit recorded at the base of the Chinle in the sections given above was not observed in the exposures along Granite Creek, where the Chinle rests on Cutler beds, nor was it observed in any exposures along Ryan Creek or farther north, where the Chinle rests on the pre-Cambrian. On the north side of Cow Creek near its junction with Ryan Creek the Chinle is 137 feet thick and consists of red sandy shale and muddy sandstone with several beds, one as much as 4 feet thick, of conglomerate of gray limestone and red shale pebbles. Farther north the Chinle is still thinner, as recorded in the following sections.

Section of Chinle formation in NW¼ sec. 33, T. 21 S., R. 25 E., north of Dry Gulch

[Measured by C. H. Dane and C. B. Hunt]

	Ft.	in.
Wingate sandstone (contact irregular, with 2 inches relief in 2 inches horizontally, irregularly truncating the bedding below angularly. At 15 feet east of the place of section this contact is above a sandstone 1 foot 6 inches thick which is very similar to the overlying Wingate and might be taken as the basal bed of the Wingate; so the significance of the irregularity is uncertain).		
Chinle formation:		
Silt, sandy, red, with a few green-gray sandy layers half an inch thick; shale flakes in the upper 4 inches	1	6
Sandstone, thin-bedded; lower 6 inches consists of horizontal beds of gray-green sandstone one-twentieth of an inch thick; this grades upward into a buff and brown ripple-bedded sandstone	6	6
Clay, sandy, red; breaks into small angular pieces with glistening surfaces	4	6
Sandstone, red, hard; makes a ledge	1	8
Silt, sandy, red, soft; shows indications of beds a quarter to half an inch thick; weathers into flat chippy fragments; unit weathers to a slope	26	
Siltstone, red, hard; makes a ledge, weathering with rounded surfaces, with calcite concretions near the top	6	6
Shale, red, soft; makes a slope	6	6
Siltstone, red, hard, calcareous cement; makes a ledge, with hard gray crystalline calcite concretions	1	6

Chinle formation—Continued.	*Ft.*	*in.*
Shale, red, soft, poorly exposed; makes a slope	6	
Siltstone, red, hard; makes a ledge with rounded surfaces	6	
Shale, silty, red, soft; weathers into small angular fragments; unit makes a slope	5	6
Siltstone, red, fine-grained, calcareous cement, with rounded red-shale pellets one thirty-second of an inch in diameter and irregularly shaped green-gray calcareous concretions three-quarters of an inch in maximum dimension. These pellets and concretions are abundant in the lower 6 inches, diminishing in numbers upward. The top of the unit is an irregular concretionary lens consisting mostly of gray finely crystalline calcite	9	
Shale, sandy, red, soft; weathers to a slope and mostly concealed	11	
Concealed	17	
	109	2

Pre-Cambrian metamorphic basement complex (contact concealed).

Section of Chinle formation at Big Hole, in Westwater Canyon

[Measured by C. H. Dane, C. E. Erdmann, and O. R. Murphy]

	Ft.	*in.*
Wingate sandstone: Sandstone, fine-grained, greenish gray at the base, with small shale pellets and flakes in the lower 2 inches and sparingly upward, grading upward within 6 inches to fine-grained buff sandstone.		
Contact. The overlying sandstone fills mud cracks in the top shale bed of the Chinle. The mud cracks are from 2 to 6 inches deep and 3 inches broad at the top, and the surfaces between them are about 4 feet across.		
Chinle formation:		
Sandstone, in irregular beds, one-eighth to one-half inch thick, cross-bedded, containing along the bedding surfaces small pellets of reddish-brown shale and gray-green sandstone, near the top apparently ripple-marked; grades laterally into dark reddish-brown pure shale	3	9
Sandstone, light gray-green, predominantly of quartz, with small dark-green shale flakes and chlorite flakes, a lens tapering out within 6 feet laterally; poor ripple cross-bedding at the top	1	6
Shale, red, pure, with irregular blue-green patches at the top	1	8
Sandstone, green-gray, medium-grained	1	5
Shale, red, near the top variegated with green mottled sandstone	2	10
Limestone, green-gray, thin-bedded, silty		10
Siltstone, calcareous, dark reddish-brown, poorly exposed on a slope	6	5

Chinle formation—Continued.	*Ft.*	*in.*
Limestone, silty, dull brick-red, dense, hard, with limestone conglomerate at base 6 inches or less in thickness	5	
Sandstone, limy, buff, in part a limestone conglomerate		6
Shale, or clay, limy, red; weathers into small angular fragments	1	
Sandstone very fine-grained, limy, silty, brick-red; weathers into crudely ellipsoidal masses	4	
Shale, limy, red; breaks into irregular lumps; makes a slope	10	7
Conglomerate, of reddish-brown and dark-gray dense calcareous pebbles		7
Sandstone, fine-grained, dull reddish-brown, irregularly bedded; breaks into small hackly fragments, with several layers of darker reddish-brown; 6 feet above the base is a zone of lenses of limestone conglomerate, as much as 8 inches thick, and above this is 6 inches of dark-red thin-bedded limy shale	11	
Sandstone, shaly, limy, with some beds of red sandy shale	21	2
Conglomerate of pebbles of limestone and shale as much as half an inch in maximum dimension; matrix of dense silty limestone; with interbedded shaly layers, which predominate in the upper half of the unit	5	10
Conglomerate, light greenish-gray, of pebbles of dark-gray limestone and reddish-brown silty sandstone as much as 1 inch in diameter, with a matrix of sandy silt constituting two-thirds of the rock		9
Sandstone, very fine-grained, very hard, almost a quartzite; conchoidal fracture	1	6
Siltstone, very fine-grained, shaly, soft; weathers to a slope	13	3
Sandstone, brownish-red, hard	2	6
Siltstone and shale, sandy, soft; weathers to a slope	3	
Sandstone, shaly, dull brick-red, thin irregular bedding, some cross-bedding	3	6
Sandstone, red, thinly laminated, with scattered grains of quartz more than 0.02 inch in diameter		5
Sandstone, gray, coarse-grained, thin-bedded		8
Sandstone, gray, coarse, and grit, with some pebbles as much as 1 or 2 inches in diameter in the basal part; average grain size from 0.02 to 0.10 inch; predominantly angular grains and pebbles of quartz, with much feldspar and minor amounts of hornblende, garnet, and igneous rock. The rock fragments are decomposed	3	6
	107	2

Contact in the large shows no perceptible irregularity or **channeling**; in detail almost everywhere concealed but where exposed shows only slight undulations.

Pre-Cambrian metamorphic rocks.

The Utah Southern State No. 1 well, in sec. 26, T. 21 S., R. 23 E., from 2,085 to 2,297 feet cut through beds assigned to the Chinle, including 32 feet of "conglomerate shale" and "variegated conglomerate" at the base, which accords with the basal grit bed of the Chinle exposed elsewhere. The Chinle rests directly on the pre-Cambrian granite and metamorphic rocks.

In Salt Valley the Utah Southern King No. 1 well cut through 510 feet of red beds below the Wingate. Of this thickness, 260 feet has been somewhat arbitrarily regarded as Chinle.

The data on the thickness of the Chinle, although incomplete because of concealment in most of the northwestern part of the area, are on the whole so extensive that the thicknesses shown on the structural cross sections (pl. 3) may be regarded as having a high order of probability and being more accurate than the thicknesses shown for any underlying formation.

Stratigraphic relations.—The Chinle rests with unquestionable unconformity upon the underlying Lower Triassic Moenkopi (where the Shinarump conglomerate is not recognized), and at places the unconformity is distinctly angular, as at a locality 2 miles south of the mouth of Cane Creek [62] and in Moab Valley [63] (both south of the area mapped).

There is a slight angular discordance between the Chinle and Moenkopi in Richardson Amphitheater, but it is difficult to recognize on account of the internal thinning exhibited by the Moenkopi. On the south wall of West Creek Canyon, east of Gateway, Colo., a slight angular discordance of less than 1° is recognizable between the Moenkopi and Chinle. At no place within the area is there such striking discordance in dip of the two formations as has been demonstrated farther west.

Conditions of deposition.—The Chinle formation represents deposition wholly under continental conditions, as shown by its fauna and the physical nature of the sediments that form it. The shells of invertebrates are widely distributed, though rare, and without exception they have been identified as fresh-water species.[64] Smooth-surfaced shells of the genus *Unio* are most common, but some gastropods have been found. Within the area mapped these invertebrates have been found at two localities. Large amounts of small fragments of silicified wood and some vertebrate bones have also been

[62] Baker, A. A., Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, p. 36, 1933.

[63] Baker, A. A., Dobbin, C. E., McKnight, E. T., and Reeside, J. B., Jr., Notes on the stratigraphy of the Moab region, Utah: Am. Assoc. Petroleum Geologists Bull., vol. 11, no. 8, p. 798, 1927.

[64] Reeside, J. B., Jr., personal communication.

found, and elsewhere the vertebrate material has been determined as in part amphibian and in part reptilian.[65]

The physical evidence of continental origin includes rapidity of lateral variation from sandstone to shale, absence of regular horizontal bedding but common occurrence of cross-bedding and mud cracks in the more sandy beds, and the abundance of the peculiar mud-pellet and limestone-pellet conglomerate. The manner of deposition of these limestone conglomerates is unknown, but it is clear that they represent the break-up and redeposition of limestone beds deposited within the formation or a concretionary segregation of limestone from unconsolidated calcareous muds or else some combination of these processes. That concretionary growth is in some way involved in their origin appears probable, because of the rarity of limestone beds in the formation and the abundance of calcareous muds with concretionary nodules of carbonates.

The basal grit of the Chinle formation is the only portion of the formation within the area for which a probable source can be selected. It seems likely that much of the grit is derived from the pre-Cambrian granite now exposed in the northeastern part of the area. It is, however, distinctly different in lithology from the conglomerates of the underlying formations derived from the same source. The average size of the material is much less than that of the Moenkopi and Cutler conglomerates, and the maximum boulder size is far less. Furthermore, the proportion of quartz in the basal grit of the Chinle is much greater, and in many places quartz is almost the only grain or pebble material present. Where feldspar is present it is for the most part distinctly weathered, and the igneous-rock pebbles that occur are for the most part decomposed. It seems probable that the basal grit represents the relatively rapid removal and redeposition of a mantle of subaerially weathered and decomposed rock which covered the old land mass to the northeast. This mantle of debris presumably accumulated during an interval that followed the deposition of the arkosic Moenkopi beds and preceded some shift in climatic conditions or change in altitude which initiated the continental deposition of the Chinle. The thicker basal grit and conglomerate of the Chinle in the vicinity of the mouth of Salt Wash, the strong foreset bedding there exhibited, and the larger average and maximum size of the material contained in it seem to the writer to accord with a hypothesis of deltaic deposition at the mouth of a stream which debouched from the southwest into the area where the conglomerate is now found. The subangular and slightly rounded shapes of the grains in this grit seem also to accord with this hypothesis and suggest a relatively rapid scouring off and

[65] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, pp. 46–47, 1917.

relatively short distance of transportation of the material at this place, as contrasted with a slower rate of accumulation for the basal grit over most of the area of its occurrence.

JURASSIC (?) SYSTEM

GLEN CANYON GROUP

Overlying the Triassic red shales is a succession of sandstone and sandy shale formations all probably of Jurassic age. These formations fall naturally into two groups, in each of which the individual formations have in common some features of origin and geographic distribution, although they differ in lithologic characteristics. For the lower group Gregory and Moore[66] proposed the name "Glen Canyon group," from exposures in Glen Canyon of the Colorado River. Typically the Glen Canyon group consists of three conformable formations—the Wingate sandstone at the base, the Kayenta formation, and the Navajo sandstone at the top. All three are exposed within the area mapped. There is no satisfactory fossil evidence to show the age of the group, and the assignment of the group to the Jurassic (?) is based on the probable history of the region as deduced from the sedimentary record. Reasons for this assignment are given at the conclusion of the description of the several formations of the group.

WINGATE SANDSTONE

Name.—The Wingate sandstone was named by Dutton[67] in 1885. The usage was extended over a wider area by Darton[68] and Gregory[69] and subsequently over much of eastern Utah.[70] The present status of knowledge of the areal extent and correlation of the Wingate sandstone with a comparison of the usage of the name by earlier writers is given in a recent publication.[71]

Lithology.—The Wingate sandstone typically crops out in a sheer cliff of reddish-buff color, vertically seamed by joints extending the full thickness of the formation and in many places streaked and coated with the blue-black surficial stain of desert varnish, which

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[66] Gregory, H. E., and Moore, R. C., Geology of the Kaiparowits region, Utah and Arizona: U. S. Geol. Survey Prof. Paper 164, p. 61, 1931.

[67] Dutton, C. E., Mount Taylor and the Zuni Plateau: U. S. Geol. Survey 6th Ann. Rept., pp. 136–137, 1885.

[68] Darton, N. H., A reconnaissance of parts of northwestern New Mexico and northern Arizona: U. S. Geol. Survey Bull. 435, pp. 49–52, 1910.

[69] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, pp. 53–55, 1917.

[70] Gilluly, James, and Reeside, J. B., Jr., Sedimentary rocks of the San Rafael Swell and some adjacent areas in eastern Utah; U. S. Geol. Survey Prof. Paper 150, pp. 69–70, 1928.

[71] Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., Correlation of the Jurassic formations in portions of Utah, Arizona, New Mexico, and Colorado: U. S. Geol. Survey Prof. Paper 183 (in press).

obscures the nature of its bedding in distant view. On fresh fracture the rock is seen to be a fine-grained light-buff sandstone, of rounded and evenly sized quartz grains. It is poorly cemented, crumbles under the blow of a hammer, and where weathered may be crushed to powder in the hand. This sandstone is horizontally bedded in layers from 2 to 50 feet thick, the layers maintaining an even thickness for distances of a mile or more. Where this horizontal bedding is most distinct the Wingate crops out as a steeply sloping cliff with alternating rounded ledges and benches, developed by the differing resistance of the horizontal layers to erosion (pl. 9, *A*). The horizontal bedding is accentuated by softer layers of reddish thin-bedded slightly argillaceous sandstone, which weather into grooves along the sloping cliffs and are locally studded in rows with solution cavities. The general horizontal bedding is also less strikingly brought out by an alternation in color of the thicker layers in various shades from nearly white through pale buff to dark reddish buff.

Within the horizontal layers cross-bedding is almost everywhere present and ranges from the smallest scale up to magnificent tangentially sweeping cross-beds 50 feet in length and with maximum slopes of as much as 30° where the bedding is undistorted. Some of the cross-bedding approximates in appearance torrential cross-bedding with numerous equally inclined beds slanting from top to bottom of a more extensive horizontal layer.

The formation contains a few thin beds of dense gray limestone and sandy limestone. These are the principal variant types in an otherwise homogeneous mass of sandstone.

The nature of a fairly typical specimen of the sandstone from Big Hole, Westwater Canyon, is shown by plate 10, *A*. The grains are principally quartz, but grains of microcline and sodic plagioclase are common. Most of the grains are well rounded. The margins of the grains are commonly stained yellow by limonite, which fills some of the interstitial areas also. Some of the feldspar grains are greatly altered to clay minerals. The grains in the thin section studied have a maximum diameter of 0.25 millimeters (0.01 inch), but most of them range between 0.05 and 0.15 millimeters (0.002 and 0.006 inch).

Distribution and topographic expression.—The Wingate almost everywhere forms only a narrow strip of outcrop, as shown on the areal map, but it is one of the most impressive formations in the area because of its cliff- and canyon-forming habit. Its most striking outcrops are in the walls of Salt and Cache Valleys, in the walls of Richardson Amphitheater and the canyons of the Colorado River above and below it, in the walls of Fisher Valley, in the canyon of the Dolores River and the tributary Cottonwood and Beaver Canyons, in Westwater Canyon of the Colorado River and the tributary Star, Marble, and Little Dolores Canyons, and in the cliffs bordering the Sand Flat, Ryan Gulch, and the north end of Pinyon Mesa. It also crops out in many smaller canyons. The Wingate sandstone, because of the wide distribution of the cliffs and canyons formed by its outcrop, is the most effective single factor in making travel through the region difficult.

The cliff-forming habit of the Wingate in the region is due partly to its lithologic homogeneity and massiveness, partly to the superior resistance to erosion of the basal portion of the overlying formation, which makes a capping for the cliffs, and partly to the rapidity with which the soft shales and sandstones of the underlying Chinle are eroded. The cliff habit of the Wingate may also be attributed in part to the vertical jointing, much of which extends from top to bottom of the formation. The jointing of the Wingate causes the recession of the cliffs by the collapse of large masses, the blocks strewing the slopes of the Chinle outcrop below the cliffs. Where erosion of the underlying Chinle is not proceeding rapidly, the Wingate weathers back to a steep bench and ledge slope.

In the Wingate cliffs are numerous deep recessions with an overhanging arch-shaped roof. The development of these alcoves is facilitated by the large-scale cross-bedding of thick beds, as a result of which a weakened or undermined block when breaking away parts along a sloping bedding plane, which may slant either along or into the cliff. Subsequent erosion in the nearly massive but soft stone tends to produce as a final result the structurally strong form of the arch.

Sections.—Because of its habit of outcrop, detailed stratigraphic sections of the Wingate sandstone are difficult to measure. Two hand-leveled sections of the Wingate are given below to show the lithology of the formation in more detail.

Section of Wingate sandstone in NW¼ sec. 33, T. 21 S., R. 25 E., north of Dry Gulch

[Measured by C. H. Dane and C. B. Hunt]

	Ft.	in.
Kayenta formation.		
Wingate sandstone:		
Sandstone, tan to buff, thin-bedded in layers 1/16 to ½ inch thick, highly crossed-bedded	41	
Sandstone, light buff, fine-grained, with wavy bedding lines; lenses of small clay pellets in lower part	6	
Sandstone, tan to buff, wavy bedding	18	
Sandstone, in beds 1/16 to ¼ inch thick, cross-bedded at high angles	7	
Sandstone, dark tan, very fine grained	8	
Sandstone, tan to buff, fine-grained, cross-bedded; ellipsoidal sandstone concretions in lower 17 feet	65	

Wingate sandstone—Continued.	Ft.	in.
Sandstone, tan to buff, fine-grained; shows angular and tangential cross-bedding; has some tendency to form a high ledge back of the unit below	45	
Sandstone, tan to buff, in beds half an inch to 3 inches thick; shows angular cross-bedding at high angles	31	
Sandstone, pinkish buff, the lower 10 feet cross-bedded angularly and tangentially at angles of 5° to 15°, the upper 20 feet irregularly horizontally bedded	30	
Sandstone, buff, in layers 6 inches to 2 feet thick, interbedded with sandy shale and some red silt in the upper part; good ripple marks and mud cracks observed in the upper part of the unit	12	
Shale, slightly sandy, and sandstone, red, irregularly thin-bedded, showing indications of ripple bedding; in part hard green-gray calcareous sandstone; unit weathers down to a partly concealed slope	12	
Sandstone, green-gray, horizontally bedded, beds a quarter of an inch to 5 inches thick	1	4
Sandstone, buff, bedding vague	1	8
Sandstone, gray and grayish red, with irregular horizontal bedding		6
Sandstone, buff, bedding vague	1	8
Sandstone, buff, soft, in horizontal beds one-sixteenth inch thick		3
Sandstone, buff, fine-grained, cross-bedded angularly, with lenses of coarser-grained sandstone a quarter of an inch thick and 2 inches long; unit makes a single prominent, persistent ledge	11	
Sandstone, red, fine-grained, with a few gray-green streaks, cross-bedded in the basal quarter of an inch with scattered coarser grains; weathers into rounded surfaces	3	
	294	5

Chinle formation (contact irregular; see p. 60).

Section of Wingate sandstone and overlying beds at Big Hole, Westwater Canyon

[Measured by C. H. Dane, C. E. Erdmann, and O. R. Murphy]

Kayenta formation:	Ft.	in.
Sandstone, brown, thin-bedded, cross-bedded; makes a slight bench; grades upward into extremely fine grained interbedded light-brown and light-green sandstone	3	10
Sandstone, buff with reddish and purplish tones, in beds from 0.1 to 2 inches thick, with intervening thinner softer beds of green shale and grayish-white sandstone; cross-bedded at angles as high as 12°. Above the lower 2 feet of the unit the shale beds are much fewer and the sandstone is in thicker beds. At 50 feet along the strike the sand-		

	Ft.	in.
Kayenta formation—Continued.		
stone beds of this unit merge into a single sandstone bed with a parting of red shale 1 inch thick at the base, and at 100 feet along the strike the bed is apparently inseparable from the Wingate sandstone below	9	
Partial thickness of Kayenta formation (estimated total thickness in this vicinity 150 feet)	12	10
Contact perfectly transitional; cross-bedding planes extend across the contact arbitrarily chosen to separate the Wingate and Kayenta formations.		
Wingate sandstone:		
Sandstone, light buff, fine-grained, horizontally bedded in beds one-eighth to one-half inch thick, or cross-bedded at angles of 1° or 2°; in the lower 6 inches are scattered lenses of dense gray limestone a quarter to half an inch thick	3	7
Sandstone, calcareous, hard, olive-brown, ripple-marked with wave length of 1 to 2 inches		6
Parting of red shaly sandstone.		
Sandstone, light gray, horizontally bedded, ripple-marked		6
Sandstone, buff; siltstone, red, sandy; and shale, green, sandy; in thin beds, ripple-marked		5
Sandstone, light buff, fine-grained, horizontally bedded	5	4
Parting of red sandy silt with scattered lenses of hard highly calcareous sandstone; extends for 50 feet laterally.		
Sandstone, fine-grained, brown, cross-bedded at low angles	5	8
Parting of red shale along which are lenses of hard calcareous, very fine-grained sandstone, a quarter of an inch thick and 1 to 3 inches long.		
Sandstone, light buff, very fine grained, with scattered lenses of gray calcareous sandstone and limestone as much as 4 inches thick and 1 foot long; horizontally bedded in beds 0.1 to 0.5 inch thick but with some cross-bedding at inclinations of 3° to 4°	13	11
Sandstone, salmon-buff, massive, friable, fine-grained; rests on an irregular surface which cuts into the underlying bed as much as half an inch	2	8
Sandstone, salmon-buff, fine-grained, thinly laminated in upper part	1	5
Sandstone, reddish chocolate-brown, orange-brown, and cream-colored, silty, thinly laminated; bedding contorted within the unit; contains near the middle a lens of reddish-gray limestone 1 inch thick and 7 inches long		8
Sandstone, greenish yellow, calcareous, with lenses and beds of pure dense gray limestone		4
Sandstone, salmon-brown, thinly laminated		1

Wingate sandstone—Continued.	Ft.	in.
Sandstone, pinkish gray, friable, poorly bedded, with partings of dark-red shale	1	
Sandstone, light buff, friable, bedding poor but apparently chiefly horizontal	6	7
Sandstone, brown, fine-grained, horizontally bedded, with gray calcareous partings and red-shale partings	13	5
Sandstone, fine-grained, reddish brown, generally horizontal bedding; weathers to a smooth rounded surface, which near the middle of the unit is studded with solution cavities from a fraction of an inch to several feet in diameter	39	7
Sandstone, brown, at the base with an overhang of 1 or 2 feet extending at least 1,000 feet along the cliff along a bedding plane, but with no discernible shaly parting along this recess	13	7
Sandstone, light buff, cross-bedded, in units 5 to 15 feet thick; alternating with sandstone, brown, fine-grained, somewhat argillaceous, generally horizontally bedded in beds 2 to 6 feet thick. The lighter-colored beds range from buff through light salmon-pink to nearly white. The cross-bedding is tangential in some beds, sweeping from top to bottom of the unit, the cross-beds truncated at the top by the darker-brown horizontally bedded units. The brown sandstones have thin partings of reddish-brown shale. They are continuous for at least 1,000 feet and probably as much as a mile laterally. They have a tendency to weather into sloping benches as contrasted with the ledges made by the lighter cross-bedded sandstone units. Asymmetric ripple bedding was observed in the brown sandstones, with the crests of successive layers superimposed	100	7
Sandstone, brown, argillaceous, horizontally bedded	6	7
Sandstone, buff, tangentially cross-bedded	28	11
Sandstone, brown, argillaceous, horizontally bedded	5	6
Sandstone, buff, in horizontal beds traceable for 200 feet along the cliff, cross-bedded on a minor scale within the horizontal beds. The cross-bedding is distinguishable because of variation in grain size. The finer-grained beds consist of perfectly rounded and subrounded grains of polished transparent quartz, the grains less than 0.01 inch in diameter. The coarser-grained beds consist of less rounded and subangular grains more than 0.01 inch and less than 0.02 inch in diameter	9	1
Sandstone, light buff, fine-grained, tangentially cross-bedded at angles as high as 25°, in units from 6 inches to 3 feet thick, alternating with sandstone, brown, horizontally bedded and cross-bedded, in layers 3 to 18 inches thick	64	5

	Ft.	in.
Wingate sandstone—Continued.		
Sandstone, buff, in horizontal beds, 1 to 6 inches thick, with some angular cross-bedding in the upper part	15	10
Sandstone, buff, in beds half an inch to 1 inch thick; shale, red, from partings to beds 0.1 inch thick; and sand, green, argillaceous, soft, in beds half an inch thick		7
Sandstone, buff, fine-grained, horizontally bedded	5	9
Sandstone, salmon-buff, fine-grained, thin-bedded, in alternating softer and harder layers	2	
Sandstone, buff, hard but friable, fine-grained; grains rounded transparent quartz with scattering black grains; in part horizontally bedded, in part with angular cross-bedding at 4° to 5°	20	4
Sandstone, buff, fine-grained, in beds a quarter of an inch to 1 inch thick; at the base ripple marks with wave length of 4¾ inches and amplitude of half an inch; these appear to be oscillation ripples, but in the upper part of the bed are asymmetric ripples of smaller size. The sandstone contains numerous small pellets of red shale	1	
Sandstone, buff, and shale, light red, horizontally bedded, locally with ripple cross-bedding, but mostly with plane bedding surfaces	3	4
Total thickness of Wingate sandstone	373	2

Contact sharp at the place of section, but only slightly irregular.

Chinle formation: Siltstone, fine-grained, containing pellets and flakes of pure red shale a quarter of an inch to 1 inch thick and green silty sandstone in irregular beds as much as 1 foot thick.

A short distance from the place where the above section was measured a thin limestone bed in the lower part of the Wingate extends for at least 250 feet along the exposure and has a width of at least 50 feet.

Section through limestone in lower part of Wingate formation

	Inches
Sandstone, argillaceous, buff, soft.	
Sandstone, calcareous, purplish gray, hard	3.5
Sandstone, calcareous, purplish gray, very fine grained, thin-bedded, platy	3.5
Sandstone, shaly, purplish gray, laminated, with darker bands 0.05 inch thick and lighter bands 0.1 inch to 0.5 inch thick	3
Sand, purple, soft	1
Limestone, gray, dense, in beds 1 inch to 3 inches thick separated by thin purple partings; bedding surfaces stylolitic; limestone is studded with small crystals of white calcite and with small cavities having similar crystal outlines	2.1
Clay, soft, white and light greenish, with scattered nodules of gray limestone as much as 2 inches in maximum dimension	2
Sandstone, fine-grained, faintly purplish gray, hard	4

Thickness.—The abundance of vertical cliff exposures of the Wingate sandstone makes it easy to determine the thickness of the formation by plane-table methods. The section of Wingate hand-leveled at Big Hole is the thickest measured within the area mapped but represents an area of unusually thick Wingate in the northeastern part of the area. According to the driller's log, the Tom McGuire et al. or Home Oil Co. well No. 2, in the SE¼ sec. 4, T. 19 S., R. 25 E., penetrated 325 feet of "brown sand" and "dark-brown sand" in the lower part of the well, which is believed to be a not quite complete thickness of Wingate sandstone. This area of unusually thick Wingate is believed to extend for some distance eastward in Colorado. Elsewhere within the area mapped the measurements of the thickness of the Wingate range from 250 to 330 feet, with most of the measurements close to 300 feet and no discernible systematic variation. The variations are probably attributable to the irregularities of the upper and lower contacts of the formation.

Stratigraphic relations.—The significance of the contact relations between the Wingate sandstone and the underlying Chinle has been variously interpreted. These relations, however, are much the same over the entire area of outcrop of the Wingate sandstone. Perhaps the most common type of contact is a sharp boundary, which may be nearly a plane surface with a sheer sandstone cliff above and softer red siltstone below. In many places the lower 50 feet of the sheer cliff is lined with thin partings of red shale. In other places these partings are thicker, and beds of red shale a few inches to 2 feet thick may occur in the lower part of the cliff. In places also beds of fine-grained buff sandstone, apparently identical in lithology with that forming the sheer cliff, may appear in the upper part of the Chinle. In such places there may be difficulty in selecting the precise contact between the two formations and a different bed may be chosen as the base of the Wingate within a lateral distance of 1,000 feet. It is curious that the red shale in the basal Wingate or uppermost Chinle contains very little or no sand or silt, whereas the shale and clay of the remainder of the Chinle are almost uniformly sandy. In many places this shale near the contact is deeply mud-cracked, the separated blocks being several feet across. The cracks are filled with sandstone identical with that of the overlying bed, and evidently the mud cracks were filled by the accumulating sand that subsequently formed the overlying bed. In places these large sand-filled mud cracks simulate channels, and some of them may be sand-filled channels. These relations have been interpreted as corroborative evidence of unconformity, but the writer regards them as not indicative of unconformity in the true sense of a considerable time lapse in sedimentation but of phenomena that might occur with lapse of time sufficient only to dry the mud. In fact, the general existence of sand-filled mud cracks at this horizon seems conclusive evidence against unconformity, for such features could be preserved only if the overlying bed was rather quickly deposited upon them. The repetition of the large-scale mud cracking and sand filling at three levels within the transition zone between Wingate and Chinle at one locality further minimizes their significance as evidence of unconformity. In addition this transition zone may in places have several zones of smaller mud cracks.

Actual channel fillings have been observed at several localities, but the evidence shows clearly that these features do not imply the channeling and erosion of a long-exposed Chinle surface upon which Wingate sediment was deposited. A sketch of the beds at the Wingate-Chinle contact at the top section measured northeast of Hittel's ranch, on the Colorado River (see p. 57), shows these chan-

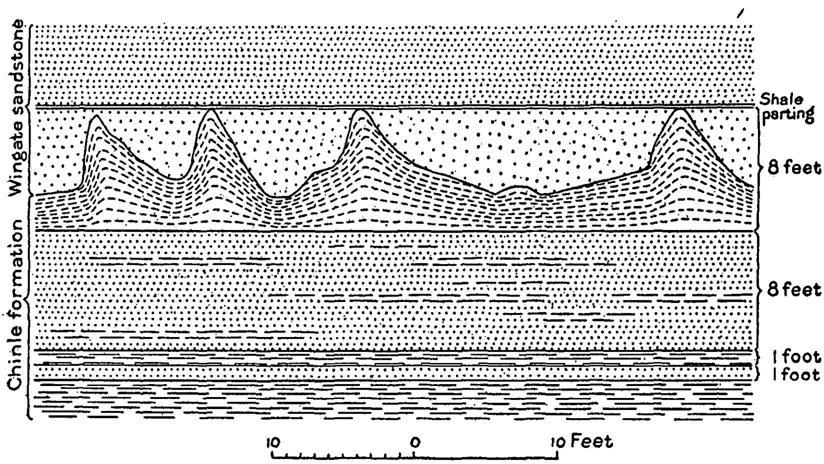

FIGURE 3.—Differential compaction of shale bed at the top of the Chinle formation beneath sandstone-filled channels at the base of the Wingate sandstone.

nels and the deformation resulting from compaction of the underlying red shale (fig. 3). The squeezing of bedding planes in the shale to conform with the rounded under surfaces of the sand-filled channels shows that the channels were cut in soft, partly consolidated shale or mud, and not in an already lithified shale exposed on an erosion surface. Bradley [62] has shown that highly irregular lenses of sand in more compactible silt may develop more regularly rounded boundaries during compaction. Although it is possible that the rounded under surfaces shown in the sketch were developed in this way, it seems more probable that they have suffered only moderate deformation and that they represent at least roughly the original shape of the channel fillings. Similar deformations of the shale where it is penetrated by the deep sand-filled mud cracks has

[62] Bradley, W. H., Origin and microfossils of the oil shale of the Green River formation of Colorado and Utah: U. S. Geol. Survey Prof. Paper 168, p. 20, 1931.

also been observed, but these narrower sand wedges are less competent than the larger channel masses, and the shale is compacted with little distortion of the bedding, whereas the mud-crack fillings are sinuously deformed in a manner analogous to that described by Bradley [63] but on a much larger scale. The writer regards the Wingate-Chinle contact as marking a widespread rather abrupt change in conditions of sedimentation, of almost identical nature everywhere but not necessarily contemporaneous. Support of this view is given by recent stratigraphic studies, which indicate that the Wingate probably becomes more argillaceous toward the margins of its area of deposition and merges laterally with the upper part of the underlying red shales of the Chinle in Utah and the Dolores in Colorado.[64]

Irregularities in thickness of the Chinle formation in the Moab district have been interpreted as due to angular discordance at the base of the Wingate sandstone,[65] but the most recent interpretation of these irregularities considers them to be due to overlap of the Chinle on previously warped surfaces and perhaps also in part to internal thinning of the Chinle[66] and thus to involve no unconformity at the base of the Wingate. Even though it should eventually be determined that these irregularities are due to angular discordance at the base of the Wingate, the discordance might be the result of local deformation and not necessarily indicate a significant erosional unconformity.

Conditions of deposition.—The manner in which a formation having the lithologic characteristics and geographic extent of the Wingate sandstone could have been deposited has already been the subject of considerable speculation. It seems scarcely worth while to add much to this speculation in the absence of extensive analytical study of the formation specifically directed toward the question of origin. Such a study has not been hitherto attempted, probably because the attention of geologists working in the region has been focused on the problems of regional correlation of the various sandstones, upon the successful accomplishment of which such analytical study must necessarily have depended. Observations of the gross lithology and stratigraphic relations of the formation, however, narrowly restrict the range of possible modes of deposition, and some conclusions may therefore be appropriately presented. The first conclusion to be drawn from the evidence is that the Wingate

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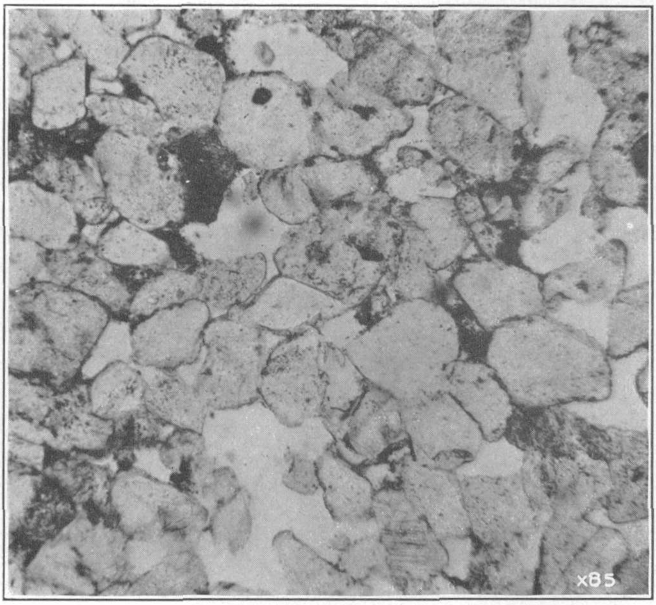
[63] Bradley, W. H., Behavior of certain mud-crack casts during compaction: Am. Jour. Sci., 5th ser., vol. 20, pp. 140–141, 1930.

[64] Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., Correlation of the Jurassic formations of portions of Utah, Colorado, Arizona, and New Mexico: U. S. Geol. Survey Prof. Paper 183 (in press).

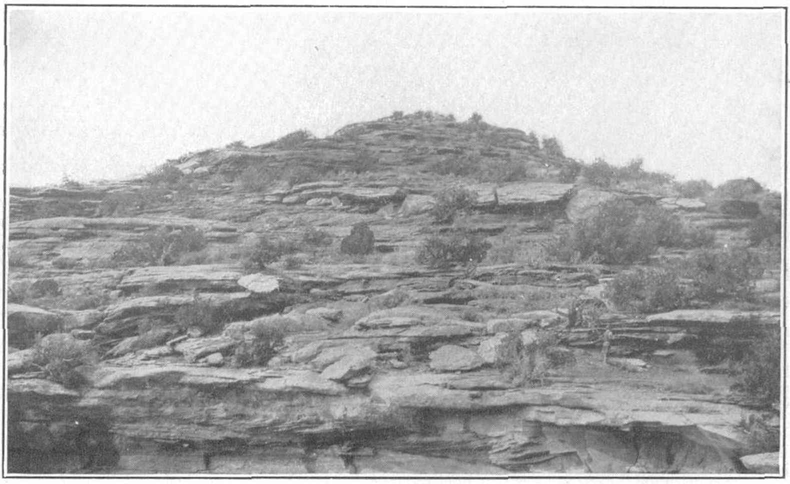
[65] Baker, A. A., and others, Notes on the stratigraphy of the Moab region, Utah: Am. Assoc. Petroleum Geologists Bull., vol. 11, no. 8, p. 801, 1927.

[66] Baker, A. A., Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, p. 42, 1933.



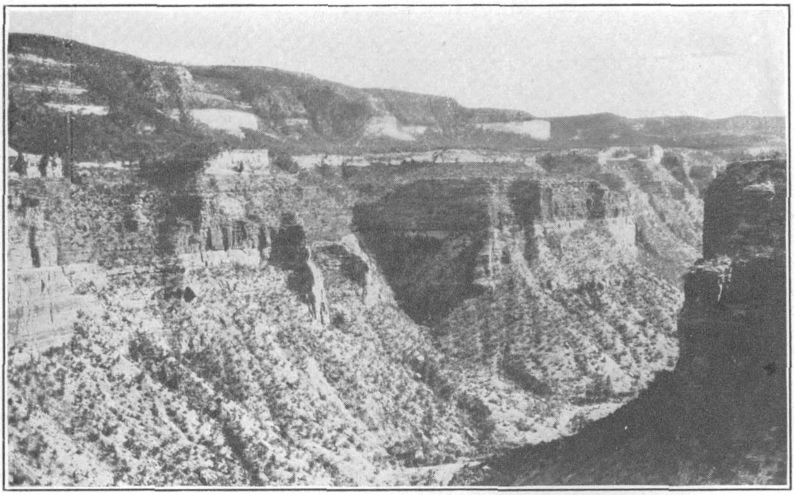
A. PHOTOMICROGRAPH OF WINGATE SANDSTONE.

Specimen from sandstone at the Big Hole, Westwater Canyon. Shows rounded grains of quartz and feldspar.



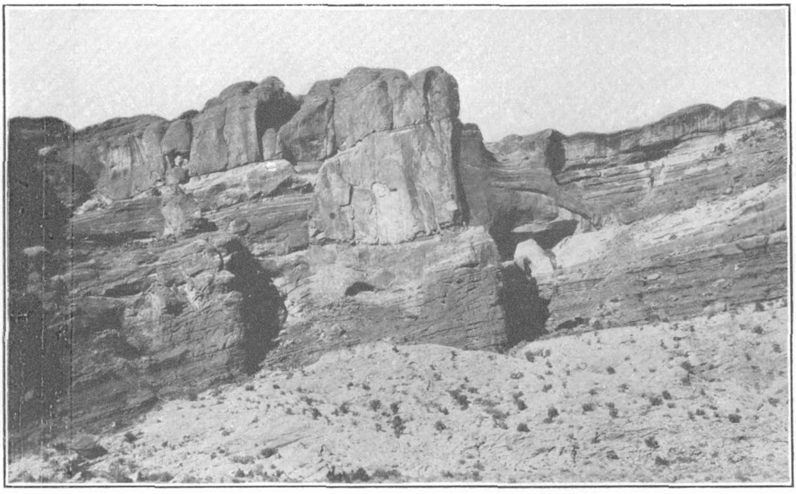
B. CHARACTERISTIC BENCH AND LEDGE OUTCROP OF KAYENTA FORMATION, BIG HOLE, WESTWATER CANYON.

Top of Wingate sandstone shows at bottom of picture, below the man at the right. Photograph by C. E. Erdmann.



A. VIEW LOOKING SOUTHEAST UP BEAVER CANYON FROM A POINT NEAR THE SOUTHEAST CORNER OF SEC. 31, T. 24 S., R. 26 E.

The Chinle and Moenkopi formations are exposed at the base of the section, with a sheer cliff of Wingate sandstone and Kayenta formation above them (the Kayenta is the upper ledge-bedded part of the cliff); the white Navajo sandstone overlies the Kayenta; and back of the bench is the cliff of Entrada sandstone and the overlying Morrison.



B. WHITE NAVAJO SANDSTONE, THIN-BEDDED CARMEL FORMATION, AND OVERLYING ENTRADA SANDSTONE 5½ MILES ABOVE MOAB ON ROAD TO THOMPSON

Photograph by C. E. Erdmann.

sandstone is wholly of continental origin. This follows from its transitional relations with both overlying and underlying demonstrably continental formations, its lateral transition into more argillaceous beds that merge with continental red shales, and the fact that to the west and south, in part to the east, and presumably to the north the Wingate does not extend to the geographic limits of the continental deposits of the underlying Upper Triassic. The Wingate overlaps the red Upper Triassic shales along the Gunnison River in western Colorado north of the San Juan Mountains and there rests directly upon the pre-Cambrian metamorphic rocks and contains as its basal bed a conglomerate obviously derived from erosion of the underlying pre-Cambrian.[67] The suggestion is clear that at least part of the finer-grained material of the Wingate is also derived from this same general region in Colorado.

The only fossils that have been found in the Wingate sandstone are dinosaur footprints observed by Miser[68] in the lower part of the sandstone along the San Juan River and by Gilluly[69] in the San Rafael Swell.

The tangential cross-bedding of much of the Wingate, the uniformly fine-grained character of the formation, and the even sorting and excellent rounding of the grains appear to be explicable as due to eolian deposition. On the other hand the general horizontal bedding of the formation over wide areas, the abundance of layers of sandstone with good horizontal lamination, and the presence in some sandstone beds of flakes and pellets of shale do not accord with conventional notions of eolian deposition. The ripple marks observed in the formation have not been identified as decisively of either eolian or water-current origin, but the association of some of the ripple marks with mud-cracked beds may be indicative of origin in water currents. The cross-bedding in the Wingate locally exhibits contortion and slumping, which seem to the writer to require water saturation of the beds. The limestone beds of the formation are obviously water-deposited, but as they are thin and nowhere extensive, their deposition in small ephemeral basins associated with eolian deposits is not unlikely. 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, with the volume of sediment deposited from water subordinate to that deposited by wind but with water-borne and water-deposited material widely distributed throughout the formation.

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[67] Reeside, J. B., Jr., personal communication.

[68] Longwell, C. R., and others, Rock formations in the Colorado Plateau of southeastern Utah and northern Arizona: U. S. Geol. Survey Prof. Paper 132, p. 13, 1925.

[69] Gilluly, James, and Reeside, J. B., Jr., Sedimentary rocks of the San Rafael Swell and adjacent areas in eastern Utah: U. S. Geol. Survey Prof. Paper 150, p. 70, 1928.

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KAYENTA FORMATION

Name.—The Kayenta formation includes a series of gray and pale lavender-gray sandstones with subordinate interbedded red shales which conformably overlies the Wingate sandstone. The formation was named from exposures near Kayenta, Ariz.[70] Its outcrop is widespread in eastern Utah, northern Arizona, and western Colorado but does not extend into New Mexico. The formation was originally called "Todilto" because of its supposed correlation with the Todilto limestone of northwestern New Mexico and extreme eastern Arizona, but this correlation was made by Gregory[71] as a "working field hypothesis", and the observations of Miser[72] along the San Juan River made it seem desirable to apply the name "Todilto" with a query to the rocks now included in the Kayenta formation. Recent stratigraphic studies[73] have shown that the typical Todilto limestone is much younger than the stratified sandstone unit between the Wingate and Navajo sandstones of Arizona, Utah, and Colorado, and the new name "Kayenta" was therefore adopted for this formation.

Character, topographic expression, and distribution.—The formation consists predominantly of sandstone, ranging in color from white to fairly dark brown, with intermediate shades of buff and tan and with many beds distinctly lavender-gray. The sandstones are composed chiefly of quartz, but contain also considerable biotite and chlorite. The average grain size is coarser than that of the underlying Wingate, and in many of the beds the diameter of the grains averages more than 0.01 inch. The grains are mostly rounded or subrounded, but rounding is less perfect and uniform than in the Wingate. The sandstone is in discontinuous beds and lenses, rarely more than 1,000 feet long and typically 20 feet or less thick. Within these beds cross-bedding of both angular and tangential types is prevalent. Much of the sandstone is thin-bedded, platy, or shaly, and there are numerous thin beds of soft red earthy sandstone, red shale, and greenish-gray shale. A minor but significant proportion of the formation consists of irregular beds of conglomerate with pebbles and chunks of shale, sandstone, and limestone.

A thin section of Kayenta sandstone made from a specimen collected at Big Hole, in Westwater Canyon, was examined microscopically. The grains are principally quartz, but grains of micro-

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[70] Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., Correlation of the Jurassic formations of portions of Utah, Arizona, New Mexico, and Colorado: U. S. Geol. Survey Prof. Paper 183 (in press).

[71] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, p. 55, 1917.

[72] Longwell, C. E., and others, Rock formations in the Colorado Plateau of Utah and Arizona: U. S. Geol. Survey Prof. Paper 132, p. 11, 1925.

[73] Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., op. cit.

cline and sodic plagioclase are common. There is more microcline than plagioclase, and the plagioclase grains present are more altered to clay minerals. Biotite and chlorite are common; other ferromagnesian minerals and apatite are rare. The grains are in part subrounded, in larger part subangular. In general the grain shape is distinctly more angular than in the thin sections of Wingate and Navajo sandstones examined. The maximum grain diameter in the section examined was 0.25 millimeter (0.01 inch), but most of the grains are less than 0.20 millimeter (0.008 inch) and more than 0.08 millimeter (0.003 inch) in diameter. To judge from the general aspect of the section, the grains are less perfectly sized than those of the Wingate. The grains are more thickly banded with limonite than those of the Wingate sandstone, and some of the chlorite also coats grains and fills interstitial spaces. There has been some recrystallization of grains to form interlocking aggregates, and the grains are locally cemented together by microcrystalline quartz.

The Kayenta typically crops out as an alternation of benches and ledges (pl. 10, *B*), the harder sandstones not only standing as low rounded ledges but in many places overhanging recessions where the softer beds have been eroded back. The basal ledges of the Kayenta formation appear to be more thoroughly cemented, and there is also less interbedded shale in the basal part, so that it resists erosion and almost everywhere forms a capping of the Wingate cliffs from which the remainder of the Kayenta rises gradually, forming wide sloping benches. As a result the Kayenta crops out over broad areas, and where the bedding is inclined the formation makes long dip slopes, which are dissected by numerous ledgy-sided canyons. In places, however, the Kayenta formation may be almost all exposed in a vertical cliff continuous upward from that of the Wingate sandstone (pl. 11, *A*).

The extensive dip slopes of the Kayenta formation give it a larger area of outcrop than many of the other formations. It is exposed most widely on the crest of the Dome Plateau, on the dip slope north of Onion Creek and south of the Dolores River, north of Steamboat Mesa, east of the Sand Flat, northwest and southeast of Westwater Canyon, and southeast of the Colorado River near Westwater. Elsewhere it crops out in narrower belts above the Wingate cliffs and below the overlying Navajo sandstone as, for example, on both sides of Salt Valley and in the encircling belts around Steamboat and Polar Mesas.

Sections.—Sections of the Kayenta were hand-leveled at several localities within the area, and three of them are included here to show the lithologic nature of the formation.

Section of Kayenta formation 1 mile east of the Colorado River, southeast of Dewey

[Measured by C. H. Dane and John Vanderwilt. The section was measured by hand level in a direction diagonal to the strike, with the clinometer set at zero. The total thickness thus obtained was 283 feet. The thickness determined by stadia was 320 feet. The unit thicknesses measured by hand level have been proportionately increased to make the total thickness correspond with that measured by stadia]

	Feet
Navajo sandstone contact transitional. The break at the top of this measured section and most measured sections is sharp, but observation of the general exposure at this place clearly shows that only half a mile distant the base of the Navajo lithology occurs about 50 feet lower stratigraphically. This is due to visible intertonguing of the Navajo and Kayenta.	
Kayenta formation. None of the beds are continuous for more than 1,000 feet and few for more than 500 feet, as they lens out or change in lithology laterally. This exposure shows a repeated alternation of benches and ledges, the characteristic topographic expression of the variably resistant sandstones of the formation.	
Sandstone, purple, somewhat argillaceous, mottled light green	1
Sandstone, white and green-gray, horizontally bedded	15
Sandstone, gray, thin-bedded, soft and crumbly	2
Sandstone, white, medium-grained, with lumps and pellets of green shale, calcareous, hard; makes a ledge; angular and tangential cross-bedding at high angles	17
Sandstone, white, some light green, some faint olive-green, extremely fine grained, soft; bedding planes do not weather out well but bedding is predominantly horizontal, with minor cross-bedding	21
Sandstone, greenish gray, fine-grained, soft; contains pebbles of green shale, and many of the grains are composed of green shale; makes a partly concealed slope	20
Shale, red, micaceous, sandy, with much muscovite; and sandstone, thin-bedded, purple-gray, in about equal amounts	9
Sandstone, gray, with very numerous angular chunks of red, gray, and violet limestone and red and green shale. This bed varies from a knife-edge to 2 feet in thickness and appears to be a lens about 6 feet wide which runs diagonally across the strike for only a few hundred feet.[74] Above this lens the beds are harder and more calcareous. Except within the area of this lens, the unit below continues up to the base of the red shale and purple sandstone unit described above	5
Sandstone, reddish brown, violet-buff, violet-gray, and purple-brown	52

[74] At a place about 2,000 feet from the measured section there is a bed, about 10 feet thick, of limestone conglomerate in the Kayenta. This is stratigraphically about 60 feet below the 2-foot bed of limestone conglomerate described.

Kayenta formation—Continued.	Feet
Sandstone, violet-gray, slightly calcareous	14
Sandstone, violet-white, cross-bedded	6
Sandstone, buff, violet-gray, reddish buff, and white	22
Sandstone, white, medium-grained; angular chunks and rounded pellets of red shale in lower 2 feet; makes a ledge	17
Slope, mostly concealed; at top exposures are cross-bedded red sandy shale, soft white sandstone in beds a thirty-second to half an inch thick, and soft light-green sandstone	22
Sandstone, buff, white, and pinkish buff, well bedded but cross-bedded	20
Sandstone, buff and violet-buff, medium-grained; one layer 6 inches thick contains muscovite flakes in quantity and a very few smaller flakes of biotite and chlorite. The flakes parallel the bedding and appear primary, but some aggregates of interlocking plates might be secondary. This unit makes a ledge	8
Shale, pure, red, and sandstone, thin-bedded, buff with faint violet tones; grades upward into the overlying unit	12
Sandstone, thin-bedded, white and faint pinkish buff	6
Sandstone, buff, hard but crumbly	27
Sandstone, white, hard, medium-grained, containing rounded pellets of pure dark-red shale	4
Sandstone, buff, some with faint pink tones, medium to coarse grained, grains well rounded, calcareous; in ledges 6 inches to 3 feet thick with intervening softer sandstone layers a few inches thick	20
	320

Contact transitional. Near the top of the Wingate the sandstone is more clearly bedded and cross-bedded on a smaller scale and at lower angle. It is also somewhat coarser-grained.

Wingate sandstone: Sandstone, buff, hard, extremely fine grained, grains rounded, bedding essentially horizontal in the upper few feet. Fresh fracture shows no bedding or only faint indications of it. Outcrop weathers to smooth rounded surfaces.

Section of Kayenta formation on south side of Ryan Gulch, 1 mile east of sec. 24, T. 22 S., R. 24 E.

[Measured by C. H. Dane and C. B. Hunt]

Carmel formation (contact concealed).

Kayenta formation:	Ft.
Sandstone, purple-gray, fine-grained	8
Sandstone, white and greenish white, very fine grained at the base and coarser toward the top. The lower foot contains a great number of bright-green flat flakes of shale 1 inch or less in diameter, concentrated on the bedding planes, which in the lower 2	

Kayenta formation—Continued.	Ft.	in.
feet are mostly horizontal. The sandstone above is cross-bedded at angles as high as 30°, the cross-bedding planes in thin beds from 6 inches to 2 feet thick. The unit makes a very prominent light-colored ledge	38	
Shale, red, and sandstone, shaly, soft, red, poorly exposed and weathering down to a soft red slope. At the top is fine-grained red silty clay which weathers into rounded lumps. This clay is streaked with green from the overlying bed, and green patches are spotted through it	30	
Sandstone, shaly, gray to red, fine grained, the lower part weathering into thin curving plates a quarter of an inch thick, the plates separated by thin films of red shale	3	6
Siltstone, sandy, soft, red, with many flakes of mica	1	
Sandstone, shaly, red		8
Sandstone, calcareous, reddish gray, very hard; grains less than 0.01 inch in diameter; makes a ledge	1	
Shale, sandy, red, and sandstone, shaly, red, soft; weathers to mostly concealed slope covered with soft red wash	12	6
Sandstone, light gray, hard, platy, probably ripple-marked	9	
Sandstone, thin-bedded, only partly exposed; crops out on wide dip slope, and thickness estimated, not measured	20	
Sandstone, purple-gray, with interbedded layers of softer, more shaly sandstone 6 to 12 inches thick. The purple color is probably due to disintegration of red-shale pellets and to red wash staining the original neutral gray. The sandstones are partly in rounded massive light-gray, purple-gray, and red-gray discontinuous ledges 1 to 10 feet thick and partly in thin-bedded brown and reddish-brown softer sandstone units of the same variation in thickness. The massive sandstones are in places spattered with red-clay pellets, some as much as an inch in length. Flakes of muscovite mica are also common in these sandstones. These massive sandstones in places rest on erosional irregularities with relief of as much as 1 foot. About 4 feet below the top of the unit is a local bed of gray concretionary limestone 6 inches thick	101	
Sandstone, very light purple-gray, very fine grained; weathers in plates a quarter of an inch to 4 inches thick; irregularly bedded; top 3 feet makes a ledge	13	
Sandstone, with red-shale pellets and chunks: makes a ledge disappearing 20 feet along the exposure	3	
Sandstone, gray, thin-bedded, horizontally bedded and cross-bedded	5	
Sandstone, purple-gray; makes a ledge	2	

	Ft.	in.
Kayenta formation—Continued.		
Sandstone, gray, thin-bedded, cross-bedded; beds half an inch to 1 inch thick; weathers out as soft underhang of overlying ledge	1	
Sandstone, light tan, subrounded to rounded grains, averaging over 0.01 inch in size; forms a ledge	13	
Sandstone, light tan to white, grains subrounded to rounded and averaging 0.01 inch in size at the top; cross-bedded at angles of 4° or less; makes a slight ledge	5	
Sandstone, light tan, in ledges 3 to 4 feet thick interbedded with softer, more shaly beds 1 to 2 feet thick. This ledge is resistant to erosion and caps Wingate sandstone cliffs; weathers dark tan and dark gray	16	
Sandstone, light tan, in beds $\frac{1}{32}$ to $\frac{1}{8}$ inch thick weathers into slabs as much as 7 inches thick; upper few inches thinly laminated and white	4	4
Sandstone, very light tan, fine-grained groundmass with scattered coarser grains over 0.01 inch in diameter; shows irregular and discontinuous horizontal bedding surfaces spaced 6 inches to 1 foot; weathers into rounded blocks	5	5
Sandstone, platy, horizontally bedded; upper part becomes laminated into beds $\frac{1}{16}$ inch thick	1	2
	293	7

Contact vague and uncertain; might be selected 10 feet below or possibly somewhat above position selected. No erosional irregularity at contact chosen at place of section.

Wingate sandstone: Ledges of relatively hard, resistant sandstone, buff or pink, stained yellow and red. At the top two ledges about 12 feet thick separated by a shale layer 1 to 2 feet thick and a similar shale layer at the top of the formation. Some tangential and angular cross-bedding with much horizontal bedding, the beds $\frac{1}{32}$ to 1 inch thick. The bedding difference is one of color variation from darker to lighter red. The sandstone is very fine grained and very evenly sorted.

Thickness.—The Kayenta formation varies considerably in thickness. In part this variation may be due to the transitional relations at both upper and lower contacts and the unsystematic arbitrary selection of contact horizons, but to a great degree it is a real variation in thickness of sediments having the Kayenta lithology.

Over the area west and southwest of Ryan Gulch the Kayenta ranges from 200 to 320 feet in thickness. The thickness of 320 feet is restricted to the section measured near Dewey, although a thickness nearly as great was measured on the south side of Ryan Gulch. The thickness in Cache Valley is about 250 feet and at the north end of Salt Valley about 200 feet. East of Scharf's ranch, on the Dolores

River, the Kayenta is slightly less than 200 feet thick, and in the vicinity of Big Hole, Westwater Canyon, it is estimated to be about 150 feet thick. The Utah Southern Oil Co.'s well, State No. 1, in sec. 26, T. 21 S., R. 23 E., passed through the Kayenta formation. The log is not sufficiently detailed to delimit the Kayenta definitely, but 226 feet of beds from 1,503 to 1,729 feet were more or less arbitrarily assigned to the formation. The log of the Tom McGuire et al. or Home Oil Co. No. 2 well, in sec. 4, T. 19 S., R. 25 E., however, quite definitely shows 202 feet of Kayenta formation from 1,148 to 1,350 feet.

There is, as partly shown by the above figures, a distinct thinning of the Kayenta formation toward the east. This continues east of the mapped area, for at the top of the Serpents Trail, west of Grand Junction, Colo., only 77 feet of sandstone represents the Kayenta.

Relation of Kayenta formation to Wingate sandstone.—The Kayenta formation rests conformably upon the Wingate sandstone. At most places there is a gradual transition from the massive sandstone of the Wingate into the more distinctly bedded sandstones of the Kayenta, and inspection of the contact from a distance shows that thin beds assigned at one point to the basal Kayenta merge laterally with massive sandstones that would be included rather in the top of the Wingate. At other places the basal Kayenta beds are sharply separated from the underlying Wingate and rest in erosional irregularities cut in the Wingate. It is clear in most places that such irregularities represent the channeling erosion of currents and that the lenses of sandstone which fit into them are the subsequent channel fillings. The irregularities are identical in character with those at the base of innumerable lenticular sandstone beds higher in the Kayenta. The writer has nowhere seen angular truncation of the Wingate by the Kayenta, and the surprisingly uniform thickness of the Wingate over great areas supports the other evidence of conformable relations between it and the Kayenta.

Conditions of deposition.—The lithologic characteristics of the Kayenta accord well with a hypothesis of fluviatile deposition for much of the formation. The sandstone of the formation is moderately well sorted but has a distinct variation in grain size as contrasted with the perfect sizing of much of the Wingate. The lenses of sandstone are almost surely channel fillings, although no evidence of elongation or sinuosity to confirm this conclusion was obtained. The cross-bedding is in part tangential but perhaps in larger part angular, and the bedding planes are in many places contorted in a manner explicable only as a result of slumping or similar movement of water-saturated, partly consolidated sediments. The limestone and shale-pellet conglomerates are similar to those of the Chinle and probably had the same mode of origin. In addition the abundance of thin-bedded shaly sandstones and red pure shales suggests the deposition of silty and finer-grained sediment as alluvium from temporary channel overflow, and the local occurrence of small limestone lenses in such shaly beds accords with deposition in this manner. Ripple marks and mud cracks have been observed but are not as common as might be expected, especially as the abundance of shale flakes and pellets in the sandstones seems possibly to represent the transportation and redeposition of dried mud fragments and mud curls. Species of the fresh-water genus *Unio* have been found in the Kayenta formation [75] at several localities but are of long-ranging and little-studied types which do not now aid in fixing the age of the formation. Gregory [76] found dinosaur tracks in the Kayenta formation at two localities in the Navajo Indian Reservation in Arizona, and on the basis of measurements and photographs Prof. R. S. Lull concluded that the forms represented were not older than latest Triassic.

Dinosaur tracks have been collected also near the top of the Kayenta formation in the Green River Desert [77] but have not yet been studied. The scanty faunal evidence thus accords with the lithologic evidence in suggesting a largely fluviatile deposition of the formation.

NAVAJO SANDSTONE

Name and correlation.—The uppermost formation of the Glen Canyon group is the Navajo sandstone, a fine- to medium-grained buff quartz sandstone, nearly everywhere tangentially bedded on a large scale and almost devoid of horizontal bedding. The name was applied to the formation as exposed in the "Navajo country" by Gregory [78] and has since been widely extended in northeastern Arizona and southeastern Utah to a lithologic unit at the same position in the stratigraphic sequence. It has also been applied rather widely to a white and pink locally banded cross-bedded sandstone extensively exposed in northwestern New Mexico, but recent studies [79] show that the Navajo thins out eastward in northeastern Arizona and disappears from the section at or near the Arizona-New Mexico line, and that the sandstone in New Mexico to which the name

[75] Baker, A. A., Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, p. 46, 1933. McKnight, E. T., Geology of an area between the Green and Colorado Rivers, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. (in preparation).

[76] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, p. 56, 1917.

[77] Baker, A. A., Geology of the Green River Desert and the east side of the San Rafael Swell, Utah: U. S. Geol. Survey Bull. (in preparation).

[78] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, p 57, 1917.

[79] Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., Correlation of the Jurassic formations of portions of Utah, Arizona, New Mexico, and Colorado: U. S. Geol. Survey Prof. Paper 183 (in press).

Navajo has been applied is a much younger formation. The Navajo also thins out to the northeast within the area mapped in this report, and farther south a similar thinning causes the disappearance of the Navajo from the section. The Navajo sandstone of the Colorado Plateau province has been in the past correlated with various portions of the La Plata sandstone in southwestern Colorado.[80] The demonstration that the Navajo disappears from the section before reaching the type area of the La Plata is made in a recent paper,[81] which also gives a complete history of the successive correlations of the La Plata with the Glen Canyon group of the plateau province and a description of the extent of the Navajo, its regional stratigraphic relations, and the correlations currently accepted.

Lithology and topographic expression.—The Navajo to the west typically crops out as great rounded knolls or domes rising above platforms or slopes floored by the underlying Kayenta formation. This form of outcrop extends into the western part of the area here mapped, appearing, for example, on the Dome Plateau and on the mesa bounded by Cache Valley, Salt Wash, and the Colorado River. Somewhat less common is the outcrop of a single nearly sheer cliff, which may merge with that of the underlying formations of the Glen Canyon group (pl. 11, *A*). In the eastern part of the area mapped, where the Navajo is thin, the typical outcrop is a low, rounded cliff which rises above the lower Kayenta outcrop and from the top of which the overlying formations have been eroded back so that the Navajo forms a cliff-bordered bench, deeply indented by the low canyons of small drainage courses.

Because of its intricate and large-scale cross-bedding, the absence of continuous horizontal bedding planes, and the general uniformity of texture, it is difficult or impossible to measure detailed sections of the formation. It is composed almost exclusively of light-buff fine-grained sand, the grains of which are well rounded or subrounded. There is some variation in color, and some of the sandstone is nearly white. The weathered rock is of darker shades than the freshly fractured surfaces. There are some thin discontinuous beds of horizontally bedded reddish buff muddy sandstone, but the great mass of the rock is clean sandstone cross-bedded without discernible system.

A thin section of the Navajo sandstone from a specimen collected near Scharf's ranch, on the Dolores River, near the feather edge of the formation, shows that the grains are predominantly quartz.

[80] Cross, Whitman, Stratigraphic results of a reconnaissance in western Colorado and eastern Utah: Jour. Geology, vol. 15, p. 644, 1907. Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, p. 52, 1917. Gilluly, James, and Reeside, J. B., Jr., Sedimentary rocks of the San Rafael Swell and some adjacent areas in eastern Utah: U. S. Geol. Survey Prof. Paper 150, p. 73, 1928.

[81] Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., op. cit.

Microcline and sodic plagioclase are less conspicuous than in the Wingate and Kayenta. The largest grain diameter is about 0.30 millimeter (0.012 inch), but the average size is probably less than 0.15 millimeter (0.006 inch). The grains are only moderately rounded, and some are angular in shape. The largest grains are best rounded. Small muscovite flakes are abundant, and a few considerably altered grains appear to have been chert. There is a considerable amount of carbonate cement. A section of a specimen collected by A. A. Baker near Hart Springs in sec. 1, T. 31 S., R. 22 E., was also examined. The grain constituents in this are much the same: a few flakes of biotite are present in addition to the muscovite, but none of the altered chert grains were observed. Microcrystalline quartz occupies part of the space between the grains The maximum grain size is about 0.25 millimeter (0.01 inch) and the average 0.10 millimeter (0.004 inch) or less; this specimen being thus distinctly finer grained than the one obtained near Scharf's ranch. The grains are rounded to about the same degree—less than the rounding observed in the Wingate sandstone but more than that observed in the Kayenta.

Beds of dense gray limestone are locally present in the Navajo in this area, as in many places elsewhere in Utah and Arizona. These are thicker and of greater areal extent than the similar limestone beds found in the Wingate and Kayenta formations.

Such limestone beds in the Navajo are found in Salt Valley, near the top of the formation in Cache Valley, near the top of the formation southeast of Dewey, and at several horizons west of Steamboat Mesa. Not uncommonly they have contorted bedding, which is apparently not present elsewhere in the Navajo, although it would be less evident in the sandstone than in the distinctly bedded limestone. The observation of crumpled bedding in a single layer of limestone 6 to 9 inches thick with undisturbed horizontally bedded limestone 2 to 3 feet thick below it in an area west of Steamboat Mesa implies that the disturbance of the bedding was confined to thin zones and that the sandstone below was not necessarily involved in the movement. For the more complex and extensive deformation, however, no more plausible hypothesis presents itself than settlement and readjustment of underlying incompletely consolidated or incoherent sand shortly after the deposition of the limestone.

The contact between the Navajo and Kayenta is definitely conformable and transitional. The boundary between Navajo lithology and Kayenta lithology is sharp at most places, occurring immediately above red shale or purple sandstone, but observation of the contact in general shows that within a distance of half a mile or less the position of the contact between the two types of lithology may differ by as much as 50 feet stratigraphically, the variation being due to visible intertonguing of the two types.

Thickness.—Within the area mapped the Navajo has a maximum thickness of about 300 feet. This is reached only in the southwest corner of the area, southwest of Elephant Butte. At the north end of Salt Valley on the east side of the valley a hand-leveled section of the Navajo sandstone was 250 feet thick. Near Dewey the Navajo is 220 feet thick, and southwest of Polar Mesa it was estimated to be 175 feet thick. A short distance east of Scharf's ranch it is less than 160 feet thick, as shown by the following section:

Section three-quarters of a mile east of Scharf's ranch, on the Dolores River

[Measured by C. B. Hunt]

	Ft.	in.
Entrada sandstone.		
Carmel formation: Sandstone, argillaceous, red; lower 8 feet consists of alternating beds, 1 to 2 feet thick, of red, muddy sandstone and a white, fine-grained, cleaner sandstone; unit forms a steep slope	25	
Navajo sandstone:		
Sandstone, white; weathers buff; upper 8 feet platy	18	
Sandstone, buff, shaly, soft; forms a niche in cliff	4	6
Sandstone, buff, cliff-forming (along Dolores River Canyon), cross-bedded on a large scale and at high angles	112	
Sandstone, buff, subrounded grains about 0.01 inch in diameter; conspicuously angularly cross-bedded	24	
	158	6
Kayenta formation:		
Shale, red, lenticular; thins out rapidly in both directions from measured section		8
Sandstone, buff to white, fine-grained, with subrounded grains; forms base of cliff	7	6
Sandstone, shaly, green-gray, with thin lenses of red, shaly sandstone; unit thins out 50 feet to the west	2	
Shale, sandy, red; contains thin greenish gray irregular shaly sandstone lenses in upper 10 inches	2	6
Sandstone, white, fine-grained; weathers in platy slabs 1 to 4 inches thick; contains small pellets of greenish gray sandy clay, averaging around 0.01 inch in diameter	15	
Shale, sandy, red.		

Northeast of this locality the Navajo thins out within a short distance, being absent northeast of a line extending from the north end of Steamboat Mesa through the mouth of Coach Creek. The Utah Southern State No. 1 well, in sec. 26, T. 21 S., R. 23 E., probably penetrated the thin northeastern edge of the Navajo, and the sand and "pink sandy shale" logged from 1,457 to 1,503 feet are assigned to this formation.

Conditions of deposition.—The writer believes that the diminishing thickness of the Navajo toward the northeast is due to internal thinning and not to angular discordance at the base of the overlying formations. Field observations rather definitely eliminate the possibility that the thinning is accomplished by the lateral transition of successively higher beds of the Navajo into Kayenta lithology, and the fact that the Kayenta thins somewhat in the same direction also makes this unlikely.

The internal thinning is not accomplished by the overlap of successive Navajo beds toward the northeast, because of the highly irregular nature of the Navajo bedding. A hypothesis of thinning because of angular unconformity at the top was entertained in the field but eventually discarded as improbable. If present such angular discordance would be difficult to detect, because of the absence of definite continuous beds within the Navajo and because of the complex cross-bedding, which makes it impossible to determine whether any extensive planes are stratigraphically horizontal. Within the area mapped there are additional difficulties. The Navajo in few places crops out as a steep slope or cliff immediately below a correspondingly well exposed outcrop of the overlying beds. The most general exposure of the Navajo near its eastern margin is in a dissected bench with long promontories from which the thin overlying softer formation has been swept back. The difficulties resulting from perspective are thus considerable and are enhanced by the existence of broad, low irregular folds. The hypothesis of angular unconformity is dismissed with more confidence because of the apparent continuity of a zone of white sandstone and red shale at the top of the Kayenta for some distance northeast of the vanishing edge of the Navajo, and also because more satisfactory exposures in Paradox Valley, in western Colorado, reveal no angular discordance. Furthermore, an angular unconformity sufficient to remove the Navajo from the section at the rate observed in the area mapped and in Paradox Valley would remove the Kayenta below within an equally short distance to the northeast, but the wide extension of even a thin body of the Kayenta to the northeast provides a cogent argument in favor of sedimentary thinning of the Navajo.

The Navajo has been generally considered as an eolian formation, since its origin as a dune-sand deposit was suggested by Gregory. The texture, cross-bedding, and general absence of silty beds accord with this view, and the limestone lenses found in the formation are most easily explained as deposited in local ephemeral basins within a dune-sand area. A zone of pebbles 2 or 3 inches in diameter found in the Navajo of the San Rafael Swell[82] provides conclusive proof of eolian deposition of the sandstone associated with it, for the pebbles were "quartz, highly polished and faceted—perfect examples of 'dreikanter'." Quartzite pebbles with surfaces grooved and polished, probably by the action of wind, have also been found near the top of the Navajo sandstone in the Green River Desert.[83]

GENERAL RELATIONS AND AGE OF THE GLEN CANYON GROUP

The lithologic and stratigraphic evidence presented in the foregoing pages indicates that the sediments of the Glen Canyon group are exclusively of continental origin, and the writer believes that the evidence favors the view that the sedimentation was uninterrupted either by significant time breaks between the formations of the group or by erosion or time interval between the underlying Upper Triassic and the base of the group. Within the area mapped the Chinle formation was partly derived from the erosion of a land area to the northeast, and the fact that conglomerate derived from underlying pre-Cambrian rocks has been found in the basal part of the Wingate sandstone in at least one locality in western Colorado shows that the Wingate was certainly derived at least in part from the same general source. A similar source appears a priori probable for the Kayenta sediments. The great westward thickening of the Navajo sandstone appears to indicate a source for that formation chiefly from the west.[84]

More definite conclusions could be drawn, however, if a thorough study of the petrographic character of the sandstone from place to place had been made. Only two thin sections of the Navajo were examined by the writer. These indicate that the composition of the Navajo is much like that of the underlying sandstones. The coarser grain of the specimen collected near the eastern edge of the formation and the occurrence in it of a few altered chert grains, which do not appear in the other section, may perhaps point toward an easterly source similar to that of the underlying sandstones.

In view of the virtual lack of fossil evidence, the assumption that each formation represents a continuous time unit appears unwarranted, and the transitional relations between the formations of the group being admitted, it appears equally plausible that the forma-

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[82] Gilluly, James, and Reeside, J. B., Jr., Sedimentary rocks of the San Rafael Swell and some adjacent areas in eastern Utah: U. S. Geol. Survey Prof. Paper 150, p. 72, 1928.

[83] Baker, A. A, personal communication.

[84] Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., Correlation of the Jurassic formations of portions of Utah, Arizona, New Mexico, and Colorado: U. S. Geol. Survey Prof. Paper 183 (in press).

tions transgress time lines and that the lower part of the Navajo sandstone in its western exposures may be contemporaneous with the sandstone of Wingate or Kayenta lithology in the eastern exposures.

It is within the limits of possibility that the entire group is of Upper Triassic age, and the opinion of Lull that dinosaur tracks from the Kayenta formation represent species not older than latest Triassic does not contravene this possibility. This extreme view, however, appears improbable, for the formation overlying the Glen Canyon group is demonstrably of middle Upper Jurassic age, there is nowhere satisfactory evidence of unconformity at the top of the Glen Canyon group, and the assignment of the entire Glen Canyon group to the Upper Triassic would imply a period of stability without either erosion or deposition extending through most of Jurassic time. The deposition of such a vast mass of largely eolian sediment would moreover unduly prolong Upper Triassic time, for the known fauna of at least the upper part of the Chinle is believed to represent fairly late Upper Triassic.[85] For these reasons it appears that the Glen Canyon group represents in large part deposition during Jurassic time. Following precedent the writer has assigned the entire group to the Jurassic with a question—a somewhat arbitrary classification which is convenient practically but which neglects the quite possible Upper Triassic age of an indefinite amount of the lower part of the sediments of the group.

JURASSIC SYSTEM

SAN RAFAEL GROUP

The San Rafael group was first defined by Gilluly and Reeside[86] as the succession of Upper Jurassic formations that crop out in the San Rafael Swell. In the type locality the group includes, in ascending order, the Carmel, Entrada, Curtis, and Summerville formations. The limestones in the Carmel formation contain a marine invertebrate fauna of Upper Jurassic age. A smaller fauna of marine invertebrates occurs in the Curtis formation and represents a somewhat later stage of Upper Jurassic time. Eastward from the type locality of the group the Curtis formation loses its identity by merging with the Summerville, but the other three formations have been traced into the area discussed in this report,[87]

[85] Camp, C. L., A study of the phytosaurs: California Univ. Mem., vol. 10, pp. 44–6, 1930.

[86] Gilluly, James, and Reeside, J. B., Jr., Sedimentary rocks of the San Rafael Swell and some adjacent areas in eastern Utah: U. S. Geol. Survey Prof. Paper 150, p. 73, 1928.

[87] McKnight, E. T., Geology of an area between the Green and Colorado Rivers, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. (in preparation). Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., Correlation of the Jurassic formations of portions of Utah, Arizona, New Mexico, and Colorado: U. S. Geol. Survey Prof. Paper 183 (in press).

where the Entrada sandstone is the thickest and most impressive formation of the group and only thin equivalents of the Carmel and Summerville formations are present.

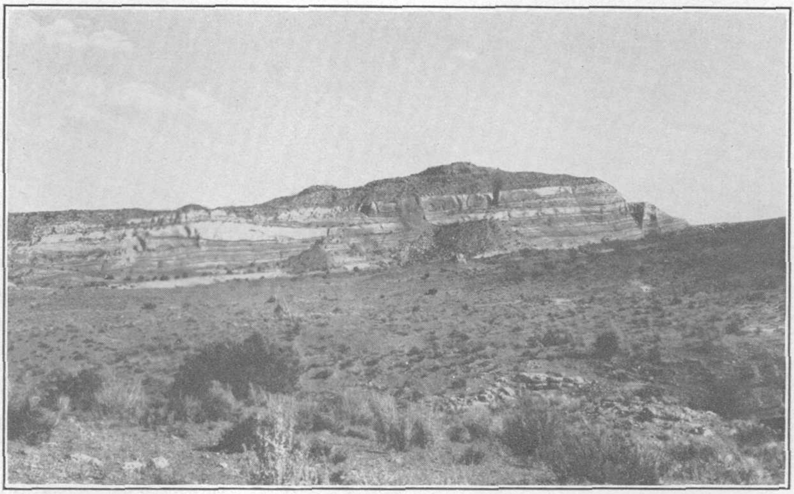
CARMEL FORMATION

Name.—The Carmel formation was named from Mount Carmel, in southwestern Utah,[88] where it was first observed by Gilbert. The term was subsequently applied to the lowest formation of the San Rafael group in the San Rafael Swell,[89] but some doubt has recently arisen as to whether this unit is precisely correlative with the Carmel at the type locality.[90] Where the formation is thickest in the San Rafael Swell it includes a basal series of gray fossiliferous sandy limestones and overlying gray, red, and green shales with much gypsum. The typical Carmel may include equivalents only of the limestone part of this series of beds. Traced to the east from the San Rafael Swell the formation thins and grades laterally into red thin-bedded sandstones and sandy shales, at many places with contorted bedding.

Lithology and distribution.—Within the area mapped the Carmel consists predominantly of soft red muddy sandstone, ranging from thin-bedded to nearly massive (pl. 11, *B*). The bedding is in many places wavy, contorted, or excessively irregular. The remarkable deformation of the bedding at this horizon extends upward into the lower part of the Entrada sandstone and is described in the discussion of that formation.

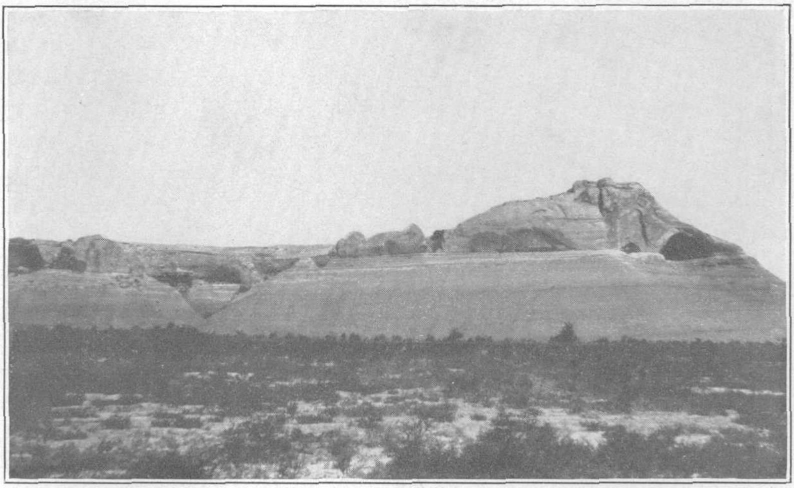
The Carmel forms a soft zone between the massive Navajo and Entrada sandstones and for that reason causes the development of a broad bench between them. The Carmel has almost everywhere been swept back from this bench and crops out as a narrow strip at the base of the overlying cliff (pl. 5). It is exposed in a continuous strip 12 miles in length paralleling Salt Valley and on the east side of it; in a more irregular strip of equal length extending southeastward on the west side of Salt Valley; in a small area in the center of the mesa bounded by Salt Wash, Cache Valley, and the Colorado River; and in a long arc curving eastward from Cache Valley through Squaw Park to Dewey and thence southeastward for about 7 miles. East of the Dolores River the formation was not mapped, but a thin zone of approximately the same lithology extends as far east as the Sand Flat. It is a thin and indefinite zone in the exposures north of Cottonwood and Sevenmile Canyons and

[88] Gregory, H. E., and Moore, R. C., The Kaiparowits region, Utah and Arizona: U. S. Geol. Survey Prof. Paper 164, p. 72, 1931.
[89] Gilluly, James, and Reeside, J. B., Jr., op. cit., p. 73.
[90] Reeside, J. B., Jr., personal communication.

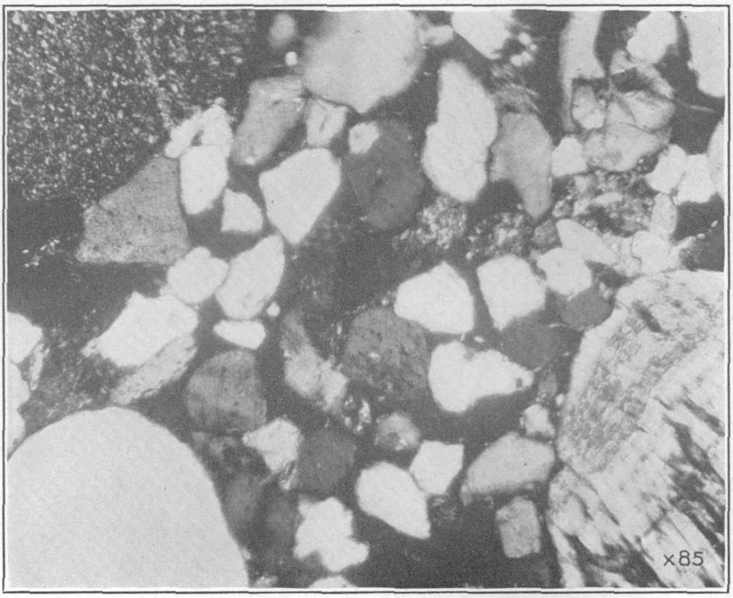


A. VIEW LOOKING SOUTHEAST FROM CENTER OF SEC. 17, T. 23 S., R. 24 E., AT CLIFF OF ENTRADA SANDSTONE.

Plunging lens of Moab sandstone member shows at left of center. Morrison formation caps the ridge Carmel formation and top of Navajo sandstone crop out on the flat in the foreground.

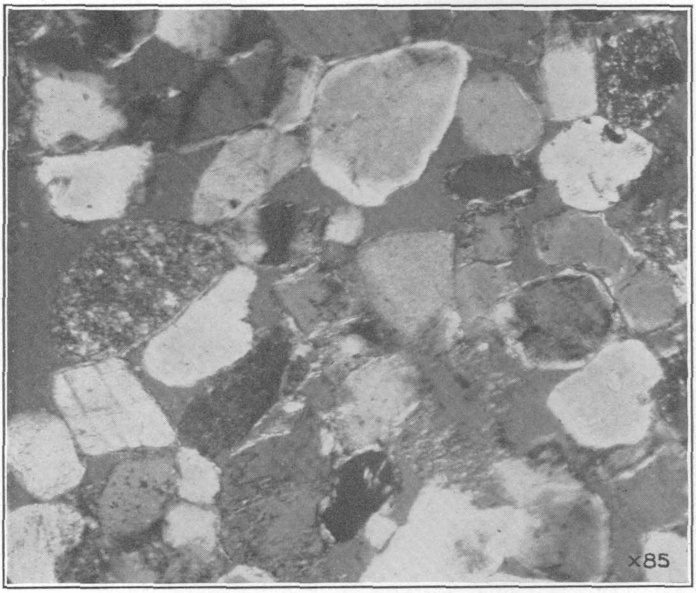


B. MOAB SANDSTONE MEMBER AND UNDERLYING BEDS OF ENTRADA SANDSTONE FROM COLORADO RIVER BOTTOM AT HALLET'S RANCH, NEAR MOUTH OF AGATE WASH.



A. PHOTOMICROGRAPH OF ENTRADA SANDSTONE.

Specimen from sec. 6, T. 21 S., R. 25 E. Shows large rounded grains of chert, chalcedony, and quartz, with finer partly rounded grains of quartz and feldspar. Crossed nicols.



B. PHOTOMICROGRAPH OF MOAB SANDSTONE.

Specimen from locality 1 mile east of east line of sec. 24, T. 22 S., R. 24 E. Partly crossed nicols.

was not mapped. It is not present in the rims encircling Steamboat and Polar Mesas.

Relations of Carmel to Navajo and Entrada sandstones.—The contact between the Carmel and Navajo is normally sharp, though without perceptible erosional irregularity. Within the area mapped no evidence of unconformity was observed. Observations in the Moab district [91] indicate that the Carmel was deposited on a slightly irregular floor of Navajo sandstone and that Carmel sediments are locally cut out where they overlap low swells on the Navajo surface. Baker believes that the wind-deposited sands of the Navajo might be expected to have a slightly irregular surface and accordingly that such irregularities as have been observed do not necessarily indicate erosion and lapse of time at this contact.

The contact of the Carmel with the overlying Entrada sandstone is conformable, locally sharp but elsewhere transitional. Where the Carmel is thickest within the area mapped the selection of its upper contact is at some places more or less arbitrary, because of an alternation of darker-red earthy sandstone and shale of Carmel lithology and lighter-red or buff cleaner sandstones of Entrada lithology. It is virtually certain that no contact selected in this part of the region could be followed for any great distance. Farther east, where the Carmel is thinner, the contact is more commonly sharp and where transition occurs it is by gradation between the two types of lithology rather than by an alternation of them.

Thickness.—In a section measured at the north end of Salt Valley 150 feet of beds were included in the Carmel formation. From this locality it consistently thins eastward, and at Dewey it is considered to be only 20 feet thick. It apparently maintains this thickness for some distance eastward, for 22 feet of red earthy sandstone was assigned to the Carmel in a section measured south of Ryan Creek, although the formation is not shown on the areal map in this vicinity.

Conditions of deposition.—A marine origin for the Carmel formation in the San Rafael Swell [92] has been postulated with confidence because of its lithology and the undeniably marine origin of its fossiliferous limestone portion. The existence of a shaly anhydrite zone and much gypsum in the upper part of the formation has been ascribed to deposition in lagoons by evaporation from marine waters. There seems no reason to doubt that the Carmel formation over much of its area of outcrop represents the initial deposit of an Upper Jurassic sea which widely invaded the western interior of North

[91] Baker, A. A., Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, pp. 47–48, 1933.

[92] Gilluly, James, and Reeside, J. B., Jr., op. cit., p. 74.

America. The thin and sandy Carmel of the area of this report represents a marginal facies of the clearly marine Carmel, but there is apparently no direct and definite evidence to show that the beds of this area were actually deposited under marine conditions. The evidence of crinkling and flowage of the partly consolidated sediments, however, indicates subaqueous deposition, and the lenticular nature of the beds in places does not preclude deposition in shallow waters at the edge of a widespread sea.

ENTRADA SANDSTONE

Name, lithology, and distribution.—The Entrada sandstone was defined by Gilluly and Reeside [93] as a thick series of well-bedded dark-red earthy sandstones with subordinate sandy shales conformably overlying the Carmel formation. Eastward from the San Rafael Swell the Entrada becomes much less earthy and better cemented, and where it enters the area described in this paper it is an orange-buff or reddish massive sandstone weathering into sheer or rounded cliffs and in places vertically jointed from top to bottom. Elephant Butte, carved from massive Entrada sandstone of this type, rises on the west side of the lower part of Salt Wash. On its west side a group of fine natural arches is cut in the sandstone, the wings of the arches resting on the softer Carmel beds. At this place the development of arches was initiated by undercutting of the Entrada cliffs from both sides by the headward erosion of small gullies, cutting on the Carmel and eventually breaking through, while the overlying Entrada sandstone mass still remained a solid mass above the window thus cut. The arches, as they now exist, probably represent the result of removal of material by wind as well as by rain wash and undercutting.

Eastward from the Salt Valley area a further lithologic change in the Entrada takes place, and it becomes a lighter-colored sandstone, regularly and beautifully banded in shades of reddish orange-buff alternating with gray and nearly white (pl. 12, *A*). These layers may be from a few inches to 10 feet thick. The bedding is locally emphasized by long rows of solution pits and cavities which stud the cliffs. Where the banding is sharp, cross-bedding at low angles is poorly developed, and is both tangential and angular within layers the thickness of the color bands. Locally the banding is vague or absent and the cliffs show large-scale tangential cross-bedding. East of the Sand Flat tangentially cross-bedded and massive sandstone predominates, and color banding is correspondingly reduced.

The sandstone of the Entrada in the area covered by this report and in western Colorado is for the most part distinguishable from

[93] Idem, p. 76.

the somewhat similar sandstone of the Navajo and Wingate formations by having the grains distributed among several sizes, with a maximum diameter of 0.03 inch. Much of the rock presents the appearance of being sorted rather definitely into a fine size and a coarser size, with a much smaller number of grains of intervening sizes. The coarse grains are mostly well rounded, with a dull or mat surface on the grains of transparent gray and colorless quartz. White grains which are hard but pulverulent are conspicuous. Salmon-colored and dark-gray grains are less common.

The double sorting into fine and coarse was identified in four thin sections of the sandstone collected at widely separated localities. In a specimen from the NW¼ sec. 5, T. 21 S., R. 25 E., near Cottonwood Spring, the large grains range from 0.35 to 0.70 millimeter (0.014 to 0.028 inch) in diameter and are very well rounded. The small grains are mostly less than 0.15 millimeter (0.006 inch) in diameter and are subrounded to subangular. Most of the large grains are quartz, some are microcline, and a conspicuous proportion are chert, some of which is exceedingly finely granular, some coarsely granular, and some partly fine and partly coarse. Several of the grains are chalcedony, with flamboyant extinction, and some of them show beautiful crenulated banding. One grain of a fine-grained aggregate of interlocking quartz with parallel needles of hornblende appears to be a schist.

The smaller grains are predominantly quartz, but microcline, sodic plagioclase, chert, hornblende, pyroxene, limonite, and carbonate rock were observed. There is also considerable interstitial cementing carbonate. Plate 13, *A*, shows the difference in grain size and large rounded grains of quartz, chalcedony, and chert.

A thin section from a specimen collected along the San Miguel River 7 miles below Placerville, Colo., shows the same type of double sizing, but the large grains range from 0.30 to 0.60 millimeter (0.012 to 0.024 inch) and are distinctly smaller than those in the section described above and not so well rounded. So far as observed the large grains are all quartz, but some of the small grains are sodic plagioclase and chert. The small grains are subangular and subrounded, but the grains have been secondarily enlarged, and the original shapes are not very clear.

A thin section from a specimen collected near the east end of Unaweep Canyon, in Colorado, contains coarse grains of quartz, microcline, chalcedony, and sodic plagioclase, with a maximum size of about 0.80 millimeter (0.032 inch). One grain of interlocking quartz and plagioclase appears to be derived from an igneous rock. The sorting is less well defined in this section than in the others examined—that is, there are more grains intermediate between the large and small sizes. The small grains are less than 0.15 millimeter

(0.006 inch) in diameter. The large grains are rounded most, but are not all well rounded.

A thin section of a specimen from the Entrada outcrop along the Moab-Thompson road about 6 miles north of Moab exhibits the usual sorting into two sizes, and the largest grains have a diameter of about 0.50 millimeter (0.02 inch). The large grains are mostly quartz, but microcrystalline chert grains are abundant. Among the small grains, quartz, microcline, plagioclase, chert, and muscovite are the most evident. Microcrystalline quartz and calcite cement the grains.

At the top of the Entrada there is a persistent lighter-colored sandstone which was called "Moab sandstone" by the late W. T. Lee in an unpublished report. The unit is definite and continuous enough to warrant recognition as a member of the Entrada and was mapped throughout the area. It generally crops out in the area from Squaw Park eastward as a vertical cliff contrasting with the steeply inclined smooth slope of the underlying sandstone (pl. 12, *B*). The color banding so common in the lower part of the Entrada is nowhere present in the Moab sandstone. At the base of the Moab there is in many places a thin bed of red sandy shale, or a group of such beds, and other discontinuous thin beds of red shale occur higher in the Moab. The base of the Moab is not, however, a definite horizon but varies stratigraphically from place to place. At or near the separating plane is usually a parting or group of partings so that the Moab member stands as a nearly massive ledge or series of ledges above a bench at the top of the Entrada cliff. The thickness is usually about 65 feet, but in places the Moab cannot be easily separated from the remainder of the Entrada. In places the apparent base is a huge cross-bedding plane which plunges 50 feet or more stratigraphically down into the Entrada and then fades out. Lenses of sandstone 100 to 200 feet in length are common in the Moab, but rare in the remainder of the Entrada. The Moab is in part tangentially bedded, but it tends more to horizontal bedding and massiveness within thick beds. Striking lenticularity of beds is observed in much of it, the lenses plunging at low angles to the bedding (pl. 12, *A*).

The Moab sandstone is composed chiefly of well-rounded transparent quartz grains. The grains are of almost uniform size as contrasted with the sorting into coarse and fine grains so common in the Entrada. This is shown in the photomicrograph (pl. 13, *B*), of a specimen of Moab sandstone collected about a mile east of the east line of sec. 24, T. 22 S., R. 24 E. The largest grain observed in this section has a diameter of about 0.40 millimeter (0.016 inch), but most of the grains are between 0.10 and 0.25 millimeter (0.004 and 0.01 inch) in diameter. The grains are subangular to rounded, with rounding on the whole better than that of the rest of the Entrada.

The grains are quite clean, and the absence of limonitic coating accounts for the nearly white color of the sandstone. The grains are largely quartz, with some microcline and less plagioclase and muscovite. Grains of chert are present but not abundant.

In the western part of the area there is at the base of the Moab a nearly continuous softer zone, and the Moab therefore tends to retreat somewhat from the top of the cliff made by the lower part of the Entrada. The Moab is everywhere overlain by a softer formation, which is swept back from its upper surface by erosion, leaving exposed a brilliant white dip slope of only slightly dissected sandstone.

Sections.—The Entrada sandstone was measured at several localities, and some of the sections are given here to show the lithology of the formation in more detail.

Section of Entrada sandstone and Carmel formation 1 mile east of Dewey

[Measured by C. H. Dane and John Vanderwilt]

Summerville formation (contact transitional).	
Entrada sandstone:	
Moab sandstone member:	*Feet*
Sandstone, white, fine-grained, cross-bedded but weathers into an apparently massive ledge	55
Shale parting, dark red.	
Sandstone, buff, hard, in horizontal beds 1 foot thick	6
Sandstone, buff or light tan, nearly massive, fine-grained	4
Thickness of Moab sandstone member	65
Sandstone, gray and light red, fine-grained, in places argillaceous, in alternating beds from a few inches to 10 feet thick, both colors occurring in thick and thin beds. Within these pseudomassive beds there is tangential cross-bedding at prevailing angles of 2° to 12°; cross-bedding tends to become more pronounced in the upper 50 feet. In the upper part there are rare thin layers of dark-red sandy shale. Depositional irregularities in bedding common	230
Total thickness of Entrada sandstone	295
Carmel formation (contact transitional):	
Sandstone, argillaceous, light brick-red, crinkly bedding, generally horizontal; blocky jointing, with the blocks weathering into smoothly rounded lumps, which protrude from vertical exposures	20
Navajo sandstone (contact shows no distinct break or irregularity):	
Sandstone, white, fine-grained, beds a few inches to 2 feet thick, irregularly varying in thickness and not cross-bedded. Intervening thin softer sandstone layers weather back and give the outcrops a distinctly bedded appearance	10
Sandstone, white and buff, tangentially cross-bedded on a large scale; thickness undetermined.	

Section of Summerville formation, Entrada sandstone, and Carmel formation 1 mile east of sec. 24, T. 22 S., R. 24 E., south of Ryan Creek

[Measured by C. H. Dane and C. B. Hunt]

	Ft.	in.
Morrison formation.		
Summerville formation:		
Shale, red, with some thin beds of white sandstone, notably a bed 2 feet thick 25 feet above the base	36	
Sandstone, white, fine-grained, with small calcareous concretions	1	
Entrada sandstone:		
Moab sandstone member:		
Sandstone, white and greenish white, very fine grained, tangentially cross-bedded	22	
Sandstone, white, in several beds with softer shaly partings	5	
Shale parting, red.		
Sandstone, white, fine-grained, a massive bed with angular and tangential cross-bedding	26	
Sandstone, red and pink-buff, soft		6
Sandstone, light tan; weathers brownish red; fine-grained	12	
Sandstone, red and pink-buff, soft		4
Sandstone, white, hard, fine grains of transparent white quartz, all rounded and well sorted at about 0.01 inch in diameter; in the top 1 foot are a few smaller dark grains and some scattered grains of red chert. Both angular and tangential cross-bedding	16	
Shale, red		2
Sandstone, tan and buff, in four beds with a red-shale parting 2 inches thick below each. The base of each of the sandstone beds has irregularities that suggest two interfering sets of irregularly developed ripples with a 4- to 5-inch wave lenth. These sandstones are like the underlying Entrada in color but lack the polished coarse grains of that part of the Entrada. They are included as the basal unit of the Moab sandstone member	5	
Thickness of Moab sandstone member	87	
Sandstone, light buff and reddish buff, fine-grained, with average grains less than 0.01 inch in diameter. Through the fine-grained sandstone are scattered many isolated coarser grains, as much as 0.02 inch in diameter, with a few larger. They are rounded, polished, and with pitted surfaces. They occur both on horizontal and cross-bedding plane surfaces. The unit is cross-bedded both angularly and tangentially at high angles	140	
Total thickness of Entrada sandstone	227	

	Ft.	in.
Carmel formation: Sandstone, earthy, massive, reddish brown, streaked with red shale, contorted or obscure bedding	22	
Kayenta formation.		

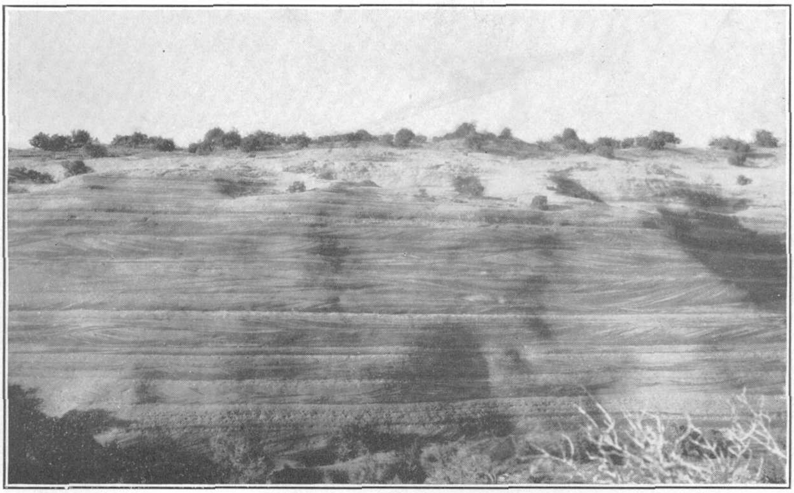
Partial section of Entrada sandstone northwest of Cottonwood Spring, in sec. 5, T. 21 S., R. 25 E.

[Measured by C. H. Dane and C. E. Erdmann]

	Ft.	in.
Summerville-Entrada contact and top of Entrada concealed by dune sand.		
Entrada sandstone:		
Moab sandstone member:		
Sandstone, white, fine-grained, sugar-textured	16	6
Sandstone, light red and white, in beds a quarter of an inch to 1 inch thick, shows "worm trails"		7
Sandstone, light gray, very fine grained, horizontally laminated; weathered slopes polygonally cracked into blocks 1 to 3 feet across	27	6
Sandstone, gray to nearly white, fine-grained, grains subrounded to subangular, cross-bedded, with small globular concretions formed by the agglutination of grains by calcareous cement	12	
Sandstone, light gray, very fine grained, horizontally laminated with layers of gray and white sandstone from 0.02 to 0.50 inch thick; scattered throughout are lenses of salmon-colored sandstone as much as half an inch thick and 4 inches long	16	2
Sandstone, brick-red, light reddish brown on fresh fracture, extremely fine grained, with obscure horizontal bedding	1	1
Sandstone, buff, fine-grained, horizontally bedded, with a few lenses as much as 1 inch long in which the grains average more than 0.01 inch in diameter		8
Incomplete thickness of Moab sandstone member	74	6
Sandstone, buff, cross-bedded at high angles, the cross-bedding surfaces running from top to bottom of the bed	2	
Sandstone, light reddish buff, tangentially cross-bedded within horizontal beds from 2 to 5 feet thick; the cross-bedding laminae due to variation in grain size, the maximum a little more than 0.01 inch in diameter, without admixed silt; at the top is a bed 1 to 2 inches thick of harder white sandstone	59	
Sandstone, brick-red to buff, tangentially cross-bedded at angles as high at 20°, with individual cross laminae from 0.01 to 0.40 inch thick running for as		

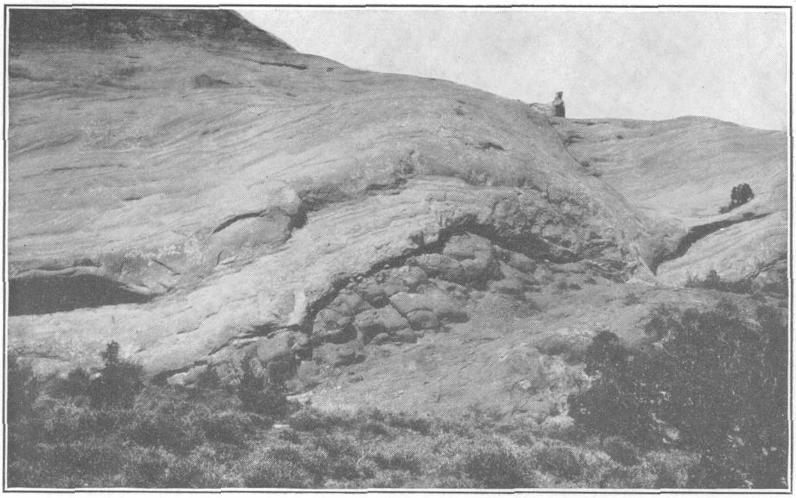
	Ft.	in.
Entrada sandstone—Continued.		
much as 30 feet, the thicker laminae internally cross-bedded; grain size from less than 0.01 inch to 0.02 inch, all the grains well rounded or subrounded, some pockets or lenses of subrounded coarser grains. This unit and the overlying one weather to smooth rounded steep slopes or cliffs (pl. 14, *A*)	38	6
Sandstone, light reddish brown, fine-grained, with irregular shale partings, irregular patches of coarse gray sandstone of variable grain size, and scattered subangular grains as much as 0.05 inch in diameter; bedding obscurely horizontal in layers 2 to 3 feet thick in the lower part and tangentially cross-bedded in upper part, transected by intraformational faults which offset the beds as much as 7 inches but fade out upward. The base of the unit is a contorted parting of green shale with a maximum irregularity of 3 feet within 50 feet along the strike	27	6
Sandstone, reddish buff, fine-grained, with discontinuous partings of red shale or silt; bedding excessively contorted and irregular; the rock has a calcareous cement and weathers into irregularly rounded masses; crops out as a sloping ledge; at the base a layer of red silt as much as one-eighth inch thick	21	
Incomplete thickness of Entrada sandstone	222	6
Contact sharp but without irregularity; one grain of quartz 0.1 inch in diameter noted at the base of the Entrada, and a small subangular pebble of quartz about three-eighths of an inch long observed about 1 inch above the contact.		
Kayenta formation:		
Sandstone, white, fine-grained, in beds 2 inches to 1 foot thick, with angular cross-bedding	6	7
Sandstone, white, fine-grained, in the basal few inches with abundant pebbles of red shale and gray limestone, in lenses as much as 9 inches thick and 5 feet long; unit as a whole is a lens which disappears within 60 feet along the strike	3	
Sandstone, light gray and greenish white, very fine grained; at the top is cut by an erosional irregularity	5	6
Sandstone, purplish gray and gray, very fine grained, with pellets of gray limestone in the lower 6 inches	5	6

Thickness.—The Entrada sandstone maintains a fairly uniform thickness over most of the area mapped. A thickness of 300 feet was determined by stadia measurement at the north end of Salt Valley, and a thickness of 295 feet was measured by the same method near Dewey. The thickness was estimated at 300 feet near the south end of Polar Mesa and slightly less than 300 feet near Agate Spring. The Utah Southern State No. 1 well, in sec. 26, T. 21 S., R. 23 E.,



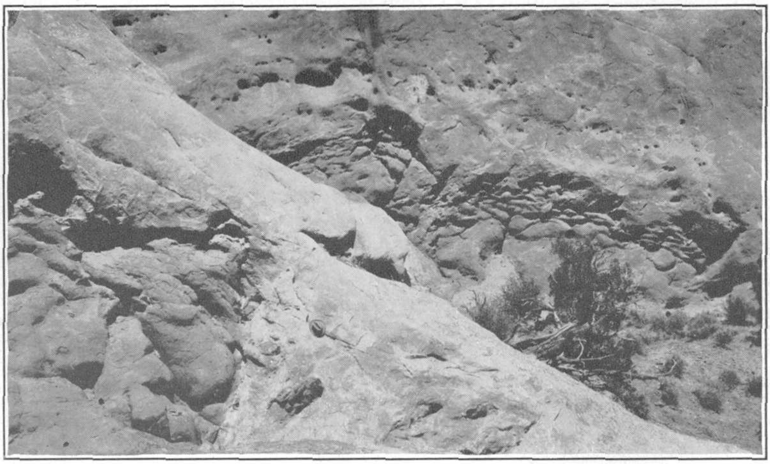
A. TANGENTIAL CROSS-BEDDING IN ENTRADA SANDSTONE IN NORTHERN PART OF SEC. 5, T. 21 S., R. 23 E.

Moisture from recent rain gives darker color to more pervious beds. White Moab sandstone member at top of exposure. Photograph by C. E. Erdmann.



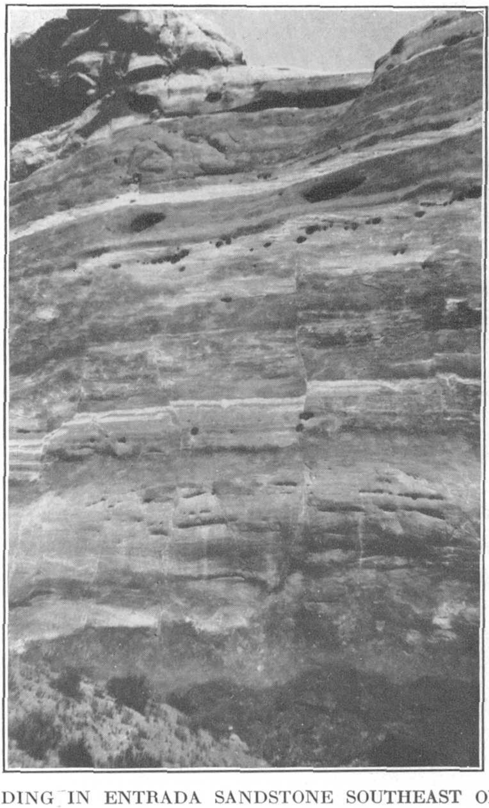
B. CARMEL-ENTRADA CONTACT A QUARTER OF A MILE EAST OF THE SOUTHEAST CORNER OF SEC. 13, T. 22 S., R. 24 E.

The rolling of the contact and the small faults offsetting it are due to movement shortly after deposition.



A. CARMEL-ENTRADA CONTACT A FEW HUNDRED FEET SOUTH OF THE PLACE SHOWN IN PLATE 14, *B*.

In the center is a large horse of the overlying Entrada sandstone, which cuts down through the Carmel; the base of the horse is not exposed.



B. FAULTED BEDDING IN ENTRADA SANDSTONE SOUTHEAST OF DEWEY NEAR CENTER OF SEC. 17, T. 23 S., R. 24 E.

The faults die out upward. Carmel formation is exposed at lower right.

penetrated 295 feet of beds assigned to the Entrada sandstone, and the Tom McGuire et al. or Home Oil Co. No. 2 well penetrated 288 feet of beds assigned to the Entrada. However, the thickness measured at the locality 1 mile east of sec. 24, T. 22 S., R. 24 E., south of Ryan Creek, was only 227 feet, and the thickness in the vicinity of Steamboat Mesa is only about 260 feet. The Entrada thins distinctly eastward from the mapped area and at the top of the Serpent's Trail, west of Grand Junction, it is only 84 feet thick.

Bedding irregularities.—The Carmel formation and the lower part of the Entrada sandstone exhibit some extraordinary irregularities in bedding, which are the result of movement in the unconsolidated or partly consolidated sediment during or shortly ofter deposition. In the western part of the area the most common type of such irregularity in the Carmel is a wavy crenulation of a group of beds. The crenulation may gradually diminish in strength upward and downward, or the top of the crenulated group of beds may be cut across by an overlying horizontally bedded series. In the eastern part of the area, where the Carmel is an earthy or muddy sandstone without pronounced bedding planes, such crenulation is less common but is present in some places and grades upward in intensity to excessive contortion, which may obscure the true bedding. In this part of the area, where the clean Entrada sandstone overlies the muddy Carmel with a sharp contact, the irregular rolling of the contact is striking (pl. 14, *B*). The disturbance extends for some distance upward into the Entrada—in some places perhaps as much as 50 feet—but gradually diminishes and is not present in the upper part of the sandstone. Still more remarkable is the invasion of the Carmel by dikes or irregular masses of the overlying cleaner Entrada sandstone (pl. 15, *A*). The contact between these dikes and the Carmel is normally sharp, but in some places the invading sandstone anastomoses into innumerable tiny stringers tapering out into the darker siltstone. In other places the two types of lithology are inextricably intermingled along the contact between a sandstone dike and the invaded Carmel. The response to the deforming movement has not been wholly plastic. The rolling contact between the Entrada and Carmel is in places offset by small faults, which extend upward into the sandstone for some distance but gradually die out into gentle flexures, which in turn ultimately disappear upward (pl. 15, *B*). The faulting observed in the Entrada does not necessarily imply any consolidation of the rock whatever at the time of movement, for Mead [94] has shown that both wet and dry sand may fail by fracture rather than yield by plastic adjustment, even under very moderate load. It seems almost certain, however, that the

[94] Mead, W. J., The geologic role of dilatancy: Jour. Geology, vol. 33, p. 690, 1925.

initiating cause of the movements observed lies in the plastic adjustment and gliding of the water-soaked sandy mud of the Carmel under differential loading. These movements may have begun even before the deposition of the overlying sand, but the observed extension of small faults upward in the Entrada nearly to the base of the Moab sandstone apparently shows that the principal bedding irregularities were developed under a covering mass of some 200 feet of sand. The differential loading necessary to produce movement in the water-soaked sand and mud was probably slight. The irregularities, at least in most places, do not extend into the rocks below the Carmel or the muddier basal part of the Entrada, and the contact at the base of the San Rafael group is sharp and undisturbed, even where considerable irregularities are observed in the basal beds. This seems to imply that the underlying rocks were at least partly consolidated before the Carmel was deposited and that the irregularities observed are due wholly to compaction and gliding of the muddy Carmel sediment. Where there is little or no Carmel or silty constituent in the basal Entrada the irregularities in bedding have not been observed.

Age.—The age of the Entrada of this area is established as Upper Jurassic by its continuity with the Entrada sandstone of the San Rafael Swell, which lies between formations both of which carry an Upper Jurassic invertebrate fauna. The Entrada extends southeastward from the area mapped into western Colorado as a conspicuous white cliff-forming sandstone known to prospectors as the "slick rim" and is correlated with assurance with the lower † La Plata of the San Juan Mountain region.[95]

Conditions of deposition.—Gilluly believes that the Entrada sandstone was deposited under marine conditions in the area of the San Rafael Swell, because of its regular horizontal bedding and association with almost certainly marine formation above and below. The details of the lithology of the formation in the area mapped by the writer seem to indicate an eolian origin for much of the Entrada. The significance of the rounded coarse grains so common in the sandstone is not certain, but they have a frosted or mat surface and correspond in appearance with coarse grains observed by the writer on level surfaces of eolian sand within the area.

Dake[96] has concluded that such minutely pitted or frosted grains are the best textural criteria we have to establish the action of wind on sand, but he conservatively points out that the sand grains may

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[95] Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., Correlation of the Jurassic formations of portions of Utah, Arizona, New Mexico: U. S. Geol. Survey Prof. Paper 183 (in press).

[96] Dake, C. L., The problem of the St. Peter sandstone: Missouri Univ. School of Mines Bull., Tech. ser., vol. 6, no. 1, p. 186, 1921.

have been frosted at some stage preceding their deposition in the area in which they are now found, provided subsequent transportation has not been sufficient to destroy the frosted surface.

The significance of the sorting of the grains into two sizes is not certain. Similar sorting is apparently produced on surfaces of windblown sand within the area by the abstraction of the finer grains, leaving a scattering residue of grains too large for the average wind to lift. Such a residue might be subsequently covered by sand and again go through the same sorting process, leaving another layer of scattered coarser grains. A similar process has been observed in water-deposited sediments.

Udden [97] has shown, however, that during deposition sorting of grains into two sizes with an absence of grains of intervening size occurs commonly in both wind-deposited and water-deposited sediments. He deduced the following " law of the secondary maximum " from the mechanical analysis of a considerable number of samples of modern sediments:

> When a transporting medium is supplied with sufficiently heterogeneous material it will tend to carry and to deposit more of two certain sizes of material than of any other sizes. The principal deposit it makes will consist of materials it can momentarily lift. With this it will leave an excess of another considerably coarser ingredient, which it can roll, smaller in quantity. This makes what we may call a secondary maximum. For water deposits the secondary maximum will consist of elements having a diameter about 16 times the diameter of the elements in the chief ingredient. For wind deposits the secondary maximum will consist of elements having a diameter about eight times that of the elements in the chief ingredient.

Some additional evidence for the relations thus empirically deduced may be drawn from the analyses of Mississippi River sediments made by Lugn.[98] He recognized six distinguishable types of Mississippi River sediment. Among these was a type termed " pudding sand ", consisting of a chief ingredient with a more or less completely isolated secondary maximum of grains of coarser size. In general the ratios of the diameters of the grains of the secondary maximum grade to those of the chief ingredient are from 16 to 1 up to as much as 64 to 1.

More recently Hodge [99] has made a study of the Permian yellow sands of northeast England, in which his mechanical analyses demonstrate a double maximum in the grain sizes of the sand. Quoting Udden's " law of the secondary maximum " and observing that the diameter of the grains in the secondary maximum of the Permian

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[97] Udden, J. A., Mechanical composition of clastic sediments: Geol. Soc. America Bull., vol. 25, no. 4, pp. 736–737, 1914.

[98] Lugn, A. L., Sedimentation in the Mississippi River between Davenport, Iowa, and Cairo, Ill.: Augustana Library Pub. 11, pp. 98, 99, 1927.

[99] Hodge, M. B., The Permian yellow sands of northeast England: Durham Univ. Philos. Soc. Proc., vol. 8, pt. 5, pp. 429–434, 1932.

yellow sands is from six to eight times that of the grains in the chief ingredient, Hodge concludes that this affords corroborative evidence of the eolian origin of the yellow sands.

The writer has made no mechanical analyses of the Entrada sandstone, but in several thin sections examined the average diameter of the larger more perfectly rounded grains is from four to six times that of the smaller grains, which make up the principal portion of the sand. Thus the relative sizes of the large and small grains fall more nearly within the range ascribed to wind-deposited sands.

So far as known, therefore, the textural characteristics of the Entrada sandstone as well as the nature of the cross-bedding and general lithologic features accord with the hypothesis that it was laid down as an eolian deposit on the margin of the Jurassic sea to the west.

The Moab sandstone was apparently laid down under different conditions, and its lithology and bedding suggest subaqueous deposition to the writer. The occurrence in it of discontinuous red-shale partings may possibly accord with this view.

The stratigraphic relations of the Entrada sandstone, the Moab sandstone member at its top, and the Summerville formation indicate that the source of the Entrada in this area lay toward the east, like that of the underlying sandstones. The Entrada overlaps all the underlying sandstones toward the east and rests directly on the Triassic and Carboniferous rocks in central Colorado.[1] The abundance of chert and chalcedony grains in the Entrada, as compared with the absence of such grains so far as observed in the Wingate and Kayenta and the occurrence of only a few grains in the eastern Navajo, may be due only to the relatively fragile nature of such grains and the larger size of the grains in the Entrada, but it suggests a new source of supply from which large quantities of chert were derived. It is curious that these chert grains should be most abundant in the two thin sections from Utah rather than in those from localities farther east in Colorado, and this fact suggests a source from the north, the direction in which possible source rocks are not exposed for a long distance. The data are obviously inadequate to afford a basis for sound speculation. The possibility that the chert and chalcedony grains are derived from the break-up of contemporaneously deposited chert seems remote in view of the almost complete absence of such beds in the known extent of the Entrada outcrop.

SUMMERVILLE FORMATION

Lithology.—In the type locality in the San Rafael Swell[2] the Summerville formation includes from 125 to 331 feet of very thin al-

[1] Reeside, J. B., Jr., personal communication.
[2] Gilluly, James, and Reeside, J. B., Jr., op. cit., p. 80.

ternating beds of chocolate-colored gypsiferous mudstone and well-laminated sandstone. Traced to the east the formation thins and the proportion of thin-bedded sandstone becomes somewhat greater. Throughout the area mapped in this report the Summerville is a thin but perfectly distinct unit, measured sections ranging from 37 to 58 feet thick. The contact at the top of the Summerville is inconspicuous because of the similarity of the response to weathering of the Summerville and the lower part of the overlying Morrison formation, which also weathers to red wash-covered slopes with projecting sandstone beds. In a weathered slope above the Entrada cliff the distinction between Summerville and Morrison may not be clear. In good exposures, however, the Summerville exhibits a strikingly even horizontal bedding (pl. 16, *A*) and a uniformly red color in varying hues, which contrast strongly with the irregularity and heterogeneity of the overlying beds. Pure shale is rare in the Summerville, micaceous silty shale is abundant, and there are all intervening gradations between sandy shale and almost clean but fine-grained sandstone, which may be only faintly red or nearly white. Thin beds of gray or purplish-gray limestone are common but rarely more than a few inches thick and nowhere form an important proportion of the formation. The sandstone beds show current ripple marks in many places. The ripple marks are consistently less than an inch in average wave length and vary little in appearance from place to place. In lower Salt Valley, Cache Valley, and some areas to the north along Salt Wash the Summerville contains huge masses of chert in remarkable amounts, and the weathered surfaces of the formation in these areas are practically paved with angular fragments of the chert. From Dewey eastward little chert is present in the formation, and chert is not abundant at the north end or on the west side of Salt Valley. It seems probable that the rather small area of large chert masses noted here is a northward extension of the similar development of chert in the Summerville noted in the Moab district.[3]

For the most part the Summerville crops out in a short, fairly steep slope beneath a harder sandstone ledge at the base of the Morrison formation, in some places at the crest of the underlying cliff but more commonly at some distance back from it. In the area along the upper part of Salt Wash and its tributaries it is more extensively exposed in broad, nearly level areas of slight relief.

Sections.—A measured section of the Summerville formation is given with the section of Entrada sandstone on page 96, and another with a section of the Morrison formation on page 109. The most detailed measured section of the formation is given below.

[3] Baker, A. A., Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, p. 51, 1933.

Section of Summerville formation near the center of the SW¼ sec. 22, T. 21 S., R. 24 E., half a mile south by west of the Denver & Rio Grande Western Railroad pump house on the Colorado River

[Measured by C. H. Dane and C. E. Erdmann]

	Ft.	in.
Morrison formation: Irregularly bedded variegated shale and white sandstone. Unconformity (?), slight erosional irregularity.		
Summerville formation:		
Shale, gray, thin-bedded; sandstone, light gray, calcareous, in beds 1 to 2 inches thick; and limestone, crystalline, horizontally banded white and light gray	3	6
Limestone, gray, dense; at both top and bottom of the bed is a layer a quarter of an inch thick of crystalline calcite the crystals in closely compacted needles perpendicular to the bedding		4
Shale, pure gray		4
Sandstone, light gray, fine-grained, calcareous		5
Shale, slightly silty, gray, thin-bedded		4
Marl, dense, light gray		4
Shale, slightly silty, gray, thin-bedded		8
Sandstone, calcareous, gray, thin-bedded		10
Sandstone, calcareous, gray, in thin beds alternating with gray shale, slightly sandy		10
Shale, silty, dark red; poorly exposed	1	5
Sandstone, dark gray, very fine-grained, in beds 1 to 2 inches thick with ripple-marked upper surfaces	2	10
Silt, red; poorly exposed	3	6
Sandstone, gray, silty, fine-grained, calcareous, in beds one-eighth to half an inch thick; conspicuously ripple-bedded, locally cross-bedded at angles of 2° or 3°	1	
Sandstone, light green, fine-grained (average grain size about 0.01 inch), in beds one thirty-second to half an inch thick		10
Sandstone, light greenish gray, mostly fine-grained, but there are some subangular grains 0.04 inch in maximum dimension		4
Sandstone, light green, fine-grained (average grain size about 0.01 inch), in beds one thirty-second to half an inch thick		10
Sandstone, light green, argillaceous, very fine grained		2
Sandstone, light greenish gray, very fine grained, calcareous, in irregular horizontal beds 1 inch to 1 foot thick; some beds show vague ripple bedding	4	10
Clay, silty, reddish brown, in rough horizontal layers from 6 inches to 1 foot thick. Scattered through it are nodules of red limestone from half an inch to 6 inches long and half an inch to 3 inches thick. These are irregular in shape, usually flattened along the bedding planes, but some are round. Some cross the bedding planes	2	6

Summerville formation—Continued.	Ft.	in.
Sandstone, gray, calcareous, very fine grained, massive, hard	1	6
Clay, silty, reddish brown, in rough horizontal layers from 6 inches to 1 foot thick. Scattered through it are nodules of red limestone like those in the clay above	5	6
Siltstone, dense, reddish gray and light gray, hard; weathers greenish gray	1	
Clay, red, almost pure, bedding obscure; weathers into rounded lumpy surfaces in vertical exposures and into small angular chips on sloping exposures	21	6
Sandstone, light olive-green, hard, fine-grained, calcareous	1	
Sandstone, friable, light green, poorly bedded	1	8
Sandstone, light gray, fine-grained, horizontally bedded in beds about one-eighth inch thick		4
Total thickness of Summerville formation	57	6

Contact conformable.

Entrada formation (Moab sandstone member): Light-gray fine-grained sandstone in vertical cliff.

Relation of Summerville to Entrada sandstone.—The Summerville rests conformably upon the Moab sandstone member of the Entrada sandstone, but there is in most places an abrupt change in lithology. Conclusive evidence of the absence of a time break at this horizon is furnished by the stratigraphic relations observed in the area between the Green and Colorado Rivers. At the north end of Salt Valley the lower part of the Moab sandstone is a thin-bedded soft gray sandstone that weathers into a slope. Westward from Salt Valley the Moab sandstone is separated from the underlying Entrada beds by a thin shale parting or shaly zone. Toward the west the Moab sandstone decreases in thickness and finally disappears as the underlying shale parting thickens and becomes identical in lithology with the Summerville formation.[4] This intertonguing relation of the Moab sandstone and Summerville formation demonstrates variability but continuity of sedimentation. For this reason the Summerville is assigned, like the underlying formations, to Upper Jurassic time. Its geographic extension to the east is uncertain. A thin red zone is apparently persistent below beds of undoubted Morrison lithology for some distance into Colorado, but its correlation with the Summerville is uncertain in the absence of detailed tracing of the zone.

Conditions of deposition.—The prevalence of current ripple marks in the Summerville formation clearly points to its deposition by currents, and the nature of these ripple marks, the gentle cross-

[4] McKnight, E. T., Geology of an area between the Green and Colorado Rivers, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. (in preparation).

bedding of some of the sandstones, and the even regular bedding of most of the deposited materials indicate deposition in rather quiet, shallow waters. The occurrence of thin beds of dense gray unfossiliferous limestone similar to those of the underlying and overlying continental formations, the local occurrence of structureless red clays, and the occasional lenticularity of the sandstones in the formation tend to make marine deposition less probable than deposition under estuarine conditions or on a very gently sloping flood plain marginal to estuarine or marine waters.

MORRISON FORMATION

Lithology and distribution.—The Morrison formation consists of a varied assemblage of beds of sandstone, shale, and conglomerate, with subordinate limestone. The formation is divisible into two parts of distinctive though intergradational lithology. The upper part consists predominantly of silty and limy mudstones banded in widely varying and brilliant hues—green, gray, pure white, red, maroon, purple, and orange-yellow (pl. 16, *B*). Associated with these mudstones are thin lenticular dense limestones, mostly of gray and subdued colors, and lenticular beds of chert-pebble conglomerate, which are locally extensive and of thicknesses measured in tens of feet. The lower part of the formation includes about equal proportions of white and light-gray cross-bedded lenticular sandstones and gray and red mudstones, with a few thin gray limestone beds (pl. 5). This lower part is recognizable throughout the area and over much of the outcrop of the Morrison formation, but it makes up a varying proportion of the formation and is not sharply separable from the upper part (pl. 17, *A*). For these reasons the lower part was not mapped as a separate unit. In this area it seems appropriate to apply to it the term "Salt Wash sandstone member", used in the San Rafael Swell[5] and first applied by Lupton.[6]

Because of the large proportion of mudstone of low resistance to erosion, the upper part of the Morrison in most places crops out over a wide area with only moderate topographic relief. The abundance of sandstone in the lower part produces steep bench and ledge slopes, and where the drainage pattern is well developed the area of outcrop of the Salt Wash sandstone member is locally rugged, with flat sandstone-capped ridges intervening between narrow winding steep-sided valleys. In a few places the entire formation is exposed in a steep slope.

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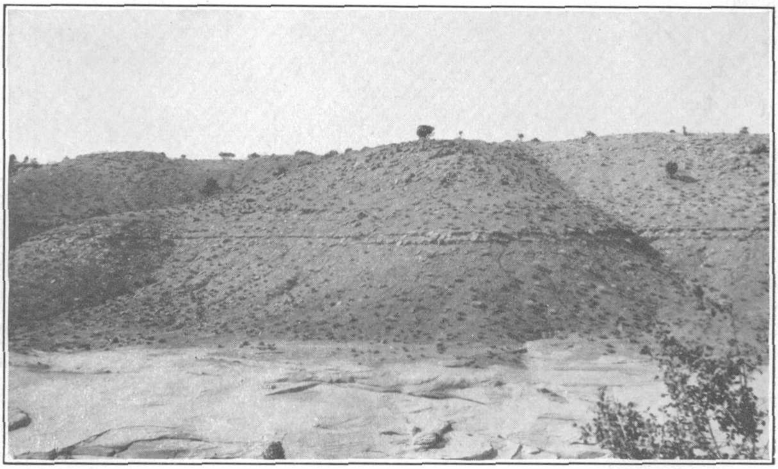
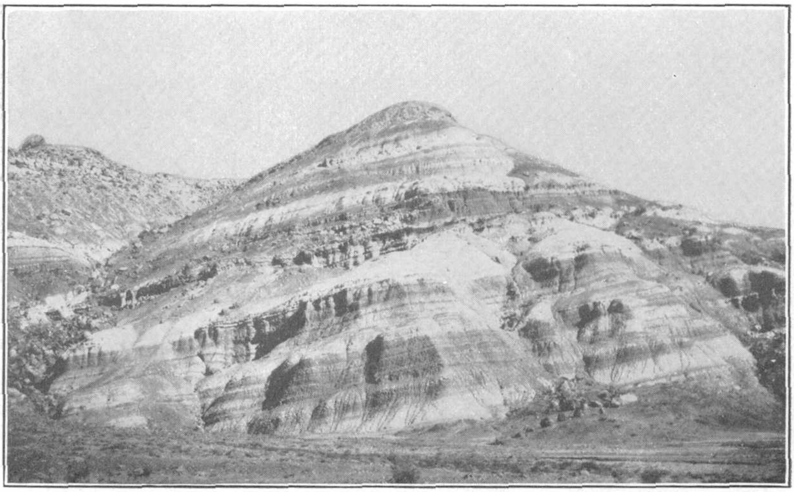
[5] Gilluly, James, and Reeside, J. B., Jr., Sedimentary rocks of the San Rafael Swell and some adjacent areas in eastern Utah: U. S. Geol. Survey Prof. Paper 150, p. 81, 1928.

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



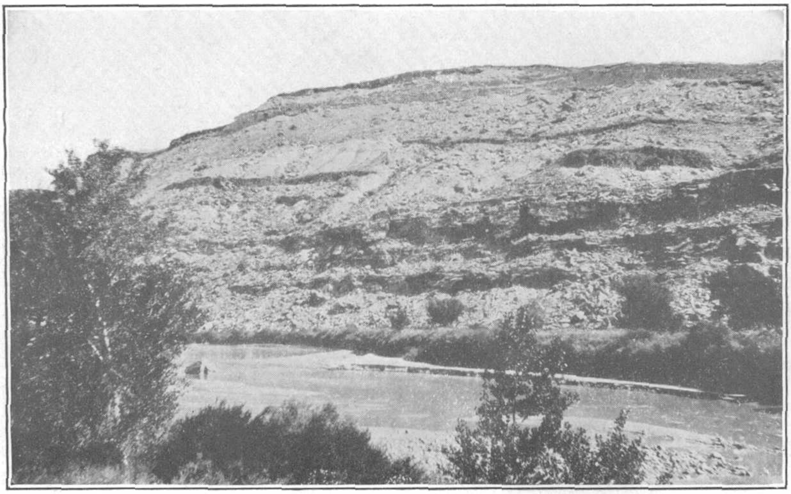
A. EXPOSURE OF SUMMERVILLE FORMATION IN NE¼ SEC. 12, T. 22 S., R. 24 E.

White sandstone at base is top of Moab sandstone member; sandstone at top of hill is probably at the base of the Morrison formation. Photograph by H. O. DeBeck.



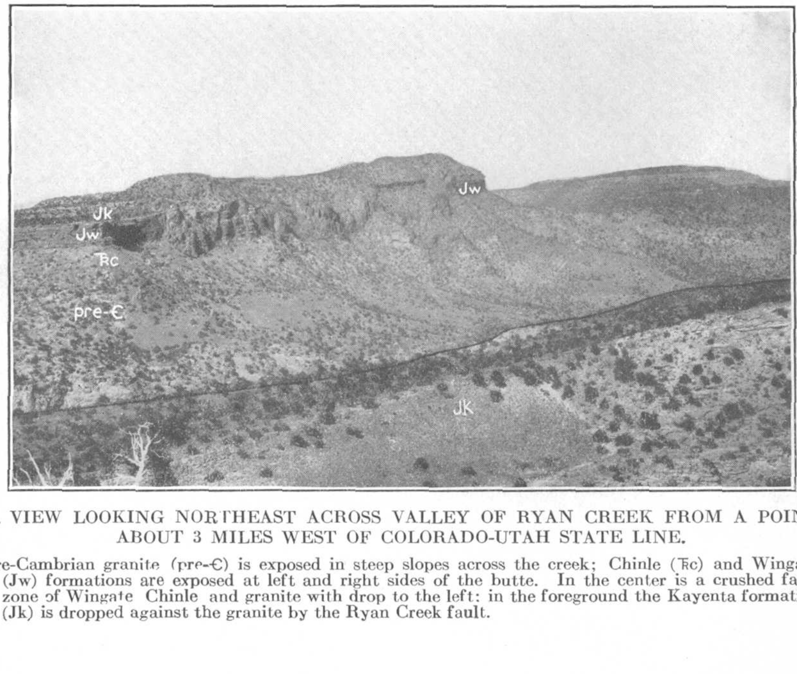
B. VARIEGATED CLAY AND SANDSTONE OF UPPER PART OF MORRISON FORMATION IN SEC. 21, T. 21 S., R. 24 E.

Photograph by C. E. Erdmann.



A. MORRISON FORMATION ON NORTHEAST BANK OF DOLORES RIVER IN SEC. 9, T. 23 S., R. 24 E.

The Salt Wash sandstone member includes the beds up to the highest prominent dark bed at the right. Note the conspicuous lenticularity of sandstone beds in upper part of exposure.



B. VIEW LOOKING NORTHEAST ACROSS VALLEY OF RYAN CREEK FROM A POINT ABOUT 3 MILES WEST OF COLORADO-UTAH STATE LINE.

Pre-Cambrian granite (pre-Ꞓ) is exposed in steep slopes across the creek; Chinle (Ꞧc) and Wingate (Jw) formations are exposed at left and right sides of the butte. In the center is a crushed fault zone of Wingate Chinle and granite with drop to the left: in the foreground the Kayenta formation (Jk) is dropped against the granite by the Ryan Creek fault.

The Morrison crops out in wide belts diverging southward from the north end of the Salt Valley anticline. The eastern belt extends eastward across the Dolores River near Dewey, spreading over a wide area along the lower part of the Dolores River and thence swinging northward toward the Sand Flat and northeastward in a strip roughly following the Denver & Rio Grande Western Railroad. It also crops out in small areas in the Salt Valley and Cache Valley faulted region and caps two large mesas south of Utah Bottoms and Steamboat and Polar Mesas.

Although the Morrison formation is highly variable in lithology laterally, the measurement of sections provides the most accurate method of observing and recording the details of its lithology. Two sections are presented as typical.

Section along a line crossing the Dolores River near its mouth, about 1 mile southeast of the Colorado River

[Measured by C. H. Dane and John Vanderwilt. Measured by stadia; detail measurements hand leveled with clinometer and adjusted to stadia observations]

	Feet
Dakota (?) sandstone:	
Shale, gray, soft, and sandstone, buff, soft; thickness undetermined.	
Sandstone, white, quartzitic, with chert pebbles as much as 2 inches in diameter; conglomerate of chert pebbles; sandstone, buff, with black and yellow ferruginous stainings and interlacing, apparently organic tubules	30
Unconformity (?), erosional irregularity at the base of the quartzitic sandstone.	
Morrison formation. The upper part of the Morrison is so extremely irregular and lenticular that no attempt was made to measure a detailed section at this point. It was divided into four zones which appeared to possess recognizable continuity. Comparison with other measured sections shows that no unit in the upper part of the Morrison is continuous over any considerable distance.	
Shale, gray, white, and light green, named in order of abundance, with some dark-maroon shale and some gray sandstone; poorly exposed on a steep slope	80
Sandstone, white, medium-grained, and a lesser amount of grit and fine conglomerate with angular and subangular pebbles of white, red, gray, and black chert, transparent and red quartz, and gray sandstone. The sandstone and grit, in beds and lenses 2 to 10 feet thick, comprise about two-thirds of the total thickness of the unit; the remainder is light greenish-gray calcareous shale and dark-maroon shale. The base of the zone is placed at the base of a particularly prominent ledge of white sandstone. The zone makes a steep slope with projecting edges	50

Morrison formation—Continued.	Feet
Shale, slightly calcareous, and marl, light green, blue-gray, dark gray, and light salmon-red; shale, sandy, dark maroon; and a few beds of brown sandstone 1 to 4 feet thick. Minor constituents are bright brick-red shaly sandstone, black marl, and very light gray pure shale. The zone crops out in a low slope. At the top are a few lenses of white and gray sandstone 2 to 6 feet thick	180
Shale, light green, calcareous, and conspicuous lenses of coarse-grained gray sandstone and grit. This zone is excessively variable. A thousand feet from the place where the section was measured the unit is almost entirely a soft light-green shale with small patches of dark green and faint rose-pink. Roughly 500 feet in the same direction from the place where the section was measured, one-third of the zone consists of brown fine-grained brown-weathering sandstone in beds 6 inches to 3 feet thick. The interbedded green-gray shales have gray calcareous nodules, and there are a few beds of gray limestone 1 to 3 inches thick. Throughout the zone as visible from the place of section there is a variable number of coarse sandstone lenses, from a few feet to 20 feet thick, which at the place of section include about one-third of the total thickness. Where observed these lenses range from coarse-grained gray sandstone, subangular-grained and cross-bedded, to grit with scattered pebbles of white and gray chert and fewer pebbles of red and dark chert. There are stringers of conglomerate in the grit. The 20-foot grit bed of this section lensed out within 200 feet in each direction. One sandstone lens observed elsewhere along the exposure was 50 feet thick at a maximum but disappeared abruptly within 300 or 400 feet laterally. Included in this zone are a few beds of gray and green-gray, very fine grained quartzitic sandstone, some with scattered pebbles of red and gray chert. The unit crops out variably as a low slope or steep slope with protruding ledges	180
Salt Wash sandstone member of Morrison formation:	
Sandstone, fine-grained, white, cross-bedded	15
Sandstone, coarse-grained, gray, with quartz grains chiefly subrounded, some rounded and subangular; and with angular pebbles of grit size and a few ½ inch in greatest dimension of flat white, gray, and red chert, red and gray sandstone, and transparent quartz	16
Sandstone, fine-grained, gray, cross-bedded. In some beds near the base carries chunks ½ inch to 6 inches long and of lesser width of gray dense limestone and soft greenish-gray sandstone. This unit and the 2 overlying ones make a conspicuous ledge	51

	Feet
Morrison formation—Continued.	
Salt Wash sandstone member of Morrison formation—Continued.	
Sandstone, gray, in beds 6 inches to 2 feet thick, with partings and interbeds of dark-red shale with green-gray mottlings	6
Shale, dark red and gray, with lenticular beds of gray sandstone 1 to 2 feet thick; poorly exposed	17
Largely concealed. In part dark-red shale; in part mottled red and gray shale containing small hard irregular calcareous lumps 1 to 2 inches in diameter; in part hard gray cross-bedded sandstone	53
Sandstone, gray, cross-bedded, moderately hard	12
Shale, dark red, and sandstone, gray, soft, thin-bedded, in about equal amounts; poorly exposed	32
Sandstone, gray, fine-grained, thin-bedded, cross-bedded; weathers dark reddish brown; makes a ledge	15
Shale, sandy, dark red, light red, and light green, and sandstone, mottled light red and gray, in irregular lenses 1 to 2 feet thick; some faintly purple sandstone beds 6 inches thick	39
Limestone, dark gray, with light-red angular stainings, dense	2
Total thickness of Morrison formation	748

Unconformity (?), irregular contact with relief of 3 to 4 inches within 3 feet laterally.

	Feet
Summerville formation:	
Shale, dark red, with lenses of gray calcareous sandstone as much as 5 inches thick which taper to a knife-edge in a few feet laterally	1
Sandstone, gray and light green streaked with light red, regularly thin-bedded	1
Sandstone, light green and gray, thin-bedded, lenticularly bedded on a small scale, apparently owing to poor ripple bedding. This sandstone is interbedded with dark-red sandy shale	8½
Shale, sandy, dark red, mottled with green beds and elliptical patches	2
Sandstone, light green, thin-bedded	4
Shale, sandy, dark-red, thin-bedded	2
Shale, sandy, dark red, bedding thin and regular but usually obscured by weathering to chippy fragments. The unit includes several beds of faint-green sandstone 6 inches thick and one bed of dark-red hard sandstone 6 inches thick	20
Sandstone, white, somewhat calcareous, mottled with light brick-red; weathers with an oolitic or pisolitic appearing surface	½
Total thickness of Summerville formation	42

Entrada sandstone.

Section west of Denver & Rio Grande Western Railroad pump house on the Colorado River

[Measured by C. H. Dane and C. E. Erdmann. Lower 427 feet measured by stadia; upper 280 feet hand-leveled, adjusted for dip]

	Feet
Dakota (?) sandstone: Coarse buff sandstone, grit, and conglomerate; basal 6 inches with subrounded chert pebbles an inch in diameter.	
Unconformity (?), erosional irregularity.	
Morrison formation:	
Clay, greenish	10
Sandstone, gray, fine- to medium-grained. Some scattered chert pebbles from an eighth of an inch to half an inch in diameter. This bed is a conspicuous lens along the cliff, tapering out within 250 feet in each direction from the place where the section was measured. At its base is an erosional irregularity, and small rill channels 1 or 2 inches deep cut in the underlying bed are filled with gray sandstone like the overlying bed	15
Shale, greenish	30
Clay, greenish, and gray conglomeratic grit, in beds 1 to 2 feet thick. Clay and grit form about equal parts of the unit. The grit consists chiefly of chert pebbles but includes numerous pebbles of green shale. Some beds consist of interlensing grit and gray limestone	15
Clay, greenish	25
Clay, red and white	25
Sandstone and grit, white, friable; some chert pebbles as much as a quarter of an inch in diameter; cross-bedded	5
Shale, variegated, red, maroon, light green, gray, and white, with some beds 1 to 2 feet thick of brick-red and white sandstone	85
Sandstone, argillaceous, limy, hard, white and red, fine-grained; weathers with a nodular surface; beds 3 inches to 1 foot thick	5
Shale, variegated, white, red, and light green	65
Concealed in large part; apparently is mostly green clay with some thin lenses of brown sandstone	100
Conglomeratic grit and dense gray limestone, interlensing. The grit is composed chiefly of red-brown and gray angular to rounded chert pebbles from a sixteenth to half an inch in diameter. There are numerous small pellets of green shale. This is the lowest conglomerate in the Morrison at this locality	1
Salt Wash sandstone member of Morrison formation:	
Chiefly shale and clay, calcareous, green and red, with scattering lenses of medium-grained gray sandstone 2 or 3 feet thick and 100 feet long	85
Sandstone, light gray, medium-grained, cross-bedded, in lenticular beds 2 to 20 feet thick and 50 to several hundred feet long. These lenticular	

	Feet
Morrison formation—Continued.	
Salt Wash sandstone member of Morrison formation—Continued.	
sandstone beds are included in gray, reddish, and green calcareous shale. The sandstone composes from one-third to one-half of the thickness of the unit. Some beds have irregular channeled bases; some change laterally to thinner-bedded sandstone with intervening beds of red and green shale. Typically with subrounded and subangular grains of transparent quartz, with subordinate salmon-colored and gray grains, the grains about 0.01 inch in diameter. The beds are hard and weather white	210
Clay, green and gray, variegated, with concretionary lenses and nodules of gray sandy limestone. These are irregularly ellipsoidal parallel to the bedding and as much as 1 foot in length. There are also beds of light greenish-gray calcareous sandstone from half an inch to 2 inches thick. This unit is variable from place to place, owing to irregular and lenticular bedding	30
Limestone, dense, gray, poorly bedded in irregular lenses and beds 2 to 8 inches thick. At another locality 500 feet distant this bed was missing, and a lenticular bed 2 feet thick of sandstone was the base of the Morrison	1
Total thickness of Morrison formation	707
Unconformity(?) slight erosional irregularity.	
Summerville formation: Gray-green and red thin-bedded calcareous shales and sandstones.	

The lower part of the Morrison contains large quantities of nodular chert locally in the exposures west of Salt Valley, and the abundance of angular fragments of chert on the weathered exposures of this part of the Morrison has given the name "Agate Wash" to the small dry wash that empties into the Colorado River near Hallet's ranch, in T. 21 S., R. 24 E. Although sandstone is more abundant in the lower part of the Morrison it is not commonly coarsely conglomeratic. Coarse conglomerate is common in the upper part of the Morrison, however, and northeast of Salt Valley there are striking ledges of conglomerate at the top of the Morrison (pl. 5). In Cache Valley also the topmost beds of the Morrison are conglomeratic. Silicified wood fragments and sections of logs more than a foot in diameter have been observed in the Morrison of this area, and reptilian bones have been reported at several localities.[7]

[7] Gilluly, James, and Reeside, J. B., Jr., op. cit., p. 81. Riggs, E. S., The dinosaur beds of the Grand River Valley of Colorado: Field Columbian Mus., Geol. ser., vol. 1, pp. 272–274, 1901.

A thin section of Salt Wash sandstone collected near the Denver & Rio Grande Western Railroad pump house on the Colorado River southeast of Cisco discloses an irregularly interlocking aggregate of grains. The original grains have been secondarily enlarged, and many of the original grain boundaries cannot be discerned. The grain size appears to have ranged from 0.05 to 0.40 millimeter (0.002 to 0.016 inch), with most of the grains between 0.10 and 0.25 millimeter (0.004 and 0.01 inch). Quartz, orthoclase, and microcline are common. Sodic plagioclase, chlorite, muscovite, and limonite were also observed.

Thickness.—The thickness of the Morrison at the north end of Salt Valley was determined to be 760 feet by stadia and hand-level measurement. The Utah Southern State No. 1 well, in sec. 26, T. 21 S., R. 23 E., passed through 682 feet of beds of Morrison lithology from 450 to 1,132 feet, as recorded in the driller's log. The logs of the Home Oil Co.'s No. 1 and No. 2 wells, in sec. 4, T. 19 S., R. 25 E., may be correlated with less precision but indicate a thickness of about 700 feet for the Morrison formation in that vicinity. No measurements of the thickness of the Morrison were made in the southeastern part of the area, but it is believed to be about 900 feet thick, definitely thicker than to the north and west.

Relation of Morrison to Summerville formation.—The contact between the Morrison formation and the underlying Summerville is locally difficult to locate with precision, because of some resemblances in lithology between the formations. In most places it can be ascertained precisely and is a sharp, slightly irregular contact regardless of whether the basal bed of the Morrison is gray limestone, shale, or cross-bedded sandstone. Within the area mapped no angular unconformity was observed, and the continuity and slight variation in thickness of the underlying Summerville formation suggest that there was not a significant erosional interval between the periods of deposition of the two formations. Angular unconformity has been reported at this contact in the San Rafael Swell.[8] This angular discordance need not be regarded as significant of an appreciable lapse of time, as is shown by the marked angular discordance also in the San Rafael Swell at the base of the Curtis formation, between formations that are both demonstrably of nearly the same Upper Jurassic age.

Conditions of deposition.—The Morrison formation was undoubtedly deposited under continental conditions. The lenticular conglomerates and sandstones represent filled stream channels that shifted from place to place on a flood plain. The limestones are fresh-water pond deposits, as demonstrated by the occurrence in

[8] Gilluly, James, and Reeside, J. B., Jr., op. cit., p. 81.

them of various fresh-water invertebrates at many localities in Colorado and Utah. The siltstones and marls of the formation may represent in part flood-plain deposits and in part lacustrine deposits associated with the limestones.

Correlation and age.—The correlation of the Morrison formation of this area and eastern Utah in general with the Morrison formation in its type locality along the Front Range in Colorado is based on the distinctive lithology of the formation and on the widespread presence of characteristic vertebrate fossils. The use of the name "Morrison" for the formation in Utah, Arizona, and southwestern Colorado supplants the term †"McElmo formation", discarded[9] in favor of the older and more general name, chiefly because it is no longer needed but in part because of loose and conflicting usage by several authors and because the †McElmo formation as originally defined contained part of the San Rafael group as well as beds of Morrison age and lithology.

The Morrison has for some years been assigned by the United States Geological Survey with question to the Lower Cretaceous. Recently considerable doubt has been cast on the evidence on which this assignment was originally based. A critical examination of all lines of evidence, but especially the fossil evidence, led Simpson[10] to conclude that the Morrison should be assigned to the Upper Jurassic. The regional stratigraphic relations of the Morrison, as well as the paleontologic evidence, seem now to afford full justification for transferring the Morrison to the Jurassic,[11] and it is so assigned in this report.

CRETACEOUS SYSTEM

UPPER CRETACEOUS SERIES

DAKOTA (?) SANDSTONE

Lithology and distribution.—The Dakota (?) sandstone of this area has a maximum measured thickness of 110 feet and consists principally of gray and buff sandstone, in part conglomeratic, and subordinately of gray well-bedded shale. The sandstone is in part soft and friable, in part indurated by calcareous cement, and some beds are practically quartzite because of siliceous cementation. Some of the sandstone is fine-grained and thin-bedded, but much of it is coarse-grained and approximates grit. Through the sandstone are stringers and lenses of conglomerate with pebbles of quartzite and black and gray chert. The interbedded shales have locally a greenish

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[9] Idem, p. 82.

[10] Simpson, G. C., The age of the Morrison formation: Am. Jour. Sci., 5th ser., vol. 12, pp. 198–216, 1926.

[11] Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., Correlation of the Jurassic formations of portions of Utah, Arizona, New Mexico, and Colorado: U. S. Geol. Survey Prof. Paper 183 (in press).

cast but are normally gray and well bedded, thus differing from the shales and clay of the underlying Morrison. Carbonaceous shales are not uncommon, and carbonaceous material and vague stem impressions may be observed in some of the sandstones.

The Dakota (?) normally crops out as a ledge capping a steep slope of the softer upper part of the Morrison formation. Because of the low resistance to erosion of the overlying soft shales they are normally swept back from the crest of the Dakota (?) ridge, and the Dakota (?) crops out in a cuesta with a dip slope made by the top of the formation (pl. 20, *A*). Where the dip is low this dip slope may have a width of several miles, but the formation normally crops out only in a narrow belt.

The Dakota (?) is exposed in a narrow strip just east of the Thompson-Moab highway on the west flank of the Salt Valley anticline, in small strips in the faulted area at the north end of Salt Valley, in small areas in the west end of Cache Valley, in small areas west of Turnbow's cabin, in a continuous strip extending eastward from the north end of Salt Valley to McGraw Bottom, on the Colorado River, and in a large area southeast of McGraw Bottom across the Colorado River. Its outcrop extends northward from McGraw Bottom in a strip somewhat broken by faulting, crosses the Denver & Rio Grande Western Railroad east of Cisco, and thence extends northeastward, widening greatly north of Cottonwood station, narrowing once more as it crosses Bitter Creek, and then widening again as it extends to the Colorado-Utah State line and the eastern limit of the mapping. Small isolated areas of conglomeratic sandstone on the crest of Polar Mesa are poorly exposed, and although they are probably basal Dakota (?) they could not be definitely identified as such.

Sections.—Because the upper part of the Dakota (?) is normally exposed on a dip slope and the precise position of the upper contact is difficult to determine, few complete sections of the Dakota (?) could be measured, although the major part of the formation is in most places very well exposed in the front of the cuesta in which the formation crops out. Three complete sections are presented to show the typical lithology of the formation.

Section of Dakota (?) sandstone in Cache Valley about 2 miles east by south of Turnbow's cabin, on Salt Wash

[Measured by C. H. Dane]

	Ft.	in.
Mancos shale: Shale, dark gray, calcareous; extremely abundant shells of *Gryphaea newberryi* Stanton.		
Contact conformable.		
Dakota (?) sandstone:		
Sandstone, medium-grained, buff and gray, cross-bedded	18	
Shale, sandy, gray, thin-bedded	10	

Dakota (?) sandstone—Continued.	Ft.	in.
Sandstone, gray, medium-grained, grains principally quartz but also gray chert	1	
Shale, sandy, brown, carbonaceous; shale, sandy, gray; and some thin beds of gray sandstone; poorly exposed	10	
Sandstone, white, fine-grained, crumbly; contains scattered grit grains of chert and black carbonaceous streaks	1	4
Sandstone, conglomeratic, buff, on fresh fracture nearly white. Composed of fine grains of subrounded to well-rounded quartz with a small proportion of darker chert grains. Through this sandstone in stringers and beds are scattered small subrounded chert pebbles, mostly dark gray but also white, black, and red. These range from three-quarters of an inch to grit size. The upper half of this bed has most of the conglomerate, but there is a pebble layer an inch thick nearly at the base	1	6
Sand, dark, fine-grained, argillaceous, carbonaceous		2
	42	

Contact, irregularity of 1 or 2 inches in a foot laterally, marked in one place by a thin film of black carbonaceous material.

Morrison (?) formation: Sandstone and conglomerate at the top.

Section of Dakota (?) sandstone about 3 miles northwest of Uvanco mine

[Measured by John Vanderwilt]

Mancos shale.

Dakota (?) sandstone:	Feet
Sandstone, yellow to brown, slabby	2–5
Shale, gray, buff; grades laterally to soft yellow sandstone	6–10
Sandstone, yellow to brown, slabby	2–4
Sandstone, buff to light yellow, soft, friable, cross-bedded	36
Conglomerate, with pebbles of white and gray quartzite as much as 3 inches in diameter and smaller pebbles of black chert	1
	47–56

Contact irregular and sharp.

Morrison formation: Green-gray mudstone.

Section of Dakota (?) sandstone at milepost 501 of Denver & Rio Grande Western Railroad, in SW¼ sec. 9, T. 21 S., R. 24 E.

[Measured by C. E. Erdmann]

Mancos shale.

Dakota (?) sandstone:	Feet
Sandstone, brown and buff, hard, cross-bedded; makes a ledge; carbonaceous and with small fragments of coal and plant impressions in the lower foot	31

Dakota (?) sandstone—Continued.	Feet
Shale, lead-gray, with a few thin layers of gray fine-grained sandstone	24
Sandstone, conglomeratic, brown, coarse-grained, with pebbles of quartz and bluish-gray and smoke-gray chert, the pebbles mostly about half an inch in diameter but as much as 2 inches; irregular upper and lower surfaces	2½
Shale, light bluish green and gray	22
Sandstone, gray and buff, soft, friable	2
Sandstone, thin-bedded, and sandy shale	2
Sandstone, gray and buff, soft, friable, coarse-grained, cross-bedded	18
Contact irregular.	101½

Morrison formation: Red and green shales.

Although carbonaceous material is present in many places in the Dakota (?) sandstone, coal has been observed at only two localities. At the top of the formation north of the Home Oil Co. wells in sec. 4, T. 19 S., R. 25 E., the following section is exposed:

Section of upper part of Dakota (?) sandstone in sec. 4, T. 19 S., R. 25 E.

Mancos shale: Shale, gray, calcareous, with abundant specimens of *Gryphaea newberryi* Stanton.

Dakota (?) sandstone:	Ft.	in.
Sandstone, gray, hard, calcareous		3
Sandstone, white and yellow stained, soft, and gray shale		6
Coal, bituminous, clean	1	
Bone and bony shale		5
Coal, bituminous, clean		6
Shale, dark, carbonaceous	1	6
Shale, sandy, gray.		

The coal bed is believed to extend only a few hundred feet along the contact, but exposures are not good at this horizon.

Section of upper part of Dakota (?) sandstone in NW¼SE¼ sec. 23, T. 19 S., R. 25 E.

Mancos shale.

Dakota (?) sandstone:	Ft.	in.
Sandstone, tan, cross-bedded	4	
Shale, dark, carbonaceous		3
Coal	1	2
Shale, carbonaceous		4
Shale, gray		3
Sandstone, ledge-forming.		

Thickness.—In the exposures just east of the Thompson-Moab Highway the Dakota (?) is from 20 to 40 feet thick and in places may be less than 20 feet. The thickness of 42 feet measured in Cache Valley is probably about the average thickness in that locality, and the thickness in the vicinity of the Uvanco mine is probably nowhere more than 60 feet. Southeast of McGraw Bottom the Dakota (?) is about 80 feet thick. Two miles northeast of McGraw Bottom a thickness of 110 feet was measured, and east of Cisco the Dakota (?) is probably 100 feet thick or more to the eastern margin of the area. In the Home Oil Co.'s No. 1 well, in sec. 4, T. 19 S., R. 25 E., the driller's log is interpreted to show 162 feet of Dakota (?), but this is probably excessive, and the interpretation of the No. 2 well in the same section includes 102 feet of beds in the Dakota (?).

Age and relation of Dakota (?) to Morrison formation.—The Dakota (?) rests everywhere on an irregular surface cut in the Morrison formation. This is regarded as an unconformity. Richardson[12] collected typical Dakota plants from the formation near Elgin and near Woodside, thus fixing the age of at least part of the formation in the early part of the Upper Cretaceous.

In western Colorado, between Delta and Grand Junction, the two upper members of the Dakota (?) formation have yielded marine fossils of the age of the typical Dakota flora.[13] Below these upper members lies a unit of thin sandstone and coal, then green shale, then the massive basal chert conglomerate. Associated with the coal zone at several localities have been found plants of Lower Cretaceous age.[14] It seems likely that in eastern Utah the Dakota (?) includes only beds of Upper Cretaceous age, but until more definite information is available it is advisable to apply the question to the name and to the correlation.

The formation in the area mapped is believed to be largely of continental origin but in its upper part may locally include some marine beds where it is transitional into the overlying Mancos shale.

MANCOS SHALE

The Mancos shale is a very thick formation of marine origin and Upper Cretaceous age consisting largely of lead-gray well-bedded shale and subordinately of bedded argillaceous sandstone and gray limestone. Only the lower part of the formation is exposed within the area shown on plate 1, but it crops out over a large area to the north, part of which is shown on a map of a contiguous area accompanying a report by Fisher[15] on the coal resources of the Book Cliffs in Utah. The lithology of the upper

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[12] Richardson, G. B., Reconnaissance of the Book Cliffs coal field, between Grand River, Colo., and Sunnyside, Utah: U. S. Geol. Survey Bull. 371, p. 14, 1904.

[13] Reeside, J. B., Jr., An *Acanthoceras rhotomagense* fauna in the Cretaceous of the Western Interior: Washington Acad. Sci. Jour., vol. 17, pp. 453–454, 1927.

[14] Reeside, J. B., Jr., personal communication.

[15] Fisher, D. J., The Book Cliffs coal field in Emery and Grand Counties, Utah: U. S. Geol. Survey Bull. 852 (in press).

part of the formation, its stratigraphic relations with overlying formations and its age are discussed in detail elsewhere.[16] The lower part of the formation in particular is poorly exposed, cropping out over broad, gently rolling surfaces, with intervening wide alluviated flats. Rock exposures are rare, even on the steeper slopes, the shale weathering to a soft gray clay mantle. The contact with the underlying Dakota (?) is in most places poorly exposed but is clearly conformable and in many places transitional through a zone of alternating sandstone and shale. The basal few feet of the Mancos at several localities has been observed to contain *Gryphaea newberryi* Stanton in great numbers.

About 350 feet above the base of the Mancos is a continuous zone of thin-bedded sandstone about 60 feet thick. The greater resistance of this sandy zone has produced a cuesta ridge, which parallels the more conspicuous cuesta made by the Dakota (?) sandstone. This sandy zone in the Mancos has been correlated with the Ferron sandstone member of the area west of the San Rafael Swell,[17] on the basis of invertebrate fossils collected and identified by Reeside, and also because it has been traced into the Green River Desert area by McKnight[18] and can be followed thence westward into the more massive sandstone of Castle Valley south of Price. On the west side of the Salt Valley anticline and farther west the Ferron sandstone is 440 feet or more above the base of the Mancos. In the vicinity of Salt Valley the Ferron sandstone consists of two sandstone layers separated by an interval of less resistant sandy shale. The two layers have been indicated on the areal map by separate lines of dots in the area west of Salt Valley and also in the vicinity of Cisco. In the intervening area only the lower sandstone is mapped. The topographic form made by the Ferron sandstone can be recognized for some distance east of Danish Wash, but the Ferron sandstone was not identified in the eastern part of the area. Nevertheless, Reeside[19] states that the same sandy zone is conspicuous near Grand Junction, in western Colorado, and also in the vicinity of Shiprock, in northwestern New Mexico.

STRUCTURE

GENERAL FEATURES

For the most part the rocks of the region are tilted at low angles and warped into broad folds. The general inclination of the beds

[16] Fisher, D. J., op. cit. Erdmann, C. E., The Book Cliffs coal field in Garfield and Mesa Counties, Colo.: U. S. Geol. Survey Bull. 851, pp. 28–31, 1934 [1935].

[17] Lupton, C. T., Geology and coal resources of Castle Valley in Carbon, Emery, and Sevier Counties, Utah: U. S. Geol. Survey Bull. 628, p. 31, 1916.

[18] McKnight, E. T., Geology of an area between the Green and Colorado Rivers, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. (in preparation).

[19] Reeside, J. B., Jr., personal communication.

is northward, toward the great structural depression of the Uinta Basin. In the eastern part of the area the beds dip northwestward away from the north end of the Uncompahgre Plateau, an oval anticlinal uplift in Colorado, some 90 miles in length, with its longer axis extending northwest to southeast. In the western part of the area the general dip of the beds is to the north, away from the laccolithic uplift of the La Sal Mountains, which lie a short distance south of the area mapped. Although the general structure is simple, it is diversified by several folds with steeply dipping flanks, the most prominent of which is the northwestward-trending Salt Valley anticline, in the western part of the area. The crest of this fold has been dropped into a trough or graben by a rather complicated system of normal faults, most of which have small displacement but a few of which have displacements of more than 1,000 feet. From the south end of the Salt Valley anticline the system of faults extends a little south of eastward through the Cache Valley graben to the Onion Creek anticline. The rocks of the eastern part of the area are displaced by many normal faults with a general northwest trend. Some of these faults also have displacements of more than 1,000 feet. In Salt Valley, in Cache Valley, and in the valley of Onion Creek masses of the Paradox formation have been pushed plastically upward through the strata as intrusions. The rocks adjacent to these intrusive masses have been steeply folded and at one locality overturned.

METHODS OF REPRESENTING STRUCTURE

The general structural relations may to some extent be visualized from plate 1, which shows the location and direction of throw of the faults traversing the area and represents the attitude of the strata in many places by dip and strike symbols. The cross sections in plate 3 have been drawn to scale and represent the inferred folding and faulting of the beds as they would be seen in the side of a trench sliced several thousand feet deep into the earth's crust. The structure is also depicted by the structural contour map (pl. 2), which represents the attitude and displacement of the strata by means of lines of equal altitude above sea level on the base of the Wingate sandstone. This map is accurate in recording surface structure only along the line of outcrop of the base of the Wingate. In areas where younger rocks are exposed it represents the subsurface structural configuration of the base of the Wingate as inferred from the visible deformation of the overlying younger beds. In areas where older rocks are exposed the map represents the inferred attitude of the base of the Wingate before erosion removed it. The structural contours are based partly on the observed amount and direction of inclination of the bedding at the surface and partly on the instrumentally determined altitudes of contacts between formations. In many of the formations the strike and dip of beds cannot be determined accurately; moreover, the measurement of strike and dip may be accurate for the particular locality where the measurement was made but not regionally significant. For these reasons in drawing the contours more reliance has been placed on the data relating to altitude than on observed strikes and dips, although in general the two classes of data are concordant. The location of the contours is primarily based on the method of equal spacing between points of different altitude.

Angular unconformities exist at the base of the Chinle and Moenkopi formations. Below each of these unconformities there is regional truncation and also local structural deformation of indeterminable amount, which is not reflected in the overlying beds. For this reason the contour map may not represent with accuracy the folds and faults in formations below the Wingate. Above the base of the Wingate, however, although there are unconformities in the stratigraphic section, there are no pronounced local differences in degree of deformation. The variations in thickness of the overlying formations have been determined and the proper correction applied in calculating the depth to the base of the Wingate at different points. This is most systematically done by the use of convergence contour sheets for the formations. The thickness of each of the formations is known in a number of localities from hand-leveled sections or from altitudes and dips determined by plane-table methods. When these thicknesses are plotted it becomes possible to draw lines or contours, each of which represents all positions of equal thickness of a formation. The contours then make evident a regularity of trend in thickening or thinning which gives a basis for interpolation or extrapolation away from the contour lines, to obtain a probable figure for the thickness of the formation at any locality, whether or not the formation at that locality is susceptible of direct measurement.

In contouring, the assumption can be made that the folding of the competent Jurassic sandstones has been of the concentric type, in which the stratigraphic thickness of the beds remains unchanged in the folds. The vertical depth to the bed contoured may be then computed by dividing the stratigraphic thickness by the cosine of the observed dip angle. This correction for dip is negligible for dips of 10° or less and amounts to less than 50 feet per 1,000 feet of stratigraphic thickness for angles up to 17°. For incompetent beds, such as those of the Morrison, Rubey [20] has shown that such a cor-

[20] Rubey, W. W., Determination and use of thicknesses of incompetent beds in oil-field mapping and general structural studies: Econ. Geology, vol. 21, no. 4, pp. 333–351, 1926.

rection need not be applied, for in similar folds with vertical axial planes the vertical thickness is the same as the original stratigraphic thickness before deformation.

The difference in degree of competence between the Mancos, Dakota (?), and Morrison beds and the underlying sandstones may well be reflected in different response to the stresses producing deformation. Although the Dakota (?) itself is a competent layer it is a thin unit included between predominantly shaly beds of less strength. That this upper group of beds folds under stresses that produce faulting in the more competent underlying sandstones is a priori probable and is rendered more probable by the observed lateral gradations in several places of faults in the older rocks into sharp but diminishing folds in the younger ones—a gradation which may in part reflect difference in response to stress although in larger part probably due to diminishing intensity of stress away from the major uplifts. As the map is of necessity contoured on the basis of the structure of the exposed rocks, it must be recognized that the representation of the structure of the base of the Wingate sandstone by contours may be less accurate in areas of outcrop of the relatively incompetent Morrison formation and Mancos shale.

DETAILS OF STRUCTURE

SALT VALLEY ANTICLINE

The Salt Valley anticline is the largest and most striking fold in the area. In general it may be described as an anticline in which at the north end the crest has been dropped in a structural trough. The flanks of the anticline stand as ridges because of the resistance to erosion of the sandstones of which they are composed. Within the trough the exposed rock formations are softer and have been eroded down to a surface of low relief, which has been widely covered with alluvium and valley fill. From the NE¼ sec. 36, T. 22 S., R. 19 E., to the NE¼ sec. 15, T. 23 S., R. 20 E., the Paradox formation is exposed in a strip nearly 5 miles long and at most about half a mile wide. It is intrusive into or separated by faults from all adjacent formations. For more than 4 miles southeast of the southeast end of this strip, the valley floor is covered with alluvium, with only scattered exposures of the Morrison and Moenkopi formations. Southeast of this stretch lies another exposure of the Paradox formation more than a mile wide at the north end but tapering southward for nearly 4 miles farther southeast. That the Paradox of this area extends for at least half a mile northwestward beneath the alluvial cover is shown by the record of the Utah Southern Oil Co.'s Balsley No. 1 well, in the center of the NE¼NE¼ sec. 31, T. 23 S., R. 21 E. On its southwest margin this exposure of the Paradox formation is separated by a fault or intrusive contact from the Chinle formation. On the northeast margin it is similarly separated from formations ranging from the Chinle as high as the Mancos shale. The Paradox formation, consisting largely of salt and gypsum, has high plasticity, and its abnormal relations with the overlying rocks are due in part to the intrusion of this plastic mass across some of the immediately overlying beds as a salt plug, or as two separate salt plugs. Along the walls of the valley the rocks are cut by numerous normal faults, with a prevailing drop toward the valley and thus toward the outcrop of the Paradox formation. The structure is thus complex and the time sequence of structural events obscure. The causes of deformation, the intrusion of the Paradox formation, and the age of the structural movements will be discussed after the details of the structure of the whole area have been briefly described.

The Salt Valley anticline, as the name is here used, ends toward the southeast a short distance beyond the limits of the exposure of the Paradox formation and west of Salt Wash. The southwest flank of the anticline dips at angles of 5° to somewhat more than 10° toward the Courthouse syncline.[21] This synclinal axis extends southeastward parallel to the axial line of the Salt Valley anticline and forms the western boundary of the structurally contoured area (pl. 2). The structure of the anticline is so complex that it cannot be adequately shown on a map of the scale of 1 inch to the mile, but nevertheless it is more satisfactorily shown on the maps (pls. 1 and 2) than by written description. Accordingly, only the general features of most significance will be described.

At the northwest end of the anticline, the crest is dropped into a graben bounded on the southwest and northeast by single faults, the throw of which increases southeastward. In this graben the Mancos is dropped against successively older formations, from the Dakota (?) to the Kayenta toward the southeast (pl. 5). The structure section A–A′ (pl. 3) shows a cross section. East of Valley City the faults bounding the graben are connected by a cross fault with a trend somewhat south of east and a downthrow to the north. South of this fault is a narrow wedge half a mile wide at the southeast end, tapering out northwestward, consisting of Morrison, Mancos, and Dakota (?) and cut by two other faults. This wedge separates the main graben of Mancos shale to the north from the intrusive body of the Paradox formation to the south.

The southwestern boundary fault of the Mancos shale graben is continuous with the western border of the Paradox intrusion. A

[21] McKnight, E. T., Geology of an area between the Green and Colorado Rivers, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. (in preparation).

narrow strip of the Jurassic rocks adjoining the Paradox formation is complexly faulted with a slight net downthrow toward the boundary of the intrusion. Some of these faults strike diagonally toward the intrusion and terminate in its margin. The eastern edge of the Paradox formation is concealed by a narrow strip of alluvium, above which rises a wall consisting chiefly of Wingate sandstone. This is cut by a few northwestward-trending faults with small downthrow toward the valley. The southeast end of the eastern boundary fault of the Mancos graben is concealed where it runs into this alluvial strip, but, by analogy with the other large boundary fault, may be assumed to be continuous with the eastern margin of the Paradox formation. Section B–B′ (pl. 3) shows the probable form and relations of the intrusion and the shape of the Salt Valley anticline at this place.

On a portion of the south side of the area of the Paradox formation a fault or intrusive contact separates the Paradox from the Morrison formation, and the Morrison here strikes southeastward beneath the alluvium of the valley in a manner which suggests that the Paradox formation does not extend much farther south.

On the west side of the valley a strip that includes parts of secs. 14, 15, 22, and 23, T. 23 S., R. 20 E., is cut by many small faults with strikes varying from southeast to nearly east and prevailing throw down to the northeast. The general effect thus produced is a dip of the rocks toward the valley. As shown on cross section C–C′ (pl. 3), this dip is believed to continue northeastward to a fault, concealed beneath the valley alluvium, which is probably continuous with the southwest boundary of the area of Paradox formation in northwestern Salt Valley. The east side of the Salt Valley anticline rises structurally higher than the west side, but this is greatly exaggerated on the section, which cuts diagonally across the anticline. The west flank of the anticline reaches its greatest structural height in the NE¼ sec. 36, T. 23 S., R. 20 E. South of this structural high there is a prevailing dip eastward toward the southern area of exposure of the Paradox formation, but the rocks are cut by only one fault of small throw.

Southeast of the Utah Southern King No. 1 well the top of the east flank of the anticline is sliced by many short faults with northwest strike. These faults have small throws, and although the net displacement is down toward the southwest the beds rise in this direction and the two effects about counterbalance. From the northeastern portion of the southern intrusion of Paradox formation an anticlinal nose plunges southeastward, the axis of the fold roughly paralleling the long direction of the intrusion but diverging somewhat from it toward the east. The southwestern flank of this anticline dips toward the intrusion of Paradox formation, which cuts across the west side of the anticline. The west side of the anticline is cut by many normal faults with a prevailing downthrow to the southwest. Structure section D–D′ (pl. 3) shows the relations of the anticline, the intrusion, and the west flank of the main Salt Valley anticline.

CRESCENT AREA

During the field work of 1927 detailed plane-table mapping in the vicinity of the Salt Valley anticline was confined to the outcrop of the Dakota(?) sandstone and underlying beds. In December 1924, however, James Gilluly and the writer made a brief examination of a small area in the vicinity of the Crescent Eagle well, in the SE¼SW¼SE¼ sec. 4, T. 22 S., R. 19 E. The strikes and dips taken during this examination have been used in compiling the present map. In the area near the wells the bedrock of Mancos shale is largely masked by the broad alluvial floors of Crescent Wash and other dry washes, but a few exposures along the deeply eroded sides of hills capped by remnants of an older alluvial terrace and in isolated higher knolls give some opportunity for observation of structure. The dips observed indicate quite clearly the extension of the northward-plunging Salt Valley anticline, and the confused dips in the SW¼ sec. 4, T. 22 S., R. 19 E., may well indicate the position of the northward extension of the western boundary fault of the Salt Valley graben. That the eastern boundary fault also extends across this area is clearly shown by the much higher position of the Dakota(?) sandstone in the Big Six Randall No. 1 well, in the SE¼ sec. 10, T. 22 S., R. 19 E., than in the Armstrong well, in the southeast corner of sec. 9, and the Crescent Eagle well, in the SE¼ sec. 4, of the same township. The log of the Big Six well shows that the normal section is present on the east side of the fault, at least down to the Navajo sandstone. The log of the Crescent Eagle well shows an abnormal section, apparently due to an intrusion of the Paradox formation in the graben, similar to the intrusions that crop out farther south in Salt Valley. Below the Dakota(?) sandstone at 1,808 to 1,829 feet only 136 feet of the green-gray shales and sandstones of the Morrison were encountered, and below these the drill penetrated only salt, limestone, black shale, and sandstone of the Paradox formation. The Armstrong well did not cut deep enough to reach this formation, and indeed it may well be possible that the intrusive mass is localized to the north and that the Armstrong well would have penetrated the normal Jurassic section if it had been drilled deeper. In extending the east fault of the Salt Valley graben to the north, Fisher's detailed plane-table mapping of the Book Cliffs in 1925 and 1926 [22] has been used as a guide.

[22] Fisher, D. J., the Book Cliffs coal field in Grand and Emery Counties, Utah: U. S. Geol. Survey Bull. 852 (in press).

CACHE VALLEY GRABEN

Extending generally S. 80° E. from the southeast end of the southern intrusion of Paradox formation in Salt Valley is a structural depression about 10 miles long and at most about a mile wide. The west half trends almost due east; the east half trends about S. 70° E. On the south this depression is bounded for the most part by a single large fault with a maximum downthrow of over 2,000 feet to the north. From the north the beds dip down into the depression, but they are also cut by many faults, almost all of which drop the beds to the south. For the western 6 miles the Mancos shale crops out in the floor of the depression, and in a strip north of it the Morrison formation extends still farther east. The erosion of these less resistant formations has proceeded more rapidly than that of the Jurassic sandstones on each side, and as a result a valley has been formed along the structural trough. That part of the valley east of Salt Wash is called "Cache Valley." The depression is accordingly called the "Cache Valley graben", although because the north margin is largely due in places to downfolding the term "graben" is not strictly applicable to all of it. The cross section of the graben west of Salt Wash is shown in section E–E′ and that east of Salt Wash in section F–F′ (pl. 3). About a mile east of section F–F′ two faults diverge from the south boundary. These faults are downthrown to the north and join the fault that bounds this part of the graben on the north, thus reducing the magnitude of the south downthrow on the northern boundary fault. The east end of the graben is very narrow and bounded by single faults on each side. The beds between these faults dip to the southeast. They are much shattered and tip up sharply with a westerly dip where the faults terminate. North of the graben near the east end of Cache Valley there are two small exposures of the Paradox formation, each intrusive into the Moenkopi formation and each exposed in the core of a sharp domal fold. The southwest flank of the northern one forms part of the flank of an almost equally sharp syncline, the form of which is that of half a bowl, with the southwestern part cut off by the north boundary fault of the graben. Section G–G′ (pl. 3) is drawn across the graben, the depression, and the adjoining domal fold to the northeast.

On the south side of the east end of the Cache Valley graben the beds dip to the east. Where the southern boundary fault of the graben dies out, the dip reverses at the low point of a synclinal fold that trends generally south through the southwestern part of T. 24 S., R. 23 E. East of the end of the Cache Valley graben the beds dip southwestward into this synclinal depression and are cut by two small faults with northeasterly trend. The syncline is bounded on the east in part by an alluvial area which probably conceals some complexly faulted and folded rocks and in part by an anticlinal flexure trending northward through the south-central part of T. 24 S., R. 23 E. This anticline is bordered on the east by a syncline that plunges northwestward through the southeastern part of the township. The east flank of this syncline rises toward the structurally complex Onion Creek anticline.

ELEPHANT BUTTE FOLDS

Southeast of the southern Paradox intrusion in lower Salt Valley the southeastern extension of the west flank of the Salt Valley anticline is folded into parallel anticlines and synclines with a general east-west trend. These are called the " Elephant Butte folds ", from the mesa of Entrada sandstone which rises as a conspicuous topographic feature west of the lower part of Salt Wash. The north end of Elephant Butte forms part of the southward-dipping flank of a narrow anticline some 6 miles in length with a curving axis concave to the north. This anticline is reflected in the surface geology, as shown on plate 1, by an area of Kayenta formation surrounded by overlying Navajo sandstone and by a long northwesterly extension from it of Navajo sandstone between belts of the overlying Carmel. The anticline has a maximum structural relief of over 300 feet above the adjoining synclinal axes and may have a closure of over 100 feet, but as it is cut by three faults with trend parallel to the anticlinal axis and downthrow on the north, one of which has a maximum throw of over 100 feet, the existence of real closure is somewhat in doubt.

North of this anticline lies a narrow syncline whose axis has a similar curve concave toward the north. The syncline is also reflected by the areal geology. It is outlined by three depression contours and thus has a closed depth of more than 200 feet. North of it the beds rise northward, but the dip again reverses and the beds dip toward the southern edge of the lower Salt Valley Paradox intrusion and the southern boundary fault of the Cache Valley graben. This reversal of dip makes a second narrow anticline about 4 miles in length which is truncated just west of Salt Wash by the southern boundary fault of the Cache Valley graben. East of Salt Wash the beds rise uninterruptedly until dropped by the fault.

A syncline trends somewhat north of east through Elephant Butte, dying out a short distance west of it. Where the axis crosses Salt Wash there is a small closed basin around which one depression contour has been drawn. The syncline is well defined on the mesa bounded by Cache Valley, Salt Wash, and the Colorado River and is reflected in the areal geology by a low-lying exposure of Carmel formation (pl. 1). As shown by plate 2 the synclinal axis swings toward the northeast from the east end of this Carmel outcrop toward a very striking structural depression, which may be considered to lie on the synclinal axis. This structural depression is shown on the areal map by a small patch of Entrada sandstone around which is exposed an inward-dipping band of Carmel formation cut across on the north by the southern boundary fault of the Cache Valley graben. This oval depression is probably more than 500 feet deep.

The general relations of the structure along this part of the southern margin of the area described in this report can be best understood by consulting also the structure contour map of the adjoining Moab district, to the south.[23] The anticlinal nose plunging northwestward south of Elephant Butte may be regarded as the major prolongation of the Castle Creek anticline. At the north end of the Castle Creek anticline, as shown in the Moab report, is a small dome. From this an anticlinal axis trends a little north of east and is crossed by an anticlinal flexure trending southeastward from the west end of the oval structural depression above described. Where these anticlinal flexures cross there is a small domal area just northwest of sec. 30, T. 24 S., R. 23 E.

YELLOW CAT DOME

The northeast flank of the Salt Valley anticline merges with the general northerly dip of the beds toward the Uinta Basin. East of Salt Valley along the upper part of Salt Wash a synclinal axis with a trend somewhat west of north separates the northeast dip away from Salt Valley and the northwest dip which prevails over the Dome Plateau. About 2 miles west of Squaw Park a distinct anticlinal flexure develops in this regional northwest dip, and an anticlinal axis trends N. 70° W. for about 5 miles. Near the southeast end of this anticline there is a structural dome with a closure of about 100 feet. This is called the "Yellow Cat dome", from the local name for the surrounding region. The closing contour is cut by a short fault of small throw trending parallel to the anticlinal axis. A fault 4 miles in length and trending N. 20° W. drops the beds about 50 feet to the north and parallels the anticline on the southwest.

ONION CREEK ANTICLINE

The Paradox formation is exposed in an irregular area about 2½ miles long and three quarters of a mile wide in the core of an anticline along Onion Creek. The east end of the anticline is concealed by the alluvial material that floors Fisher Valley, but a small

[23] Baker, A. A., Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, pl. 2, 1933.

area of Paradox formation just northwest of the center of sec. 34, T. 24 S., R. 24 E., indicates that the Paradox formation underlies some of the concealed area. On the north the Paradox has a fault contact with the Cutler formation (pl. 7, *A*), which is considerably shattered and along the western part of the contact is cut by several smaller faults. There are two domal folds in the Cutler just north of the western part of the Paradox area. Farther east the structure is obscure, but there appear to be several closely compressed folds parallel to the contact. West of the Paradox area the general dip is toward the west. A normal fault extends a little south of west from the west end of the Paradox area, dropping the beds to the north.

Along the southern margin of the Paradox area formations ranging from Cutler to Entrada lie with fault or intrusive contacts against the Paradox. At the west end of the southern margin the beds dip to the southwest, away from the Paradox. Farther southeast the beds are tilted vertically against a small area of Paradox exposure and dip away from it to the southwest. In the intervening area between these places where the dip is to the southwest a great block dips to the northeast, toward the Paradox formation, and is bounded on each side by large faults. Cross section H–H′ (pl. 3) shows the inferred relation along a line cutting across this dropped wedge, the adjoining mass of Paradox formation, and the folded Cutler to the north. North of the Onion Creek area the beds dip northeastward, toward the Sagers Wash syncline.

COTTONWOOD CANYON GRABEN

The broad alluvial flat of Fisher Valley completely conceals the structure south and east of the Onion Creek area. This hiatus in exposures is as unfortunate as it is unusual, for the buried structural geology is undoubtedly complex. The Cottonwood Canyon graben extends northeastward from Fisher Valley. Its width is about 1½ miles and its exposed length about 4 miles. It is bounded on the southeast by a single fault with downthrow to the northwest and with one short fork near the middle which has the same direction of throw. The displacement of the main fault is over 1,000 feet at the southwest end and diminishes regularly northeastward. On the northwest the graben is bounded by several subparallel faults, most of which drop the beds to the southeast, although two of them have the opposite direction of throw. The largest of these faults is the one farthest northwest, which has a downthrow of 1,500 feet to the southeast at its southwest end. The depth of the graben is greatest toward the southwest end. The beds within the graben slope northeastward but less steeply than the beds on either side. The dip on the northwest side is greater than on the southwest side. As a result the graben as a whole shows a drop to the northwest near its northeast end but less displacement near the middle and toward the southwest end. It seems probable that the buried southwestern extension of the graben is connected in some way with the intrusive mass of the Paradox formation that crops out on Onion Creek. The Cottonwood Canyon graben is shown near the west end of section I–I′ (pl. 3).

SAGERS WASH SYNCLINE

The axis of the Sagers Wash syncline extends southeastward along the lower part of Sagers Wash, across the Colorado River near McGraw Bottom, nearly through the location of Scharf's ranch, on the Dolores river, and thence southeastward through the south end of Steamboat Mesa. The axis diverges but little from a straight line. On the southwest the beds dip northeast, toward the axis, and on the northeast they dip south of west. The axis of the syncline thus plunges toward the northwest. The dips of the flanks are most pronounced from McGraw Bottom to a point a short distance southeast of Scharf's ranch. Northwestward from McGraw Bottom the syncline diminishes somewhat, and farther northwest it probably diminishes still more in the area of outcrop of the Mancos shale. Southeast of Scharf's ranch the syncline is a broad, low downwarp. The syncline is formed by the northwest flank of the Uncompahgre Plateau anticline and the regional dip northward and eastward from the La Sal Mountain uplift. It continues southeastward for some distance into Colorado and probably extends parallel to the axis of the Uncompahgre Plateau uplift and as far southeast as the south end of the plateau. Structure sections C–C′ and I–I′ (pl. 3) both show the Sagers Wash syncline, but as both cross it diagonally, neither shows the maximum structural relief.

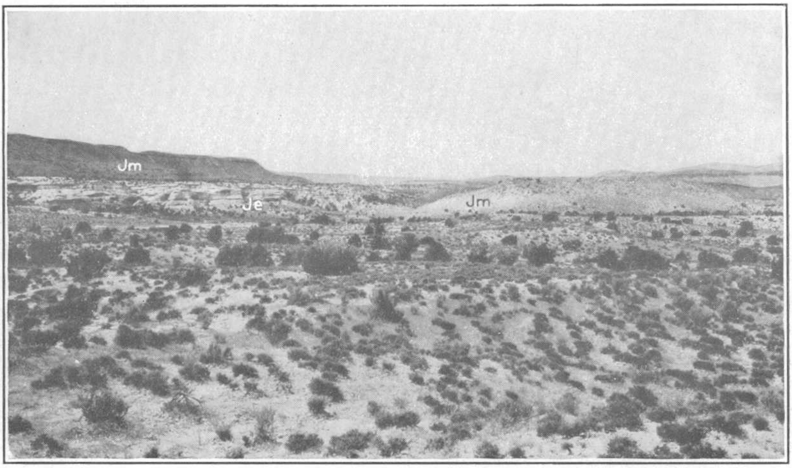
RYAN CREEK FAULT ZONE

The area of general southwestward dip north of the Sagers Wash syncline is bounded on the north by the Ryan Creek fault zone. This extends from the eastern margin of the area mapped, along Ryan Creek, nearly to its junction with Renegade Creek and thence northwestward to the northwestern part of T. 22 S., R. 24 E. At the east end there is a single fault with a maximum downthrow of about 1,000 feet to the southwest (pl. 17, *B*), the Kayenta and Wingate formations being dropped well below the top of the pre-Cambrian metamorphic rocks. Because of steeper westward dip on the north side of this fault, the throw gradually diminishes westward, and where this fault joins another of similar direction of throw at a point about 3 miles west of the Colorado-Utah State line the throw is only about 250 feet. This second fault continues about 3 miles farther northwest, with a maximum throw of about 300 feet. An irregular fault with a northwesterly strike and downthrow to the north extends about 6 miles northwestward from a point half a mile south of the junction of the two faults described above. The eastern 4 miles of this fault forms the southern boundary of a narrow graben. The maximum throw of this southern boundary fault is about 500 feet. Within the east half of the graben the beds dip 5°–18° NW., but in the west half they have only a gentle westward dip. The north boundary of the west end of the narrow trench is a complex group of faults, of which four are shown on the map, and a steep southward downflexure of the strata, which diminishes farther west, where it is cut by a short fault of small downthrow to the north. Structure section I–I′ (pl. 3) cuts across this narrow graben near its west end. The fault that bounds the graben on the south extends westward beyond it and conspicuously cuts off a cliff of Entrada sandstone in sec. 13, T. 22 S., R. 24 E. (pl. 18, *A*), the downthrow of 250 feet to the north bringing Morrison against the Entrada. This fault dies out in the Morrison formation in the NE¼ sec. 14, T. 22 S., R. 24 E., but its direction of displacement is duplicated by an échelon fault that begins in the SW¼ sec. 13 and extends northwestward across the Colorado River. This fault has a maximum displacement of about 600 feet. Part of the stress that produced this fault was taken up by folding and squeezing of the shaly beds in the Morrison. The fault northwest of the Colorado River forms part of a group of interlacing faults of small throw, mainly down to the northeast. This group extends to the upper contact of the Dakota(?) sandstone but apparently does not break the cuesta made by the Ferron sandstone member of the Mancos shale.

In its west half the Ryan Creek fault zone thus has a downthrow to the north; about 4 miles of the middle part of it is a narrow graben, the net effect of which is a small downthrow to the north; and the eastern part of the zone is a single fault of large downthrow to the south. This fault is known to continue eastward for perhaps 6 miles into Colorado. Three small faults of similar strike but downthrow to the north which cut across Granite Creek south of the Ryan Creek fault zone also extend into Colorado. The eastern extension of these faults is approximately shown in plate 19.

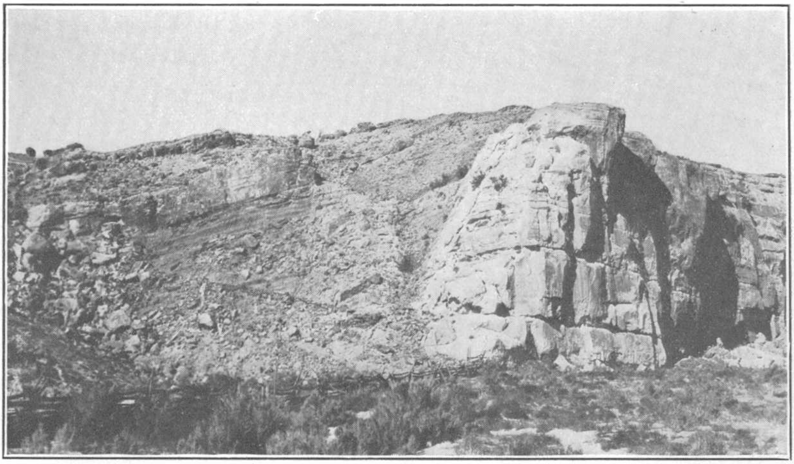
DRY GULCH FAULT

The Dry Gulch fault enters the area from the east near the southeast corner of sec. 32, T. 21 S., R. 26 E., and extends only slightly north of west along Coach Creek and thence along Dry Gulch to



A. FAULT CONTACT OF ENTRADA SANDSTONE (Je) AND MORRISON FORMATION (Jm) IN SE¼ SEC. 13, T. 22 S., R. 24 E., ALONG RYAN CREEK FAULT ZONE.

Morrison formation crops out normally above the Entrada at the left.



B. MORRISON FORMATION DROPPED AGAINST MOAB SANDSTONE MEMBER OF ENTRADA SANDSTONE BY THE DRY GULCH FAULT NEAR SOUTHEAST CORNER OF SEC 27, T. 21 S., R. 24 E.

Colorado River bottom in foreground. Photograph by C. E. Erdmann.

the Colorado River, across which it breaks up into a zone of small faults that extend to a point about 2 miles southeast of Cisco. Where it enters the area from the east the throw is only about 150 feet down to the south. The fault is believed to terminate a few miles east of the Utah-Colorado line. For 10 miles west of the edge of the area it is a single fault, although two small faults of similar direction join it from the north in the northern part of sec. 31, T. 21 S., R. 25 E. The maximum throw is about 700 feet, down to the south, along the middle part of Dry Gulch, where the Kayenta formation is dropped against the pre-Cambrian metamorphic rocks. It continues as a single fault to the cliff west of the alluvial bottom of the Colorado River (pl. 18, *B*) but forks at the top of the cliff, and both forks die out in less than half a mile to the west in a zone of steep dips, generally to the south, in the Morrison formation. Farther west, in sec. 27, T. 21 S., R. 24 E., the Morrison beds are sharply folded and squeezed, with numerous irregular short faults. It is evident that where the fault passes wholly into the less competent Morrison beds, the stress has been largely taken up by sharp folding.

A fault striking N. 75° E. with a maximum downthrow to the south of about 500 feet extends for 2 miles in secs. 28 and 29, T. 21 S., R. 24 E. It offsets the Ferron sandstone member of the Mancos shale and may extend somewhat farther west than is shown on plate 1, but could not be traced through the poor exposures of the shale.

SAND FLAT GRABEN

Between the Dry Gulch fault and the Ryan Creek fault zone is a tract 5 miles in width along the Colorado-Utah State line and narrowing westward to slightly less than 3 miles, in which the dip is generally toward the west—somewhat toward the northwest in the eastern part of the tract and somewhat toward the southwest near the Colorado River, in the western part. Where the net throw of the Ryan Creek fault zone is down toward the north the tract between it and the Dry Gulch fault is a graben. This graben is called the "Sand Flat graben" because the area known as the "Sand Flat", near the Colorado River, is definitely in a structural trough between the boundary faults on the north and south. A shallow syncline prolongs this trough westward and southwestward from the place where the complexly faulted westward extension of the Dry Gulch fault and the Ryan Creek fault zone die out. Where the throw of the Ryan Creek fault zone shifts to the south the graben character of the tract north of it is destroyed. Section I–I′ (pl. 3) is drawn near the eastern limit of the area that falls within the graben. A fault about 5 miles in length cuts southwestward diagonally across the wide eastern part of the tract between the Dry Gulch fault and the

Ryan Creek fault zone. The maximum throw is about 200 feet to the southwest. This fault starts from the west in an area of outcrop of the Wingate and Kayenta formations, offsets the Wingate-Chinle and Chinle-pre-Cambrian contacts as a single fault, and enters an area of pre-Cambrian granite through which it was not traced. It apparently continues southeastward and drops the formations to the southwest in exposures southeast of the head of Cow Creek, but a mile farther to the southeast it emerges in the cliff north of Ryan Creek as a complicated shatter zone (pl. 17, *B*). The projection of the strike of the single fault as observed farther northwest would extend toward the east side of this shatter zone. The total displacement of the shatter zone is estimated to be about the same as that of the single fault.

SOUTH CISCO ANTICLINE

North of the Dry Gulch fault the prevailing dip is toward the northwest, rather uniformly so east of the Colorado River. West of the Colorado River the rocks are flexed into two plunging anticlines. The eastern one of these, which is not named, is sharply outlined by the outcrop of the Dakota(?) sandstone (pl. 20, *A*). The axis of this fold trends about N. 45° W. through the northeastern part of T. 21 S., R. 24 E. On the southwest flank dips as high as 16° SW. have been observed, but on the other flank the rocks dip toward the northwest at low angles.

The South Cisco anticline lies north of the westward synclinal prolongation of the Sand Flat graben, and its axis has a general westward trend. Its northward-dipping flank and the southwestward-dipping flank of the anticline described in the preceding paragraph produce a shallow synclinal flexure. This anticline is a short distance south of the town of Cisco. The name "Cisco dome" has been generally applied to the large gas-producing closed anticline that lies some miles northwest of Cisco, and accordingly the name "South Cisco anticline" is applied to the small fold south of Cisco station. The anticline is only slightly indicated by the outcrop of the Ferron sandstone member of the Mancos shale. The fold is largely in the overlying Mancos shale, which is poorly exposed and the exposures of which are without distinctive key beds so far as could be determined by examination as carefully as was warranted by the degree of detail of the writer's work. The contouring of this anticline is thus provisional. The broad structural terrace on the anticline shown on plate 2 is largely based on the fragmentary information available on the wells drilled in this area, although supported to some extent by strike and dip observations in the Mancos shale. The contours have been drawn with assurance where data on altitude and strike and dip observations were available at the Dakota(?)-

Mancos contact or on the Ferron sandstone in the lower part of the Mancos shale. The unreliability of dip observations in the shale itself is perhaps greater because of the trend of the extension of the Dry Gulch fault into the area south of Cisco station. The wells drilled, however, penetrated the Dakota (?) sandstone at depths less than would be expected if the structure were a simple monocline.

LITTLE DOLORES RIVER FAULT ZONE

A fault with a maximum downthrow of about 500 feet to the northeast and a strike of about N. 60° W. starts as a small break in the Morrison about a mile northeast of Cottonwood station and cuts across the strata for about 7 miles, curving toward the east near its southeast end and terminating in a northwestward-dipping monoclinal flexure. About a mile southeast of the eastern termination of this fault another fault begins in the pre-Cambrian metamorphic rocks and extends southeastward. Where this fault crosses the Colorado-Utah State line it has a downthrow to the northeast of about 200 feet. It continues for several miles southeastward along the valley of the Little Dolores River. These two faults may be called the "Little Dolores River fault zone."

This zone is one of folding as well as faulting. In the area between the smaller southern fault and the southeast end of the larger fault there is a definite northeastward dip, and the smaller fault terminates northwestward in an anticlinal flexure. This anticlinal flexure continues northwestward to the Colorado River, north of which it is even more sharply defined where the beds dip northeast at angles as high as 60° adjacent to the large fault. Northeast of the fault the dip is also to the northeast, and the fault appears to be a break in a sharp anticlinal fold in competent beds. The fold, of course, continues for some distance northwestward beyond the place where the fault dies out. Northeast of the anticlinal flexure there is a corresponding syncline, which is most pronounced northwest of the Colorado River. Section I–I′ (pl. 3) crosses the fault near the river.

HARLEY ANTICLINE

West of the Colorado River and north of the synclinal flexure that parallels the Little Dolores River fault zone on the north is a large area in the east half of T. 19 S., R. 25 E., in which the prevailing dip is gently westward. A synclinal flexure trending south through sec. 3 and a narrow anticlinal fold west of it interrupt this regular westward dip. Two wells have been drilled on this anticlinal axis, and it has been called the "Harley dome." As there is at most a very small closure, the fold is here called the "Harley anticline." It is indicated plainly on the surface by the curving outcrop of the

Dakota (?) sandstone, and dips as high as 12° NW. have been observed on the northwest flank. A dip of 24° NE. observed in the Mancos shale northwest of the Dakota (?) outcrop indicates the probable continuation of the anticlinal axis for some distance to the northwest.

[*Note.*—Since the preparation of this report a geologic and structure map of this fold, made by C. E. Dobbin, of the conservation branch of the United States Geological Survey, in May 1932, has been released for public inspection in the offices of the Geological Survey at Casper, Wyo., Salt Lake City, Utah, Denver, Colo., and Washington, D. C. This detailed map, on a scale of 4 inches to the mile, indicates a closure of about 90 feet, contours being drawn on the top of the Dakota (?) sandstone.]

BITTER CREEK ANTICLINE

The axis of the Bitter Creek anticline extends southeastward through the northeast quarter of T. 19 S., R. 25 E., into T. 19 S., R. 26 E. The anticline is separated from the Harley anticline by the shallow syncline referred to above, but most of the west flank is made by the gentle regional westward dip, into which the west flank of the Harley anticline is continuous. The east flank of the Bitter Creek anticline is a sharp down flexure to the northeast at angles as high as 19° (pl. 20, *B*). This flexure diminishes in steepness southeastward, and the southeast end of the Bitter Creek anticline is a very slight anticlinal roll on the regional northwestward dip. Northeast of the Bitter Creek anticline the beds also dip to the northwest.

GENERAL NATURE OF FAULTS

So far as known all the faults in the area are of the normal type—that is, downthrown on the hanging-wall side of the fault surface. It is true that most of the faults of larger displacement crop out along valleys or at the base of lines of cliffs, and in such places the inclination of the fault surface is not revealed and the actual outcrop of the fault line may be concealed by talus or valley fill. The few exposures of inclination along these larger faults show that they are of normal type where observations can be made, and the multitude of smaller faults afford more numerous exposures of faults of definitely normal throw. Probably a majority of the faults, however, have surfaces that are vertical or only slightly inclined. With this in mind the cross sections show the faults as vertical unless a decided inclination of the fault surface is definitely known. This arbitrary procedure has greatly simplified the cross sections and has the advantage of eliminating the necessity of speculative and unfruitful adjustment of the relations of intersecting faults. It is perhaps hardly necessary to point out the probability that some of the closely spaced faults intersect, offset, or join, in depth, as well as on the surface.

The physiognomy of the faults is varied. Where a fault passes through a sandstone or separates two sandstones of similar texture the fault may be a scarcely decipherable line, no more conspicuous than the joints or surface weathering cracks in the sandstone. In other places the same sandstones may be thoroughly shattered for a distance of tens of feet or even more from the fault line. The textural differences among the various Jurassic sandstones are slight but in normal stratigraphic sections are accentuated by varying response to weathering. In the faulted areas the identification of individual sandstones is more difficult, and this difficulty is enhanced by local color variations in the sandstones where affected by faulting. For example, the shattered masses of Wingate sandstone assume a white or light-gray hue quite different from the normal buff or reddish tones of the formation. In the lower end of Cache Valley the typically light-buff or gray-white Navajo sandstone becomes distinctly orange-red at one place, approximating the color of the Entrada sandstone.

Most of the faults are sharp, clean breaks rather than shatter zones, and in many of them drag is inconspicuous or absent. With diminishing throw such faults may terminate in apparently regular homoclines. In others, where there is appreciable drag on each side, the fault may pass laterally into a monoclinal fold. This is more common where the fault passes from the Jurassic sandstone into the less competent shale and sandstone of the Morrison and into the Mancos shale.

AGE OF DEFORMATION

The sedimentary rocks of the area reveal the results of deformation at several different periods. They record the rise of a land mass to the east, probably beginning in early Pennsylvanian time and continuing intermittently until at least the end of Lower Triassic time. The west edge of this land mass roughly coincided with the present west edge of the Uncompahgre Plateau. Regional tilting of the sedimentary rocks away from the axis of the uplift is shown by angular unconformity between the Permian and Lower Triassic beds and also between the Lower Triassic and Upper Triassic. The regional tilting at these times was accompanied by local folding. The most conspicuous deformation, however, is that which involved the Mancos shale, of Upper Cretaceous age, and accordingly was later than the Mancos and also than the conformable series of Upper Cretaceous rocks subsequently deposited upon it. The geologic history recorded in the stratigraphic succession of Upper Cretaceous rocks cropping out in the Book Cliffs and Uinta Basin, to the north, offers the possibility of more accurate dating of this post-Cretaceous folding and faulting.

This stratigraphic succession of Upper Cretaceous rocks is described in great detail in several recent papers. Erdmann [24] reports a notable unconformity at the base of the beds he tentatively assigns to the Tertiary. This unconformity cuts out 1,000 feet or more of the underlying Hunter Canyon formation at the top of the Mesaverde group.

Fisher,[25] working in the Book Cliffs of Utah, found no direct evidence of such pronounced unconformity between the Tertiary and Upper Cretaceous. Above the Farrer member at the top of the Price River formation of the Mesaverde group and below the red and varicolored beds of the Wasatch he recognized a unit of light-colored sandstones with some shale which he called the "Tuscher formation," assigning it with some doubt to the Tertiary. The considerable variation in thickness of the Tuscher and the underlying Farrer member of the Price River led him to suspect disconformities both above and below the Tuscher. It may be that the Tuscher represents the sandstone of Tertiary (?) age below which Erdmann found such a distinct unconformity and above which he believed there was a probable disconformity beneath the overlying variegated shales of the Wasatch. The beds of the Mesaverde group are shown by both Fisher and Erdmann to be a continuous sequence of sediments intertonguing with each other and with the underlying Mancos shale.

It seems inherently probable that the post-Cretaceous period of deformation reflected in the faulted anticlines of the Salt Valley and adjoining regions is recorded in the stratigraphic section by unconformity. If so, the earliest period at which this deformation could have occurred appears to be the interval between the end of the Upper Cretaceous sedimentation and the deposition of the earliest Tertiary. It is worth while to note Erdmann's observation [26] that the Wasatch formation and the underlying sandstone referred by him to the Tertiary (?) were laid down after the underlying formations, classed at present as of Cretaceous age, had been uplifted as a broad arch and then deeply eroded. The axis of this uplift, according to Erdmann, lies in the vicinity of West Salt Creek and appears to trend to the north or northwest. Gilluly [27] has attributed the major folding of the San Rafael Swell to post-Cretaceous and

[24] Erdmann, C. E., The Book Cliffs coal field in Garfield and Mesa Counties, Colo.: U. S. Geol. Survey Bull. 851, p. 48, 1934 [1935].

[25] Fisher, D. J., The Book Cliffs coal field in Grand and Emery Counties, Utah: U. S. Geol. Survey Bull. 852 (in press).

[26] Erdmann, C. E., unpublished manuscript.

[27] Gilluly, James, Geology and oil and gas prospects of part of the San Rafael Swell, Utah: U. S. Geol. Survey Bull. 806, p. 127, 1929.

pre-Wasatch time, largely on its structural analogy with the Waterpocket Fold, where essentially flat-lying Wasatch rocks overlie the folded late Cretaceous strata.[28]

The transitional and intertonguing relations of the fluviatile Wasatch and overlying lacustrine Green River formation have been demonstrated by Bradley and Sears.[29] The Green River is succeeded above by the Bridger formation, and the Bridger in turn by the Uinta. The major relations of the Bridger and Uinta formations are not wholly clear. According to Bradley [30] there is possibly a diastrophic break between the Green River and Bridger formations, although this is open to question.

The major stratigraphic relations summarized above make it clear that the downwarping of the Uinta Basin occurred at the end of the Cretaceous period and was a result of, or was simultaneous with, the major folding and uplift of the Uinta Mountains, to the north,[31] the San Rafael Swell, to the southwest, and the conspicuous uplift of the Uncompahgre Plateau, to the southeast.

The gentle basinward dip of the Eocene formations of the Uinta Basin reflects differential vertical movements of post-Eocene time, but these may be plausibly ascribed to either depression of the basin under the loading of Eocene sediments or to rejuvenation of vertical uplift in the surrounding elevated areas. Sears [32] believes that the Uinta Mountains were uplifted somewhat during post-Eocene time, causing folding in the adjacent Eocene beds. There is little direct evidence of such post-Eocene uplift in the region of the La Sal Mountains, but the laccolithic mountains of the Colorado Plateau have been generally considered to be early Tertiary.[33]

More recent faulting has been observed in the east end of Cache Valley. At this place a calichelike layer overlies some of the faults

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[28] Dutton, C. E., Geology of the High Plateaus of Utah, pp. 280–281, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1880. Gilbert, G. K., Geology of the Henry Mountains, pp. 12–13, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1877.

[29] Sears, J. D., and Bradley, W. H., Relations of the Wasatch and Green River formation in northwestern Colorado and southern Wyoming: U. S. Geol. Survey Prof. Paper 132, pp. 96–100, 1924. Bradley, W. H., Shore phases of the Green River formation in northern Sweetwater County, Wyo.: U. S. Geol. Survey Prof. Paper 140, p. 125, 1926. Bradley, W. H., Origin and microfossils of the oil shale of the Green River formation of Colorado and Utah: U. S. Geol. Survey Prof. Paper 168, p. 8, 1931.

[30] Bradley, W. H., op. cit. (Prof. Paper 168), p. 22.

[31] Sears, J. D., Geology and oil and gas prospects of part of Moffat County, Colo., and southern Sweetwater County, Wyo.: U. S. Geol. Survey Bull. 751, p. 229, 1924.

[32] Sears, J. D., Relations of the Browns Park formation and the Bishop conglomerate and their role in the origin of Green and Yampa Rivers: Geol. Soc. America Bull., vol. 35, p. 301, 1924.

[33] Gould, L. M., The role of orogenic stresses in laccolithic intrusion: Am. Jour. Sci., 5th ser., vol. 12, pp. 119–127, 1926. Thorpe, M. R., The Abajo Mountains, Utah: Am. Jour. Sci., 4th ser., vol. 48, pp. 379–389, 1919. Gilbert, G. K., Geology of the Henry Mountains, pp. 78–89, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1877. Baker, A. A., Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, pp. 78–79, 1933; Geology of the Monument Valley and Navajo Mountain region, San Juan County, Utah: U. S. Geol. Survey Bull. 865 (in preparation).

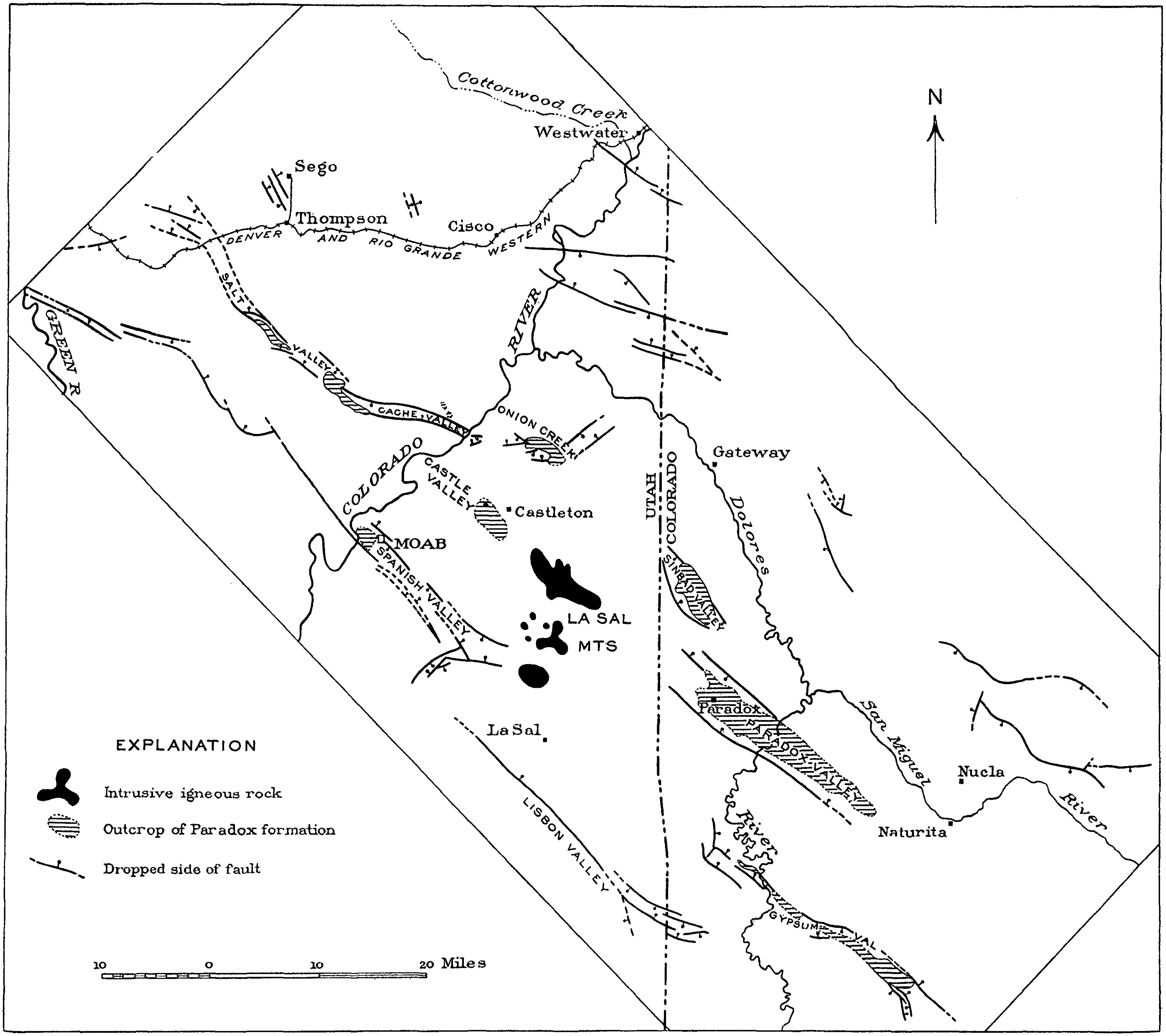
in the graben. This layer is several feet thick and consists partly of unconsolidated silt and sand and partly of the same material cemented with a white plastery material. It rests in places on the Jurassic sandstones and in places on what is obviously the talus derived from higher valley walls during an older erosion cycle. Over one of the faults the caliche layer is displaced 12 feet in the same direction as the fault displacement of 200 feet in the Jurassic sandstones. This displacement of 12 feet is evidently a comparatively recent renewal of movement along a larger fault. Similar renewal may have occurred elsewhere, but evidence of it has not been detected.

RELATION OF THE STRUCTURE OF THE AREA TO THE REGIONAL STRUCTURE

The Salt Valley anticline and related structural features mapped in detail by the writer form part of a larger system of faults and folds. This larger system consists of eight major units—the Salt Valley, Spanish Valley, Castle Valley, Onion Creek, and Lisbon Valley anticlines, in Utah, and the Sinbad Valley, Paradox Valley, and Gypsum Valley anticlines in Colorado. (See pl. 19.) Each of these conforms in some respects to a common type, though each possesses individual peculiarities. The general form of the anticlines is a closely compressed fold from 10 to more than 30 miles in length, elongated in a northwesterly direction, paralleling the trend of the axis of uplift of the Uncompahgre Plateau, to the east. In all the anticlines except Lisbon Valley the gypsiferous beds of the Paradox formation are exposed, and in most of them these gypsiferous beds have transgressed their normal stratigraphic position under compressive stress and have intruded overlying beds of various ages. Along the anticlinal crests and extending northwest and southeast from them are narrow fault trenches or grabens, which also exhibit regional parallelism with one another and with the anticlines. In the center of this group of faulted anticlines rise the igneous intrusive masses of the La Sal Mountains. Plate 19 gives a picture of the geographic relations of the major faults of the system to the igneous intrusions of the La Sal Mountains and to the normal faults with downthrow to the southwest, away from the Uncompahgre uplift. For clarity of presentation the anticlinal axes have been omitted.

INTRUSIVE RELATIONS OF THE PARADOX FORMATION

That the Paradox formation has under severe compressive stress actually moved upward across stratigraphic boundaries and acted as a partly plastic mass is well established by the field observations.



GENERALIZED MAP OF PART OF EASTERN UTAH AND WESTERN COLORADO, SHOWING RELATION OF PRINCIPAL FAULTS TO OUTCROPS OF THE PARADOX FORMATION, THE LA SAL MOUNTAINS, AND THE SOUTHWEST FLANK OF THE UNCOMPAHGRE PLATEAU.

The cross section of the southwest side of Fisher Valley (fig. 2) shows the Paradox with intrusive relations to the Hermosa, the next formation overlying it. The isolated mass west of the main area of Paradox exposure (to the left in the diagram) is not included between the exposures of Hermosa as a bed but rather as an offshoot of the principal Paradox mass intruding sill-like between Hermosa beds. The vertical dips at the intrusive contacts show the severity of the compression that led to the rupturing of the anticlinal roof and the squeezing of the plastic Paradox beds upward. On the southwest side of Castle Valley about 2 miles south of the Round Mountain igneous plug there is an exposure similar to the one shown in the cross section.[34] At this place, however, the rocks exposed against the intrusive mass are beds probably near the base of the Cutler, and the dip of the intrusive contact and of the lowest Cutler beds is an overturned dip of 82°. These are the only two localities observed by the writer at which the intrusive relations of the Paradox formation are extensively exposed and not complicated by faulting. That similar extreme compression has prevailed elsewhere is shown by the outcrop of Hermosa beds along the northeast flank of Gypsum Valley, in Colorado. This outcrop of Hermosa dips toward the valley at 75°, probably an overturned dip though not determinable as such, for the Morrison is faulted against the Hermosa on the side toward the valley and the Jurassic sandstones on the other side. Hermosa beds also crop out on the west side of Sinbad Valley[35] and are recorded as dipping 60° E. (toward the valley). The relations as later described by Cross[36] and previously quoted on page 27 make it probable that these Hermosa beds are overturned adjacent to the Paradox intrusion, but they are bounded by a fault on the southwest.

The exposures cited show the manner in which the Paradox formation has acted as an intrusive mass, although probably not far removed from its original stratigraphic position. An idea of the manner of intrusion near the top of an intrusive mass is given by the two small exposures of Paradox at the southeast end of Cache Valley. The locations of these are shown on both the areal and structural contour maps. The southern and larger one, which intrudes the Moenkopi, is 150 feet wide and 500 feet long, the long dimension trending about N. 15° W. At the north end the gypsiferous mass forks into two tapering "veins." A sketch cross section at this place

[34] Baker, A. A., Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, p. 61, 1933.

[35] Peale, A. C., Geological report on the Grand River district, Colorado: U. S. Geol. and Geog. Survey Terr. 9th Ann. Rept., p. 71, 1877.

[36] Cross, Whitman, Stratigraphic results of a reconnaissance in western Colorado and eastern Utah: Jour. Geology, vol. 15, p. 671, 1907.

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is shown in figure 4. There are steep quaquaversal dips in the Moenkopi away from the intrusion, but between the tapering "veins" the intruded shales are much broken and show violent and irregular changes in dip.

The exposures of the smaller area of Paradox are not as good, but it is about 300 feet long, striking N. 45° W., and 50 feet wide in the center, tapering gradually toward each end. On both flanks the Moenkopi dips away steeply at angles as great as 80° immediately adjacent to the intrusion. The dips at the ends are also away from the intrusion.

Wells that have been drilled on the areas of outcrop of the intruded Paradox formation have encountered thick beds or masses of salt below an upper zone of gypsiferous beds similar to those exposed at the surface.[37] Although some of the "salt" reported may actually be gypsum or anhydrite and although it is apparently mixed with

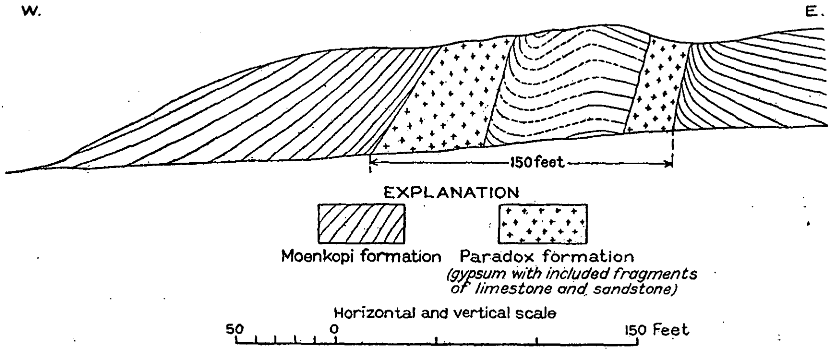

FIGURE 4.—North end of small intrusion of Paradox formation in east end of Cache Valley, looking north at exposure along transverse gully.

gray limestone and black shale, thick masses of rock salt are found beneath the surface capping, in which rock salt is not present except as a minor admixture. The K. Levi well, on the Salt Valley anticline, after passing through 775 feet of gypsum, lime, and shale, encountered rock salt. The Crescent Eagle well probably encountered the Paradox formation at 1,965 feet, and at 2,060 feet it penetrated "salt rock," which was found at intervals nearly to the bottom of the test. Potash salts [38] were reported from this well at 3,150 feet and 3,910 to 3,917 feet. The King No. 1 well, in Salt Valley, went

[37] Harrison, T. S., Colorado-Utah salt domes: Am. Assoc. Petroleum Geologists Bull., vol. 11, no. 2, pp. 117–125, February 1927. Prommel, H. W. C., and Crum, H. E., Salt domes of Permian and Pennsylvanian age in southeastern Utah and their influence on oil accumulations: Idem, vol. 11, no. 4, pp. 373–393, April 1927; Structural history of parts of southeastern Utah from interpretation of geologic sections: Idem, vol. 11, no. 8, pp. 816–820, August 1927. Baker, A. A., Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, pp. 85–92, 1933.

[38] Lang, W. B., Potash investigations in 1924: U. S. Geol. Survey Bull. 758, pp. 29–43, 1926.

from limestone into salt at 1,652 feet and continued in salt with some gray lime and black shale to 3,829 feet, the total depth. No gypsum-anhydrite zone can be differentiated in this well if indeed it is present. Government potash core test 24, in the southeast corner of sec. 13, T. 23 S., R. 20 E., less than half a mile south of the King No. 1 well, apparently entered the Paradox formation at 910 feet and passed through more than 200 feet of sand, black and gray clay, and gypsum before reaching salt, anhydrite, and gypsum beds with shale breaks at a depth of 1,160 feet. In the Onion Creek area, according to Harrison,[39] drilling wells after reaching a depth of 200 or 300 feet report salt and anhydrite with shale and thin lime. At the surface the exposures consist of broken gypsum, shale, and limestone.

The relations described, together with the collapse structures that are so prevalently associated with the intrusive masses, led Harrison to ascribe the occurrence of large amounts of rock salt in depth, as contrasted with very minor amounts at the surface, to abstraction of the salt by differential solution from the upper part of the intrusions and its redeposition at depth, under present conditions of exposure. The hypothesis of differential solution has also been invoked by Goldman [40] and others to explain the cap rock of the salt domes on the Gulf coast in the United States. The formation of a "salt table" or residual gypsum cap [41] as a result of subsurface solution of salt has also occurred on some German salt stocks where an intrusive salt core has approached the surface and come into contact with ground water. As a result of this process, "solution grabens" have developed there above the salt.

The hypothesis of differential solution is an attractive one to explain some features of the Paradox intrusions of eastern Utah and western Colorado. All the Paradox intrusions so far investigated have beneath the surface large quantities of salt but at the surface consist of gypsum and insoluble shale and sandstone. Their relation to the present topography is therefore a direct one. If this fact alone is considered it would seem to imply that the solution is taking place now and has occurred primarily during the period of development of the present topography. That some solution is occurring at the present time is shown by the remarkably saline springs along Onion Creek and also by similar but much less saline springs along the lower part of Salt Wash.

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[39] Harrison, T. S., op. cit., p. 117. (Onion Creek is termed Salt Creek throughout Harrison's paper.)

[40] Goldman, M. I., Origin of the anhydrite cap rock of American salt domes: U. S. Geol. Survey Prof. Paper 175, pp. 83–114, 1933.

[41] Stille, Hans, The upthrust of the salt masses of Germany, in DeGolyer, E. L., and others, Geology of salt-dome oil fields, p. 151, Am. Assoc. Petroleum Geologists, 1926.

The exposures of the Paradox along Onion Creek are somewhat dissected, and the masses of gypsum there exposed above the level of the stream have been much corroded and extensively dissolved by the downward percolation of surface water and have an excessively irregular and honeycombed surface. The rock is undoubtedly cavernous beneath the surface, for in many places it reverberates with a hollow sound underfoot. Such solution must be active down to the level of the ground-water table. However, if the solution has taken place primarily in recent time, it seems that there should be much more obvious evidence of recent collapse structures such as sink holes, landslides, and determinably recent step faults in association with the Paradox exposures, and also extensive displacement and tilting of alluvial surfaces where they are near to intrusive masses of the Paradox, as in Fisher Valley, Cache Valley, and Salt Valley. That such features of recent origin should be present is emphasized by the pronounced subsidence or collapse structures that are demonstrably older than the topographic features—for example, the oval structural depression south of the east end of Cache Valley. However, graben faulting after the topographic surface acquired approximately its present form is described by Baker [42] as occurring in the southern part of the Moab district, and similar evidence of recent movement may be more prevalent than is yet realized. Baker also expresses his belief that movement of some of the salt masses has taken place within recent time.

The paucity of evidence of deformation or movement due to recent solution may be accounted for by the history of the development of the topography. As further pointed out in the section on geomorphic history, erosion in the canyons had at a somewhat earlier time progressed so that the streams had nearly if not quite reached a base-level comparable with that existing at present. A reversal of the cycle resulted in valley filling and the formation of extensive mature colluvial and alluvial surfaces, which were subsequently dissected during the present erosional cycle. It seems likely that collapse structures due to solution during the earlier erosion cycle would be obscured by the valley filling of later date, and it seems further that the earlier solution process would have left relatively insoluble masses to be reworked by solution during the present cycle, with the result that present solution activities would have less conspicuous consequences.

Nevertheless, there appear to be several reasons, as given below, for doubting that recent large-scale solution of the intrusive masses of Paradox formation has occurred.

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[42] Baker, A. A., Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, pp. 72–74, 1933.

If the explanation of solution is valid, subsidence and brecciation must have occurred to explain the intimate admixture of broken fragments observed in the outcrops of the Paradox formation. But the preservation of such normal intrusive relations as are exhibited in the cross section of Fisher Valley (fig. 2) appears impossible if the gypsiferous mass now exposed is a residue from which an originally large proportion of soluble salts has been removed. Even though the beds are locally brecciated, there is no large collapse structure nor even any evidence of slump of broken material from the intruded formations, which would have accompanied any subsidence of the gypsiferous shale and sandstone residue.

In general the brecciation observed within the gypsiferous areas is intense along shear zones and much less so short distances away, in places with abrupt changes in intensity. This suggests brecciation under squeezing stresses rather than collapse into solution voids, although if there were an adequate overlying load the structures developed by either method might be analogous. In Sinbad Valley, Colorado, the gypsiferous series over large areas shows only relatively minor brecciation, and stratigraphic sequences of tens of feet and more are unbroken, though the beds are tilted erratically. These exposures present the appearance of including all the beds ever present in the section. Along the boundaries of the mass, however, are outcrops of much more contorted and brecciated beds, largely of gypsum. These relations suggest that the limestone and shale beds in the center of the valley are actually a capping carried up from below by the pressure of an intruding plastic mass, part of which is still revealed along the margins of the intrusion. The moderate and erratic tilting of large blocks of relatively more rigid strata further suggests the removal of relatively small amounts of the underlying material and consequent collapse. This does not necessarily imply differential solution of the salts, for the bordering gypsiferous phase again offers no evidence of such differential solution. In fact, although no bedded chlorides were observed at the surface, scattered cubical crystals of salt were found in included sandstone layers, in which they were apparently an original constituent.

Furthermore, the relations of the small plugs in lower Cache Valley seem to the writer to show that the gypsiferous material of which they are composed was intruded as such and is not a residue from which more soluble salts have been recently extracted. The strata are domed quaquaversally about each of the masses, and immediately adjoining the masses the strata are sharply tilted by drag. Each mass contains many fragments and chunks of limestone and thin-bedded gray sandstone in all sizes up to slabs several feet in length, presumably derived from the shattering of beds of limestone and sandstone of the Paradox formation. Each mass also contains smaller fragments of brown and red shale like that of the immediately adjacent rocks. Finally and most conclusively, the masses taper toward the ends, and one of them forks at one end, each fork terminating as a veinlike stringer of gypsum.

It appears to the writer, therefore, that the lack of rock salt in the surface exposures of the Paradox formation may be due in part to the original stratigraphic distribution of materials within the formation, the upper part of which consisted largely of shale, limestone, and gypsum, or more probably anhydrite, and the lower part consisted of the same constituents but included also thick beds of halite and minor amounts of potash salts. Under the lateral stress that folded the strata into anticlines the more highly mobile beds of the Paradox formation acted as a partly plastic, partly rigid mass and were squeezed as a paste through the overlying beds along the anticlinal crests. If the difference between the mobility of the upper anhydrite portion and that of the lower halite portion was sufficiently less than the difference between the mobility of the formation as a whole and that of the overlying limestone, sandstones, and conglomerates, then intrusion by the formation as a whole would occur, with the less plastic upper portion brecciated and forced upward above the more plastic lower portion. Some intrusion of the gypsiferous upper portion by the lower salt-bearing portion may have occurred, and it seems probable that a differentiation must have been taking place as a result of which there was a gradual migration upward of the most mobile constituents of the formation, a process which had it been carried to its end must eventually have led to the formation of plugs of relatively pure rock salt. In places, as in Sinbad Valley, it appears probable that the upper shale, sandstone, and limestone portion of the formation possessed a rigidity which caused it to be carried upward with comparatively little brecciation as a capping above more plastic underlying beds, thus developing border contacts which partook more of the nature of steep faults than of intrusive contacts. From the occurrence of purer masses of gypsum along the edge of the Sinbad mass it might be inferred that movement along these faults was aided or accompanied by the squeezing of more plastic material into the zone of most active movement. The mechanism of the intrusion was undoubtedly more complex than has yet been visualized, and the relative importance of differences of plasticity of the various materials during intrusion as compared with differences in solubility of the materials during or subsequent to the intrusion in producing the observed distribution of materials will be correctly evaluated only after more detailed study of the salt and gypsum masses has been made.

PHYSICAL CONDITIONS OF FLOWAGE OF THE SALT IN THE PARADOX FORMATION

The pressure and temperature conditions under which salt flows have been investigated under laboratory conditions by Geller,[43] who determined flow pressures of halite and other minerals at temperatures from 76° to 301° C. The pressures were determined by compressing powdered mineral in a steel cylinder until the mineral coalesced and flowed out at the junction between the steel cylinder and the resistance plate on which the cylinder and powdered mineral rested. Examination of the material after the application of pressure showed that below the pressure at which the compressed material began to escape it was still a powder, but that after the pressure of escape was reached the material was a coherent pastille which in thin section exhibited evidence of plastic flow in the deformed shapes of grains. Van Tuyl [44] has more recently published the results of a laboratory study of flowage of rock salt by compressing, in a steel cylinder, cores from a well drilled on the Paradox salt fold. The flowage point was taken as that at which a removable wire began to bind in a hole of the same diameter, which had been previously bored through the salt. At 20° C. the pressure of flowage was 29,000 pounds to the square inch; at 65° C., 21,000 pounds; at 105° C., 14,600 pounds; and at 155° C., only 11,000 pounds. These flowage pressures were only one-sixth of the pressures obtained by Geller at comparable temperatures. It seems clear that this widely different result is attributable to difference in method, and that the pressure at which slight movement occurs in an already solid block is much less than that at which a powder may be compressed to a coherent solid and then flow. Of the two the lower pressure determined by Van Tuyl would seem to have more geologic significance, although Geller obtained some mathematical and physical verification of the theoretical correctness of his results. Geller observed only very slight differences in the flow pressures when the salt was saturated with water, oil, or petroleum. Van Tuyl records the results of a few experiments with varying time, which showed that the pressures required for flowage were decreased onethird or more by increasing the time of applied pressure to as much as 65 hours. A careful quantitative study of the time-pressure curve would be extremely valuable. It is highly probable that the pressure approaches a minimum value asymptotically and that such experiments would indicate with some accuracy the pressures that

[43] Geller, A., Über das Verhalten verschiedener Minerale der Salzlager bei höhen Drucken und wechselnden Temperaturen: Zeitschr. Kristallographie, Band 60, Heft 5/6, pp. 414–472, 1924.

[44] Van Tuyl, F. M., Contribution to salt-dome problem: Am. Assoc. Petroleum Geologists Bull., vol. 14, no. 8, pp. 1041–1047, 1930.

might be effective with time of geologic duration. To judge from the scattered observations of Van Tuyl, the pressures of long geologic time would be not less than half of the pressures required for deformation in a short time.

In general, laboratory study has not yet reached the degree of completeness of consideration of the time element that would permit safe comparisons to be made with geologic processes. For example, the saturation of Geller's test powders with water showed no appreciable result on the flowage pressures. Long-time tests might show remarkably different results, or the mass movement of salt geologically might occur by crystal gliding, or by minute mylonitization, the effects of which might be largely or completely obscured by subsequent recrystallization.

No adequate studies of the flowage of anhydrite and gypsum have been made. Van Tuyl's preliminary studies show higher pressures than those of halite; and Geller, as might be expected from the high pressures he determined for the flowage of halite, obtained no results on gypsum at temperatures up to 65° C. and pressures up to 40,000 kilograms per square centimeter nor on anhydrite at the same pressures and at temperatures up to 200° C.

A geologic approach to the determination of necessary pressures for flowage has been made by Lees,[45] who studied the low mountains made by the salt cores of south Persian salt domes. Where these are of considerable size the salt flows away in "glaciers." Lees estimates, with a possible error of as much as 50 percent, that the thickness of the load of salt necessary to produce flowage is 1,100 meters. This corresponds with a load of roughly 3,000 pounds to the square inch. As the maximum surface temperature probably does not exceed 50° C. for long periods and as the temperature below the surface is probably less, even with a diathermal substance such as salt, the assumption of a temperature of 50° C. is liberal. The flow pressures estimated by Lees are thus only about one eighth of those obtained by Van Tuyl in the laboratory at comparable temperatures. It seems probable to the writer that part of this difference may be due to additional factors promoting the flowage of salt in "glaciers" on the surface. Harrison [46] has suggested that slipping along clay partings, recrystallization of anhydrite as gypsum, and solution and evaporation of salt are some of these additional factors. However, Baker [47] believes that flowage has occurred in the salt in the vicinity of Cata-

[45] Lees, G. M., Salzgletscher in Persien: Geol. Gesell. Wien Mitt., Band 20, pp. 29–31, 1927; reviewed by Barton, D. C., Am. Assoc. Petroleum Geologists Bull., vol. 14, no. 10, p. 1358, 1930.

[46] Harrison, J. V., The geology of some salt plugs in Laristan: Geol. Soc. London Quart. Jour., vol. 86, no. 344, p. 509, 1930.

[47] Baker, A. A., Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, pp. 79–80, 1933.

ract Canyon under present conditions, where the load is less than 3,000 feet of section. The pressure at which flowage takes place would seem there to be not greatly different from that estimated by Lees, although the temperature may be greater.

For purposes of comparison with the data given above the pressure and temperature prevailing in the Paradox formation at the end of the Carboniferous and at the end of the Cretaceous have been calculated roughly. A reasonably accurate notion of temperature gradients in the upper mile of the earth's crust has been obtained in various places in the United States by Van Orstrand and others. As might be expected, the results differ widely in different localities. In a theoretical discussion of temperatures within the earth's shell to depths of 300 kilometers Adams [48] selected as an average of Van Orstrand's observations of superficial thermal gradient 32° C. per kilometer, which is about 1° F. for 57 feet. A gradient of 1° F. for 60 feet may be accepted as more convenient for use. It is improbable that the superficial thermal gradient at the end of the Cretaceous was greatly different from that of the present time, and this difference is of small importance compared with the local differences of the gradient which exist today and surely also existed at the end of the Cretaceous. The geologic setting of the area makes it probable that the gradient was relatively high, both because of the relatively poor conductivity of the stratigraphic section and because of the proximity of the La Sal Mountains, whether or not their igneous rocks were intruded contemporaneously with or at some time subsequent to the post-Cretaceous folding. It appears probable that long before the actual intrusion of the magma its potential subterranean presence would have been reflected in higher gradients. For this reason an estimate of the thermal gradient of 1° F. for 60 feet to a depth of 7,000 feet seems conservative.

Theoretically the depth-temperature curve should be a curve with the temperature gradient diminishing with depth, but the theoretical curve deduced by Adams [49] shows that at the depths under consideration the departure from a straight-line relation is negligible for the rough approximation here intended. On the assumption that a thickness of 2,500 feet of Carboniferous rocks covered the Paradox formation, the total thickness of overlying beds at the end of the Cretaceous period and before folding was 12,150 feet, including the formations of Carboniferous, Triassic, Jurassic, and Cretaceous age. This would produce a temperature at the top of the Paradox 200° F. higher than the temperature at the surface. On the assumption that the earlier folding and erosion had exposed the Paradox forma-

[48] Adams, L. H., Temperatures at moderate depths within the earth: Washington Acad. Sci. Jour., vol. 14, no. 20, p. 471, 1924.

[49] Idem, p. 468.

tion at the end of the Carboniferous period, then the thickness of beds overlying it at the end of the Cretaceous was 9,650 feet. This would produce a temperature at the top of the Paradox formation roughly 160° F. higher than that at the surface. Brooks[50] has estimated on the basis of elaborate statistical studies of climatic factors that the mean annual temperature during Upper Cretaceous time was 39° F., and that during lower Eocene time it was 48° F. The mean annual temperature at the time of folding may therefore be conservatively taken as 40° F., giving a temperature at the top of the Paradox formation of 340° F. (115° C.) if the Carboniferous section had not been removed before the deposition of the Mesozoic and 200° F. (93° C.) if it had been removed.

To determine the probable approximate pressure upon the Paradox formation, the thickness in feet of sandstone, shale, and limestone in the overlying stratigraphic section was estimated. Sandstone was estimated to have a weight of 150 pounds to the cubic foot, shale 160 pounds, and limestone 170 pounds, and the weight in pounds of a column 1 foot square was computed and then transformed to pressure in pounds to the square inch. If the thickness of Carboniferous rocks above the Paradox was 2,500 feet, the total section amounted to 12,150 feet, and the resulting pressure was roughly 13,000 pounds to the square inch. If earlier folding and erosion had removed the Carboniferous beds above the Paradox before Mesozoic deposition, the thickness of the overlying section was only 9,650 feet, and the pressure before the post-Cretaceous folding was roughly 10,500 pounds to the square inch. At the end of the Carboniferous period the pressure upon the Paradox formation was of the order of 3,000 pounds to the square inch and the temperature perhaps 30° C.

From the figures above given it is evident that the plasticity of the salt in the Paradox formation at the end of the Carboniferous period is probable if the figures of Lees are acceptable. On the other hand, the much higher pressures and temperatures existing at the end of the Cretaceous period would produce flowage in the salt, even if the much higher pressures and temperatures indicated by the laboratory investigations of Van Tuyl as necessary for flowage are more accurate. The influence of the differential pressures under which the rocks were folded cannot be evaluated but would tend to produce plastic flow of the salt under a smaller static load.

GEOLOGIC DATE OF THE INTRUSION OF THE PARADOX FORMATION

The undoubted existence of deformation of at least moderate degree between Permian and Lower Triassic time and between Lower

[50] Brooks, C. E. P., Climate through the ages, p. 233, New York, R. V. Coleman, 1926.

Triassic and Upper Triassic time should be considered in attempting to date the intrusion of the Paradox formation. Local angular discordance of at least 5° between the Cutler and Moenkopi and angular discordance of lesser amount between the Moenkopi and Chinle in the southwestern part of Richardson Amphitheater indicate that there was at least moderate folding at this early time. The angular truncation of the Cutler by Moenkopi and of the Moenkopi by the Chinle toward the Uncompahgre uplift shows that these movements were of considerable magnitude and affected wide areas. In line with this evidence is the angular unconformity between the Dolores and Cutler formations in the San Juan Mountains and the occurrence of faults in the Cutler [51] which did not affect the later beds in the Ouray district of the San Juan Mountains. It remains to be shown whether or not these post-Permian and pre-Jurassic movements were located along the axes of the subsequent post-Cretaceous folds, and if so whether they were of sufficient intensity to produce the transgressive irruption of the Paradox formation into the fold axes or to allow the exposure by erosion of the Paradox formation along the anticlinal crests before the deposition of the Moenkopi or Chinle.

If there were such movements it is desirable to consider the further possibility that part or all of the present anomalous relations of the Paradox formation can be explained on the basis of such pre-Jurassic folding (or irruption) followed by post-Cretaceous folding and faulting during which the Paradox formation behaved normally as part of the stratigraphic section without actual intrusion of overlying beds. Within the area mapped and in the similar anticlines in western Colorado examined by the writer no evidence has been observed that the relations of the Paradox formation can be explained by such post-Permian or Middle Triassic movements. Furthermore, such earlier movements as can be recognized within this area were not directly related to the present anticlinal folds. Prommel and Crum [52] have, however, expressed the belief that five periods of disturbance and erosion prior to post-Cretaceous time can be identified as local impulses on the Colorado River anticlines below Moab and on the Nequoia arch. Baker's study of the Moab anticline [53] has also shown that there has been an increased growth of that fold during successive periods of folding. It is clear that such earlier folding during or after the deposition of the Cutler would result in thinning of the Cutler toward the uplifted areas.

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[51] Burbank, W. S., personal communication.

[52] Prommel, H. W. C., and Crum, H. E., Structural history of parts of southeastern Utah from interpretation of geologic sections: Am. Assoc. Petroleum Geologists Bull., vol. 11, no. 8, p. 818, August 1927.

[53] Baker, A. A., Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, pp. 64–66, 1933.

Similar thinning of the Moenkopi and perhaps of the Chinle might be expected, dependent upon the time at which the folding occurred. Although no unconformity has been recognized between the Cutler and the underlying Rico and Hermosa beds, it is possible that uplift during deposition might be reflected in local thinning of these formations also. Too little is known of them for such possible thinning to be identified. The Rico has not been recognized in the area mapped, and the Hermosa crops out only on the southwest flank of the Onion Creek intrusion of the Paradox formation. The complete thickness here is not known, but it is more than 855 feet and apparently normal. The King No. 1 well, in Salt Valley, penetrated only 550 feet of Hermosa, but there the thickness of the formation away from the anticlinal axis is not known. The section is thin by comparison with the known thickness elsewhere, but this may be due to regional thinning toward the north rather than to thinning over a local anticlinal fold. However, Government potash core test 24, less than half a mile south of the King No. 1 well and somewhat nearer the axis, apparently did not pass through limestones of Hermosa type before reaching the Paradox formation. The absence of the Hermosa in this well might be due to thinning out over the anticline, or it might be due to transgressive movement of the Paradox beds. The Hermosa is not known to crop out in the Paradox Valley anticline, and only a partial and probably short section is exposed in Sinbad Valley. In "the Klondyke," at the south end of Gypsum Valley, San Miguel County, Colo., an incomplete section of the Hermosa was partly measured and partly estimated by the writer to be 1,600 feet thick, which compares favorably with the thicknesses recorded in the San Juan Mountain region.

The great thickness (more than 1,700 feet) of the Cutler exposed immediately adjacent to the Onion Creek intrusion of the Paradox certainly does not accord with a hypothesis of an older anticline at this place. There is, furthermore, a progressive diminution of dip away from the area of most intense deformation, and this diminution is an argument for a single period of deformation at the end of Cretaceous time. If the deformation had been repetitive there would be more of a change in dip at the unconformities in the section. The total thickness of the Cutler is not exposed in Castle Valley, and the relations of the Cutler to the overlying Moenkopi are not sufficiently known to determine definitely whether there has been thinning toward the anticlinal axis. There is, however, a suggestion of such thinning, for dips in the Cutler along the northeast flank are much steeper than in the Moenkopi farther away from the center of the valley. This difference in dip is believed to be due to unconformity. On the other hand, there is apparently a regularly progressive diminution of dip on the southwest side of the valley away from the area of most intense deformation.

On the southwest wall of Castle Valley, south of the area mapped, the Cutler is truncated from northwest to southeast by a component of angular unconformity, and the massive sandstone at the top of the Cutler west of Pace's ranch is apparently cut out toward the east by the unconformity at the base of the Moenkopi and does not appear on the east side of the valley or farther east. The writer's conclusion is that there may be some thinning toward an anticlinal axis but that at present this is quite subordinate to the preponderating truncation of the Cutler from west to east.

The variation in thickness of the Moenkopi is due in large part to the unconformity at the base of the overlying Chinle and reflects local uplift after Moenkopi deposition and subsequent truncation before the Chinle was deposited. This predicated local uplift, however, shows little coincidence with the elongated post-Cretaceous anticlines. The thickest section of Moenkopi within the area mapped is on the north side of the Colorado River just east of the extension of the Cache Valley graben. Here 860 feet of beds are included in the Moenkopi. To the southwest, across the Castle Creek Valley, it thins, but the thinning appears to be regional toward the south. Complete sections of the Moenkopi are not exposed to the southwest and west until the vicinity of Moab is reached, so that possible thickening away from the valley in this direction cannot be detected, but the inference that the thinning across the lower end of Castle Valley is progressive and not toward and away from an anticlinal axis receives some confirmation in the pronounced thinning upstream of the Moenkopi exposed in the southwest wall of Castle Valley. Exposures of the Moenkopi in the vicinity of the Onion Creek anticline are quite adequate to make it certain that there is no appreciable thinning over this fold, although there is progressive thinning across it toward the Uncompahgre Plateau. In Colorado the greatest known thickness of the Moenkopi was measured adjacent to the intrusion of the Paradox formation exposed in Sinbad Valley, suggesting that at or during the time of deposition there was a surface depression on the site of the present anticline. The beds assigned to the Moenkopi in Paradox Valley are only 200 feet thick, but this comparative thinness is almost certainly due to the proximity of the Uncompahgre uplift rather than to thinning over the anticline. Moenkopi beds are not definitely known to crop out in Gypsum Valley or farther south in Colorado. Without analyzing the evidence in detail it may be said that the variations in thickness of the Chinle also exhibit no definite relation to the anticlinal folds.

Although the information available from surface outcrops affords little indication of formation thinning over anticlines coinciding with and antedating the post-Cretaceous folding, the driller's record of the King No. 1 test (in sec. 13, T. 28 S., R. 20 E., on the northeast flank of the Salt Valley anticline) shows an abnormally thin section of only 510 feet between the base of the Wingate sandstone and the "black and gray limes" that must represent the Hermosa formation. There is no basis in the driller's record for separating the Chinle, Moenkopi, and Cutler, but in the cross section C–C′ (pl. 3) 260 feet is taken for the Chinle, 50 feet for the Moenkopi, and the remaining 200 feet for the Cutler. This gives a thickness for the Chinle which may be nearly normal. The Moenkopi is obviously very thin compared with the 860 feet measured near Richardson. This northwestward thinning is believed to be due to the erosional unconformity at the base of the Chinle. Marine fossils identified by G. H. Girty as probably Lower Triassic, and hence Moenkopi, were collected from small isolated outcrops involved with the Paradox formation only a few miles to the southeast in Salt Valley. It does not seem likely that such marine fossils would occur in the Moenkopi where it was less than 100 feet thick when originally deposited, especially in view of the known lithologic character of the Moenkopi where intraformational thinning has been recognized. On the cliff wall west of the Moab-Thompson road north of the Colorado River is exposed a progressive northward truncation of the Moenkopi which cuts it out of the section. The Moenkopi is also rather abruptly truncated southward at the place where the river cuts through the cliff wall. The progressive northward truncation at this place also leads the writer to believe that the thinness of the Moenkopi in the King No. 1 well is due to regional northward truncation rather than to truncation over an isolated uplift on the site of the present Salt Valley anticline. Slight evidence pointing toward the same conclusion is the definite westward bending of the north end of the line of the truncated edge of the Moenkopi and Cutler along the Uncompahgre uplift. Progressive thickening of the Moenkopi to the east away from the King well is shown in the cross section, but no Moenkopi is included in the section west of the King well. Possibly a similar explanation might be advanced for the thin Cutler recorded in the well, but there is much less definite reason to adopt it. The writer believes that uplift in the northern part of the area of the Salt Valley anticline occurred after the deposition of the Cutler; that similar uplift occurred after the deposition of the Moenkopi; that there is no evidence to show whether or not the uplift subsequent to the deposition of the Cutler paralleled the present Salt Valley anticline; and that such evidence as is available points to regional uplift, subsequent to the deposition of the Moenkopi, which did not follow the trend of the present Salt Valley anticline.

To some extent at least the Jurassic formations reflect, by their thinning, regional uplift during their deposition. It is significant that as a group they thin eastward toward the Uncompahgre uplift, in the same direction as that in which the much more pronounced truncation of the Pennsylvanian, Permian, and Lower Triassic occurs. With the facts above set forth in mind it is interesting to observe that the convergence sheets used in the preparation of the contour map showed no thinning over the Salt Valley anticline. There is a slight regional thinning of the Navajo sandstone and perhaps also of the Kayenta formation northeastward, toward the north end of the valley, which accords with the speculation that the thinning of the Permian and Lower Triassic in the King well is due to uplift at or north of the north end of Salt Valley rather than to local thinning across the anticline.

The study of the Colorado River anticlines below Moab [54] has afforded evidence which indicates that recurrent folding took place along the lines of the present anticlines and that the present structure is thus a summation of movements repeated at several different periods. A similar repetitive folding is recorded in the structural arch of the Uncompahgre Plateau, and it seems natural to suppose that repetitions of folding along long established lines of weakness have also occurred within the areas in eastern Utah and western Colorado examined by the writer. Nevertheless, the evidence presented on the preceding pages seems to show that many of these folds were formed along new lines during the deformation at the end of the Cretaceous period and do not augment preexisting folds. Recurrence is not known over the Onion Creek anticline, is at least doubtful over the adjoining Castle Valley anticline, and is not known over the similar anticlines in western Colorado. Although there is some evidence pointing to earlier folding on the northern part of the Salt Valley anticline, nothing has yet been found to show that the present anticline follows the trend of an older fold.

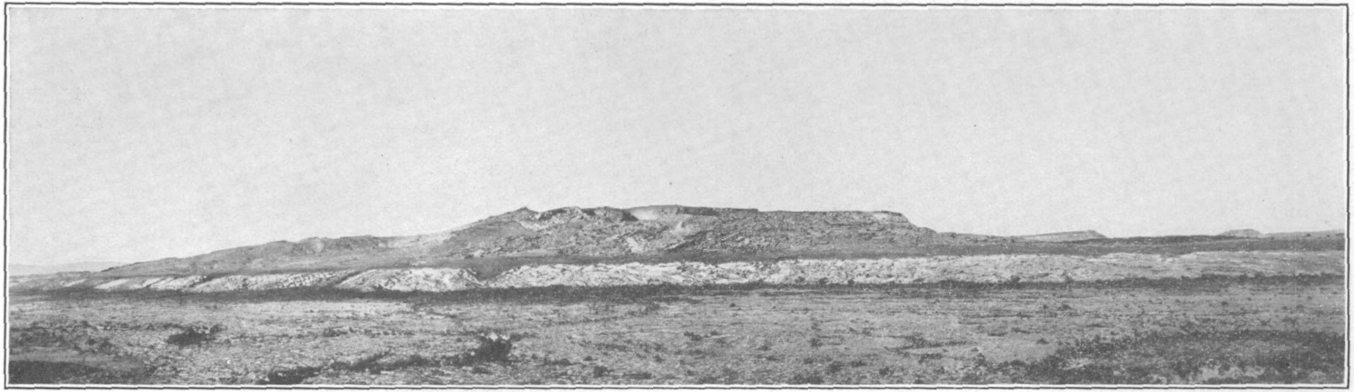
STRUCTURAL HISTORY

The association of the intrusions of the Paradox formation with the more pronounced anticlines over the area known to be underlain by the Paradox is definite and so uniform that a genetic relationship is assured. The association of graben faulting with the other two features is equally striking, and it seems probable that some genetic

[54] Prommel, H. W. C., and Crum, H. E., Structural history of parts of southeastern Utah from interpretation of geologic sections: Am. Assoc. Petroleum Geologists Bull., vol. 11, no. 8, pp. 817–818, August 1927. Baker, A. A., op. cit. (Bull. 841), pp. 65–66.

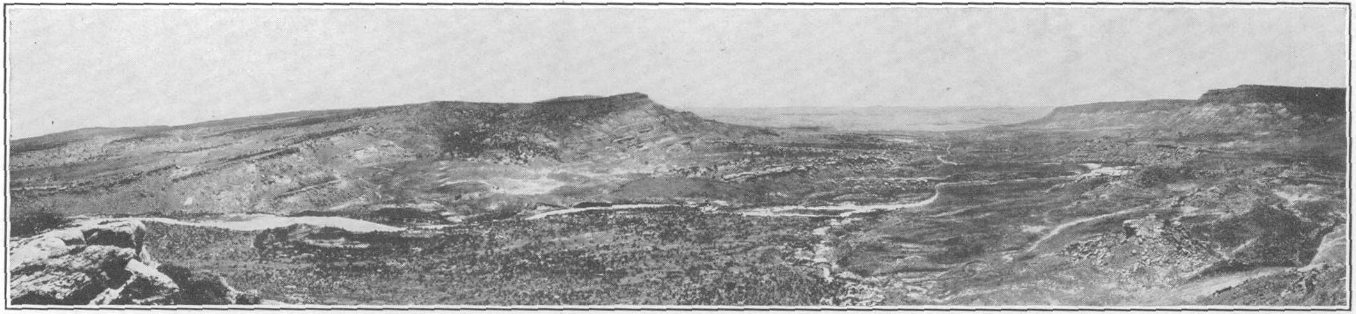
relationship exists here also. If there is such relationship, is the faulting related to the anticlines, to the intrusions, or to both? A partial answer should be given by a comparison of the relations between faulting and folding where the Paradox formation is present with the relations between the faulting and folding exhibited where the Paradox does not form part of the stratigraphic section—as, for example, on the northwest flank of the Uncompahgre Plateau. From plate 19 it is clear that the faults cutting the pre-Cambrian basement rocks along the west flank of the plateau uplift show a parallel relation to the axis of the fold, although in detail they diverge widely from it. By viewing the area east of the Sagers Wash syncline as a unit it is possible to visualize the development of a broad smooth fold on the northwest flank of the Uncompahgre Plateau upon which at a later stage more localized and more intense deformation occurred. But this later deformation must have included faulting as well as folding, for the field relations show that faulting and folding were contemporaneous. It seems much more probable that the whole structure was developed during a single stage of deformation. Within this area the most interesting structural feature is the complex line of faulting which forms the south boundary of the block that has been called for convenience the "Sand Flat graben." This block is a graben only in roughly its western half, because of the fact that the south line of faulting reverses its throw from down on the north in its west half to down on the south in its east half. As may be seen most readily from the structural contour map, this reversal takes place by the overlapping of faults of different direction of throw. Along the strip, several miles in length, where the faults overlap, they are roughly parallel and have opposing throws. Between them lies a structural trench a variable fraction of a mile in width, which on the north side is partly bounded by steep down folds rather than by a fault. The Sand Flat graben is much broader, having a width of several miles, but the boundary faults approach one another toward the west as their throw diminishes. Although the faults die out in the incompetent Mancos shale, a shallow structural depression continues the line of the graben several miles farther west. The existence of these grabens demonstrates conclusively that there were in operation during the post-Cretaceous deformation stresses of a regional nature, which were competent to produce structural trenches by faulting and local intense folding in a rock section of high rigidity and without the presence of the Paradox formation.

The writer is inclined to regard the larger faults in the western and southern parts of the area also as due to the irregular distribution of stress through the crust at the time of the post-Cretaceous defor-



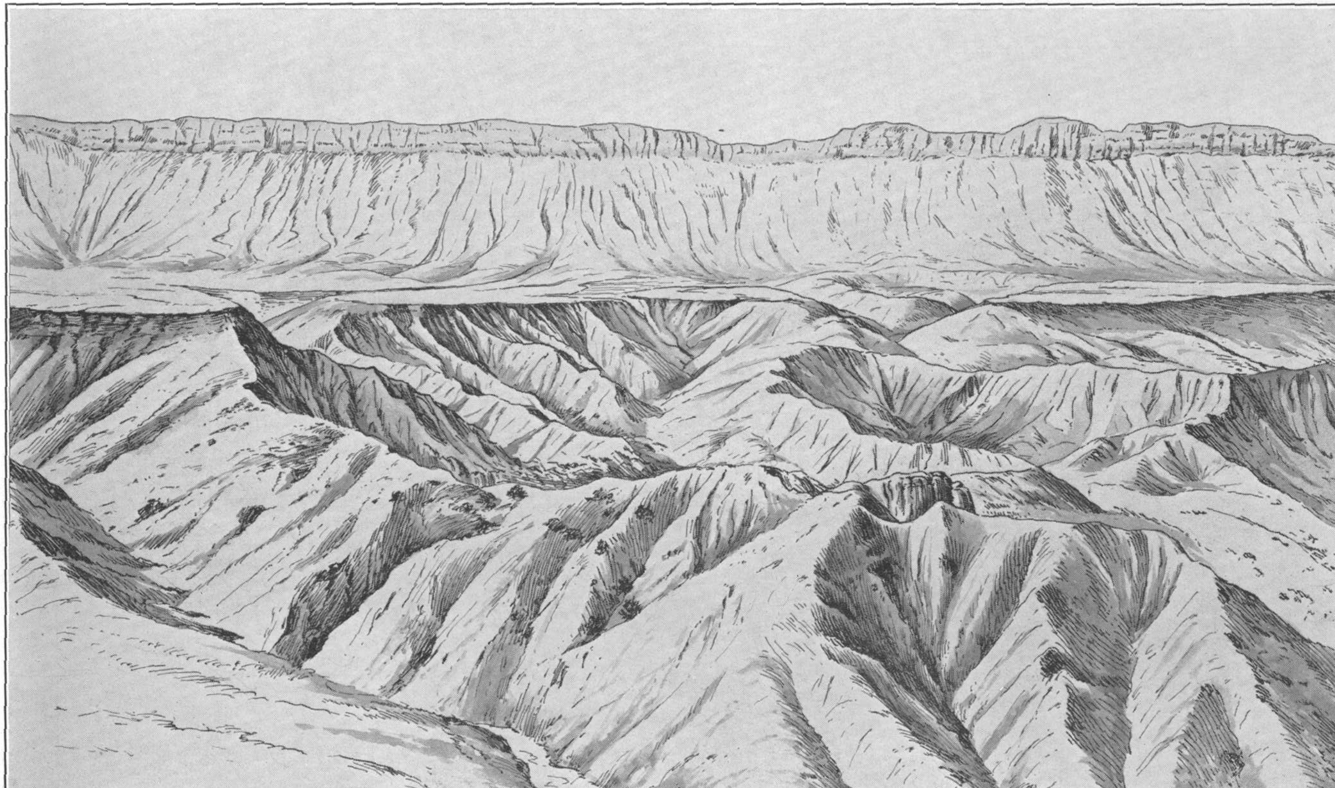
A. ANTICLINAL FOLD OUTLINED BY CUESTA RIDGE OF DAKOTA (?) SANDSTONE.

View looking northeast from a point in sec. 8, T. 21 S., R. 24 E. Flat of Mancos shale in foreground; Morrison formation within the ridge. Photograph by C. E. Erdmann.



B. BITTER CREEK ANTICLINE FROM SE¼ SEC. 1, T. 19 S., R. 25 E.

View looking southeast. Basal Dakota (?) sandstone caps the ridge at right and shows also in left foreground as a ledge capping the dip slope; ledges and slopes of Morrison formation show in Bitter Creek Valley. North end of Pinyon Mesa can be seen in the distance.



ALLUVIAL FILL OF FISHER VALLEY DISSECTED BY DRY WASHES AT THE HEAD OF ONION CREEK.

Wingate sandstone on the skyline, with Chinle, Moenkopi, and Cutler below in the steep slopes of the valley walls.

mation. The larger faults and the large folds would then be approximately contemporaneous responses to this variable stress, the folds possibly having in part been formed slightly earlier. The intrusion of the Paradox formation occurred in response to the same stress and naturally followed the lines of least resistance, which would normally be along the anticlinal crests. In the north Salt Valley area the intrusion appears to have followed the line of one of the large faults, and it is quite possible that the intrusion took place simultaneous with or even after the development of the fault, taking advantage of a plane of weakness to insinuate itself upward. The probable Paradox intrusion beneath the Crescent area seems to be wholly within a graben block, and the two small intrusions in Cache Valley are neither within a graben nor on a major anticline. The lack of a consistent relation between the intrusions and the structure is not surprising. Some of the great numbers of salt plugs in southern Persia [55] are on the crests of anticlinal folds, others are on the plunging ends of folds, some have broken through the sides of domes, and a few are not visibly associated with any major fold.

The minor complex faulting in Salt Valley was in part probably subsequent to the intrusion of the Paradox and a result of abstraction or redistribution underground of the plastic and also soluble material, as a result of which collapse of overlying beds occurred. The writer's conception is that this collapse faulting and the development of circular or oval depression folds occurred shortly after the intrusion and possibly contemporaneously with other intrusion elsewhere, rather than as a wholly subsequent event at a definitely later time.

The anticlines may have been formed on the sites of post-Carboniferous folds, or at least the stresses that formed them may have been distributed or controlled by the position of such older anticlines. The writer believes, however, that within the area he has studied the structure now visible is the result primarily of a deformation which occurred at the end of Cretaceous lime.

GEOMORPHIC HISTORY

The rocks of this area are now undergoing active erosion, and the smaller streams present clear evidence that they are actively degrading their channels, in many places cutting on bedrock. So far as known the Colorado River within the area is cutting on bedrock only in Westwater Canyon, where it crosses the resistant pre-

[55] Harrison, J. V., The geology of some salt plugs in Laristan: Geol. Soc. London Quart. Jour., vol. 86, no. 344, p. 509, 1930.

Cambrian rocks. Many of the smaller intermittent drainage courses, however, enter the Colorado at very steep grades, even as cascades over cliffs. This is also true of the small drainage courses entering the lower part of many of the larger canyons tributary to the Colorado—for example, Salt Wash. This offers some evidence that the Colorado throughout its length in the area is degrading or has until recently been degrading. There is some reason to believe that the active erosion of the present cycle is due to a comparatively recent rejuvenation of the Colorado River as a result of which the channel of the river has been lowered, thus accelerating degradation and headward erosion in the tributary streams, which have not yet been fully recorded in the headwaters of the streams draining from the crest of the Uncompahgre Plateau. The normal valley profile where the streams cut into the pre-Cambrian rock is a steep V-sided trench, above which the softer Chinle shales have been swept back, leaving a broad bench above which in turn rise the cliffs of Wingate sandstone. Near the headwaters of Coach Creek and the Little Dolores River the valley profile has reached only the stage at which the streams have just begun to cut small notches in the hard pre-Cambrian rocks, although the valleys are fully as wide as in the lower parts of the stream courses. The valley cross sections near the Colorado River are thus much farther advanced in the erosional cycle.

At several places in the area there is evidence of a preceding erosion cycle followed by a period during which erosion ceased and extensive valley filling occurred. This preceded the rejuvenation of the Colorado that produced the present erosive activity. The most remarkable evidence of this is the great alluvial fill of Fisher Valley, now being dissected by gullies at the head of Onion Creek (pl. 21). This earlier erosion cycle must have cut almost as deeply into the bedrocks as the present one, to judge from the thickness of alluvial fill in Fisher Valley.

The caliche surface in Cache Valley, which records the final deposit of an aggradational cycle, lies several hundred feet above the present valley floor, at an altitude of about 5,300 feet, and rests in part on bedrock but in part on old talus derived from the valley walls, which are somewhat higher than the level of the caliche surface. The alluvial floor of upper Salt Valley, which lies at a lower altitude (5,000 feet or less), may belong to the same period of aggradation and possibly be the northward-sloping continuation of the surface in lower Cache Valley. The Salt Valley alluvial floor is now being dissected from the southeast by a small tributary of Salt Wash. The Fisher Valley alluvial fill stands at an altitude of more than 5,500 feet, and it seems likely that this also is of the same period.

This preceding erosion cycle was, however, only a minor fluctuation, of which there may have been many during the prolonged erosion that stripped the uppermost Cretaceous and Tertiary beds from the area.

Gravel terraces occur at several levels at various places along the Colorado River. The highest of these terraces is at the Big Hole, in Westwater Canyon, where the gravel stands more than 600 feet above the present river level. They probably represent only a temporary phase of river deposition and are not contemporaneous with the more general alluvial surfaces at higher levels.

The smaller streams of the area are in general controlled by the structure, flowing in the direction of dip slope and forming fault-line valleys. Minor deviations from structural control are common, nevertheless. The larger streams, particularly the Colorado and Dolores Rivers, pursue courses which are apparently uncontrolled by the bedrock structure and which may be inherited from courses developed on a more nearly level Tertiary surface that masked the complexity of the underlying bedrock structure. The Colorado River suggests a general structural control by the manner in which it swings around the northwest end of the Uncompahgre Plateau. It seems improbable that this course is due to successive slip-off on dip slopes, because of the slight slip-off exhibited by the river on the Chinle in Westwater Canyon before it trenched itself in the highly resistant pre-Cambrian rocks. Another possible explanation is a warping of the Tertiary surface due to slight additional vertical movement along the Uncompahgre axis in Tertiary time, for which there is no direct evidence within the area. That at least one important change in the major drainage has occurred is indicated by the remarkable gorge of Unaweep Canyon, transversely crossing the crest of the Uncompahgre Plateau east of Gateway, Colo., and cut deeply in the pre-Cambrian rocks. This gorge is now occupied by small streams flowing east and west from a central divide, but it seems most readily explicable as the deserted channel of a much larger stream. Peale considered it to be most probably an old course of the Gunnison, from which the stream was deflected by the continued uplift of the plateau.[56] As the Dolores River follows in general the regional syncline between the La Sal Mountains and the plateau, it seems probable that the course of this stream was determined by the surface warping that accompanied the post-Cretaceous folding or by Tertiary repetition of such warping. The present course of the Colorado may have been similarly determined at the same time.

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[56] Peale, A. C., Geological report on the Grand River district: U. S. Geol. and Geog. Survey Terr. 9th Ann. Rept., pp. 58–59, 1877.

ECONOMIC GEOLOGY

OIL AND GAS

HISTORY OF DRILLING

The first test for oil and gas in this area was made in 1899 and 1900 by P. D. Jones, of Duluth, at a place about 2 miles south of Whitehouse, on the Denver & Rio Grande Western Railroad. The location of the well has been previously given[57] as sec. 13, T. 22 S., R. 22 E., but the location has been indicated on the map as in the SW¼SE¼SE¼ sec. 6, T. 22 S., R. 23 E. This location is based on the opinion of E. Barton, of the conservation branch of the United States Geological Survey, who visited the site of the well a few years ago.[58] Lupton reported that the well was drilled to a depth of 1,800 feet. No trace of oil or gas but much bad water was encountered. At 1,600 feet water carrying copper in solution is reported to have been struck.

Two tests have been drilled in T. 22 S., R. 20 E., on the northeast flank of the Salt Valley anticline. The Raddatz Syndicate (Hope Syndicate) No. 1, in the NW¼NE¼ sec. 21, T. 22 S., R. 20 E., was drilled to a depth of 1,400 feet from July to December 1925. The Travis, McCormick et al. (E. J. Raddatz) No. 1 was drilled to a depth of 1,450 feet at about the same time and abandoned in January 1926.

The first well drilled on the Salt Valley anticline was the Western Allies (K. Levi), in sec. 5, T. 23 S., R. 20 E. This was drilled to a depth of 825 feet during the fall of 1918 and spring of 1919 and encountered salt and epsomite at a depth of 775 to 825 feet, after first passing through 100 feet of gypsum, lime, and shale and 675 feet of shale and broken lime. A small showing of oil and gas was obtained from the salt at the bottom of the well. In 1931 this well was deepened to 1,258 feet. The Utah Southern Oil Co. drilled a deep test hole (King No. 1), in the SE¼NE¼SE¼ sec. 13, T. 23 S., R. 20 E., which was spudded in May 27, 1928, and completed October 23, 1929. This hole was abandoned at 3,829 feet, owing to the parting of casing and a cave in black shale. The log of the well follows:

Log of Utah Southern Oil Co.'s King No. 1 well

	Feet
Kayenta and Wingate formations:	
Red shale	30
Brown sandstone	380
Sandstone	505
Fine white sandstone	510

[57] Lupton, C. T., Oil and gas near Green River, Grand County, Utah: U. S. Geol. Survey Bull. 541, p. 118, 1914.

[58] Larsen, R. M., personal communication.

	Feet
Chinle, Moenkopi, and Cutler formations:	
Hard red shale	530
Shale, mostly red	610
Red rock	645
Red rock and shale	675
Red rock and hard shells	705
Red shale	725
Sand	740
Red rock and shells	755
Hard red rock	775
Fine red rock	795
Red rock	835
Red rock and shell	855
Red rock and shell	950
Red rock (oil show)	995
Red rock	1,020
Hermosa formation:	
Gray lime	1,060
Black lime	1,105
Black and gray lime	1,125
Black lime	1,155
Gray lime	1,175
Black lime	1,185
Gray lime	1,295
Broken black lime	1,325
Gray lime	1,340
Broken gray lime	1,365
Gray lime	1,430
Broken gray lime	1,450
Black lime; salt water at 1,478–1,480 feet	1,500
Gray lime	1,570
Paradox formation:	
Salt and lime	1,640
Lime	1,652
Salt	2,170
Salt; lime streaks	2,180
Shale and lime	2,200
Gray lime	2,270
Black lime	2,280
Black lime and shale	2,290
Gray lime	2,315
Salt and lime	2,360
Salt	2,780
Shale break	2,785
Broken shale, lime	2,810
Salt	2,915
Broken lime and shale	2,965
Broken gray lime	3,001
Salt	3,569
Gray lime	3,615
Limy shale	3,620
Lime	3,630
Lime and shale	3,650

	Feet
Paradox formation—Continued.	
Gray lime	3,680
Salt	3,765
Heaving black shale, mud and conglomerate, and lime breaks	3,810
Black shale, cave	3,829

United States Government potash core test 24, in the southeast corner of sec. 13, T. 23 S., R. 20 E., less than half a mile south of the King No. 1 well, was completed in October 1931 at a total depth of 1,731 feet. Samples from this well were examined by R. K. Bailey, of the Geological Survey. The following log of the well has been summarized and correlated by the writer from Mr. Bailey's descriptions.

Log of Government potash core test 24

	Feet
Kayenta formation:	
Sand, red and white, fine, calcareous	25
Sand and clay, red, fine to coarse, calcareous	30
Wingate sandstone:	
Sand, white and red, fine, calcareous	145
Sand, red and white, fine, calcareous; trace of gypsum	170
Missing	175
Dolomite, gray, slightly limy and clayey; some sand, white	190
Sand, red and white, fine, calcareous	345
Chinle shale:	
Missing	360
Sand, red and white; trace of red and gray clay	375
Sand, red and white, fine; some red clay, calcareous	445
Clay, red, some gray, sandy, fine, calcareous	455
Sand, red and white, fine; some clay, red, calcareous	495
Sand, red and white, fine; trace of red clay, calcareous; some white claylike material	500
Missing	510
Sand, red and white, fine; trace of red clay, calcareous; some white claylike material	520
Sand, red and white, fine; some clay, red, calcareous	610
Moenkopi (?) and Cutler formations:	
Sand, red and white, very fine; 30 to 40 percent of clay, red and gray; trace of calcareous material	625
Sand, white, some red, fine to very coarse; some clay, red, calcareous	645
Sand, white and red, fine; trace of red clay, calcareous; trace of mica	675
Sand, white and red, fine to coarse; some red clay	750
Sand, red and white, fine; trace of red clay; trace of mica	780
Sand, red and white, fine; 0 to 50 percent of clay, red and gray; trace to 20 percent of gypsum from 795 to 805 feet; trace of mica in a few beds	845
Sand, red and white, fine; trace of red and gray clay; trace of mica	910

Paradox formation:	Feet
Sand, white, some red; 50 percent of clay, black, some red; some gypsum, calcareous	915
Sand, white, some red, fine; 10 to 80 percent of clay, black, dark gray; trace to 10 percent of gypsum	985
Gypsum, sand, and clay	990
Clay, gray and dark gray; sand, white and red, fine; and gypsum	1,030
Clay, black and gray, trace of red; 10 to 20 percent of gypsum, 10 to 30 percent of sand, white, fine, calcareous	1,110
Sand, red and white, fine; 20 to 50 percent of gypsum; some clay, red and gray, calcareous	1,130
Missing	1,145
Gypsum; sand, red and white, fine; clay, red and gray, calcareous	1,160

The first salt was encountered at 1,160 feet. The core record of the lower part of the well is given under the heading "Gypsum, salt, and potash" on page 175.

The Utah Southern Oil Co.'s Balsley No. 1, in the center of the NE¼NE¼ sec. 31, T. 23 S., R. 21 E., in the southern part of Salt Valley, was reported in the Inland Oil Index for January 1, 1932, as drilling below 5,100 feet in salt. This well encountered showings of oil at 3,397, 3,415, and 3,432 feet. About 300 barrels of light green oil at 37° Baumé gravity were recovered in a 2-day bailing test, and the well was estimated to be good for 15 barrels daily.[59] Drilling was subsequently resumed, but in November 1932 drilling was stopped in black shale and salt at a depth of 6,120 feet.[60]

The Crescent Eagle Oil Co. started drilling some time in 1920 in the SE¼SW¼SE¼ sec. 4, T. 22 S., R. 19 E., and continued intermittently until October 1925, when the hole was bottomed at 4,009 feet. Several showings of oil and gas were found in the Mancos shale and the Dakota (?) sandstone. In July 1922, from an iron-stained sandy lime at a depth of 1,981 feet, a strong flow of salt water was encountered with high-gravity oil with or just below the water. Drilling was continued, and from 2,060 to 2,130 feet of beds logged as rock salt were penetrated. Below the rock salt an estimated gas flow of 5,000,000 cubic feet a day was encountered. The gas was very moist, with a high gasoline content. On September 1, 1924, a gas, oil, and water blowout from a depth of 3,205 feet blew oil and water 40 feet over the top of the derrick. In March 1925, at 3,911 feet another blowout occurred, and during a subsequent 6-hour test it was reported to have run 960 barrels of salt water and 60 barrels of oil. A month later it was apparently making mostly salt water with a trace of oil. The hole was eventually bottomed at 4,009 feet, still

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[59] Oil and Gas Jour., July 2, 1932, p. 44.
[60] Idem, Nov. 24, 1932, p. 62.

making a little gas and oil through water. In February 1927 there was still a small flow of light-green oil.

The almost complete log of this well follows:

Log of Crescent Eagle Oil Co.'s well

	Feet
Surface wash	54
Mancos shale:	
Blue shale; sulphur water at 200 feet	200
Gray-blue shale	260
Dark-blue shale	325
Hard gray lime	327
Blue lime shale	329
Hard blue-gray lime	350
Blue to brown shale	417
Blue lime shale	420
Blue shale; salt water at 487 feet	487
Dark-gray sandy shale; showing of gas	500
Black shale; particles of calcite	533
Gray to black lime shale	545
Black shale; salt water at 570 feet	570
Blue to gray sandy lime shale	582
Light-gray to brown sandy shale	585
Drab sandy lime	595
Bluish-gray sandy shale	600
Hard gray lime	645
Hard black lime or lime shale	674
Dark-gray lime, shale; some clayish material resembling bentonite	757
Light-gray lime shale with clayish material	760
Black lime shale	780
Black sandy shale; showing of oil and gas	787
Blue to black shale	818
Black lime shale; salt water; gas and oil colors	824
Light-gray shale; showing of oil and gas	869
Dark-gray lime shale; showing of oil and gas	874
Light-gray sandy lime	888
Hard sandstone; showing of oil	890
Sandy lime, very hard; showing of oil	900
Gray sandy shale; showing of oil	903
Light-gray shale	1, 142
Black lime, showing good gas conditions	1, 147
Light-gray shale	1, 177
Dark-blue shale	1, 217
Gray lime shale	1, 250
Gray shale	1, 395
Drab shale with varying lime content	1, 630
Light-gray lime shale; oil and gas	1, 670
Blue shale	1, 690
Light-gray shale	1, 755
Blue shale	1, 808

	Feet
Dakota (?) sandstone:	
Hard drab sandstone	1,811
Sand; showing of oil	1,814
Hard shelly sandstone	1,829
Morrison formation:	
Hard greenish-blue shale	1,843
Greenish-gray shale, soft and cavey	1,875
Iron-stained sandy material, coarse-grained	1,878
Light-green shale	1,895
Light-gray lime shale	1,910
Light-green shale	1,965
Paradox formation:	
Iron-stained sandy lime; heavy salt water at 1,981 feet; very strong showing of high-grade gravity oil with or just below water	1,981
Fine-grained iron-stained sand	1,982
Fine-grained gray sand; oil and gas	1,984
Hard white sand	1,988
Gray iron-stained fine-grained sand	2,003
Gray to white sand	2,007
Fine-grained rusty sand	2,013
Black to brown lime shale	2,022
Dark-brown sandy shale	2,060
Rock salt	2,130
Sand measure producing an estimated wet-gas flow of 5,000,000 cubic feet	2,132
Salt rock	2,155
Black sandy shale	2,160
Conglomerate	2,190
Black shale	2,200
Dark-gray to black shale	2,325
Salt and black shale	2,470
Black shale	2,495
Black shale and salt	3,015
Black shale; oil and gas	3,130
Gray banded shales and sand; oil and gas	3,205
Gray sandy shales; oil and gas	3,225
Brown sandy shale	3,325
Black shale	3,345
Shale and salt	3,420
Gas, sand	3,475
Sandy shale; oil, gas, and water	3,660
Sand	3,680
Sand	3,700
Shale	3,708
Sand	3,730
Salt shale and sand	3,900
Sand; oil, gas, and water	3,911
Very hard sand	3,948
Very hard sand	3,962
Very hard sandy lime formation	3,972

It appears probable that the Dakota (?) sandstone was penetrated from 1,808 to 1,829 feet and that the green shales reported to 1,965 feet are the upper part of the Morrison formation. The iron-stained sandy lime with heavy salt water and light oil, cut from 1,965 to 1,981 feet, may be a sand in the Morrison, but it seems most probable that this bed represents a sand at the top of the Paradox formation and that from 1,965 feet to the bottom the hole was drilled through this formation.

The Crescent Oil Syndicate spudded in a test (McCarthy No. 1) in the SW¼SW¼ sec. 27, T. 21 S., R. 19 E., in January 1925, which was drilling at 2,200 feet on March 28, 1930.

A validating hole of the Utah Oil & Refining Co. was drilled 80 feet in the SW¼ sec. 10, T. 21 S., R. 19 E., during July 1924.

The Armstrong Co. drilled a well in the southeast corner of sec. 9, T. 22 S., R. 19 E., from September 1926 to March 1927. This test reported a saturated oil sand from 1,210 to 1,217 feet but no production. This sand may have been in the Dakota (?) sandstone. The test was abandoned at 1,220 feet.

The Big Six Oil Co. commenced drilling Randall No. 1, in the SE¼NE¼SE¼ sec. 10, T. 22 S., R. 19 E., June 26, 1928, and suspended in October 1928, at a depth of 1,710 feet. The correlated log of this well is as follows:

Log of Big Six Oil Co.'s Randall No. 1 well

	Feet
Surface wash: Shale and gravel	40
Mancos shale:	
Shale, blue; bailer of water per hour at 110 feet	200
Hard limy shale; 12½-inch casing cemented at 165 feet	215
Blue shale	240
Dakota (?) sandstone:	
Shale and sand; some sulphur, gas, and water	265
Sand	280
Morrison and Summerville formations:	
Shale	300
Lime shell	305
Shale	315
Conglomerate	320
Blue lime shell	335
Conglomerate	340
Purple shale and hard shells	395
Gray sand	410
Blue shale	420
Gray sand	430
Gray shale	435
Red shale	458
Sand, gray; some petroleum, gas, and water, which rose 400 feet	460
Shale	490
Red shale; 502 feet of 10-inch casing	580

Morrison and Summerville formations—Continued.	Feet
Hard shell	583
Shale	670
Sand; salt, sulphur, water	690
Red shale	750
White sand; showing of oil	795
Red shale; some lime	850
Limy shale	870
Blue and red shale	900
Red shale	1,000
Entrada sandstone and Carmel formation:	
White sand; 880 feet of water in hole	1,075
Red sand, hard; 895 feet of water in hole	1,125
Pink limy sand; acid consumes one third of sample	1,345
Red shale	1,352
Pink limy sand	1,425
Navajo sandstone:	
Red sand and conglomerate; 1,200 feet of water in hole	1,470
Pink limy sand. Hole caved and bit lost	1,710

The Brendell Oil & Gas Co.'s No. 1, in the NW¼NE¼NE¼ sec. 9, T. 22 S., R. 19 E., was drilled only 100 feet in September 1928, but in December 1928 it was reported that drilling would resume. In August 1932 this well had reached a depth of more than 3,400 feet.[61]

Several shallow wells have been drilled on the South Cisco anticline. Information on these wells has been obtained from several of the trade journals and from records of the Geological Survey but is somewhat confusing and contradictory. The Arizona Utah Oil & Gas Co. started operations in this vicinity in October 1921. Its No. 1 well, in the SE¼ sec. 13, T. 21 S., R. 23 E., reported oil shows from 464 to 741 feet and was drilled to a depth of 1,000 feet, at which operations were suspended in November 1923. The same company's No. 2 was drilled 50 feet from No. 1 to obtain fuel for drilling No. 1. This well is reported to have struck 500,000 cubic feet of gas at a depth of 557 or 585 feet. It was abandoned at a depth of 645 feet. The No. 1 well, also known as Cisco Oil & Refining Co.'s Booth No. 1, was late in 1926 deepened to 1,242 feet before abandonment. A sample from a depth of 1,045 feet seen at the well by the writer was red shale, probably from the Morrison formation, and another sample from 1,240 feet was light-colored fine-grained sandstone, probably from the lower part of the Morrison but possibly from the Entrada sandstone.

Two other shallow holes were drilled in the SE¼ sec. 13—the Cisco Oil & Refining Co.'s Booth No. 2 or Arizona Utah Gas & Oil No. 3, abandoned at 535 or 553 feet in August 1923 but reported to have shown 500,000 cubic feet of gas, and the Cisco Oil & Refining

[61] Oil and Gas Jour., Aug. 25, 1932, p. 73.

Co.'s Bevo No. 1, 175 feet east of Booth No. 1, which reported a show of oil at 482 feet, drilled in July to September 1926 and abandoned at 575 feet. Three wells were drilled during the same period in sec. 24. The Arizona Utah Gas & Oil Co.'s No. 4, or Cisco Oil Refining Co.'s No. 1, in December 1923 penetrated an oil-bearing sand from 552 to 556 feet, and it was reported that the well would produce from 1 to 10 barrels a day and that it might have been a commercial producer except for water interference. In January 1927 it was said that heavy black oil was being bailed from this well at the rate of a barrel a week, and it is reported that oil may still be bailed from the well. The hole was abandoned at about 570 feet. Arizona Utah No. 5, or Cisco Oil Refining Co.'s No. 2, 400 feet north of No. 4, in the early part of 1924 was a dry hole abandoned at 550 or 590 feet. Arizona Utah No. 6, or Cisco Oil Refining Co.'s No. 3, drilled somewhat later in 1924, was a dry hole abandoned at 550 feet but reporting oil shows at 360 feet. The Peerless Oil Co., of Grand Junction, Colo., drilled a shallow well in the NE¼NW¼ sec. 25, T. 21 S., R. 23 E., in July and August 1924 and reported shows of oil and gas from the Dakota (?) sandstone at 390 feet. The hole was abandoned at 631 feet. Logs are not available from any of these wells, but it is evident that the oil shows and small gas production were obtained from various parts of the Dakota (?) and probably also from sandstone or conglomerate beds in the upper part of the Morrison.

The Utah Southern Oil Co. commenced drilling its State No. 1 on February 11, 1930, in the SE¼ sec. 26, T. 21 S., R. 23 E. The log of this well is as follows:

Log of Utah Southern Oil Co.'s State No. 1 well

	Feet
Mancos shale:	
Blue shale	20
Blue shale	133
Shell	137
Blue shale	150
Gray sandy shale	175
Gray shale	195
Blue shale	210
Gray shale	230
Soft gray shale	263
Gray sandy shale	270
Gray shale	275
Blue shale	278
Black shale	280
Gray shale	380
Dakota (?) sandstone:	
Gray sandy shale; quite a lot of sand and cuts close	390
Gray shale, sandy	410
Very hard shell	411

	Feet
Dakota (?) sandstone—Continued.	
Hard sand and shale	420
Hard sand	425
Sand with shells	440
Sand with little water	450
Morrison formation:	
Grayish-green shale	460
Green shale	480
Green shale with lime shells	490
Sand and conglomerate	495
Green shale	510
Hard lime shell	514
Lime and shale	515
Gray shale	530
Gray lime	535
Lime shell	539
Gray shale	541
Lime and green shale	544
Gray shale	545
Gray lime; hole makes 5 bailers of water in 12 hours from base of Dakota sandstone, 450 feet	550
Green shale with lime shells	562
Red shale	580
Red shale, caving badly	583
Variegated shale	592
Red and blue shale	605
Variegated shale	620
Mixed shales, showing some sand	630
Variegated shale with lime shells	650
Red shale, hole caving	675
Lime shell	678
Variegated shale	690
Brown shale, with water from above practically exhausted	710
Variegated shale	715
Brown shale	730
Variegated shale	735
Brown shale	755
Hard sharp sand; small showing of black oil at 760 feet	762
Brown shale	768
Lime shell	769
Brown shale	775
Brown shale; set 12½-inch pipe at 792 feet	792
Gray shale	815
Shell	816
Gray shale	819
Gray lime and sand	825
Gray sandy lime	830
Brown and green shale mixed	850
Brown shale	858
Gray sandy lime, hard	863
Brown shale	888
Sandy lime shell	889
Blue shale	898

	Feet
Morrison formation—Continued.	
Gray sand; small showing of black oil at 900 feet	905
Gray sand; carried water	921
Fine white sand	932
Gray sand	958
Sandy lime	963
Sandy lime with thin streaks of brown shale	973
Gray sandy shale	980
Sandy lime	984
Sand; showing of oil and gas; hole caving, and water within 200 feet of floor	992
Sandy shale	1,004
Sand and variegated shale	1,012
Sticky red and blue shale	1,017
Variegated shale	1,032
Red shale	1,043
Variegated shale	1,065
Red and blue shale	1,069
Variegated shale	1,128
Sandy lime	1,132
Summerville formation:	
Sticky shale	1,139
Lime shell	1,142
Red shale	1,153
Variegated shale	1,162
Entrada sandstone:	
Hard shell	1,163
Fine light-gray sand; showing of black oil. Sand seemed to be well saturated with oil from 1,163 to 1,195 feet, less from 1,195 to 1,200 feet, but did not come into hole very much. Tools covered with oil after pulling out through hole full of water	1,200
White sand, carrying water, which rose to top of hole	1,228
White sand	1,380
Sand and shale, pink	1,390
Sand	1,455
Pink shale	1,457
Navajo sandstone:	
Sand	1,475
Pink sandy shale	1,490
Sand	1,503
Kayenta formation:	
Red shale	1,525
Sand	1,529
Variegated shale	1,532
Red sandy shale	1,541
Variegated shale	1,543
Sand	1,544
Red shale	1,561
Sand	1,562
Red shale	1,584
Red sand	1,586
Red sandy shale	1,590
Red shale	1,603

	Feet
Kayenta formation—Continued.	
Red sandy shale	1,639
Sticky shale	1,644
Ran core barrel; showed streaks of variegated shale and sand	1,650
Hard pink sand; ran casing at 1,653 feet	1,665
Hard red sand	1,684
Gray sand	1,729
Wingate sandstone:	
Pink sand	1,795
Hard gray sand	1,797
Fine gray sand	1,916
Chalky sand, very sticky	1,959
Fine sand; hole showed water at 1,982 feet	1,998
Chalky sand	2,025
Coarse sand, showing a few pieces of variegated shale	2,034
Fine chalky sand	2,058
Sand streaked with red rock	2,064
Limy sand	2,085
Chinle formation:	
Red rock	2,100
Soft red shale	2,106
Red rock	2,155
Red sticky shale	2,160
Red beds	2,265
Sticky conglomerate shale	2,281
Variegated conglomerate shale; hole caving badly	2,291
Variegated conglomerate; ran casing at 2,291 feet	2,297
Pre-Cambrian: Granite	2,431

Two wells have been drilled on the Harley anticline, which trends northwest in the northern part of T. 19 S., R. 25 E., and extends into the next township on the north. The Home Oil Co. or H. H. Bashor No. 1 well, 1,300 feet south of the north line and 954 feet west of the east line of sec. 4, T. 19 S., R. 25 E., was spudded in May 25, 1925, and completed September 15, 1925, at a total depth of 802 feet. This well reported 250,000 cubic feet of gas from 488 to 518 feet and 4,000,000 cubic feet from 538 to 584 feet. The Tom McGuire et al. or Home Oil Co. No. 2 (now known as "Weightman-Fallgren No. 1"), 1,532 feet south of the north line and 725 feet west of the east line of sec. 4, T. 19 S., R. 25 E., was spudded in April 9, 1926, and completed May 3, 1926, at a total depth of 1,675 feet, with 250,000 cubic feet of gas reported from 564 to 581 feet and 5,000,000 cubic feet of gas reported from 860 to 945 feet. Both wells were started at or near the top of the Dakota(?) sandstone. The No. 1 well probably stopped at or near the base of the Morrison, but the Weightman-Fallgren well penetrated into the Wingate and probably nearly reached the underlying Chinle shales. The driller's logs and a correlation of them are given below.

Log of Home Oil Co. or H. H. Bashor No. 1 well

	Feet
Dakota (?) sandstone:	
Conglomerate	48
Shale, coal blossom	74
Coal	78
Clay shale	104
Hard sand	162
Morrison formation:	
Shale	211
Lime	221
Bentonites	278
Sandstone	291
Bentonites	488
Sand, brown; 250,000 cubic feet of gas	518
Shale, red	538
Sandstone, hard and soft, in layers; 4,000 000 cubic feet of gas	584
Shale, red	604
Sand, oil-colored	692
Sand and shale; salt water at 670 to 758 feet	757
Shale, red	771
Sandstone	802

Log of Tom McGuire et al. or Home Oil Co. No. 2 well (Weightman-Fallgren No. 1)

	Feet
Dakota (?) sandstone:	
Conglomerate	38
Sand	70
Coal	75
Lime	78
Coal	80
Hard lime	90
Shale	95
Hard sand	102
Morrison formation:	
Shale	105
Sand and lime	135
Shale	145
Lime	148
Lime and bentonite	200
Sand	218
Red sand	230
Gray shale	247
Hard sand	250
Sand	270
Hard sand	285
Red rock	297
Hard shale	300
Gray shale	325
Red rock	340
Gray shale	348
Red rock	395
Red shale	415

Morrison formation—Continued.	Feet
Soft sand	420
Hard sand	423
Red rock	448
Gray shale	465
Red shale	520
White sand	525
Blue shale	537
Sandy lime	545
Gray shale	556
Hard lime	558
Shale	564
Sand; 250,000 cubic feet of gas	581
Red rock	617
Sand	622
Red rock	642
Lime and red shale	665
Hard shale	670
Gray shale	685
Hard shale	688
Sand	697
Gray shale and lime	766
Hard lime	773
Bentonite	777
Hard sand	795
Summerville formation:	
Red lime	845
Lime	858
Hard lime	860
Entrada sandstone:	
Sand; 5,000,000 cubic feet gas	945
Pack sand	1,148
Kayenta formation:	
Hard shale	1,153
Red rock and sand; water at 1,145–1,350 feet	1,220
Red rock	1,350
Wingate sandstone:	
Brown sand	1,612
Dark-brown sand	1,675

On June 7 or 8, 1929, the H. H. Bashor No. 1 well, sec. 4, T. 19 S., R. 25 E., was visited by Messrs. Swedenborg and Barton, of the United States Geological Survey. The volume of gas flowing from the well was found to be 390,000 cubic feet, and the gravity 0.64. The gasoline content was determined by measuring a quantity of the gas as it flowed from the well by an Oberfell meter through charcoal and subsequent distillation in the Geological Survey laboratory at Midwest, Wyo. The metered gas was corrected to the volume the gas would occupy at a temperature of 60° F. and a pressure of 15.025 pounds to the square inch. The condensed gasoline (those vapors that condense in a bath of 32° F.) amounted to 0.055 gallon of gasoline to 1,000 cubic feet of gas. The absorbed

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gasoline (those vapors that do not condense in the bath but are absorbed in naphtha) amounted to 0.007 gallon of gasoline to 1,000 cubic feet of gas. The total gasoline in the gas (the volume of condensed gasoline plus the increase in the volume of the naphtha in the absorber (amounted to 0.062 gallon to 1,000 cubic feet or gas. On Sept. 5, 1930, C. C. Anderson, of the United States Bureau of Mines, obtained a closed-in pressure test of 26 pounds to the square inch. In May 1931 the flow from this well was estimated by E. W. Henderson, of the United States Geological Survey, to be from 50,000 to 75,000 cubic feet a day.

A sample of the gas from this well analyzed in the laboratories of the Bureau of Mines showed the following:

Carbon dioxide	0.26
Oxygen	.20
Methane	51.30
Ethane	2.27
Nitrogen and helium, by difference	45.97
	100.00
Helium content	2.25

At the No. 2 well (Weightman-Fallgren No. 1), in September 1931, J. D. Cerkel, of the United States Geological Survey, obtained an open-flow test, after correcting for the gravity of the gas, of 1,820,000 cubic feet a day and a closed-in pressure test of 157 pounds to the square inch. An analysis of the gas from 860 to 945 feet in this well, made in the laboratories of the Bureau of Mines, is as follows:

Carbon dioxide	1.1
Oxygen	.0
Methane	5.1
Ethane	2.3
Nitrogen and helium, by difference	91.5
	100.00
Helium content	7.02

A small area on the crest of the Harley anticline, partly in T. 18 S., R. 25 E. (unsurveyed), and partly in T. 19 S., R. 25 E., was set aside as Helium Reserve No. 2 by Executive order dated June 26, 1932, on the basis of the above analyses and detailed structural mapping of the crest of the anticline by C. E. Dobbin, of the United States Geological Survey. (See p. 134.)

OIL AND GAS POSSIBILITIES

The drilling done thus far has failed to obtain commercial production, and the showings of oil and gas encountered have not been sufficient to warrant optimism for the results of further drilling. On the other hand, the showings demonstrate that oil and gas are not completely lacking in the region, and as the drilling now completed has not exhaustively tested it, there still remains some possibility of commercial production.

Among the important factors to be considered in judging the oil possibilities of a region are the existence of suitable source beds or the demonstration of the presence of oil or gas in some amounts, the disposition of the strata into suitable structural forms to trap and retain accumulations of oil, the arrangement of the strata into such alternations of pervious and impervious beds that oil may be accumulated in the more porous layers sealed off by less pervious beds, and the presence of circulating underground water to facilitate migration and collection of the oil. The Cutler formation, the Triassic beds, and the entire Jurassic section of the region are apparently devoid of any source beds from which oil might be derived. The known source beds are thus confined to the Upper Cretaceous and the Carboniferous Hermosa and Paradox formations. As the exploration already made has found oil either in the Dakota(?) or in association with the Hermosa and Paradox, it is clear that further exploration should be directed to testing these formations. Gas showings have been obtained from beds in the Morrison and at the top of the Entrada, but the lenticular nature of the Morrison sands reduces the probability that any commercial production of gas will be obtained in them. The Dakota(?) has given indications of containing small amounts of oil on the South Cisco anticline, but within the area mapped it lies at shallow depth beneath the Mancos shale and is nowhere so folded that large accumulations may be expected. The Carboniferous formations are therefore a more probable source of production. These rocks were either not deposited or have been removed by erosion in the eastern part of the area, northeast of a line that is perhaps roughly coincident with the axis of the Sagers Wash syncline. The resinous shale found at one locality in the Paradox formation contained minute globules of free oil, and the pure black shales of the formation probably also contain considerable organic matter. No oil seeps in the region are known to the writer, but oil seeps have been reported in Fisher Valley.[62] The structure associated with the intrusions of the Paradox formation is complex and is probably not wholly revealed by the surface exposures. Nevertheless, there may be uptilted reservoir beds along the flanks of the intrusions appropriately disposed to serve as collecting reservoirs. The King No. 1 well, in sec. 13, T. 23 S., R. 20 E., although not closely adjacent to a Paradox intrusion, appears to have been located on an anticline but obtained only small showings. A possible site for drilling adjacent to the Paradox intrusion in southern Salt Valley is the probable

[62] Hill, J. M., Notes on the northern La Sal Mountains, Grand County, Utah: U. S. Geol. Survey Bull. 530, p. 118, 1913.

anticlinal area in the NE¼ sec. 36, T. 23 S., R. 20 E. The flanks of the two small domes around Paradox intrusions in the east end of Cache Valley might possibly contain some trapped oil. The two domal areas in the Cutler formation just north of the area of Paradox intrusion along the Onion Creek anticline are other possible drilling sites. In view of the general failure to obtain commercial production from wells already drilled in the Moab district, prospects are not encouraging, but the history of drilling the salt domes of the Gulf coastal region shows that many unsuccessful wells may be drilled before oil in commercial amounts is discovered even in areas that are now highly productive. In the Crescent area encouraging showings have been struck, but as the surface geology in that area is poorly exposed and probably not closely indicative of the underground structure, further exploration will be largely haphazard.

In the Yellow Cat dome only a small closure is shown by the surface rocks, but it is not unlikely that a more pronounced anticline in the Carboniferous rocks underlies this area. In the structure sections (pl. 3) the thickness of the Carboniferous rocks has been inferred from their known thickness on the outcrop elsewhere, with a resultant diminution in magnitude of the anticline at depth. This is the more conservative interpretation, but the possibility of an underlying anticlinal fold with more steeply sloping limbs and greater closure should also be considered.

It is possible that wells might be drilled through the squeezed intrusive cores of Paradox formation into underlying more competent beds. It is further likely that these underlying beds would be folded into more gentle and regular anticlines without the intense squeezing and complex faulting that has accompanied the intrusion of the Paradox and affected all overlying beds. These hypothetical more regular anticlines, so far as known, should parallel in a general way the structure revealed at the surface. The drilling depths at which rocks below the Paradox should be encountered can scarcely be predicted, but the General Petroleum Co.'s Wilcox No. 2 well, in Paradox Valley, Colo., started in the Paradox formation at the surface and was abandoned at 6,300 feet without, so far as known, having cut through the formation, even at that depth. The Utah Southern Balsley No. 1 well, in sec. 31, T. 23 S., R. 21 E., in Salt Valley, had not cut through salt and black shale, believed to be part of the Paradox formation, at a depth of 6,120 feet, as reported in November 1932.

The nature of the underlying rocks is also uncertain, but it seems likely that limestone equivalent in lithology and age to the Madison or Leadville might be expected. The Madison limestone has been productive at a few localities in Wyoming and Montana, but beds of equivalent age are not known to be petroliferous in Colorado.

GYPSUM, SALT, AND POTASH

The exposures of the Paradox formation in Salt Valley and on Onion Creek contain many beds and less regular masses of gypsum, and common salt has been shown to be present at slight depths. The exploitation of these mineral resources in competition with more regularly bedded and advantageously situated deposits elsewhere seems unlikely. Of greater interest is the occurrence of soluble potash salts within the formation. The occurrence of these salts was first reported from the Crescent Eagle well, in T. 22 S., R. 19 E.[63] Since these salts were described cores of the Paradox formation from the King No. 1 well, in Salt Valley, have been examined in the laboratory of the United States Geological Survey, and contents of potash as high as 13 percent have been found.

A Government test well for potash was started in July 1931 and completed in October 1931, at a total depth of 1,731 feet, in the southeast corner of sec. 13, T. 23 S., R. 20 E. The first salt was encountered at a depth of 1,160 feet. A log of the core is given below.

Log of core from United States Government potash test 24

	Thickness		Depth	
	Feet	Inches	Feet	Inches
Salt; few polyhalite blebs	14		1,192	
Clear salt	14		1,206	
Salt; gypsum seams	13		1,219	
Salt; shale breaks	7		1,226	
Clear salt	7	6	1,233	6
Broken salt	16	6	1,250	
Dirty salt	6		1,256	
Salt; some shale	1	2	1,257	2
Shale		6	1,257	8
Dirty salt	3	4	1,261	
Shale		6	1,261	6
Dirty salt	5		1,266	6
Clear salt	14	6	1,281	
Salt; some shale and polyhalite	10		1,291	
Clear salt	14	6	1,305	6
Salt; shale streaks	5		1,310	6
Clear salt	44	6	1,355	
Salt	24	6	1,379	6
Salt and shale	5		1,384	6
Clear salt	47	6	1,432	
Salt	16		1,448	
Salt; polyhalite blebs	1		1,449	
Salt	8	9	1,457	9
Salt	25	3	1,483	
Clear salt	23		1,506	
Salt	49		1,555	
Salt; anhydrite bands	3		1,558	
Clear salt	46		1,604	
Clear salt; anhydrite blebs	24	6	1,628	6
Clear salt	4		1,632	6
Salt; shale breaks	1		1,633	6
Clear salt	48	6	1,682	
Salt; shale breaks	8		1,690	
Salt	12		1,702	
Clear salt	29		1,731	

[63] Lang, W. B., Potash investigations in 1924: U. S. Geol. Survey Bull. 785, pp. 38–39, 1926.

Several shallow test holes have been put down by Babcock & Armstrong. No. 1 A, in the SE¼SW¼ sec. 32, T. 23 S., R. 21 E., was completed in September 1929 at a depth of 559 feet. No. 1 B, only a few feet from No. 1 A, was completed in March 1931 at a depth of 906 feet. No. 2, in the NW¼SW¼ sec. 32, T. 23 S., R. 21 E., was completed in July 1930 at a depth of 945 feet. No. 7, in the NE¼ SE¼ sec. 31, T. 23 S., R. 21 E., was started in October 1930 and reached a depth of at least 216 feet. The existence of potash salts in the Paradox formation is well established, but in view of the probable severe contortion and brecciation of the beds, the possibility of commercial exploitation is somewhat dubious.

URANIUM AND VANADIUM ORES

The occurrence of ores of uranium and vanadium in the Mesozoic sediments of eastern Utah and western Colorado has been known since 1898. Several prospects in the broken area of Wingate sandstone in Richardson Amphitheater were operated in 1903 and 1904, and the occurrence of ore and history of development are described by Boutwell.[64] In the San Rafael Swell and elsewhere in Utah similar ores in the Shinarump conglomerate and the Morrison formation have been exploited. In western Colorado vanadium and uranium ores are found principally in the lower part of the Morrison formation.

In the area mapped attempts have been made to develop deposits of uranium and vanadium ore in the sandstones of the lower part of the Morrison formation at two localities. In the NW¼ sec. 6, T. 23 S., R. 22 E. (unsurveyed), the Uvanco mine, locally called the Yellow Jacket mine, exploited ores from the Salt Wash sandstone member of the Morrison formation. This operation consisted of a large number of "gopher holes" 5 or 6 feet deep and a few tunnels some tens of feet long. These workings are scattered over an area of half a square mile. Most of them are located at the base of sandstone beds, although a few are at the top of sandstones. The sandstone beds of the Salt Wash member of the Morrison formation are 10 to 20 feet thick at this place and consist of white to faintly yellow fine-grained quartz sand. Although discontinuous, they are not as markedly lenticular as the sandstones and conglomerates in the upper part of the Morrison. The ore occurs as streaks of black sandstone parallel to the bedding and less commonly along fractures or joints. The streaks or lenses are for the most part only a few inches thick and from 2 to 20 feet in length. The richest ores are reported to have been found in silicified wood. The mine is about 8 miles by

[64] Boutwell, J. M., Vanadium and uranium in southeastern Utah: U. S. Geol. Survey Bull. 260, pp. 200–210, 1905.

automobile from a point on United States Highway No. 50 near Sagers, on the Denver & Rio Grande Western Railroad.

The most extensive operations within the area were those of the Keystone Metals Reduction Co. on Polar Mesa, in the SE¼ T. 24 S., R. 25 E. (unsurveyed), and the NE¼ T. 25 S., R. 25 E. Polar Mesa is a roughly oval elevation 5 miles long and at most 2½ miles wide, with the long axis trending between north and northeast. It is encircled by a cliff of Entrada sandstone, known to the prospectors in this region as the "slick rim." The south base of the mesa can be reached by automobile from Castleton, about 15 miles distant, but the road is difficult to traverse, even for an experienced driver under favorable weather conditions. A road was built up the south end of the mesa while operations were in progress but is now impassable. Castleton is about 30 miles from the Denver & Rio Grande Western Railroad at Cisco by a county road. The sandstone ledges of the lower Morrison are more conspicuous, thicker, and more regular than farther west. Sandstone also is more abundant in the upper part of the formation than at the more westerly outcrops, and the Salt Wash sandstone member cannot be differentiated.

The main mining operations were carried on at the west side of the mesa near the rim, on two slightly overlapping claims, the Elva M. No. 1 and No. 2. These claims are patented, and the plats are on file at the Salt Lake land office. The "discovery shaft", Imp No. 1, is a small "gopher hole" 30 by 50 feet excavated in soft sandstone down to the surface of a harder mass of sandstone, apparently an aggregate of irregular lenses. This harder sandstone contains silicified stem and branch fragments, and there are beds of carbonaceous plant fragments half an inch to an inch thick at the base of some of the lenses. Little "ore" is exposed at this place. The Imp No. 2 working is a tunnel 100 feet long with an angle bend to the south for an estimated distance of 50 feet farther. At the opening red shale and gray clay are exposed beneath a hard sandstone roof, which continues to the end of the workings. The tunnel is apparently mostly in sandstone at the end. Two other openings south 200 feet along the rim from these are apparently the latest workings—one a "gopher hole" and the other a 50-foot tunnel. Above these workings on the rim are the Imp No. 3 and Imp No. 4 shafts. Imp No. 3 is a timbered and lined shaft estimated to be 100 feet deep; Imp No. 4 is larger and estimated to be 150 feet deep.

There is a considerable amount of "ore" in the dumps of these shafts. Carbonaceous shales and sandstones are present, and some of the ore appears to be a replacement of these carbonaceous beds. In other specimens the yellow carnotite and a dark greenish gray mineral are spotted through apparently clean sandstone. Other workings are on the south and east sides of the mesa, usually at the base of sandstone layers.

The ore was hand-sorted at the workings. At the tunnel workings it was sacked in cement bags and probably packed by mule to the mill. From the shafts it may have been hauled by wagon to the mill at the north camp, at the head of the road from Castleton. Here it was again hand-sorted on a platform, and uranium and vanadium ores separated. The treatment consisted of breaking in a small jaw crusher, pulverizing in an inclined stamp mill, and gravity and centrifugal (?) settling in air by a system of blowers and large galvanized-iron settling containers. Arrangement was made for re-treating material that was not up to the standard on the first treatment. The product was packed on mules about 10 miles to a subcamp, 5 miles southeast of Dewey, at the end of a wagon or auto road connecting with the county road to Cisco. Dewey is roughly 12 miles from Cisco and the railroad.

The lack of water on the mesa was a serious difficulty. Two small earth tanks provided water for stock. Drinking water was packed up from springs below the mesa on both the east and west sides—an adequate but inconvenient supply. It is possible that some water may have been hauled by wagon from Beaver Creek, a distance of perhaps 6 miles. The company operated a small sawmill, using the yellow pine timber on top of the mesa for construction work and timbering. The date of mining operations is not known, but a sheriff's sale of several claims on Polar Mesa was held at Moab on November 15, 1926.

The discontinuous nature of the ore bodies makes prospecting economically impossible except along the outcropping ledges of sandstones which encircles the mesa. It is quite likely that ore bodies similar to those which have been exploited could be found by careful search, but it is obvious that mining conditions are so unsatisfactory that profitable exploitation is dubious.

Prospecting of similar ore was begun in July 1929 by a Mr. Adams east of Polar Mesa, across Beaver Creek Canyon. This area is reached by car or wagon from Castleton or by horse from Gateway, Colo., which is roughly 30 miles from the Denver & Rio Grande Western Railroad at Whitewater. Ore would have to be packed from these prospects at least down the south wall of Gateway Amphitheater, which is about 2,000 feet high, or, as an alternative, hauled over the Castleton-Cisco route.

OTHER METALLIC MINERALS

A little more than 6 miles southeast of Dewey a small fault strikes N. 58° E. and dips 75°–80° NW. The maximum throw on this fault is not over 8 feet. It cuts the lower Morrison sandstones, which are brecciated in some places along it. A small silver prospect has been developed on the brecciated and mineralized portions. The location of the prospect is shown on plate 1. The ore consists of veinlets of calcite, barite, bornite, and chalcocite, with malachite bordering the seams and abundant malachite and azurite stains in the sandstone adjacent to the seams. Native silver was not seen in place, but specimens of native silver collected by C. A. Scharf, who now owns the prospect, were seen. The native silver occurs in a black salty material, which is probably silver chloride. There are perhaps 100 feet of shallow workings. Since owning the prospect Mr. Scharf has shipped four or five sacks of hand-picked ore.

The gravel of the Colorado River below Dewey was dredged on a small scale and placered for native gold in parts of 1927 and 1928, but the amount of gold recovered is not known to the writer.

The pre-Cambrian granite is cut by numerous quartz and pegmatite dikes, and some of these are mineralized and have been prospected. Few of these were examined. The Prince Albert No. 4 claim is on the north side of Ryan Creek, 1½ miles east of Cow Creek. Here the ore is found in a pegmatite dike. The conspicuous ore minerals present are chalcopyrite, chrysocolla, and azurite, in a gangue of fluorite, calcite, and the quartz and feldspar of the dike. About 1,000 feet east of this prospect is another known as the Sure Shot mining claim, similarly situated in a pegmatite dike.

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