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GEOLOGY OF THE MUDDY MOUNTAINS NEVADA

WITH A SECTION THROUGH THE VIRGIN RANGE TO THE GRAND WASH CLIFFS, ARIZONA

BY

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GEOLOGY OF THE MUDDY MOUNTAINS, NEVADA

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INTRODUCTION

LOCATION OF THE AREA

The Muddy Mountains are in the eastern part of Clark County, Nev., north of the "Great Bend" in Colorado River. On the east the range is separated by Virgin River from the Virgin Mountains, which extend into Mohave County, Ariz. The area covered by the present report crosses both ranges and the Grand Wash Cliffs, farther east. Its greatest length is 52 miles and runs east and west. Its extent is approximately 1,000 square miles, and more than 85 per cent of it lies in Nevada, in the St. Thomas quadrangle. Grand Wash and the Grand Wash Cliffs are in the western part of the Mount Trumbull quadrangle, in Arizona. Both these quadrangles are covered by reconnaissance topographic maps of the United States Geological Survey.

The Los Angeles & Salt Lake Railroad, a part of the Union Pacific system, traverses the valley west of the Muddy Mountains. A branch of this road runs from Moapa down Muddy Creek Valley to St. Thomas, a distance of 21 miles, passing Logandale, Overton, and Kaolin. These four small communities are the only settlements in the area mapped. Bunkerville, Mesquite, and Littlefield are small settlements in Virgin River Valley north and west of the Virgin Mountains.

NATURE AND PURPOSE OF THE REPORT

The region in southeastern Nevada and northwestern Arizona which includes the Virgin and Muddy Mountains has more than one strong appeal to the geologist. It is practically unmapped and hence has the lure of the unknown. The pioneer scientists who traversed the plateau and Great Basin regions gave only passing notice to these ranges, and the difficulties presented by climate, by the scarcity of settlements, and by the lack of satisfactory base maps have discouraged later efforts, so that a large area still presents opportunities for scientific exploration. Moreover, the location of the region near the boundary between the Basin Ranges and the plateau province gives it a critical interest, because the stratigraphic, structural, and physiographic relations of basin to plateau must be deter-

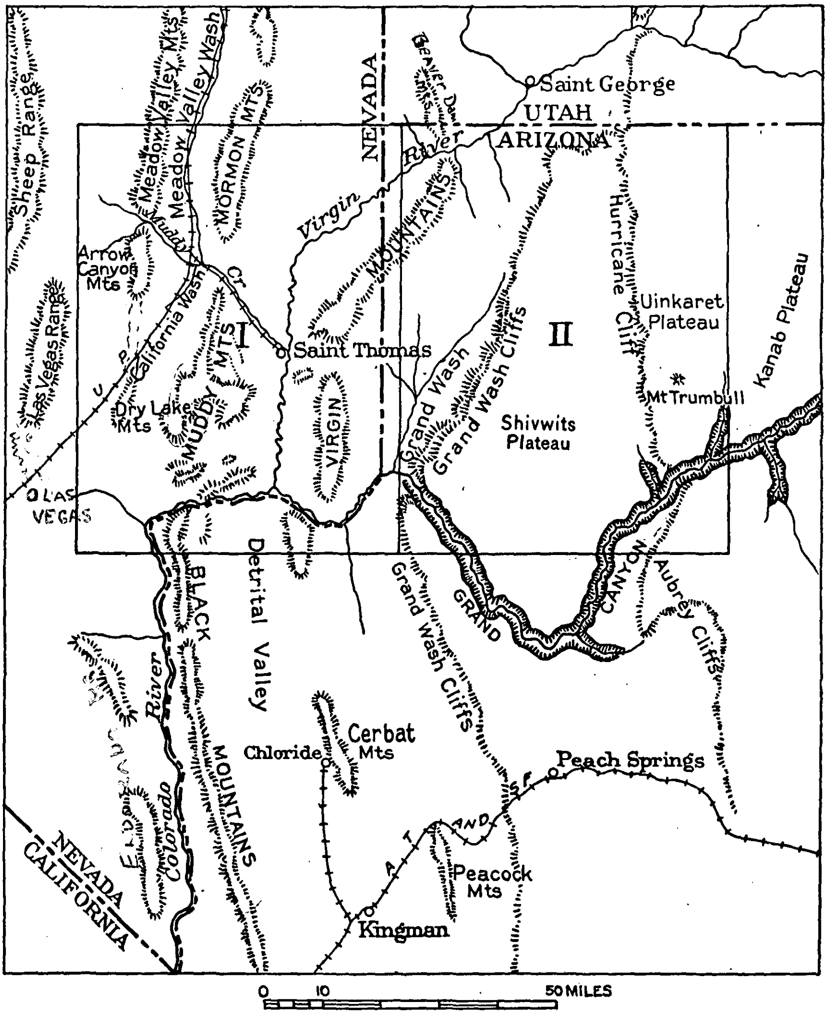

FIGURE 1.—Index map showing the position and relations of the Muddy Mountains. I, St. Thomas quadrangle; II, Mount Trumbull quadrangle

mined largely by a study of this border zone. Are the rocks west of the Grand Wash Cliffs fundamentally different from those on the east? What is the nature and what the age of structure lines dividing the two provinces? To what extent does the physiography of the region help in unraveling the more recent geologic history? These questions concern matters that are not only of interest in themselves but also fundamental in the larger problems touching the origin and development of the plateau, the eastern portion of the Great Basin, and the Colorado River system.

The present report is largely descriptive, aiming to picture with as much detail as possible the rock formations, the major structure, and the most conspicuous surface forms found in the Muddy Mountains and a small part of the Virgin Mountains and in parts of associated valleys. The maps accompanying the report are not accurate, because the present base maps covering the region are of a reconnaissance nature and do not permit exact representation of areal geology or of topographic expression. In general, however, rock formations and structure lines are shown in the correct positions and in proper relation. The Muddy Mountains were selected for the most thorough study, because they are far enough west of the plateaus to reveal differences in stratigraphy if they exist. Results determined in this area are supplemented by a section to the Grand Wash Cliffs, which connects a typical portion of the Basin and Range country with the western edge of the plateau and furnishes a basis for comparison of rock formations. Fundamental interpretations and correlations, however, can not be completed until a larger area has been studied; the best results will of course follow detailed mapping, which in turn must await the preparation of suitable topographic base maps.

FIELD WORK

The greater part of the field work on which this report is based was done in the summer and fall of 1919. The original intention was to cover the entire Muddy Mountains and the northern part of the Black Mountains, an area bounded on the north by Muddy Creek, on the east by the lower part of Virgin River, on the south by Colorado River and Las Vegas Wash, and on the west by California Wash. After four months of work, however, it was decided that study of a section across the Virgin Mountains and Grand Wash would be more profitable than completion of the survey to Colorado River, inasmuch as the essential rock formations and structure of the Muddy Mountains had already been determined. Accordingly three weeks was spent making a reconnaissance of an area extending about 5 miles on each side of the road from St. Thomas to the Bronze-L mine.

In preparing the areal map the present topographic base was of assistance in a general way only, because both the altitudes and the horizontal locations represented on it are at best only approximate and in many places are highly inaccurate. Bench marks established in the Muddy and Virgin Valleys during the winter of 1918–19 by the United States Reclamation Service were of value as starting points for traverse lines. The old Arrowhead automobile road was mapped partly by plane table and partly by compass, from

St. Thomas to California Wash, and furnished convenient tie points. Other control points were located by plane table and alidade, and from these locations pace and compass traverses were run to determine formation boundaries. A few altitudes were determined by the alidade, but for the most part approximations were obtained with aneroid and hand level. The southern part of the area was mapped less satisfactorily than the northern part because short time and the difficulties of the work made it impossible to determine many locations accurately. The country is very rugged, water is scarce, and settlements are confined to Muddy Creek Valley. East of St. Thomas practically all locations on the base map were accepted. Many stratigraphic sections in all parts of the area were measured with the tape or with the hand level and some by pacing. In the summer of 1924 certain points in the area were revisited briefly and some additional data were obtained.

PREVIOUS WORK

Several of the older surveys touched the Virgin and Muddy Mountains, but the chief purposes of those expeditions did not concern this region, and the literature contains very short notes on both ranges. The Whipple party in 1854 passed south of the region, crossing the Colorado in the vicinity of Needles. In 1858 Lieut. J. C. Ives ascended the Colorado to the mouth of Las Vegas Wash, which he thought was Virgin River.[1] In 1869 Lieut. George M. Wheeler went from the mouth of Virgin River down the Colorado as far as El Dorado Canyon, but no detailed account of his trip is available.[2] In 1871 Wheeler ascended Colorado River from Camp Mohave to Diamond Creek, in the Grand Canyon, taking with him as geologist G. K. Gilbert, who made a brief report on the rocks found in Boulder, Virgin, and Iceberg Canyons and at the mouth of the Grand Canyon.[3] In the same year A. R. Marvine, the geologist with another party of the Wheeler Survey, traversed Grand Wash throughout its length and made notes on the geology of that valley, of the Virgin Mountains, and of the Grand Wash Cliffs.[4] Wheeler[5] mentions a traverse made in 1872 from the foot of Grand Wash to the mouth of Virgin River, but no details of the journey and its results have been published. Dutton[6] makes brief mention of the Grand Wash Cliffs and valley in his description of the plateaus and the Grand Canyon.

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[1] Ives, J. C., Report upon the Colorado River of the West, p. 87, 1861.
[2] Wheeler, G. M., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 1, p. 155, 1889.
[3] Idem, vol. 3, pp. 35, 162–163, 185, 1875.
[4] Idem, vol. 3, pp. 193–198, 1875.
[5] Idem, vol. 1, p. 155, 1889.
[6] Dutton, C. E., Tertiary history of the Grand Canyon district: U. S. Geol. Survey Mon. 2, p. 12, 1882; The physical geography of the Grand Canyon district: U. S. Geol. Survey Second Ann. Rept., p. 126, 1882.

In 1903 Spurr[7] summarized all available geologic data concerning the Muddy and Virgin Mountains, giving as the only addition after the old surveys mentioned some observations made by R. B. Rowe on exposures immediately south of Muddy Creek. Nothing further had been published on the region when field work was undertaken for the present report. Work of a reconnaissance nature has been done in neighboring regions by Ball,[8] Lee,[9] and Hill.[10]

Brief papers based on certain phases of the work have been published by the present writer.[11]

ACKNOWLEDGMENTS

The writer wishes to acknowledge his indebtedness to the Dana Research Fund of Yale University, which made possible the field work for this report. Acknowledgment is also due to the United States Geological Survey, which furnished surveying instruments and field equipment, although the writer was not then a regular employee of that organization. Mr. Harold S. Cave, at that time a graduate student in the University of Missouri, spent several weeks in the field and gave valuable assistance. During the preparation of the report, which was first submitted as a thesis in the Graduate School of Yale University, continued interest and advice from Profs. Charles Schuchert and H. E. Gregory were of especial assistance. Other members of the faculty also gave helpful suggestions.

GEOGRAPHY

SURFACE FORMS AND DRAINAGE

TOPOGRAPHY OF THE ST. THOMAS QUADRANGLE

With the commanding Grand Wash Cliffs as his viewpoint, Dutton looked westward and wrote:

> This [Grand Wash] fault is the boundary of the Grand Canyon district and of the plateau country itself. The region beyond is a sierra country with the same characteristics as the Great Basin of Nevada and western Utah.[12]

An observer stationed high in the Muddy Mountains realizes the truth of this statement with peculiar force. Forty miles directly to the east the Grand Wash Cliffs stand clearly defined, the sky line

[7] Spurr, J. E., Descriptive geology of Nevada south of the fortieth parallel and adjacent portions of California: U. S. Geol. Survey Bull. 208, pp. 131-133, 136-138, 1903.

[8] Ball, S. H., A geologic reconnaissance in southwestern Nevada and eastern California: U. S. Geol. Survey Bull. 308, 1907.

[9] Lee, W. T., Geologic reconnaissance of a part of western Arizona: U. S. Geol. Survey Bull. 352, 1908.

[10] Hill, J. M., The Grand Gulch mining region, Mohave County, Ariz.: U. S. Geol. Survey Bull. 580, 1915.

[11] 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, pp. 39-62, 1921; The Muddy Mountain overthrust in southeastern Nevada: Jour. Geology, vol. 30, pp. 63-72, 1922.

[12] Dutton, C. E., U. S. Geol. Survey Second Ann. Rept., p. 126, 1882.

and the edges of strata drawn as straight as ruled lines on a blackboard. Elsewhere uniformity is absent. If the observer looks in other directions he sees successive ranges and valleys forming a broken, complex country of many units. Each range has a distinct individuality, which is clearly shown in its surface form.

A description of any unit in this "sierra country" must include both range and intermontane valley, for each range is inclosed by broad valleys, as a picture is set in a frame. On the east the Muddy Mountains are bounded by the Virgin Valley, which with its dissected terraces is 10 miles or more wide. The river flood plain is broad and flat and has an average altitude above sea level of about 1,000 feet. The old terraces, now eroded to various levels, rise several hundred feet higher. On the south the Muddy Mountains are separated from the Black Mountains by two large washes, the Bitter Spring and the Callville. The divide between these valleys reaches an altitude of about 2,500 feet. Bitter Spring Wash, in an open valley several miles wide, descends to Virgin River at slightly less than 1,000 feet above sea level, whereas Callville Wash, with a more abrupt descent and narrower valley, reaches the Colorado at about 700 feet. The western boundary of the Muddy Mountains is the right fork of California Wash, a great trough 8 to 10 miles in width, its floor formed by long slopes of waste from both sides. From an altitude of 2,800 feet at its head this valley extends northward 30 miles, joining Muddy Creek at 1,600 feet above the sea. From this point Muddy Valley extends southeastward to Virgin River, completing the isolation of the Muddy Mountains.

Farther afield mountain units of naked rock rise on every side. Immediately to the north is the southern limit of the Mormon Mountains, a broad mass of dark limestone carved into prominent rugged peaks and ridges. Beginning 4 or 5 miles north of Muddy Creek, as a narrow chain of hills which rise about 2,500 feet above sea level, this range increases in width and height until it averages 10 miles wide and 4,000 feet in altitude. Several peaks exceed 6,000 feet. The highest altitude in the range, 7,500 feet, is attained by Mormon Peak, 20 miles north of Muddy Valley. In the Virgin Mountains this height is slightly exceeded by Virgin Peak, 16 miles northeast of St. Thomas. In this range limestone strata dip steeply southeast and form many asymmetric peaks leaning northwestward on the mass locally known as Bunkerville Mountain. Between this mass and the Mormon Mountains stretches Mormon Mesa, a nearly even surface more than 15 miles wide. From a distance much of it appears as level and smooth as a sheltered lake.

Directly east of St. Thomas the continuity of the Virgin Mountains is broken by a low gap through which the Grand Wash Cliffs are visible from the Muddy Valley. The gap has a north-south width of 5 to 8 miles, and within it the summit of the divide is only 2,300 feet above sea level, though scattered hills near by rise several hundred feet higher. For this pass the name St. Thomas Gap is proposed. South of it the range continues to Colorado River as a series of ridges and peaks which reach a maximum altitude of about 5,000 feet.

About 20 miles south of St. Thomas the Black Mountains rise abruptly, from the wide Bitter Spring Valley. This comparatively low range, with sharp peaks and serrate ridges carved from dark igneous rock, extends southwestward beyond Colorado River, which has cut through it in Boulder Canyon. The highest peaks have an altitude of more than 3,000 feet. On the north and west, adjacent to Bitter Spring Valley, these mountains include some of the rock formations that are common in the Muddy Mountains.

At 7 or 8 miles west of the Muddy Mountains the low Dry Lake Mountains separate the two forks of California Wash. This range is only a few miles in length, and the highest points reach little above 3,000 feet. From the surface of the broad, waste-filled California Wash it appears merely as a chain of low hills. In a direct prolongation northward are the more imposing Arrow Canyon Mountains, which in turn are continued north of Muddy Valley in the Meadow Valley Mountains, 10 miles west of the Mormon Mountains. Still farther west, beyond the limit of the St. Thomas quadrangle, Las Vegas Range, Sheep Mountain, Spring Mountain, and other high north-south ranges bound the view.

TOPOGRAPHY OF THE MUDDY MOUNTAINS

Northern division.—The Muddy Mountains consist of a high nuclear mass, from which low ridges and hills extend to the north and to the southwest, giving a total length of more than 30 miles. The maximum width is 13 miles, exclusive of associated fans, terraces, and intermontane valleys. Including these features the Muddy Mountain area considered in the present report has a maximum width of 22 miles and covers about 600 square miles. (See pl. 1.)

The greatest width of the mountains proper is at the north side of the high nucleus, immediately south of the old Arrowhead automobile road. Here a high and abrupt mountain wall, extending from east to west and fronting northward, divides the mountain area topographically, structurally, and stratigraphically. From many high points immediately south of this dividing line a comprehensive view of the entire range may be obtained. An observer stationed on one of these points in turning from south to north is conscious of a distinct change, expressed in lower general altitude, in different structure lines and surface forms, and even in the changed colors of the dominant rocks.

The principal elements in the topography of the northern division are the following, in succession from west to east:

1. A waste-covered surface sloping gently westward into California Wash.
2. Twin ridges of dark limestone nearly 2 miles apart, extending nearly south from Muddy Creek.
3. A continuous L-shaped valley, from 1 mile to 2½ miles wide, paralleling the limestone ridges to the dividing mountain rampart, then turning eastward and following the steep wall to its eastern limit. This feature is known as the Valley of Fire.
4. An extremely rugged and picturesque area of dissected red sandstone, the highest points reaching 500 feet above the Valley of Fire. This area parallels the L-shaped valley and has a maximum width of 3 miles.
5. An area 2 to 3 miles wide of rounded hills and hogback ridges.
6. A belt 1 to 4 miles in width made up of remnants of even surfaces separated by clay badlands. The even surfaces descend in steps toward Muddy Creek and Virgin River.
7. The present valleys of Muddy Creek and Virgin River.

In this northern division of the Muddy Mountains the highest parts are the twin ridges near the west side, which will be referred to as Weiser Ridge and California Ridge. California Ridge begins abruptly south of Muddy Creek, but the creek cuts through Weiser Ridge in a narrow gorge, north of which a chain of isolated limestone hills extends toward the Mormon Range. The ridges are nearly equal in general altitude, rising 300 to 600 feet above the adjacent valleys. Their average height above the sea is about 2,500 feet, and isolated sharp peaks reach slightly less than 3,000 feet. The width of each ridge ranges from a few hundred feet to more than half a mile. To a point 9 miles south of Muddy Creek the ridges maintain their identity as separate units. There they unite abruptly into a single broad divide, dissected by the headward branches of washes and in large part covered by rock waste, above which isolated hillocks and short ridges of bedrock project.

The valley between the ridges will be referred to as Weiser Valley, from the name of the ranch near its northern limit. A small part of its south end drains into California Wash through a gap in California Ridge. The rest of the valley is drained by a long wash leading northward and emptying into Muddy Creek.

From the higher ground the Valley of Fire appears to be a uniform trough with a smooth bottom, but at close range its floor is seen to be gashed by washes into many minor irregularities. Its drainage is accomplished through three main channels. At the north a wash 6 miles long traverses the valley to Muddy Creek. The run-off from the central portion of the valley goes into Overton Wash, which cuts directly through the high ground on the east to join Muddy Creek. The southern part of the valley sends its flood water to Virgin River through a long wash locally known as the Bitter, but referred to in this report as Little Bitter Wash to distinguish it from the larger Bitter Spring Wash farther south. Considerable areas of the Valley of Fire are covered by a thin accumulation of rock waste. Wherever washes have reached, however, they have exposed large surfaces of the underlying rocks, which exhibit many hues of red, yellow, brown, and gray, and these colors, in the bright light and intense heat of the desert, make the local name for the valley singularly appropriate.

The most scenic surface forms of the region are in the red sandstone, which is carved into amazingly intricate patterns. Spires, domes, and serrate ridges are characteristic of the area, and in this setting a few scattered remnants of mesas capped with gravel are very conspicuous. The largest of these remnants is 6 miles west of St. Thomas. Its even top, nearly a mile in length, is a striking feature in the landscape. Several long washes reach back from Muddy Creek into the sandstone and carry most of the drainage from its surface. The eastern part of the area drains to Virgin River through Little Bitter Wash. East and north of the red sandstone belt the topography changes in character but does not decrease in ruggedness. The low ridges and irregular hills characteristic of the area are dominated by a prominent hogback, which will be called Overton Ridge. Its sharp crest is more than 200 feet above the beds of washes that cross it in narrow canyons. Between this ridge and Muddy Valley flat-topped mesa remnants appear as islands surrounded by a rugged surface of dissected clay.

The valley of Muddy Creek is wide and open in most of its course, its old flood plain ranging from half a mile to more than a mile in width. (See pl. 2, *A*.) Immediately below the Weiser ranch, however, the valley is confined to narrow limits between high rock walls for more than a mile. This gorge is known as the Narrows, and the most restricted portion, in Weiser Ridge, will be called Weiser Gap. Virgin River also is confined to an inner valley only a few hundred feet in width for more than a mile south of the Gentry ranch. Above and below this constriction the river has a wide, flat-bottomed valley.

Southern division.—The ridges and hills north of the Valley of Fire are little more than foothills of the Muddy Mountains. The highest relief begins with the steep front bounding the valley on the south. This front is the northern limit of a large rugged mass of dark limestone and dolomite, which rises wall-like to an average height of 1,000 feet above its surroundings—scattered peaks reaching 500 to 2,000 feet above its general level. Toward the northeast this mass presents a sharp point or corner, one steep wall extending west of south and bordering the high outer levels of the Virgin Valley, the other leg of the angle running almost due west along the Valley of Fire. If this side is followed westward about 13 miles, another sharp corner is reached, from which a west wall extends toward the south, bordering the broad California Wash. This wall is as steep and high as those on the northern and eastern sides. These three abrupt boundaries of the limestone mass give the impression of a solid block with a rough but continuous table-land on top. But if the observer climbs to a high point or goes to the south side he learns with some surprise that the mass forms three sides of a hollow square inclosing a basin. The inclosure is almost completed on the south by Bitter Ridge, formed by the upturned edges of white beds that floor the basin. The striking appearance of these white rocks suggests the name White Basin by which the feature is known. (See pl. 2, *B*.)

The greatest length of the limestone mass that borders White Basin on three sides, in an air line from the northeast point to the rim west of Muddy Peak, is 20 miles. A line from the northwest corner to the southern limit of the basin is about 10 miles long. The width of the inclosing ridge averages nearly 3 miles. Although the feature is essentially a unit, it may also be considered a combination of three long blocks or ridges. The eastern block has a general direction 30° west of south, starting at the east end of the Valley of Fire. Its length is 7 miles, and it averages about 2 miles in width. Both sides are extremely steep. The eastern front is cut by several deep canyons, which descend from the top of the mass in a succession of almost unsurmountable steep grades and high falls. Peaks rising above the general level have a pyramidal and symmetrical appearance. The highest, which stands in the southern half of the block, rises more than 1,500 feet above the east base.

The part of the inclosing wall which extends east and west has a steep northern front, but its surface slopes more gradually toward White Basin. A number of sharp peaks rise above the general level, and short stream channels have cut the top surface into very rugged form. The valleys leading southward follow the general slope and reach the interior basin without the sheer drops found in canyons emptying to the north. Several washes have considerable length, following a course parallel to the long axis of the block before turning toward the lower ground. The largest of the valleys leading toward the north have comparatively gentle and uniform grades until they approach the side of the mountain, where they plunge sharply downward to the Valley of Fire.

The western arm of the limestone ridge is more complex than the other two. At its north end it is wedge-shaped, tapering to a low, sharp point, which will be called Piute Point. Extending directly southward for a distance of 8 miles the solid block of limestone ends abruptly against an arm of White Basin. Toward the southwest the block continues as a unit, though it is altered in character. A broad, low gap through the mountain furnishes an easy passage from White Basin to California Wash and almost isolates Muddy

Peak and its companion peak, which rise abruptly at the south end of the divide. The peaks are formed on parallel oblong masses about 3 miles in length, the long axes extending slightly east of south. They are separated by a deep narrow canyon leading southward into Callville Wash. Muddy Peak proper is slightly the higher and has a blunt top of dark limestone, whereas the east peak culminates in a tall sharp point of gray limestone and appears higher than the other. Both peaks are more than 5,500 feet above sea level and rise at least 3,000 feet above the mountain base.

The light-colored floor of White Basin is framed conspicuously by the dark limestones of the mountain mass. The south boundary of the basin is less striking, because it is lower and is made of the same rocks that line the basin bottom. Arms of the basin extend into irregularities of the mountain wall as a lake reaches into embayments. The average altitude of the floor is about 2,400 feet above sea level. Seen from the rim it appears comparatively even, but it is rolling and much dissected by washes. The general slope is toward the southeast, and a large wash leading in that direction carries the greater part of the drainage. It crosses Bitter Ridge through a gorge to join Bitter Spring Wash. Three other large washes cut through the ridge—two near the southwest corner of the basin and the other at the extreme southeast corner. All these washes join the Bitter Spring Valley drainage.

Bitter Spring Valley and the upper reaches of Callville Wash form a wide expanse of comparatively low altitude. From the precipitous southern face of Bitter Ridge the valley extends southward with a width of 6 miles or more. Its apparently even floor is actually rough in detail, a network of washes cutting the soft underlying formations into an intricate pattern, and several conspicuous buttes of conglomerate and sandstone rise above the general level. On the south the valley ends against abrupt ridges comparable in height to Weiser and California Ridges, in the northern part of the Muddy Mountains, but trending southwestward toward Las Vegas Wash.

GRAND WASH CLIFFS AND VIRGIN MOUNTAINS

The Grand Wash, in western Arizona, marks a difference in topography so profound that the observer can not fail to recognize the valley as a definite boundary line. A great expanse of the plateau country is visible eastward from the top of the upper cliff. The Shivwits Plateau, lowest of the major subdivisions of the plateau province, stretches 25 miles to its eastern boundary at the Hurricane Ledge. In detail the surface of the plateau is rolling, but as a unit it is an almost even tract broken by steep-walled canyons, which cut deeply into the horizontal strata, and by isolated buttes, which rise several hundred feet above the general level. The Hurricane Ledge stands as a great wall trending south, but from a distance of 25 miles it does not cut off a view of the higher points on the Uinkaret Plateau, which it bounds on the west. The masses of Mount Trumbull, Mount Logan, and Mount Emma loom distinctly, dark from their cover of pines as well as from the dark lavas of which they are built.

Turning now to the west the observer sees a transition from high country to low which is so abrupt as to be startling. No less striking is the sudden disappearance of uniformity from the landscape. Although when viewed from the Shivwits Plateau the country on the west appears uniformly low, it has actually great and numerous differences in altitude. The first glance shows an apparent chaos of jagged, sharp-backed ranges and isolated pointed peaks, some of which rise to or above the Shivwits level. Some masses, like that of the Virgin Mountains, loom with commanding proportions. Other ranges are low and apparently nearly buried in the waste that fills the bordering valleys. Each ridge is a block or fragment of a crust that has been broken and tilted until no portion remains in its former attitude.

When examined in detail the apparently chaotic landscape assumes some degree of order. The descent into Grand Wash is seen to consist of two gigantic steps instead of a single precipitous drop. The edge of the upper cliff is continuous but greatly convoluted, retreating eastward in coves and bays where deep canyons from the plateau cut through. This cliff is capped by heavy limestone and sandstone layers, which form an almost sheer bluff hundreds of feet in height. At the base red Supai sandstone extends in a long concave slope to a limestone bench 2 to 6 miles wide and nearly 1,500 feet below the Shivwits Plateau. The bench appears almost level until viewed in profile, when it is seen to tilt eastward 2° or 3°, following the dip of the underlying strata. This surface will be called the Grand Wash Platform. It is gashed by deep canyons, whose walls descend almost vertically or in a series of narrow steps, the platform surface maintaining its level almost to the rims. Short branch canyons reach out, ending in very steep V-shaped valleys in which the strata have been eroded to resemble steps of an amphitheater.

The edge of the lower cliff, like that of the upper, forms a very sinuous line, owing to the deep canyons which issue into Grand Wash. In profile the cliffs are strikingly different. The upper cliff drops almost sheer through the thickness of the Kaibab and Coconino formations and the upper part of the Supai, though a few slight reentrants and narrow benches mark the positions of the soft sandstone layers. At the base is a long talus slope which grows gentler outward, merging imperceptibly into the Grand Wash Platform. The lower cliff descends in a series of bluffs and distinct benches, and few of the bluffs present continuous faces more than 50 feet high except in the walls of comparatively recent canyons. Steep talus slopes mantle the base of the cliff throughout most of its length. The total height of the lower cliff is fully 2,000 feet. It is seen to best advantage in the lower parts of canyons like Pigeon Canyon, which is a narrow gorge exposing in nearly vertical walls the entire thickness of the formations beneath the Grand Wash Platform. Only the most persistent of the benches break the continuity of the walls, which are quite unclimbable except where they recede at the entrance of branch canyons. At such places, by exercising care and patience, the traveler can work his way to the top and study every stratum in the section.

West of the cliffs Grand Wash Valley, 10 to 12 miles wide, extends from the country far to the north down to Colorado River. Seen from the Grand Wash Platform the valley appears as a low, nearly level expanse, complexly etched by a network of washes. Clays partly stripped of their recent gravel covering appear as spots of toy badlands, separated by the gray surfaces of gravel-capped mesas. On the west side, in the vicinity of Pakoon Spring and farther south, basaltic lava flows stand out like great smears of black paint on the landscape. The dry beds of Grand Wash and its tributaries show every detail of their windings as if drawn with pencil on a map. Near Colorado River the loose detritus which floored the valley has been largely removed, exposing low ridges of limestone and increasing the ruggedness of the surface. These ridges, which extend parallel to the wash, become more prominent farther west, where they form part of the southern Virgin Mountain block. (See pl. 4, *A*.)

In detail the floor of Grand Wash Valley is more irregular than appears from a general view. Remnants of a former even gravel-covered floor now stand 200 to 400 feet above the main washes, which have cut through the thick gravel fill into red and yellow clays. Large areas of the clays have been entirely denuded and carved into typical badlands. This is the origin of the rugged masses locally known as the Gyp Hills, near the east side of the valley. On the west the topography of the valley is influenced by two buried lava flows, 75 feet apart in the gravel. Grand Wash has cut through the sheets of lava, and on the east side of the wash their edges appear in steep gravel bluffs. West of the wash the flows have been cut away over a width of 2 to 3 miles, and a gravel-covered surface 200 feet above the stream grade occupies the space where they were. West of this terrace the lavas are again prominent in an irregular, flat-topped ridge extending from a point near Pakoon Spring southward. Through this ridge a gorge known locally as Black Canyon has been cut by a tributary of Grand Wash. North from the canyon a sharp ridge of eastward-dipping Kaibab limestone emerges from beneath the gravel and lava and extends northward past Pakoon Spring. In this report this ridge will be called Pakoon Ridge.

On the west Grand Wash Valley is bounded by the Virgin Mountains, divided into two distinct masses by St. Thomas Gap. Within the gap the surface is rugged on a minor scale, but the road connecting the Grand Wash and Virgin Valleys finds an easy grade by following washes that head at the broad, low divide.

CLIMATE

In the Muddy Mountain region the climate exhibits daily and seasonal variations characteristic of the arid Southwest. The discomfort of an excessively hot day is largely forgotten during the pleasant night that almost invariably follows. From October to May the delightful weather is a real recompense for the intense heat common from June to September. The clear, dry air makes the effects of the sunshine intense, but it also insures comfort in the shade and allows rapid radiation after the sun has set.

Within the period during which exact records have been kept the maximum temperature recorded in the Muddy Valley is 117° F. In midsummer temperatures of 110° or greater are common. High temperatures are also experienced on the plateaus to the east, but the lower altitude in the Muddy Mountain region makes the heat there especially oppressive. On many days there is almost no breeze or if it blows it is like the breath from a furnace. The highest peaks receive more relief from breezes, but the areas thus affected are comparatively small. On the other hand, during the winter months the lower altitude around St. Thomas keeps the temperature more equable and agreeable than that of the plateaus.

Rainfall in the area is scant and uncertain. Since 1907 the annual average in the Muddy Valley has been about 6 inches, and the maximum is about 9 inches. Most of the rain falls during thunderstorms, the heaviest of which commonly occur during July and August. Other rains may be expected in February and March, and showers may fall during other months. General rains are of rare occurrence. The most common storm is the local shower, which forms quickly and delivers its rain in a sudden downpour. Not infrequently local areas receive the greater part of the annual precipitation in one or two "cloudbursts." In the winter some snow usually falls at the higher altitudes. Occasionally the mountains are whitened to their bases, and at altitudes above 4,000 feet snow banks sometimes lie for weeks. Snowfall in the large valleys is very rare.

VEGETATION

Vegetation in the Muddy Mountains and adjacent areas is very sparse, although the number of plant species is apparently large. Individual plants stand far apart, foliage is reduced to a minimum, and many varieties have an inconspicuous gray color, which blends with the landscape. No forest trees are present in the Muddy Mountains, even on the highest peaks, but juniper and piñon grow in small groves on the Virgin Mountains and on the Grand Wash Cliffs above an altitude of 5,000 feet. In the Muddy Mountain area the mesquite (*Prosopis*) and the desert willow (*Chilopsis linearis*) approach most nearly to tree dimensions. Both grow along intermittent stream courses at low and moderate altitudes. Near springs some of the mesquites reach a height of 25 feet and have trunks 8 to 12 inches thick, but specimens of this size are rare. A variety of mesquite which has a twisted beanpod is locally called "mescrew." "Catclaw" (*Acacia greggi*) is a similar but smaller shrub that also grows in the sandy beds of washes. "Creosote brush" (*Covillea glutinosa*), sometimes erroneously called "greasewood," is the most common shrub at low altitudes. Its dark-green foliage is especially conspicuous on the level terrace surfaces, where the bushes have a uniformity of height and spacing that suggests young orchard trees. True greasewood (*Sarcobatus vermiculatus*) is not abundant except at altitudes above 2,500 feet. Sagebrush (*Artemisia*) also seeks the higher slopes. "Mormon tea" (*Ephedra viridis*) is a very common plant in the valleys and on the lower terraces. Many species of cactus are widely distributed. The thick "barrel" cactus (*Echinocactus*) is abundant on rocky slopes and even on bare limestone mountain walls. Prickly pear (*Opuntia*) of several species and other branching forms grow in the valleys and on terraces. No specimens of yucca were seen in the Muddy Mountain area. The reason is not apparent, for in St. Thomas Gap and in California Wash the large treelike forms, locally called "Joshua trees" (*Yucca arborescens*), are abundant, and a species commonly called "Spanish dagger" is widely distributed in the Virgin Mountains and in Grand Wash Valley.

The most common grass is "sand grass" (*Calamovilfa gigantea*), which grows in bunches on fan slopes and mesas. It is cured by the sun and is nutritious even when it appears dead. After rains fresh green stems shoot up quickly from the dry bunches. Grama grass (*Bouteloua*) grows best at moderately high levels. "Burro grass" is a small plant, which grows in isolated bunches on gravelly mesas and even on rocky fan slopes. It is relished by horses and is apparently nutritious. "Salt grass" grows in the Virgin and Muddy Valleys. It is eaten by cattle, but horses do not eat it readily.

ECONOMIC RESOURCES

Agriculture and stock raising.—In the Muddy Valley approximately 5,000 acres is under cultivation and supports a population of a little less than 1,000. The soils are valley silts, more or less sandy, and although alkaline salts are present, rendering some of the land unfit for agriculture, many of the farms produce excellent yields. Grain and alfalfa are the principal crops. Cantaloupes were once grown extensively, but the acreage given to them is decreasing steadily. Some deciduous fruits are grown successfully, and dairy products are increasing in importance. Along Virgin River within the area studied only small areas of land are farmed at present.

Although the country is desert the open range produces considerable grass, and some of the inhabitants make stock raising their principal occupation. The number of cattle supported by a given area is necessarily small, because the feed is scattered and its growing periods, which follow rains, are short; but the use of the range would be greatly increased if watering places were everywhere available. Some sheep are raised, but the larger flocks are kept during a part of the year on the high plateaus to the east.

Water resources.—Muddy Creek is a permanent stream fed by large springs whose combined flow averages about 50 second-feet. These springs are situated about 8 miles northwest of Moapa and issue from gravel which overlies Pennsylvanian limestones. The water reaches the surface with a temperature of about 90° F. and contains 835 parts per million of solids, chiefly sulphates.[13] At the springs the water is beautifully clear, but in the valley it becomes charged with fine silt and clay, which give it a murky appearance even when it has not been made muddy by recent rain. The springs supply the valley with water for irrigation as well as for domestic use, and with proper conservation even more land could be reclaimed with the present water supply.

Virgin River is normally a permanent stream, with some water even in the driest and hottest parts of the year, but at intervals the channel is nearly dry in the lower 25 miles of its course. Even at such times, however, there is a considerable subsurface flow in the sands. The few ranches along the river have an ample supply of water, and during the greater part of the year a large volume drains from the region. The flow is heaviest while snows are melting in the mountains of southwestern Utah and after heavy rains, when the channel carries a flood that keeps it unfordable for hours or even days at a time. At all times the water is heavily laden with silt, which gives it a dark-red or brown color, and like that of the Nile it is especially desirable for irrigation on account of its sediment, which adds fertility to the soil. The water has a high alkaline content and except when it is diluted by floods has a disagreeable taste. The water from shallow wells sunk in the valley floor has the same alkaline quality.

[13] Carpenter, Everett, Ground water in southeastern Nevada: U. S. Geol. Survey Water-Supply Paper 65, p. 63, 1915.

A number of springs are scattered through the region, most of them charged with sufficient sulphates to be termed bitter. The largest is Rogers Spring, which issues from a fault, and flows nearly 2 second-feet. Its temperature is about 80° F., and it is highly charged with mineral. At Bluepoint there is a smaller spring of a similar nature. Bitter Spring, also with a high sulphate content, comes from saline Tertiary beds. Sandstone Spring is in Jurassic (?) sandstone, slightly above the base. The flow is small but permanent, and the water is very palatable. Cottonwood Spring is small, but the water is good. It issues from Tertiary fanglomerate. Another spring in this formation in Kaolin Wash flows at least a miner's inch of excellent water, and a large water pocket in Magnesite Wash is kept full by seeps from the same fanglomerate.

East of Virgin River springs are rare, but a larger proportion yield good water. Red Bluff Spring issues from Triassic beds with a strong flow of brackish water. Mud Well, in the same formation, is strongly saline. Horse Spring is on or near a fault and has relatively good water. At the Whitney ranch, north of St. Thomas Gap, excellent springs in the pre-Cambrian and Paleozoic rocks supply water sufficient to irrigate several acres of fruit. Pakoon and Buckhorn Springs come from joints in basic lava flows buried in Quaternary gravel, and both yield a good supply of excellent water.

Rock tanks are the only source of water in many parts of the region, and comparatively few of these are large enough and have sufficient protection from the sun to enable them to hold water through the long periods between rains. The largest tanks in the Jurassic (?) sandstone, however, contain water at all seasons. The Tertiary fanglomerate also has some permanent holes, the best of which are in Overton Ridge; but the limestones of the region, although they have many large depressions, seldom afford permanent water holes, probably because of closely spaced joints that are open enough to act as leaks. In the sandstone, however, small joints tend to seal because of the comparatively soft and loose character of the rock and the presence of sufficient cement to prevent serious leakage between the grains. The best tanks are either plunge pools dug out below falls or potholes worn in the beds of washes by whirling pebbles. Scour basins on the outer side of meanders are of some importance, and many small depressions in the rock floors of washes hold water for several days after a rain. Some of the potholes are 10 to 20 feet deep with a diameter of only 5 or 6 feet and thus are highly effective in preserving water, as they have a large capacity with a small evaporation surface. Plunge pools either have a roughly circular plan or are oblong with rounded ends. They expose larger water surfaces than the potholes but usually have the advantage of larger capacity, and many of them are in narrow canyons where direct sunshine is of short duration. Black Willow Tank (pl. 3, *A*), the largest in the area, is a plunge pool in which the open basin varies greatly according to the amount of sand and gravel present in the depression. In June, 1919, the water body was approximately 20 feet in diameter and had a maximum depth of 10 feet. After a heavy flood in July the diameter had grown to 50 feet and the maximum depth to at least 15 feet. The pool then contained a large body of gravel and sand, which obscured the lower rim and furnished storage for considerable water besides that in the open pool. Other tanks vary in the same way. Small rains often fill them with gravel and sand in which good water can be obtained by digging to a shallow depth. These "gravel tanks," as they are called locally, have the advantage that they do not become polluted and crowded with small organisms like the open pools. Heavy floods usually clear out the detritus and leave free water holes.

Kaolin and Magnesite Washes have tanks that are combined potholes and plunge pools, formed on a surface of firmly cemented fanglomerate dipping downstream 40° to 45°. In the process of deepening and widening the upstream slopes have steepened until the water falls into the pools almost vertically. Boulders loosened from the fanglomerate serve as grinding stones, and although they are of limestone and hence quickly wear out they are continually replaced. In Kaolin Wash two of these holes have formed one above the other, and as they have become enlarged the dividing wall has been cut through. The upper hole averages 15 feet in diameter and is 37 feet deep.

Cattlemen have taken a suggestion from the natural tanks and are building reservoirs by placing concrete dams across narrow canyons. North of Muddy Peak a reservoir of this kind has been formed in sandstone to water cattle which graze in California Wash.

MINERAL PRODUCTS

The only metal produced in the region in 1919 was copper, which was mined in the lower Grand Wash Cliff at the Grand Gulch and Bronze-L mines and hauled by team to St. Thomas.[14] Copper and zinc properties in the Southern Virgin Mountains were worked at one time, and the Key West claim, 18 miles northeast of St. Thomas, is a large low-grade prospect of copper reported to contain platinum in quantities as much as half an ounce to the ton.[15] The northern part of the Black Mountains near Colorado River has prospects of iron and manganese which may become of value if transportation facilities are improved.

In the Virgin Valley rock salt has been mined for local use since the first settlements were established, and in 1919 occasional ship-

[14] Hill, J. M., The Grand Gulch mining region, Mohave County, Ariz.: U. S. Geol. Survey Bull. 580, pp. 39–58, 1915.

[15] Bancroft, Howland, Platinum in southeastern Nevada: U. S. Geol. Survey Bull. 430, pp. 192–199, 1910.

ments were made, the price being $6 a ton f. o. b. St. Thomas. Large quantities of the salt are available (see pl. 3, *B*), and its production may well increase, for it is of good quality, easily worked, and only 5 miles from the railroad, with a moderately smooth road for hauling. It is now utilized chiefly by local stock raisers.

A large sedimentary deposit of magnesium carbonate west of Kaolin has promising possibilities. Although it is not pure magnesite, the percentage of impurity is relatively small, and the quantity of material is very large. The outcrops are only 3 miles from the railroad, with a good grade for hauling, and the deposit is easily accessible for mining. A detailed description is given in the discussion of the Horse Spring formation.

Gypsum is very abundant in the region. Many of the deposits are large and fairly pure, but at present some of them are too far from transportation to be of value. In the summer of 1919 a mill was built about 4 miles below Moapa, near the St. Thomas branch railroad, to utilize a widespread surface deposit of gypsum capping light-colored clay. This is not the purest deposit in the area, but the impurities are relatively small in amount, whereas the available supply of gypsum is large and transportation facilities are very convenient.

By far the most valuable mineral product of the area is borax. In 1920 colemanite was discovered in White Basin by John Perkins, of St. Thomas. The discovery stimulated active prospecting, and early in 1921 a very large deposit was found near Callville Wash. south of Muddy Peak. It is now being mined by the West End Chemical Co. The deposits have been described by Noble[16] and Gale.[17] The colemanite occurs in the Horse Spring formation and is mentioned further in the description of Tertiary sediments.

HUMAN HISTORY

Shortly after the discovery of gold in California wagon trains from the East began using a route that followed Virgin River southward to Muddy Valley, traversed that valley to Old California Crossing above the Weiser ranch, and turned southwest in California Wash. Later a shorter route was established across Mormon Mesa, cutting off the long detour through the present site of St. Thomas. Callville was established at the "Great Bend" of Colorado River in the same period as a boat landing from which stores coming up the river could be shipped to settlements in Utah. The old Callville trail by way of Bitter Spring may still be followed. This river settlement was also reached by a route through California Wash.

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[16] Noble, L. F., Colemanite in Clark County, Nev.: U. S. Geol. Survey Bull. 735, pp. 23-39, 1922.

[17] Gale, H. S., The Callville Wash colemanite deposit: Eng. and Min. Jour., vol. 112, pp. 524-530, 1921

Travelers crossing the region frequently had trouble with the Muddy Indians, a branch of the Piute tribe. Old trails made by these Indians are still visible, and crude picture writing made by them or their predecessors decorates the rocks around water holes in the Virgin, Muddy, and Arrow Canyon Mountains. Pits in which they baked "mescal" stalks are another relic of their roving existence. Mormon writers mention missions sent to these Indians before the settlement of Muddy Valley. The present representatives of the tribe live on a reservation between Moapa and Muddy Springs.

The first white settlers in Muddy Valley were Mormons from Utah, who founded St. Joseph (now Logandale) and St. Thomas in 1858. They supposed the region was a part of Utah until 1865, when they were asked to pay taxes to Nevada for a portion of the time they had lived in the valley. To avoid doing this they deserted the settlement, and the valley was not occupied by whites again until 1883, when people from Utah established the present communities. Until the building of the San Pedro, Los Angeles & Salt Lake Railroad (now part of the Union Pacific system) in 1904 the settlements were reached only by wagon roads from Utah and from points on the Atchison, Topeka & Santa Fe Railway in Arizona and California. The branch line to St. Thomas was built in 1912.

STRATIGRAPHY

AGE, DISTRIBUTION, AND GENERAL CHARACTER OF THE ROCKS

West of the Grand Wash fault zone the rock formations are divided into two especially conspicuous groups. The older is a thick series resting on pre-Cambrian crystalline rocks and having Mesozoic sediments as its highest members. This group is in general equivalent to the Paleozoic and Mesozoic succession exposed in the Grand Canyon and the adjacent plateaus, and as in that succession its limestone, sandstone, and shale formations above the metamorphic rocks have remarkable angular conformity among themselves. The second group has a distinctly younger aspect and is separated from the older group by an unconformity of the first order. Below this great break the youngest rocks exposed are not more recent than the middle of the Mesozoic era, whereas the oldest rocks of the younger group are probably later than middle Tertiary. Therefore the detailed history of entire geologic periods is lost in this region. Other unconformities within the younger group indicate continued unrest and incomplete sedimentary record since the crustal disturbance that first tilted the older rocks.

In the Virgin Mountains the pre-Cambrian metamorphic rocks are well exposed, and sections of Paleozoic formations present in the region are continuous. (See pl. 1.) In the Muddy Mountains the oldest rocks recognized are of Devonian age, and an unknown thick-

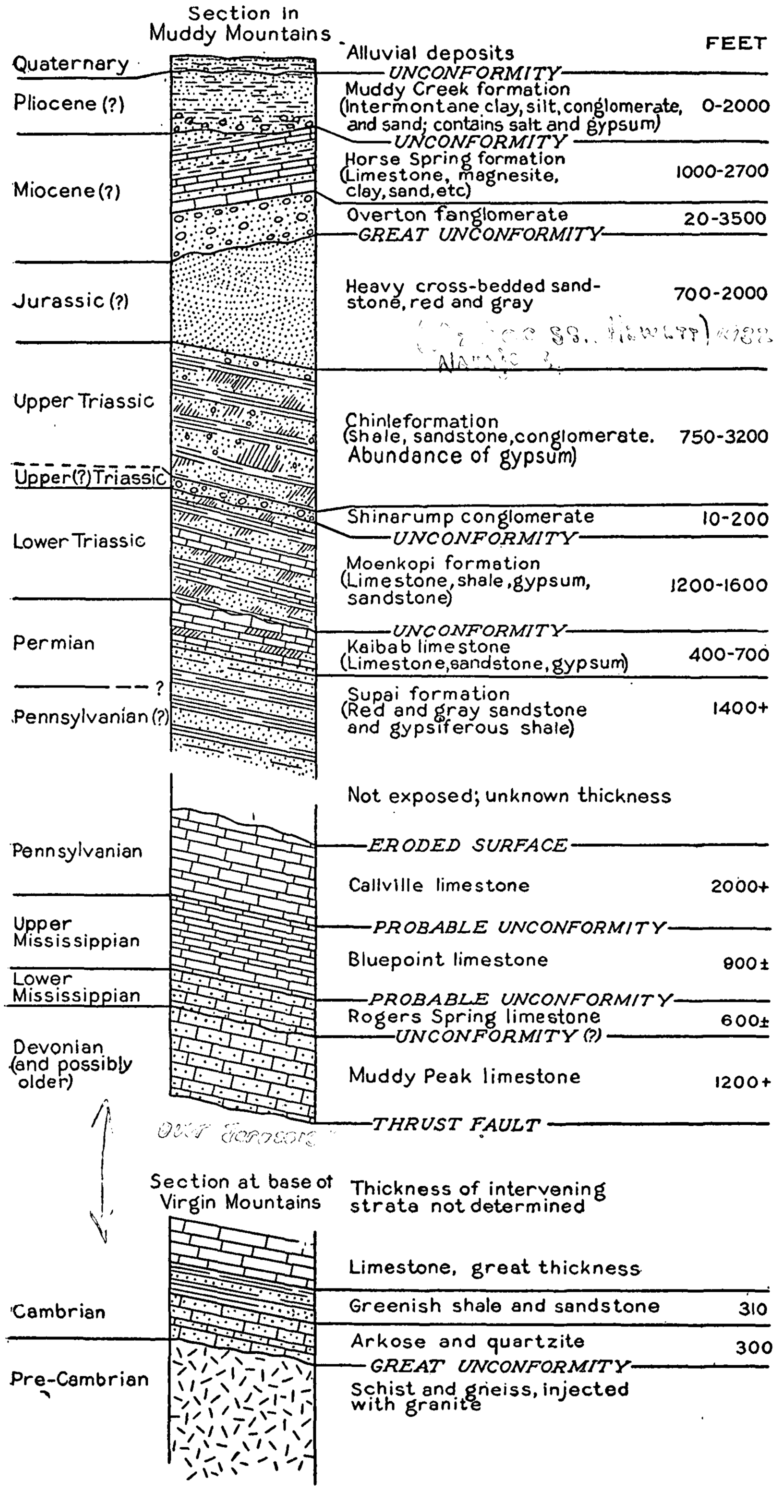


Figure 2.—Columnar section of rock formations in the Muddy Mountain region

ness of Pennsylvanian sediments is not exposed. Inasmuch as no full detailed study was made in the Virgin Mountains, the description of the Paleozoic formations will necessarily be somewhat incomplete. Mesozoic and later formations are exposed in both ranges in normal succession except for lost intervals represented by unconformities.

PRE-CAMBRIAN ROCKS

A large belt of metamorphic rocks forms the core of the Virgin Mountains northeast of St. Thomas, extending without apparent break from a point near the Gentry ranch northeastward beyond the limits of the St. Thomas quadrangle. Similar rocks are exposed near the Whitney ranch, on the east flank of the range, also south of St. Thomas Gap and in Boulder Canyon. They consist of gneiss and schist of many varieties, extensively injected with granite and other coarse-grained igneous rocks, the whole forming a complex that corresponds well in general character to descriptions of the Vishnu schist in the Grand Canyon. Dark hornblende and mica schists are interspersed among lighter-colored quartz schists that are locally very garnetiferous. Pink and gray coarse-grained granites are conspicuous, both later than the schists. The gray granite is the older and is exposed in large masses, whereas the pink variety is ordinarily found in pegmatite veins or in very thin sheets injected along planes of schistosity. North of the Gentry ranch these planes trend northeastward and dip steeply northwest, but considerable deviation from this trend and attitude was seen in other parts of the area.

PALEOZOIC ROCKS

EARLY PALEOZOIC ROCKS

Near the Key West mine the crystalline rocks are overlain by a dull-red cross-bedded conglomeratic arkose, which is clearly made up of fragments derived from the metamorphic and granitic complex. Above the arkose lie beds of gray quartzite and coarse quartz sandstone, interbedded with a few layers of greenish sandy shale which becomes more conspicuous upward. The total thickness of these basal beds is several hundred feet and above them are limestones thousands of feet thick, ranging in age from Cambrian (?) to upper Paleozoic. The sandstone and shale at the base of the sedimentary series are strongly suggestive of the Tapeats sandstone and Bright Angel shale of the Grand Canyon district. If this correlation is correct there may be in the overlying limestones representatives of St. Croixan (Upper Cambrian) time corresponding to the Muav limestone in the Grand Canyon and the Hamburg limestone of the Eureka district. It is also possible that the thick section contains Ordovician and Silurian formations, as rocks of both periods occur at Eureka.

The following section was measured south of the Whitney ranch, on the southeastern flank of the northern Virgin Mountain block.

(See pl. 4, *B*.) In the southern Virgin Mountain block a similar Paleozoic section is exposed in the series dipping eastward from the area of crystalline rocks.

Measured section in ridge south of Whitney ranch and west of Grand Wash

[Beds dip under waste at top. Section is incomplete]

	Feet
Paleozoic, undetermined:	
Dolomite, dark gray, thin bedded; some limestone near top	1, 500
Sandy and shaly beds with included thin layers of dolomite	90
Crystalline dolomite with thin sandy beds	45
Cream-colored and gray dolomite in heavy beds; green staining near top	575
Alternating limestone and dolomite, generally thin-bedded, gray, cream-colored, and nearly white	375
Cambrian (?):	
Muav limestone (?)—	
Dark-gray compact limestone; has massive appearance in cliffs but in many places weathers into thin layers; has light-gray and brown mottling; very uniform in character except for a few thin gritty layers of a light-buff color	775
Bright Angel shale (?)—	
Paper shale, micaceous, green and maroon; near base are thin limestone layers with trilobites	65
Thin layers of limestone with trilobites	6
Compact dark-gray limestone forming cliff; has many alga-like patterns near base; brown mottling near top; appears massive but has thin lamination	45
Thin micaceous shales, largely sandy, with recurring sandstone layers, predominantly olive-green with some brownish beds; contains abundant casts of worm trails	195
Tapeats sandstone (?)—	
Thin-bedded sandstone, brownish, gray, and olive-drab, with recurring layers of cross-bedded gray quartzitic sandstone (like that below); forms slope, with broken outcrop; many layers knobby, with markings like worm trails	95
Sandstone and quartzite, cross-bedded, in layers ranging from a few inches to 5 feet thick; near base strongly arkosic and reddish brown; grows more quartzose and gray upward; generally of medium and fine grain, with conglomerate lenses, not noticeably coarser at base	200
Unconformity; granite below shows disintegration to shallow depth.	
Pre-Cambrian: Mica gneiss, mica schist, and coarse, lustrous amphibolite; gray gneissoid granite intrudes the schistose rocks and in turn is cut by dikes of coarse-grained pink granite; granite also cut by dike of fine-grained dolerite, which ends at the unconformity.	

From the section above it is seen that clastic formations corresponding closely in character and thickness to the Tapeats sandstone and the Bright Angel shale are present in the Virgin Mountains. Apparently the Muav limestone thickens west of the known plateau sections, as the limestone extending upward from the trilobite-bearing beds in the Whitney ranch section resembles the Muav closely and is clearly a unit through a thickness of at least 775 feet. The upper limit of Cambrian strata in this section is unknown and will be difficult to determine, for secondary dolomitization in the upper part of the section is very thorough, and fossils have been largely effaced or made unrecognizable.

In the Muddy Mountains the oldest exposed strata are limestone and dolomite at the base of an overthrust plate. These beds have suffered brecciation and probably chemical alteration, and no trustworthy fossil evidence was found in the lower 1,000 feet of the section. However, at several horizons there are limestone and dolomite beds containing an abundance of concentric forms, probably algae, identical with forms commonly seen in the Upper Cambrian of other Nevada sections. Very probably several hundred feet at the base of the section belongs in the Cambrian, but as definite evidence is absent it is thought best to include these beds in one formation with the overlying Devonian.

DEVONIAN SYSTEM

MUDDY PEAK LIMESTONE

Distribution and thickness.—Limestone and dolomite of Devonian age are the oldest rocks of the Muddy Mountains in which recognizable fossils have been found. They lie in the great block that has been thrust over Jurassic (?) sandstone in the highest part of the range. Excellent exposures of Devonian strata may be seen immediately south of the Valley of Fire, where they form part of the abrupt mountain front parallel to the old Arrowhead road. The most satisfactory sections of the Devonian, however, occur in the vicinity of Muddy Peak Basin, especially on the north side of the Muddy Peak mass and near the north end of the basin, 6 or 7 miles north of the peaks. There erosion of the domed strata has revealed the overthrust contact and exposed the lowest beds concerned in the movement. Because of the excellent exposures of Devonian rocks and the predominance of limestone in this locality the name Muddy Peak limestone is proposed for the formation.

All the strata between the overthrust and the Mississippian beds are included in one formation. Further work will probably show that some of the lower beds belong to older periods. Devonian fossils were found in a zone approximately 50 feet thick more than 300 feet below the recognized Carboniferous. Between this fossiliferous zone and the overthrust lie at least 1,000 feet of limestone and dolomite in which no fossils were found. As the strata are of the same general nature and as no marked break could be found in the series, the entire thickness of 1,300 feet is tentatively considered a unit. The upper boundary is drawn with somewhat greater certainty. Although the fossil zone is far below the Carboniferous, limestones lithologically similar to the fossiliferous beds continue upward without apparent break to an irregular contact suggesting an unconformity, above which the rock is of noticeably different character and yields lower Mississippian fossils.

Lithology.—In general the Muddy Peak limestone and dolomite are dense and hard, and many beds have a siliceous appearance. The beds range from 2 to 20 feet in thickness. In color they are either distinctly dark or decidedly light, beds or zones of the two colors alternating. The change from one color to the other commonly occurs abruptly, producing broad, sharply contrasting bands, which are conspicuous in many steep cliffs. The dark phase of the rock is greatly predominant. Lenses and thin layers of fine-grained sandstone occur at a few horizons, especially near the top of the section. Shattered beds immediately above the plane of overthrust are especially carbonaceous and have a disagreeable fetid odor when freshly broken. Brecciation and shattering is so extreme through a thickness of 100 to 500 feet that any fossil evidence must have been largely obliterated. (See pl. 5.) Some of the lower beds, however, show the circular pattern suggestive of algae, numerous sections appearing on weathered surfaces or even in freshly broken specimens. Small chert nodules occur at many horizons, and in many beds there are irregular white fillings of crystalline calcite and dolomite that resemble shells and corals.

Fossils, age, and correlation.—The fossiliferous zone is persistent in thickness and character. Wherever found these beds are dark, dense, and extremely hard. Fossils are rarely found by breaking the rock. Most of the specimens obtained stand in relief on the edges of beds, and at first glance they resemble the small brown nodules of chert that weather out with them. Species are few, and no forms are found in abundance except the corals and gastropods. Essentially the same assemblage of forms is found in all sections studied.

The following lot, from a locality south of the Arrowhead fault and about 2 miles west of the White Basin fault, has been identified by E. O. Ulrich:

Heliophyllum sp. undet. (calyx less than half an inch in diameter).
Zaphrentis sp. undet. (calyx 1 inch or less in diameter).
Small stromatoporoid, genus and sp. undet.
Atrypa aff. A. reticularis (differs from the typical form in having finer plications).
Platyschisma? ambiguum Walcott.

Ulrich says: "This faunule evidently represents that of the Devonian Nevada limestone described by Walcott."[17a]

Another small lot found near the same locality was identified as follows by Edwin Kirk:

> Cyanthophyllum sp.
> Atrypa reticularis Linné.
> Platyschisma? near P. mccoyi Walcott.

The following lot was collected on the east side of Muddy Peak Basin, 5 miles north of Muddy Peak:

> Syringopora sp.
> Cyanthophyllum sp.
> Atrypa reticularis Linné.
> Cyrtia? n. sp. near C. norwoodi Meek.
> Platyschisma? near P. mccoyi Walcott.

Kirk made these identifications also and comments as follows on the two lots:

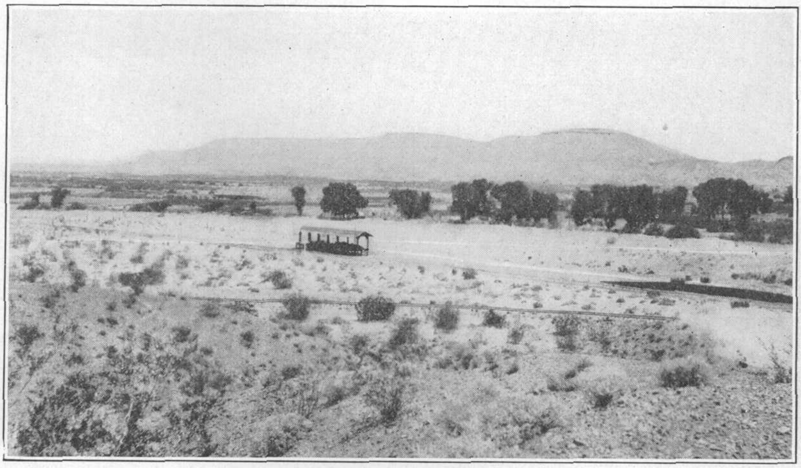
> This fauna occurs in the Eureka district, Nev., but can not accurately be placed in the section there. It has never been found intermingled with typical Upper Devonian species. Tentatively I think it should be held as Middle Devonian, and I think it will finally be placed there.

Section of Muddy Peak limestone.—In the following measured section the beds dip 30°–35° S. 15° E. The contact at the top with dark Mississippian limestone is slightly irregular.

Section of Muddy Peak limestone south of Arrowhead fault, 2 miles west of White Basin fault

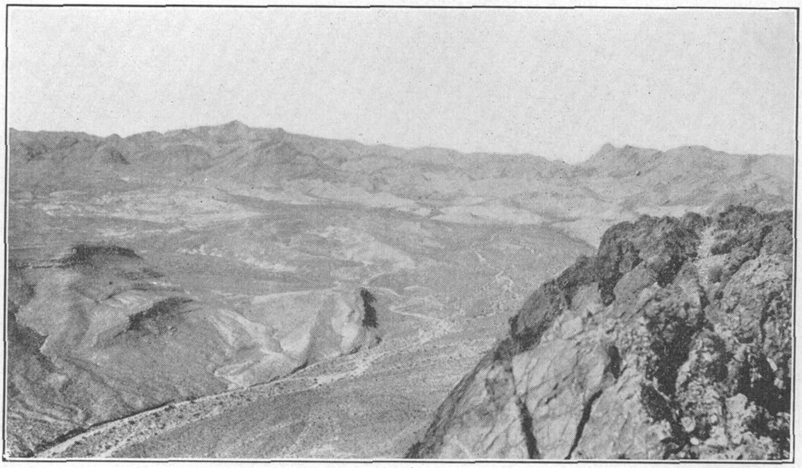
	Feet
1. Light-gray limestone, dense to finely granular; forms conspicuous band on hillside	200
2. Dark lead-colored limestone, dense and hard, in beds 3 to 5 feet thick; contains small quantity of chert	45
3. Light-gray limestone	5
4. Dense lead-colored limestone	7
5. Light-gray limestone with thin partings	4
6. Dark carbonaceous limestone	8
7. Light-gray limestone, conspicuous between dark beds	5
8. Dark hard dolomite in heavy beds	50
9. Lead-colored coarsely granular limestone; weathers to yellowish gray	12
10. Heavy-bedded dark carbonaceous limestone, very hard; has many nodules of chert irregularly distributed; contains Devonian fossils	35
11. Gray crystalline dolomite, sandy near base	3
12. Fine-grained gray sandstone, with calcareous cement	2
13. Lead-colored limestone, coarsely granular, in two heavy beds	6
14. Dark carbonaceous limestone, almost black near base; contains many small nodules of chert	4

[17a] Walcott, C. D., Paleontology of the Eureka district: U. S. Geol. Survey Mon. 8, 1884.



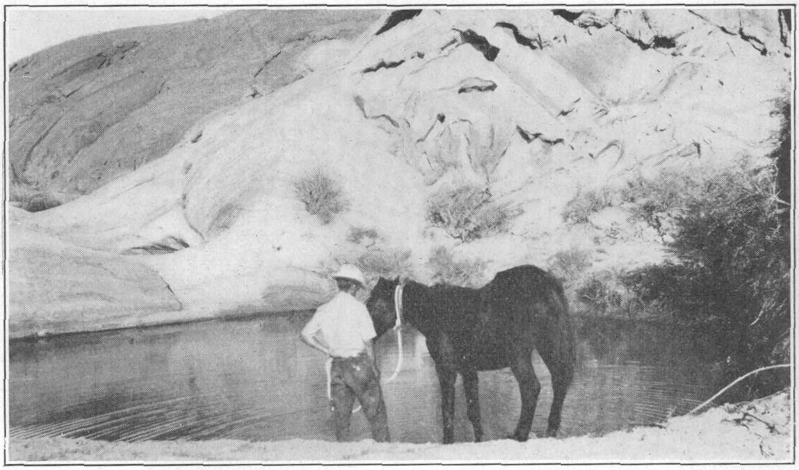
A. MUDDY VALLEY AT ST. THOMAS

Mormon Mesa, in the background, is about 700 feet higher than the valley

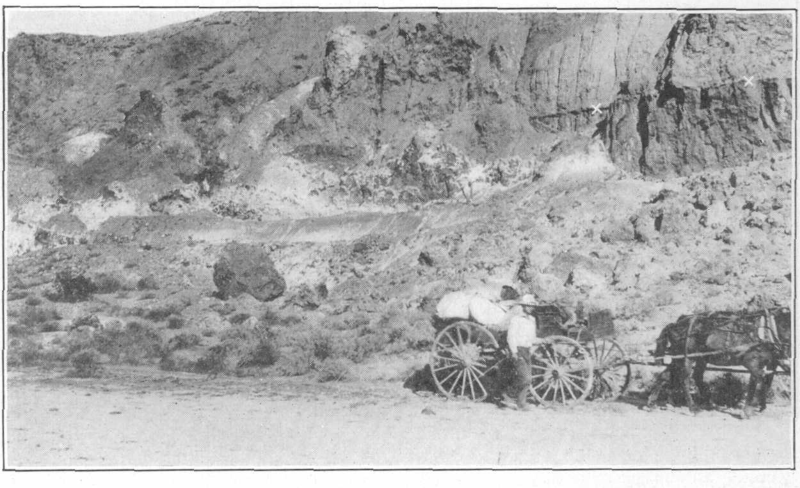


B. VIEW NORTHWEST ACROSS WHITE BASIN FROM SOUTHEAST CORNER

High peak in left background is 8 miles distant

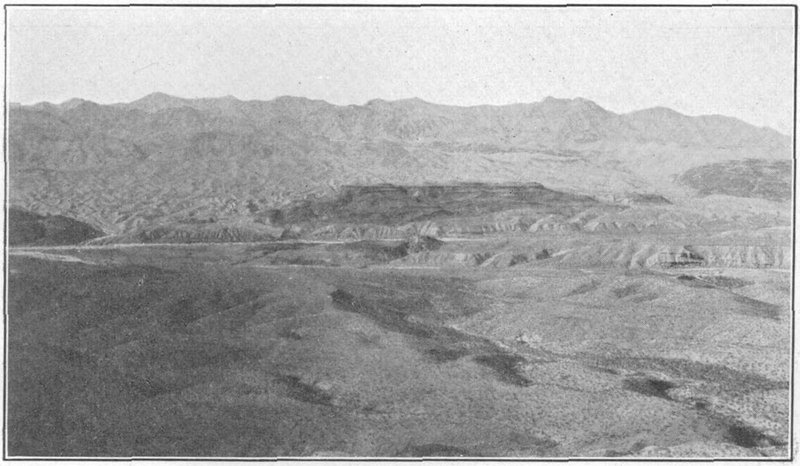


A. BLACK WILLOW TANK, A PLUNGE POOL IN SANDSTONE



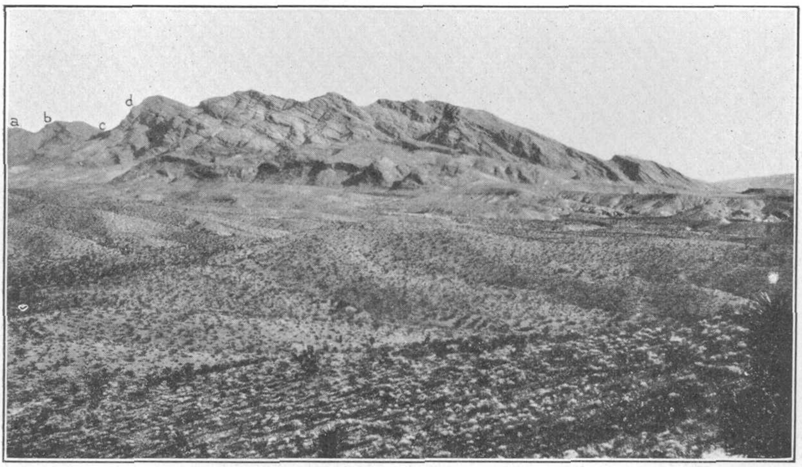
B. OUTCROP OF ROCK SALT IN VIRGIN VALLEY

x, *Top of salt; gypsiferous clay above*



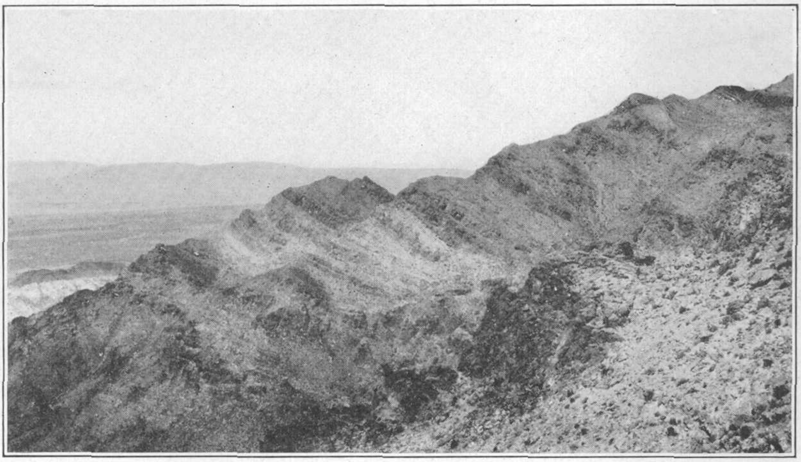
A. VIEW WEST ACROSS GRAND WASH

Southern block of Virgin Mountains in background; dissected Quaternary and Pliocene (?) deposits on floor of valley. Basalt lava forms the dark areas west of the wash



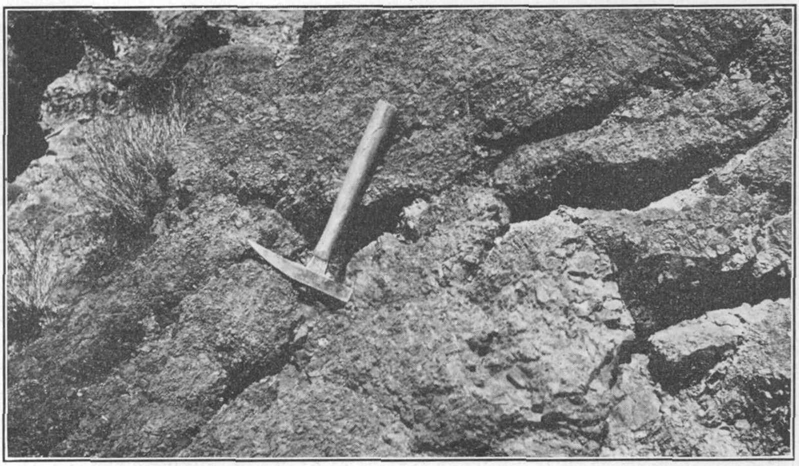
B. VIEW NORTHEAST ACROSS ST. THOMAS GAP FROM POINT NEAR MUD WELL

a, Pre-Cambrian gneiss, schist, and granite near Whitney ranch; b, Cambrian (Tapeats?) sandstone and quartzite; c, Cambrian (Bright Angel?) shale; d, Cambrian (Muav?) limestone; at right of d, thick section of Paleozoic dolomite and limestone



A. MUDDY PEAK LIMESTONE NORTH OF MUDDY PEAK

About 600 feet of strata shown in section. Note crushed appearance of beds. Gray Jurassic (?) sandstone beneath the limestone at extreme left



B. SHATTERED MUDDY PEAK LIMESTONE 300 FEET ABOVE THE BASE

	Feet
15. Interbedded gray limestone and dolomite in regular beds 2 to 10 feet thick, dense to finely granular, light to dark gray, badly shattered	600
Fault contact with Jurassic sandstone.	
	986

CARBONIFEROUS SYSTEM

EXTENT AND THICKNESS

Rocks of Mississippian, Pennsylvanian, and Permian age are present in the region, but a continuous section is not found at any place in the Muddy Mountains. In the high part of the range there are at least 3,500 feet of limestones containing Mississippian and Pennsylvanian fossils. Probably a thicker section of the same rocks is exposed on the east side of Muddy Peak, where the edges of strata dipping 20°–40° SE. crop out continuously through a horizontal distance of nearly 3 miles; but the true succession of beds in this place is difficult to determine, owing to crumpling and minor thrusting which attended a large thrust movement. In all parts of the overthrust mass an undetermined thickness of strata has been removed by erosion, and everywhere the highest remaining beds are older than the Supai formation. Both north and south of the thrust block the Supai and younger formations appear, but the base of the Supai was not identified at any place. The thickness of strata belonging between the lowest exposure of Supai and the highest beds in the thrust block can only be conjectured from a knowledge of the Carboniferous sections in the Virgin Mountains and the Grand Wash Cliffs.

The work done by the writer in the Virgin Mountains throws little light on the older Carboniferous sediments, for the section studied in detail includes nothing below the Supai formation. Study of the thick sections north and south of St. Thomas Gap will be of great value in correlating the Muddy Mountain Carboniferous and that of the plateau region.

A section in the lower part of the Grand Wash Cliffs near the Bronze-L mine shows sediments approximately 1,500 feet thick. Coarsely crystalline white, gray, and pinkish rocks, partly or wholly dolomite, reach more than 900 feet above the base of the cliff. Hill reports rock of similar appearance several miles to the north, although he calls it limestone.[18] Above these beds lie 600 feet of alternating sandstones and compact limestones, reaching to the top of the cliff and to the base of the red Supai sandstones. Gilbert's section at the mouth of the Grand Canyon describes a similar series, and Hill

[18] Hill, J. M., The Grand Gulch mining region, Mohave County, Ariz.: U. S. Geol. Survey Bull. 580, p. 45, 1915.

finds the same beds continuing northward in the cliff. Nothing comparable either to this series or to the underlying granular dolomite occurs in the Muddy Mountains. Hence we must assume either that the older Carboniferous strata change in character materially and rapidly westward or that several hundred feet of rocks corresponding to the beds in the lower cliff are not now exposed in the Muddy Mountains.

It is quite evident that the Carboniferous below the Supai formation changes greatly in thickness and character westward from the Shinumo quadrangle, Ariz., where Noble measured a total of 645 feet between the Supai and the Cambrian, of which 75 feet belongs in the Devonian.[19] At the mouth of the Grand Canyon Gilbert noted 2,750 feet of limestone and associated beds between the Supai (basal formation of his Aubrey group) and the Cambrian clastic sediments.[20] Beds 75 feet thick at the base of the limestone series are described as "marbled" and probably belong to the Muav limestone. Part of the remainder may be Devonian, as the Muddy Mountain Devonian is only 50 miles distant. It is probable, however, that at least 2,000 feet of Gilbert's section belongs to the Pennsylvanian and Mississippian series. Evidence that the great thickness of Carboniferous rocks continues and probably increases to the north and west is given by a section in Arrow Canyon, near the west side of the St. Thomas quadrangle, where an incomplete measurement made by the writer showed 3,080 feet of limestone, the greater part of which contains Pennsylvanian fossils.

An excellent opportunity to study the Carboniferous rocks is offered by the Virgin, Mormon, and Arrow Canyon Mountains, and by ranges farther west, in the Las Vegas quadrangle.

CARBONIFEROUS OF THE MUDDY MOUNTAINS

INCOMPLETENESS OF EXPOSURES

The base of the Carboniferous in the Muddy Mountains is marked by an irregular surface, which appears in section as a slightly wavy line at the top of light-colored limestones assigned to the Devonian. In the broken blocks that make up the high part of the range it is difficult to find sections giving even a fairly complete thickness of the Carboniferous without duplication caused by thrust or by normal faulting. Only partial sections that certainly show a normal succession of beds are considered, and the writer feels, therefore, that the thickness actually measured is less than the total thickness exposed. In all sections of the Pennsylvanian strata the amount removed by erosion at the top can only be conjectured.

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[19] Noble, L. F., A section of the Paleozoic formations of the Grand Canyon at the Bass trail: U. S. Geol. Survey Prof. Paper 131, p. 26, 1922.

[20] Gilbert, G. K., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, pp. 162-163, 1875.

In the entire section of Mississippian rocks there is a recurrence of features that are generally similar, and no certain evidence of any physical break was seen. Division into formations is made largely on the basis of fossils, but a definite stratigraphic break may appear on closer examination. Two distinct Mississippian faunas are recognized, but as they were not found in close succession in any section the dividing horizon can be assigned only tentatively by comparing sections from different localities. Divisions represented on the map are not exact because the contacts were not traced continuously.

MISSISSIPPIAN SERIES

ROGERS SPRING LIMESTONE

Distribution and lithology.—The supposed contact between the Devonian Muddy Peak limestone and the lowest Carboniferous stratum can be seen in sections south of the Arrowhead fault, along the White Basin fault scarp, and on the north side of the Muddy Peak mass. Everywhere there is above the contact surface limestone different from that beneath, but there are no beds of clastic material. Limestones above the unconformity are distinctly granular, in part coarsely crystalline, thus showing a contrast to the dense texture that is almost universal in the Devonian beds. Crinoid stems and sections of other fossils are abundant from the very base of the Carboniferous, and very cherty zones are prominent.

The lowest Carboniferous beds are recognized along the Rogers Spring fault scarp, and the name Rogers Spring limestone is proposed for the formation. The beds are regular and as a rule massive, although the lower portion is thin-bedded. Typically the beds are dark gray and of granular texture, cleavage faces of calcite showing in abundance on freshly broken surfaces. Some variations in color occur—to light gray on the one hand and to very dark gray or almost black on the other—and in a zone 70 to 80 feet thick, lying more than 200 feet above the base, the granular texture gives place to a prevailing dense texture. This zone is also distinguished by a great abundance of gray chert, arranged in thin layers and long lenses, making up from a third to a half of the rock and giving an appearance of thin bedding. All the beds contain much carbonaceous matter, which is evident in the color and in a disagreeable fetid odor from all freshly broken specimens. In the darkest layers the bituminous character is especially pronounced.

Heavy beds of dark fine-grained dolomite and apparently siliceous limestone in Muddy Peak and in the Rogers Spring horst probably belong in the Rogers Spring limestone. Some of the dolomite layers are marked with small but conspicuous green specks. A thin section of the typical granular limestone from this formation shows many minute fragments of crinoid stems and other fossils. No noncalcareous clastic materials were identified in this section.

Fossils and correlation.—The following fossils were collected on the west side of Muddy Peak, approximately 200 feet above the top of the Devonian. The identifications were made by G. H. Girty:

Triplophyllum sp.	Productus sp.
Leptopora aff. L. typa.	Camarotoechia metallica.
Leptaena analoga.	Spirifer centronatus.
Schuchertella aff. S. chemungensis.	Spiriferina solidirostris.
Chonetes loganensis.	Reticularia cooperensis?

Girty refers this fauna definitely to the lower Mississippian, correlating the beds with the Madison limestone of Utah, Wyoming, Montana, and other Western States. Collections made at other localities, especially south of the Arrowhead fault, contain *Spirifer centronatus* as the only recognizable form except corals. Girty pronounces one of these collections to be probably lower Mississippian. The relation of the beds at these localities to the top of the Devonian leaves no doubt that the horizon is very close to that at which the larger fauna was collected. *Spirifer centronatus* is the most common fossil seen in the Rogers Spring limestone, and its range apparently extends through several hundred feet.

Thickness.—With data now available the top of the formation can not be drawn satisfactorily. Two miles northwest of Bitter Spring fossils of upper Mississippian age were found about 600 feet above the top of the Devonian, and south of the Arrowhead fault numerous specimens of *Spirifer centronatus* were found 500 feet above the same horizon. No distinct lithologic change was observed at either locality, but on the fossil evidence, which is admittedly not conclusive, the Rogers Spring limestone is assumed to have a thickness of about 600 feet.

BLUEPOINT LIMESTONE

Lithology and distribution.—In general lithologic features the limestones of upper and lower Mississippian age are very similar. In the younger formation there is a larger percentage of very dark, extremely carbonaceous rock, and coarse granular texture is less common than in the Rogers Spring formation. Dark-gray to nearly black heavy-bedded limestone, having a finely granular or dense texture and containing many large festoons of corals, is a very common phase of the upper Mississippian near Bluepoint, and the name Bluepoint limestone is proposed for the formation. Heavy beds of lighter gray are not uncommon. Gray chert in layers or nodules occurs at some horizons but in general is less abundant than in the older limestone. One of the fossiliferous zones northwest of Bitter Spring is thin bedded, the layers ranging from 1 inch to 4 inches thick through a total thickness of 8 feet. Elsewhere the beds are rarely less than 6 inches thick and are more commonly measured in feet.

Thickness.—Neither the top nor the bottom of the formation was accurately located, and therefore only an approximate thickness can be given. In the section west of the White Basin fault the lowest Pennsylvanian fossils recognized are Spirifers, occurring in a hard, dense limestone, and immediately beneath is a thick zone of gray granular limestone containing an abundance of chert and large festoons of corals. This zone resembles the Mississippian lithologically, and it will be tentatively included in the Bluepoint limestone, thus placing the top of the formation just below the lowest recognized Pennsylvanian. This horizon is approximately 900 feet above the assumed upper limit of the Rogers Spring limestone.

Fossils and correlation.—Girty has identified the following collections, both found 2 miles northwest of Bitter Spring on the White Basin fault scarp. The first lot was obtained from gray crystalline limestone about 600 feet above the base of the Rogers Spring formation and believed to be near the bottom of the Bluepoint limestone.

Triplophyllum sp.	Productus aff. P. scitulus.
Cyathaxonia sp.	Pustula aff. P. indianensis.
Fenestella sp.	Pustula aff. P. arkansana.
Chonetes aff. C. loganensis.	Spirifer sp.

The second lot was collected about 50 feet higher, from dark limestone in part dense and in part coarsely crystalline.

Triplophyllum sp.	Leptodesma aff. L. spergenensis.
Derbya aff. D. kaskaskiensis.	Pleurotomaria n. sp.
Chonetes aff. C. loganensis.	Paraparchites sp.
Composita aff. C. subquadrata.	Bairdia sp.
Conocardium n. sp.	

Girty pronounces both collections upper Mississippian, mentioning as the closest western equivalant the fauna of the Brazer limestone of northern Utah and southern Idaho. Professor Schuchert[21] states that the Rogers Spring and Bluepoint faunas indicate widely different stages of the Mississippian, the former probably having as its equivalent in the Mississippi Valley the Fern Glen, whereas the Bluepoint is "upper Tennesseean"—that is, Chester. These correlations indicate a break of such magnitude that the two formations may be separated by an erosion surface, although the writer failed to detect it.

PENNSYLVANIAN SERIES

CALLVILLE LIMESTONE

Distribution and lithology.—Limestones of Pennsylvanian age were identified with certainty in the Muddy Peak mass and on the south side of the block that lies west of the White Basin fault. Limestone of the same age also caps the high pyramidal peaks on the Rogers

[21] Schuchert, Charles, personal communication.

Spring horst. The greatest thickness measured is 2,000 feet, near the northeast corner of White Basin, but all sections that were studied appear to be incomplete, and the total may be considerably more than 2,000 feet. The strata of this age are here grouped as one formation and named the Callville limestone. In general appearance the limestone resembles the older Carboniferous rocks, except that it is typically thin-bedded, with only a few massive layers. The rock most characteristic of the formation is dark gray, and many layers are almost black, the shade apparently depending on the content of bituminous matter. Sand is not noticeable in the formation, but at intervals layers of a shaly nature occur. Typically the beds are hard and dense, coarse granular texture occurring as a subordinate feature. Chert is abundant but less so than in the Mississippian limestones, appearing as rounded nodules and short lenses more commonly than in layers. Sections of fossils are abundant at many horizons, but good specimens are easily collected at only a few.

Fossils and correlation.—Two localities yielded a large number of fossil specimens, but comparatively few species are represented. The following forms were found in dark hard limestone 2½ miles northwest of Muddy Peak, near a faulted tongue of Tertiary limestone.

Productus cora.	Spirifer cameratus.
Pustula nebraskensis var.	Spirifer sp.
Dielasma bovidens.	

Near the northeast corner of White Basin the typical dark-gray limestones yielded the following species:

Triplophyllum? sp.	Spirifer rockymontanus.
Productus cora.	Spirifer cameratus?
Pustula nebraskensis.	Composita subtilita.
Pustula nebraskensis var.	Edmondia sp.

Girty refers both faunas to the Pennsylvanian and correlates the limestone with the Magdalena group of New Mexico.

PENNSYLVANIAN EAST OF THE MUDDY MOUNTAINS

In the fault scarp east of Virgin Valley and several miles southeast of St. Thomas limestone beds lithologically like the Callville limestone lie beneath the Supai formation. No fossils were collected at this locality.

The end of the Tramp Range, on the south side of St. Thomas Gap, is a steep mountain front containing several hundred feet of dark-gray limestone in regular beds of moderate thickness. The following fossils were found near the base of the exposure:

Stenopora sp.	Spirifer rockymontanus?
Productus semireticulatus.	Squamularia perplexa.
Rhynchopora illinoisensis.	Myalina sp.
Spirifer cameratus?	

Girty refers this list to the Pennsylvanian, and the beds are presumably the time equivalent of the Callville limestone.

In dense limestone beds at the top of the lower Grand Wash Cliff, immediately below the thick red beds in the Supai formation, the following species were found in a thin band which contains a large number of individuals.

Stenopora sp.
Rhombopora lepidodendroides.
Pustula nebraskensis.
Composita subtilita.

Girty pronounces this fauna probably Pennsylvanian, and its stratigraphic position makes it certainly of that age or younger. The horizon is probably in the lower part of the Supai formation as redefined by Noble, and higher than any part of the Callville limestone seen in the Muddy Mountain block.

SECTION IN LOWER GRAND WASH CLIFF

Section in lower Grand Wash Cliff near the Bronze-L mine

	Feet
Top of cliff.	
1. Dense gray limestone in beds 18 to 30 inches thick, fossiliferous	100
2. Alternating layers of gray gritty limestone and fine-grained sandstone; some layers yield Pennsylvanian fossils	80
3. Cross-bedded red sandstone, fine grained, thinly laminated, and hard; calcareous cement; true beds 1 foot to 6 feet thick	100
4. Alternating heavy beds of dark-gray dense limestone and fine-grained sandstone	25
5. Heavy bed of dark dense limestone, apparently siliceous	12
6. Pink sandstone, medium to coarse grained, highly cross-bedded	25
7. Dense, hard lead-colored limestone, in two heavy beds, each 3 feet thick	6
8. Fine-grained gray to pink cross-bedded sandstone, with a few layers of dense limestone	100
9. Gray cherty limestone and fine-grained sandstone	75
10. Dense lead-colored limestone, alternating with gray sandstone	35
11. Fine-grained white quartzitic sandstone	15
12. Dense gray and granular white limestone	25
13. Alternating layers of fine-grained quartzitic sandstone and dense gray limestone (base (?) of Supai formation as redefined by Noble)	80
14. White and pink dolomite, coarsely granular, in beds of different thickness, cherty in some zones; has porous or vuggy structure	825
15. Gray crystalline limestone in heavy, regular beds; lenses of sandstone present	150
Talus slope in Grand Wash Valley.	
	1, 633

PENNSYLVANIAN (?) SERIES

SUPAI FORMATION

Distribution.—The Supai formation appears west of the Grand Wash Cliffs in a number of fault blocks capped by Kaibab limestone. In the Grand Wash and in the Virgin Mountains all the blocks are tilted eastward, exposing the Supai on their west faces. The most conspicuous outcrop seen from the Muddy Valley is in the lower part of the high fault front extending south from Red Bluff Wash, where several hundred feet of red sandstone stands in a steep face under a capping of Kaibab limestone. The westernmost outcrops observed are adjacent to the twin limestone ridges south of the Weiser ranch, where the strata are overturned toward the east, exposing westward-dipping beds of Supai on the west sides of the ridges. South of Muddy Peak, near Callville Wash, the Supai appears in its normal position in the face of a fault block capped by the Kaibab. This is the most southern exposure observed.

Character and thickness.—The Grand Wash Cliffs afford the only complete section of the Supai seen in the region, and even there the exact lower limit of the formation is not certain. Darton[22] has suggested that the alternating sandstones and limestones at the top of the lower cliff should be included, and this suggestion appears to be in harmony with the usage of Noble in his latest classification of formations in the Grand Canyon.[23]

The strata at the top of the lower cliff are very different lithologically from the typical red Supai, but there is a transition in character between the two groups of beds. As shown in the measured section given above limestone alternates with sandstone near the top of the cliff. The limestone that ends the series is overlain by gray sandstone made up of fine quartz grains firmly cemented with calcium carbonate. A short distance above the base these beds lose their resistant character, and the prevailing Supai color begins to appear, at first in beds of a pale pink tint which alternate with gray layers, but within 200 feet brick-red becomes predominant, and through the remainder of the formation it is almost universal. In fact, a large part of the sandstone appears to be deep red on weathered surfaces, although the ordinary color of the fresh rock is a bright red, like that of a freshly burned red-clay brick. Some gray layers occur throughout the exposure, and in the upper 300 feet there are several heavy gray and yellow beds which appear as conspicuous lines in the bright-red lower portion of the nearly vertical upper Grand Wash Cliff.

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[22] Darton, N. H., A reconnaissance of parts of northwestern New Mexico and northern Arizona: U. S. Geol. Survey Bull. 435, p. 26, 1910.

[23] Noble, L. F., A section of the Paleozoic formations of the Grand Canyon at the Bass trail: U. S. Geol. Survey Prof. Paper 131, p. 59, 1923.

The total thickness of the sandstone in the section east of the Bronze-L mine is 1,050 feet. The top 300 to 400 feet stands as a steep cliff under the Coconino and Kaibab formations. Most of the lower red beds are comparatively weak or at best contain only scattered resistant layers. This portion of the formation underlies a concave, waste-covered slope a mile or more wide, the sandstone appearing only in isolated hills or in the beds of long washes that head near the base of the cliff. (See pl. 6, *A*.)

In this section the bedding is typically regular. Cross-bedding, ripple marks, and other shallow-water features are rare. The sand grains are fine and very even in size. The red color is apparently due to iron oxide, but calcium carbonate is the principal cementing material. Many beds in the lower portion are very loosely cemented, and this condition causes the weak character near the base. Throughout the formation zones of thin layers alternate with beds from 2 to 10 or even 20 feet thick. Heavy beds predominate in the portion standing in the cliff.

Sections in fault blocks near Grand Wash are incomplete but resemble the upper portion of the cliff section. Three miles north of the mouth of the wash about 600 feet is exposed, and the ridge west of Pakoon Wash shows a maximum of 250 feet. The first marked change in the character of the sandstone appears in the block immediately west of Horse Spring Valley, where cross-bedding on a large scale is characteristic of the formation below the upper 400 feet. In sections farther west cross-bedding is a conspicuous feature. The outcrops in Weiser Valley exhibit cross-bedding on a scale comparable to that in the Jurassic (?) sandstone, and in fact the Supai formation here resembles that sandstone through a thickness of several hundred feet. Beds of gypsum are associated with the Supai in this locality and appear in the California Wash section. In the entire Muddy Mountain area great variety marks the formation, as is evident by a comparison of the following sections:

Section of Supai formation on east side of Weiser Valley 2 miles south of Muddy Creek

[Beds form an anticlinal fold, overturned to the east. Kaibab limestone, dipping 70°-75° W., forms ridge 500 feet high on east side of valley]

	Feet
1. Talus slope with outcrops of massive porous gypsum and red gypsiferous shale	150
2. Massive sandstone, cross-bedded on large scale; general color is pale red or pink, but large irregular masses are gray, others brick-red; true bedding is distinct, dipping 70° W.; mass forms irregular dissected ridge rising 60 to 100 feet above valley floor, with sharp spires reaching 50 feet higher	750
3. Dense dark-gray limestone, heavy bedded and resistant	25
4. Pink sandstone and gray sandy shale	20
Wash channel.	
	945

Section of Supai formation at "summit" on old Arrowhead road, 15 miles west of St. Thomas

[Overlying heavy-bedded Kaibab limestone forms high ridge; dips 50° SW. in overturned block. Supai dips 45°-55° S.; strikes N. 60° W. at top, nearly west at base; ends on south against waste covering fault adjacent to Devonian limestone]

	Feet
1. Fine-grained pink calcareous sandstone, badly shattered	16
2. Dense to finely crystalline gray limestone	5
3. Fine-grained pink argillaceous sandstone, badly jointed	25
4. Hard bed of fine-grained pink calcareous sandstone	1
5. Fine-grained, heavy-bedded pink argillaceous sandstone	12
6. Firm bed of pinkish-gray calcareous sandstone	1
7. Fine pink calcareous sandstone, poorly indurated	11
8. Hard, gritty dark-gray limestone	1
9. Fine-grained pink argillaceous sandstone, poorly indurated	80
10. Massive white gypsum	7
11. Fine-grained pink argillaceous sandstone, poorly indurated	16
12. Massive gray gypsum, thinly laminated on weathered surfaces	9
13. Brick-red sandy clay with white gypsum seam	12
14. Fine-grained gray to pinkish-white sandstone, heavy bedded and poorly indurated	35
15. Fine-grained gray and pinkish sandstone with lenticular beds	60
16. Reddish-brown sandy shale	4
17. Fine-grained pinkish-gray sandstone with calcareous cement; zones of regular beds 6 to 10 inches thick alternate with heavy lenticular beds; cross-bedded on small scale; becomes heavier bedded and cross-bedded on larger scale in lower half	450
18. Massive impure gypsum, gray and pink	15
19. Interbedded fine-grained pink and brick-red sandstone and gypsiferous sandy clay containing numerous beds of impure gypsum; sandstone has irregular, lenticular beds, cut by many seams of white gypsum	325
20. Heavy-bedded and cross-bedded gray and yellowish sandstone, fine, even grain, jointed and shattered	400
	1,485

Correlation.—No fossils were found anywhere in the sandstones of the Supai, and therefore its recognition in widely separated outcrops depends on its lithologic character and its relation to other rocks. These criteria taken together leave no doubt regarding its identification at any locality, for everywhere it has a thick series of fine-grained sandstones closely associated with the Kaibab limestone, which is easily recognized both by lithology and by fossil evidence. The formation was not studied sufficiently to determine whether or not it can be subdivided in the same way that Noble has divided it in the Grand Canyon region.[24] The discovery of plant fossils there brings

[24] Noble, L. F., op. cit., p. 60. See also Schuchert, Charles, On the Carboniferous of the Grand Canyon of Arizona: Am. Jour. Sci., 4th ser., vol. 45, p. 353, 1918.

the base of the Permian below the Hermit shale, formerly regarded as the top of the Supai. Fossils of probable Pennsylvanian age found in the limestones at the top of the lower Grand Wash Cliff indicate that the Permian does not extend to the base of the Supai, and it is possible that the formation is divided between the two epochs. Noble thinks that the entire Supai is probably Pennsylvanian, with the distinct unconformity below the Hermit shale marking the base of the Permian.[25]

PERMIAN SERIES

COCONINO SANDSTONE

Character and thickness.—If the Coconino were not known as a distinct formation elsewhere, it might be treated in this report merely as a phase of the Supai. From a thickness of 335 feet in the Shinumo quadrangle it has thinned to only 40 feet in the upper Grand Wash Cliff. The thinning is not at a uniform rate, however, as Reeside and Bassler[26] report only 90 feet of Coconino near Kanab Creek. Exposures in the Grand Wash show a maximum thickness of 75 feet, but the formation becomes still thinner toward the Muddy Mountains until in the westernmost outcrops of the Aubrey group the Coconino has lost its identity. In the section south of Sawtooth Ridge sandstone typical of the Coconino is less than 20 feet thick. In Weiser Valley and California Wash nothing resembling the formation could be identified. In spite of its thinness, however, the Coconino remains true to the physical characteristics that distinguish it in the Grand Canyon. It is a massive bed of fine-grained gray to cream-colored quartz sandstone, conspicuously cross-bedded. The structure as well as the color divide it sharply from the underlying Supai formation. In the Grand Wash Cliffs the upper beds of the Supai are thick and massive but are entirely regular, without cross-bedding, and bright red is the dominant color to the top. Although there appears to be no evidence of a decided unconformity, the abrupt appearance of cross-bedding and consistent gray color is sufficient indication of a marked change in conditions of sedimentation. At the top of the Coconino the change in structure is likewise abrupt. Regular beds of sandstone alternating with limestone layers show another phase of sedimentation, the deposition of the Kaibab limestone.

Cementation of the Coconino is irregular. The cementing material is chiefly carbonate, but silica is present in varying amounts. In places the sandstone is almost as hard as quartzite, whereas adjacent portions are moderately firm or even poorly cemented.

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[25] Op. cit., p. 62.

[26] Reeside, J. B., and Bassler, Harvey, Stratigraphic sections in southwestern Utah and northwestern Arizona: U. S. Geol. Survey Prof. Paper 129, p. 69, 1922.

Correlation.—As the Hermit shale below the Coconino in the Grand Canyon region and the Kaibab limestone above it are now recognized as Permian, the Coconino must be of Permian age also, although no diagnostic fossils have been reported from the sandstone itself. Girty[27] suggests that the stratigraphic position and lithologic character of the formation invite correlation with the Abo and Yeso divisions of the Manzano group in New Mexico, which is now classified as Permian. This correlation is made especially probable by the similarity of the Kaibab fauna to that of the San Andres limestone, the upper member of the Manzano group.

KAIBAB LIMESTONE

General character and distribution.—Next to the thick limestones of the Callville and older formations the Kaibab limestone makes the most conspicuous topographic features of the Muddy Mountains Those familiar with the formation in the plateau region easily recognize it in the upturned strata at the Narrows near Muddy Creek. Some change in character and thickness is to be expected in the hundreds of miles separating this locality from the Kaibab Plateau, but probably no formation common to the two regions exhibits less variation. Hard gray cherty limestone makes up the essential part of the formation wherever it has been observed, and its thickness at Weiser Valley is almost identical with that at Cataract Creek[28] or at Fossil Mountain.[29]

An incomplete section of the Kaibab caps the upper cliff, east of Grand Wash, the edge forming an almost sheer bluff. Tilted fault blocks and eroded folds exposing complete or partial thicknesses are found in Grand Wash Valley, in the Virgin Mountains, and in the Muddy Mountains both north and south of the high central mass. The topographic expression of the limestone in these blocks is a long, sharp ridge with nearly even top, and this characteristic of the formation, with its dark color and its association with the red Supai, makes the Kaibab easy to recognize even from some distance.

Lithology.—The greater part of the formation consists of two heavy limestone members. Each contains a great abundance of chert in nodules and lenses, which give a false appearance of thin bedding. The typical limestone is dark gray or lead colored, slightly crystalline, and very hard. There are all varieties of texture from very dense to coarsely granular. Not all the bedding is distinct, but as a rule the layers are several feet in thickness.

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[27] Girty, G. H., personal letter.

[28] Darton, N. H., A reconnaissance of parts of northwestern New Mexico and northern Arizona: U. S. Geol. Survey Bull. 435, pp. 29–30, 1910.

[29] Noble, L. F., The Shinumo quadrangle, Grand Canyon district, Arizona: U. S. Geol. Survey Bull. 549, pp. 70–71, 1914.

The upper limestone member is everywhere thicker than the lower. In the ridge just east of Grand Wash the lower division is 150 feet thick, and the upper is incomplete owing to erosion. West of Horse Spring Valley a complete section shows 270 feet in the upper member and 160 feet in the lower. At Weiser Valley both are slightly thicker, but they have about the same ratio. In the upper cliff the divisions are separated by a zone of sandstone and shale 40 feet thick. In the fault block at the mouth of Grand Wash the division is made by 25 feet of red sandstone, whereas the section at Horse Spring Valley and all others farther west have a gypsiferous zone between the limestones. Darton[30] mentions white gypsum at a corresponding horizon in the Cataract Creek section, but this does not appear to be a common phase of the thin dividing member, although recent work by D. F. Hewett and the writer has shown that gypsum in the middle member of the Kaibab as well as above the upper limestone member is common in Spring Mountain, 50 miles west of the Muddy Mountains. Near the head of Overton Wash, west of the Valley of Fire, fully 100 feet of gypseous layers mark the horizon. Where the beds are tilted this soft material has been cut out, leaving a double ridge of limestone separated by a valley with very regular parallel walls.

Between the lower heavy limestone and the base of the formation lies a series of comparatively thin beds, which differ from place to place in thickness and character. In the upper cliff the series consists of alternating sandstone and limestones. These beds are placed in the Kaibab rather than in the Coconino because they grade naturally into the upper formation, whereas at their base the strong cross-bedding of the Coconino ends sharply, giving an impression either of unconformity or of changed conditions of sedimentation. West of Grand Wash the sandstones at this horizon give place to pink and white gypsum associated with a small amount of shale, but very probably these layers belong in the underlying Supai rather than in the Kaibab.

Locally on the east flank of Weiser Ridge the upper limestone member is overlain by gypsiferous shaly beds, which are capped by a few feet of thin-bedded limestone. Probably these beds were continuous at the end of Kaibab time and were partly removed during the pre-Triassic erosion interval. Reeside and Bassler[31] found similar beds at the top of the formation in southwestern Utah and northwestern Arizona and called them the Harrisburg gypsiferous member.

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[30] Darton, N. H., op. cit., p. 30.
[31] Op. cit., pp. 58–59.

Fossils and correlation.—Wherever the thick limestone members occur they contain fossils, but as a rule it is not easy to collect specimens. Although sections of shells, corals, and crinoid stems show plainly on weathered surfaces, attempts to break the forms out are futile unless the rock is weathered to a proper stage. In some localities the upper limestone at the edge of the Shivwits Plateau is weathered so that the matrix is soft, but the fossils are uninjured, and these localities yield an abundance of certain forms. In both limestones *Productus* is the most common genus. Many localities yield no other forms.

Girty has identified the following species, found at the localities indicated:

At the top of the upper cliff 4 miles southeast of the Bronze-L mine:

Fistulipora sp.
Leptopora n. sp.
Phyllopora n. sp.
Cystodictya sp.
Enteletes? n. sp.
Derbya sp.
Productus ivesi.
Productus occidentalis.
Productus semireticulatus.
Marginifera lasallensis?
Pustula subhorrida.
Productus montpelierensis.
Rhynchopora n. sp.
Squamularia aff. S. guadalupensis.
Composita subtilita.
Griffithides sp.

In the Kaibab fault block near the mouth of Grand Wash:

Batostomella sp.
Productus ivesi.
Productus occidentalis.
Pustula montpelierensis.
Composita subtilita.
Echinocrinus sp.

In the ridge west of Horse Spring:

Productus ivesi.
Productus occidentalis.
Pustula montpelierensis?

In Weiser Ridge, 2 miles south of Narrows:

Zaphrentis sp.
Batostomella sp.
Meekella? sp.
Productus ivesi.
Productus occidentalis.
Squamularia aff. S. guadalupensis.
Composita mexicana.

In California Ridge, 2 miles south of Muddy Creek:

Productus ivesi.
Productus occidentalis.
Pustula montpelierensis.
Marginifera? sp.
Acanthopecten colorad ensis.

Girty pronounces these faunas Permian, corresponding to the Manzano group of New Mexico and the Phosphoria formation and upper part of the Park City formation of Utah and Idaho. He adds:

> The suggestion that this fauna indicates a correlation with the Manzano group of New Mexico should be qualified to this extent, that the faunal resemblance lies especially with the San Andres limestone, the highest member of the Manzano group, thus tending to correlate the Kaibab with the San Andres.

MEASURED SECTIONS

Section in upper Grand Wash Cliff, east of Bronze-L mine (pl. 6, A)

	Feet
Kaibab limestone:	
1. Light-gray to cream-colored limestone, in part granular, containing large lumps of chert; hard on fresh surfaces but weathers soft and crumbly; very fossiliferous; sandy near base; thickness incomplete; caps highest points or buttes in dissected surface of Shivwits Plateau	65
2. White sandstone, fine grained and calcareous, interbedded with limestone	20
3. Slope with no outcrops, covered with talus from limestone above; has gray and pink soil containing fragments of fine-grained pink sandstone and gray sandy shale	40
4. Thin-bedded light-gray limestone weathering almost white, in layers 2 to 8 inches thick	8
5. Gray limestone, chiefly heavy bedded, dense to crystalline, lead-colored, with zones of lighter gray; contains bands of chert which give heavy beds a thinner-bedded appearance; hard and resistant, the entire thickness forming a sheer cliff	140
6. Loosely cemented very fine grained yellow to buff sandstone, calcareous cement; bottom 3 to 4 feet forms a reentrant; no clear line of separation from limestone at top	7
7. Very fine grained sandstone with calcareous cement; top beds firm and hard, resemble limestone; bottom 4 to 5 feet, yellow and very loosely cemented, forming reentrant in cliff; buff to gray above	45
8. Heavy bed of hard calcareous gray sandstone; weathers yellow	3
9. Thin-bedded limestone, dense and hard, gray to buff; forms thin plates separated by yellow to gray calcareous shale	3½
10. Heavy bed of hard, fine-grained gray sandstone; has appearance of limestone	2
11. Bright-yellow heavy-bedded sandstone, loosely cemented, fine grained; weathers to short slope	12
	345½
Coconino sandstone: Sandstone, fine to medium grained, gray to yellowish, heavy bedded and very cross-bedded; much of it has thin lamination in cross-bedding; top 2 to 4 feet horizontal bedding, not cross-bedded	40
Supai formation: Red sandstone, in beds, 2 to 12 feet thick, alternating with zones of thin-bedded sandstone, upper 100 feet in heavy beds, with several pink and gray layers, prevailing color brick-red to deep red; some beds are loosely cemented; very fine grained, and slightly argillaceous	1,050

Section of Kaibab limestone 2 miles south of Mud Well

[Unconformity at top, above which is Lower Triassic limestone and gypsum]

	Feet
1. Interbedded gray sandstone and chert	9
2. Light-gray limestone in regular layers 6 to 8 inches thick	6
3. Sandy limestone, hard, but weathering to soft red sandy mass	4
4. Hard gray limestone in heavy beds, abundance of chert, fossils numerous	250
5. Alternating layers of dense limestone and red to yellow sandstone	25
6. Fine-grained soft yellow sandstone	3
7. Gray shale, gritty	6
8. Massive white gypsum and red gypsiferous clay	75
9. Dense, hard light-gray limestone in thin layers	12
10. Sandy limestone in thin layers; weathers yellow	3
11. Hard, heavy-bedded gray limestone, granular to dense, very cherty	160
	553

Red Supai sandstone with regular beds at top but very cross-bedded lower in section. Coconino sandstone not identified in the section.

Section in Pakoon Ridge, 1½ miles north of Black Canyon

[Rocks dip 25° E. beneath lava]

	Feet
Kaibab limestone:	
1. Hard gray limestone in heavy beds, very cherty, fossiliferous; top eroded and thickness incomplete	150
2. Hard fine-grained gray to pink sandstone, heavy bedded	7
3. Fine-grained yellow sandstone, loosely cemented	25
4. Hard fine-grained gray sandstone	10
5. Very fine grained sand, almost uncemented	40
Coconino sandstone: Fine-grained gray sandstone, very cross-bedded, with thin lamination	35
Supai formation:	
1. Fine-grained pink to gray sandstone	25
2. Red sandstone with some gray beds, regular bedding	100
Base of ridge.	

Section in ridge near mouth of Grand Wash (on east side of wash)

[Beds dip 30° E., dip flattens to 20° at north end of ridge]

	Feet
Kaibab limestone; thickness incomplete; eroded top disappears under cover of waste:	
1. Heavy-bedded gray limestone with abundance of chert in lenses and layers	125
2. Red sandstone, coarse grained and loosely cemented; contains angular blocks of limestone locally	25
3. White limestone in thin regular layers	6
4. Hard gray limestone in heavy beds; contains chert in layers and lenses	175
5. Yellow fine-grained sandstone in thin beds; forms bench	3

	Feet
6. Dense gray limestone, very hard, heavy bed; has some chert nodules	30
7. Gray gritty shale; forms reentrant	1
8. Hard fine-grained sandstone; weathers yellow	3
9. Bright-yellow fine-grained sandstone; forms bench	16
10. Heavy bed of fine-grained cross-bedded sandstone	4
11. Gray and pink sandstone, hard and thin bedded	7
12. Fine-grained sandstone with thin lamination	45
	440
Coconino sandstone: Very cross-bedded gray to yellow sandstone, fine to medium grain	75
Supai formation: Regular beds of sandstone, deep red to bright red with gray layers at intervals; base not seen	350
Base of ridge.	

MESOZOIC ROCKS

TRIASSIC SYSTEM

MOENKOPI FORMATION

Distribution and general character.—Resting on the Kaibab limestone and separated from it by an erosional unconformity is a thick series of beds, extremely varied both vertically and horizontally but possessing certain characteristics that identify the formation unmistakably wherever it is exposed. In the Muddy Mountains the lower part of the series is made up principally of limestone in very thin but regular layers, with minor quantities of sandstone, shale, and gypsum. The upper part consists of thick shales, more or less gypsiferous, with less sandstone and limestone. East of the Virgin Valley much of the limestone in the lower part is replaced by gypsiferous beds. The total thickness in Horse Spring Valley is 1,634 feet (615 feet of limestone and gypsiferous beds at base); in the Valley of Fire, west of Logan, 1,598 feet (803 feet of limestone at base); and on the East Fork of Boulder Wash, near Sandstone Spring, 1,221 feet (570 feet of limestone at base). No unconformity was found anywhere within the series.

The topographic expression of these strata is peculiar. Commonly the formation is found in tilted fault blocks or on the limbs of folds, dipping steeply with the Kaibab limestone. The weak shales at the top are beveled to form valley floors, whereas the more resistant limestones expose their edges on the steep slopes of ridges whose tops are invariably the Kaibab. Short, deep V-shaped valleys, ending at the Kaibab and spaced with remarkable uniformity, cut across the edges of the thin limestone layers, forming segments which curve upward as huge arcs and expose every inch of the strata for study. (See pl. 7, *A*.) Excellent sections of this sort flank the ridges extending southward from the Weiser ranch.

This group of strata occupies the same stratigraphic position as the Moenkopi formation of New Mexico, Utah, and Arizona; and inasmuch as it is very similar lithologically to that formation, the name Moenkopi is here extended to include these corresponding rocks in the Muddy Mountains.

Lithology.—The base of the formation differs from place to place. In some sections it appears quite conformable on the Kaibab, and in no place is there any perceptible angular divergence. That an unconformity exists, however, is shown by the local occurrence of a conglomerate which is made up of Kaibab fragments and which in places fills shallow valleys on the top surface of the Kaibab. The best exposure of this basal conglomerate was found 2½ miles south of the Narrows, on the east side of Weiser Ridge, where cemented angular pebbles and boulders of limestone and chert fill a conspicuous valley-like depression at the top of the Kaibab. South of Mud Well the conglomerate has a firm limestone cement and lies in regular beds 2 to 4 feet thick.

Immediately above the unconformity pink or yellow sandstone commonly occurs. The limestones that overlie this sandstone are made up of hundreds or even thousands of thin layers, most of them measured in inches with 4 feet the maximum thickness. Thin layers of calcareous shale are interspersed freely. Gritty limestone layers with ripple marks are common (pl. 6, *B*), and two well-defined zones of cross-bedded fine-grained sandstone resemble beach deposits. Gray is the common color, but some layers of both limestone and shale are bright yellow and others are brick-red. At the top of the lower member most sections have a thick transitional zone occupied by limestone in extremely thin layers, interlaminated with primary gypsum. The shales above are gray, pink, and chocolate-colored, with an abundance of both primary and secondary gypsum. Interbedded brown micaceous sandstone has an abundance of small, regular ripple marks. The shales have thin lamination, contain considerable mica, and are commonly gritty from included fine sand. They end in a distinctly irregular surface overlain by the Shinarump conglomerate.

Probable origin.—The thin limestones at the base of the formation are clearly marine, as shown by included invertebrate fossils. The physical conditions during their deposition, however, must have been somewhat peculiar. Frequent interruption in sedimentation is shown by the thin bedding and the many alternations of limestone with shale and sandstone. That the waters were shallow is shown by the common occurrence of short, regular ripple marks. The formation of limestone in shallow water precludes the presence of high lands in the vicinity, but the many layers of sand and mud testify to low land at no great distance. The occurrence of gypsum near the top indicates temporary partial or complete isolation from the open sea, perhaps in a hot, dry climate. Frequent shifting of strand lines is indicated by recurring beds of cross-bedded sandstone, one of which shows abundant casts of starfishes.

Near the top of the limestones tracks of small reptiles occur in calcareous shale, and these, with the change from limestone to gypsiferous shale and sandstone, indicate the beginning of land conditions. In the thick shales at the top of the formation the numerous irregular layers of cross-bedded and ripple-marked sandstone, the abundance of gypsum, and the prevailing red color suggest lagoon and delta conditions in a dry climate along the margin of a slowly withdrawing sea. Final complete emergence and change from sedimentation to erosion are recorded in the surface of unconformity on which the Shinarump conglomerate was deposited.

Fossils, age, and correlation.—Many of the limestone layers contain an abundance of fossil shells, but good specimens are difficult to obtain, and as a result many identifications are doubtful. Moreover, a large percentage of the fauna is made up of new species. The following lists show the unsatisfactory nature of the fossil evidence.

From Weiser Ridge near Narrows:

Aviculopecten utahensis.
Aviculopecten sp. 1 and 2.
Aviculopecten n. sp.
Pseudomonotis n. sp.
Pseudomonotis sp.
Myalina n. sp.
Myophoria n. sp.
Myophoria aff. M. lineata.
Pleurophorus? n. sp.
Pseudomelania? n. sp.
Starfish impressions.

From ridge north of Summit Canyon:

Aviculopecten sp. 1 and 2.
Pteria n. sp.
Myalina n. sp.

From Sandstone Spring Valley:

Aviculopecten sp.
Pleurotomaria? sp.
Murchisonia? sp.

From St. Thomas Gap near Mud Well:

Aviculopecten utahensis.
Aviculopecten sp.
Myalina sp.
Myalina? n. sp.
Pteria? sp.
Sedgwickia? n. sp.
Pleurophorus? n. sp.
Myophoria sp.
Myophoria n. sp.
Pseudomelania sp.

Girty[32] says:

Most of these collections, and probably all of them, belong in the beds which Walcott identified as Permian in his Kanab Canyon section and which are now, on pretty satisfactory evidence, referred to the Lower Triassic. This is the group of beds that was called "Permo-Carboniferous" in many of the older reports, especially those dealing with the geology of Utah. * * * As this Lower Triassic fauna has never been described, it is not practicable to give lists that describe it in more than a general way.

Finally it can be stated with considerable assurance that the "Permian" of the Grand Canyon region is the same as the "Permo-Carboniferous" of the

[32] Girty, G. H., personal letter, Mar. 11, 1920. See also New York Acad. Sci. Annals, vol. 20, p. 239, 1910.

Wasatch Mountains, and those beds have been traced both stratigraphically and paleontologically into Idaho, where they prove to be the well-known Lower Triassic series from which Smith and Hyatt have described so many genera and species of ammonites, especially ammonites of the *Meekoceras* group. As a matter of fact, I have many ammonites of this type from the "Permo-Carboniferous" of the Wasatch range, others from the San Rafael Swell, and still others from the "Permian" of the Grand Canyon region, though this type of fossils grows rapidly rarer southward.

On the basis of this correlation the unconformity between Moenkopi and Kaibab represents the interval between the Paleozoic and Mesozoic eras. Here, as in other western sections, it is a record of comparatively quiet continental conditions without mountain-making disturbances. Schuchert [33] shows that the Lower Triassic sea was a Pacific invasion reaching eastward into Wyoming and that it gradually withdrew the way it came. Evidence of shallow water and of frequent oscillation of the strand throughout the Moenkopi epoch suggests that the land was at no great distance, and the thinning of limestone with corresponding increase of gypsum and shale toward the south and east indicates that the permanent shore was in that direction. The typical Moenkopi formation of northeastern Arizona consists largely of shale and sandstone, with scant evidence of marine life. In this respect it resembles the upper half of the formation in southeastern Nevada. The Kanab Valley "Permian" more nearly resembles the Moenkopi of this area in its complete development. [34] All descriptions of the formation in New Mexico, Utah, and Arizona show that it is very distinctive in lithologic character and fossil content.

Important new data on the Moenkopi in the plateau region, from field work contemporaneous with that in the Muddy Mountains, have been given by Reeside and Bassler.[35]

Measured sections.—A large number of sections of the Moenkopi were measured. The selections here given show the nature and thickness of the beds in sufficient detail.

Section of Moenkopi formation in Valley of Fire opposite Logan Wash

	Feet
1. Bright-red to chocolate-brown shale, in part sandy, cut by many irregular gypsum-filled joints	400
2. Brown sandstone, medium to coarse grained, in beds a fraction of an inch to 12 inches thick, ripple marked, blackened on exposed surfaces by desert varnish; forms rounded ridge 5 to 10 feet high	60
3. Pink, finely laminated shale, gypsiferous and cut by irregular joints filled with secondary gypsum	175

[33] Schuchert, Charles, Paleogeography of North America: Geol. Soc. America Bull., vol. 20, p. 579, pl. 86, 1909.

[34] Walcott, C. D., The Permian and other Paleozoic groups of the Kanab Valley, Ariz.: Am. Jour. Sci., 3d ser., vol. 20, pp. 221-225, 1880.

[35] 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, 67-77, 1922.

	Feet
4. Thinly laminated gray limestone; weathered portions separate easily into thin, slatelike slabs, but fresh rock is very firm; weathered sections appear gypsiferous; top portion contains thin layers of pink gypsiferous shale	160
5. Very hard, dense yellowish-gray limestone, in beds a fraction of an inch to 18 inches thick; shows fine lamination on weathering; gritty	6
6. Chiefly covered by talus, with outcrop of thinly laminated shaly gray limestone	25
7. Fine-grained, gritty bright-yellow limestone, finely laminated on weathered surface	2⅓
8. Pink and yellow mottled, very arenaceous limestone or limy sandstone; bands average 1 inch thick	12
9. Bright-yellow gritty limestone	2½
10. Yellow and pink, thinly laminated limy shale, containing fine sand; has reptile tracks, rain prints, and abundant dendritic patterns	10
11. Gray to yellowish limestone, thin bedded; bedding shows pulsating tendency; beds several inches to 2 feet thick grade into zones of thinly laminated shaly limestone, and this is repeated several times; ripple marks, even on heavier beds; gritty character common; some fossil sections on weathered surface	55
12. Fine-grained dense limestone, in beds averaging several inches thick; contains narrow zones of thinly laminated shaly limestone; beds near base contain small chert nodules; fossil sections on surfaces	19
13. Pink and yellow limestone breccia; weathers to earthy, porous mass	9
14. Bright-yellow, pink, and brick-red shaly limestone; weathers easily	50
15. Firm red limestone; has gritty feel	3
16. Thin-bedded gray limestone; some zones thinly laminated, others contain firm beds 1 to 3 feet thick; all beds are fine grained and firm when fresh; color gray when fresh but on weathered surfaces changes from yellow to pink and purple, giving a splotched and streaked appearance; some beds contain abundance of fossils, but none come free readily	102
17. Yellow to pink limy shale	6
18. Thin-bedded gray limestone weathering to yellow	3
19. Gray limy shale, thinly laminated	12
20. Limestone, single bed, dense	1
21. Limy shale, gray	17
22. Gray limestone, thinly laminated in part, with two beds each 1 foot thick	8
23. Thinly laminated gray limy shale	5
24. Limestone, dense, single bed	⅓
25. Thinly laminated gray limestone, gritty	2
26. Thinly laminated limy shale with thin layers of limestone	12
27. Gray to pink dense gritty limestone, single bed, very fossiliferous	1
28. Thinly laminated fine-grained calcareous sandstone	11

	Feet
29. Thin-bedded gray limestone interbedded with soft calcareous shale	18
30. Thinly laminated fine-grained calcareous sandstone; contains abundance of starfish casts	9
31. Limestone layer, 2 to 20 inches thick, interbedded with soft sandy shale; limestone fossiliferous	12
32. Thin-bedded calcareous fine-grained sandstone	3
33. Interbedded thin calcareous sandstone and soft shale.	4
34. Dense, hard, sandy limestone, very fossiliferous	3½
35. Interbedded thin limestone and soft shale	5
36. Dense, hard, gritty limestone, finely crystalline in places, fossiliferous	4
37. Interbedded thin layers of sandy limestone and soft gray shale	55
38. Thin-bedded gray sandy limestones	19
39. Thin-bedded fine-grained calcareous sandstone, pink on weathered surfaces	6
40. Gray gritty limestone, in beds 2 to 12 inches thick; some beds fossiliferous	12
41. Thin-bedded fine-grained sandstone, like No. 39, ripple marked	2
42. Interbedded thin limestone layers and gray shale	10
43. Sandstone, like No. 37, ripple marked	3⅔
44. Gray limy shale	3
45. Dense gray gritty limestone in layers 2 to 12 inches thick	4
46. Pink soft shale	3
47. Brick-red fine-grained calcareous sandstone; shows thin lamination on weathered edge	1½
48. Interbedded thin gray limestone and soft gray and pink sandy shale	11
49. Dense, resistant gray limestone in beds 3 to 10 inches thick	10
50. Very thinly laminated gritty calcareous shale with gypsum beds; weathers to form low trough behind limestone wall	90
51. Resistant gray limestone, in beds 1 to 7 inches thick	3
52. Thin-bedded gray sandy limestone; weathers brown	1
53. Thinly laminated brown calcareous shale, with bands and spots of green	18
54. Heavy-bedded pink sandy limestone	11
55. Brown and pink calcareous gritty shale; contains gypsum beds	50
56. Pink to pinkish-gray limestone; very firm and dense when fresh, but some layers weather to soft clayey substance; some beds gritty; heavy beds, 2 to 8 inches thick, separated by thinly laminated zones; beds near base contain many nodules and lenses of gray chert; bottom beds are brecciated	58
	1,598

Dense, resistant, heavy-bedded Kaibab limestone, with abundance of chert. The unconformity between Kaibab and Moenkopi formations in this section is very inconspicuous.

Section of Moenkopi formation in Sandstone Spring Valley

		Ft.	in
1.	Brown gritty shale and limy sandstone layers	30	
2.	Pink gritty clay with very thin layers of brown fine sandstone	20	
3.	Brown conglomeratic sandstone with calcareous cement	2	
4.	Gray gypsiferous clay	10	
5.	Coarse gray sandstone, thin bedded and cross-bedded	10	
6.	Fine calcareous sandstone, hard		6
7.	Brown gritty shale, thinly laminated, with a few thin layers of hard calcareous sandstone; some thin green layers	50	
8.	Pink gritty clay shale, thinly laminated; contains many very thin layers of calcareous green to gray sandstone	200	
9.	Similar to above but with no sandstone except a few brown layers near base	205	
10.	Brown clay, gypsiferous, interbedded with many thin layers of brown sandstone	90	
11.	Gray sandstone, medium grained	2	
12.	Brown platy sandstone and gritty shale	20	
13.	Pink shale, gritty, with thin beds of gray gypsum and gypsiferous sandstone	40	
14.	Thinly laminated gray limestone interlaminated with gypsum; contains thin beds of pink shale near top	100	
15.	Gray limestone, dense, in beds averaging 2 inches thick, regular bedding; has white gypsum along bedding planes and in numerous joints; beds become heavier near base; yellow gritty beds included near base; some beds strongly ripple marked	65	
16.	Dense, gritty yellow limestone in beds 4 to 8 inches thick	5	
17.	Dense gray limestone, thickest beds 12 inches thick; some beds contain chert nodules; many beds are gritty	30	
18.	Yellow dense, gritty limestone, in beds 1 to 6 inches thick	4	
19.	Thinly laminated gray shaly limestone	1	4
20.	Thinly laminated gray limestone, firm	3	
21.	Dense gray limestone		6
22.	Pink gypsiferous clay interbedded with thin gray limestone	9	
23.	Gray to yellowish limestone, firm; layers average 1 inch thick; at base interbedded with thin layers of pink gypsiferous clay	5	
24.	Gray limestone, dense and finely crystalline, beds 2 to 10 inches thick	2	6
25.	Yellow calcareous shale		8

	Ft.	in.
26. Dense to finely crystalline limestone; regular beds 2 to 12 inches thick; near base thin layers of yellow shale are interbedded	10	
27. Heavy bed of gray limestone; weathers to yellow; sections of fossils show on weathered edges of bed	4	6
28. Dense gray limestone in beds 2 to 12 inches thick, very fossiliferous	5	
29. Yellow calcareous shale with thin beds of yellow and gray limestone	19	
30. Fine gray calcareous sandstone; forms thin plates	2	
31. Calcareous sandstone and gritty clay	4	
32. Thinly laminated gray fine-grained sandstone	5	
33. Gray dense limestone in thin platy layers	1	8
34. Gray gypsiferous clay with thin layers of gray limestone	5	
35. Dense gray limestone		10
36. Yellow calcareous clay	3	
37. Gray limestone, heavy bed with thin partings showing on weathered surface	3	
38. Yellow calcareous clay	2	6
39. Thinly laminated fine-grained gray sandstone		10
40. Purple and gray shale	3	
41. Gritty yellow sandstone with shaly lamination		8
42. Purple gritty limestone, thin bedded	1	4
43. Yellow and purple gritty limestone	10	
44. Fine-grained gypsiferous sandstone and gritty clay, brown and gray	9	
45. Gray gritty limestone		4
46. Sandy gypsum with thin layers of yellow gritty limestone	5	
47. Gray gritty limestone		3
48. Pink and purplish clay shales with many thin beds of bluish and pure white gypsum	230	
	1,221	
Heavy-bedded cherty gray Kaibab limestone; exposed	225	

Section of Moenkopi formation in Horse Spring Valley

	Ft.	in.
Shinarump conglomerate.		
1. Yellow to brown gritty shale, little exposed	30	
2. Gray sandstone, medium to fine grained, in layers 2 to 12 inches thick, the thicker layers cross-bedded, with thin, irregular lamination; sand is quartz cemented with calcium carbonate; interbedded with gray shale, gritty and probably calcareous, weathering to loose clay	75	
3. Lime conglomerate; pebbles of sandstone and limestone more or less rounded, largest 1 inch long, fine and coarse in flat lenses, fingering together; quartz sand in matrix	3	
4. Gray calcareous shale grading downward into pink clay shale	6	

	Ft.	In.
5. Pink and brick-red clay shale, gypsiferous, with many thin layers of gray and bluish-gray fine-grained muscovitic sandstone, regularly laminated	425	
6. Fine-grained brown quartz sandstone, cross-bedded on small scale within layers 2 to 4 inches thick; shows well-defined strike joints 2½ feet apart and local dip joints	2	6
7. Brown shale; weathers in small flakes	4	
8. Gray quartz sandstone, firm, cross-bedded, single layer		5
9. Brown gritty shale	14	
10. Sandstone with fine, even quartz grains, loosely cemented, heavy bedded, with small cross-bedding	35	
11. Pink gritty gypsiferous clay, with thin beds of gray sandstone, fine grained and muscovitic, a few thin layers of gray gypsum	95	
12. Alternate beds of pink gypsiferous clay and thin-bedded gray gypsum; beds average 4 feet thick; gypsum beds consist of interlaminated thin gray gypsum and gray to pink clay shale	80	
13. Interbedded gray gypsum, thinly laminated, and hard thin-bedded limestone, which weathers white	25	
14. Interbedded gray calcareous shale, gray thinly laminated gypsum, and thin-bedded white limestone	175	
15. Fine-grained gray quartz sandstone with lime cement; layers 2 inches thick		8
16. Gray calcareous shale	10	
17. Hard gray limestone, single layer		8
18. Gray calcareous shale; probably contains gypsum	35	
19. Hard gray limestone; shows sections of fossils		4
20. Gray calcareous shale	3	
21. Interbedded thin layers of hard gray limestone, in part gritty, and gray calcareous shale	26	
22. Hard gray limestone, in beds 3 to 6 inches thick, separating into thin slabs when weathered	5	
23. Dense limestone weathering white; heavy bed with thin lamination lines on surface	3	
24. Gray limestone, dense, separating into extremely thin, regular slabs	4	
25. Dense gray limestone weathering white and yellowish, in beds 1 to 8 inches thick	8	
26. Lime conglomerate		8
27. White limestone, becoming gypsiferous near base, thinly laminated	10	
28. Gray gypsum with some interbedded gray gypsiferous shale, thinly laminated	65	
29. Hard gray limestone, in layers 6 to 10 inches thick, yellowish calcareous shale interbedded	15	
30. Interbedded white limestone, yellowish-gray calcareous shale, and gray gypsum, all thinly laminated	60	

	Ft.	in.
31. Similar to above but predominantly pure-white and gray gypsum with interbedded pink clay, which gives the whole a pink appearance on outcrops	60	
32. Covered with waste, with scattered outcrops of gray bedded gypsum, evidently occupied by gypsum in the main	150	
33. Massive gray gypsum, base of above, preserved by harder rock below	7	
34. Thinly laminated carbonaceous limestone; weathers black, resembling coal; has strong odor; some gypsum interbedded	7	
35. White and gray massive gypsum, a few pink zones, impure with clay, also some impure limestone layers. Base covered with waste	110	
36. Hard gray to white limestone, dense to finely crystalline; beds average 12 to 15 inches thick	10	
37. Soft gypsiferous limestone	6	
38. Hard fine-grained sandstone with rich lime cement; very irregular small lenses of white and buff, interfingering; passes into limestone below, without break	8	
39. Hard light-gray to almost white limestone; some beds weather buff; layers 8 inches to 6 feet thick; contains abundant globular and lens-shaped chert nodules; sections of brachiopods on surfaces	35	
40. Massive gray gypsum discolored by included pink clay	25	
Kaibab limestone.		
	1,634	

SHINARUMP CONGLOMERATE

Distribution and general relations.—South of the Narrows of Muddy Creek and near the west side of the Valley of Fire the nearly smooth floor is broken by a discontinuous ridge 10 to 40 feet high, consisting of conglomerate and conglomeratic sandstone in layers which dip 60° W. Similar beds occur near the Arrowhead road in the east-west limb of the Valley of Fire. In Weiser Valley the conglomerate beds are vertical and project 20 to 30 feet above the softer formations as a wall 30 feet wide. Some phase of this conglomerate is present wherever the Triassic rocks are exposed. At many places where no visible outcrop occurs the horizon is marked by weathered-out pebbles lying on the surface, and where no genuine conglomerate is present a coarse conglomeratic sandstone takes its place. It is one of the most persistent deposits in the region, although its thickness is nowhere greater than 200 feet, and in some sections it is less than 10 feet thick.

This formation at once suggests the Shinarump of Arizona and Utah, because of its stratigraphic position and general appearance.

Detailed study leaves no doubt that this is the proper correlation. The conglomerate rests on a surface of erosional unconformity and thus marks the division between the Moenkopi formation and the Upper Triassic shales, just as it divides the DeChelly sandstone from the Chinle formation in the Navajo country and Walcott's so-called "Permian" of Kanab Valley from higher Triassic beds.

Composition and structure.—In its most typical development the Shinarump begins with a conglomerate layer made up of rounded pebbles of quartzite, quartz, and chert, with a minor amount of sand in the interpebble spaces and a cement of brown iron oxide. West of Logandale this layer is about 10 feet thick, but the thickness varies along the strike. The pebbles average nearly 2 inches in diameter, and many of them have been shattered by rock movements since their deposition. Above this layer there are interfingering lenses of finer conglomerate and coarse gray sandstone. The following description by Gregory[36] was written for the Shinarump of the Navajo country but is equally accurate for the formation in southeastern Nevada:

> The Shinarump is everywhere lenticular; lenses of conglomerate overlap lenses of coarse or fine sand, and plasters of pebbles many feet in area or long, narrow cobble pavements appear and disappear within the formation in a capricious manner. Cross-bedding is characteristic; short laminae meet each other at large angles, and longer beds form smaller angles with the horizon. * * * In many places pebbles are irregularly grouped like raisins in a pudding, and here and there lines of pebbles one-sixteenth inch to 2 inches in diameter simulate strings of beads.

Silicified wood is present throughout the formation. Chunks and logs lie at all angles in the cross-bedded sandstone. Small fragments, some apparently water worn, occur as pebbles. In the upper 30 feet logs are especially abundant. Most of the trunks are fragmentary and short, but some have a length of 30 feet. This part of the formation is a coarse sandstone, but it lacks the conglomeratic character of the lower beds. The sand grains are gray, but the cement has a green tint. About the logs there are irregular splotches of yellow, brown, and red.

Conditions of deposition.—The origin of the Shinarump conglomerate has been much discussed, but no general agreement has been reached. In the Muddy Mountains the formation presents the same problems as in Arizona, and the solution of the general problem must now take account of this increase in the area of the known distribution of the conglomerate. The following points are worthy of note:

1. The Shinarump conglomerate is now recognized from western New Mexico to the Muddy Mountains of Nevada, a distance of more than 300 miles.

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[36] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, p. 39, 1917.

2. Although it has many local variations, its general characteristics are remarkably constant. It is significant that the same description fits equally well the most eastern and the most western known exposures.

3. The materials of the conglomerate in the St. Thomas quadrangle may have been derived, in large part, from the Coconino and Supai sandstones and from the chert in the Kaibab limestone, provided those formations were exposed at the time the conglomerate was laid down.

4. Although the formation reaches a maximum thickness of more than 200 feet, this is exceptional. Locally it thins to almost nothing, and the average is not more than 50 feet.

5. Apparently the materials were deposited on a moderately irregular surface.

It is suggested that the formation represents deposition by slope wash and temporary streams, in a wide interior region with moderate relief and arid or semiarid climate.

CHINLE FORMATION

Distribution and general character.—The variegated shales and sandstones above the Shinarump conglomerate correspond in stratigraphic position and in lithologic character to the Chinle formation of the Navajo country,[37] and the same name will be used for the series in the Muddy Mountain region. Thicknesses obtained in measured sections differ as follows:

	Feet
Near Sandstone Spring	785
Horse Spring Valley	741
Valley of Fire:	
Near White Basin fault	1, 167
Near Overton Wash	3, 050
West of Logandale	2, 975

These measurements indicate a continuous thickening toward the north and west, amounting to more than 2,000 feet in 20 miles. Study of measured sections discloses also marked changes of general lithologic character in the same directions.

In general the formation is characterized by the following features:

1. It grades upward from the Shinarump conglomerate in all sections, with no sign of unconformity. In fact, the Shinarump conglomerate might be considered the basal member of the formation.

2. The formation is a series of shales, marls, sandstones, and gypsum beds, all of which change greatly from place to place, but the aggregation of beds forms a unit very similar in all sections.

3. Silicified wood similar to that in the Shinarump conglomerate is found in several members of the Chinle formation. This is true of no other series of beds in the area.

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[37] Gregory, H. E., op. cit., pp. 42–48.

In all sections shales of many colors make up the larger part of the formation, but the relative amounts of shale and sandstone vary within wide limits from place to place. Much of the shale contains considerable fine sand, and all thick shale members have many thin layers of sandstone; but if only the sandstone layers recognized specifically in measured sections are considered, the proportion of sandstone to shale varies as follows:

West of Logandale	1:10
Near Overton Wash	1:10
Near east end of Valley of Fire	1:3
Sandstone Spring Valley	1:2

Therefore, in general, the percentage of shale increases with the thickness of the section. In all the thinner sections sandstone layers are well defined, many are coarse or conglomeratic, and their superior resistance exaggerates their apparent importance with relation to the shale. The sand layers are either lenticular or wedge-shaped, interfingering with the shales, but many of the more extensive beds change in thickness almost imperceptibly.

Details and peculiarities.—In the section opposite Logandale bright colors are conspicuous, and in the shale beds immediately succeeding the Shinarump conglomerate colors are oddly mixed, yellow, pink, green, and purple alternating in bands and patches. This shale is muscovitic and contains an abundance of calcium carbonate, a distinct characteristic also of a lavender zone at a higher horizon. Flakes of muscovite are common in both the shales and the sand layers at this locality. The large proportion of shale is indicated by the measured section, but it should be noted that much of this shale contains fine sand in considerable quantities, and thin layers of fine-grained sandstone are very common. Limestone layers included in the chocolate-colored shales and sandstones are lead-colored, dense, and hard, and although the layers are thin they are very regular. In the thicker sandstone layers cross-bedding on a small scale and small ripple marks are common. Gypsum is found at many horizons but is most abundant in the upper portion. A thick bed of nearly pure gypsum near the top extends with uniform thickness for several miles. (See pl. 7, *A*.)

In the section on the old Arrowhead road sandstone layers are the most conspicuous part of the formation. Cross-bedding is common, indicating currents in shallow water at the time of deposition. An alternation of coarse-grained sandstones with clay shales also records rapid changes in conditions of sedimentation. Massive sandstone layers with grains of uneven size, most of them conglomeratic and containing a rich lime cement, are repeated many times in the section. Thin conglomerate layers with small pebbles mainly of chert may be termed limestone conglomerates because of a firm calcareous matrix that makes up a considerable percentage of the rock. Fine-grained micaceous sandstone layers are intricately cross-bedded on a small scale. Silicified trees, embedded in clay shale or fine sandstone, lie on top of coarse sandstone layers. A conspicuous lavender bed of clay rich in calcium carbonate is notably persistent, and near its base it includes a layer of chert which locally has the translucence of chalcedony.

In all sections the top part of the formation consists of pink sandy shales and sandstones, but this zone thins perceptibly toward the south and east. Between the Chinle formation and the overlying Jurassic (?) sandstone there is no sharp lithologic break. In the transition zone beds of red sandy shale alternate with layers of fine-grained red sandstone, which become thicker and more numerous until sandstone is continuous. In some sections the division between the two formations may be made on the basis of color. Deep-red sandstone, regularly bedded, changes abruptly to brick-red sandstone that has the cross-bedding characteristic of the Jurassic (?) formation. The plane or thin zone below which variability in material and structure is the rule and above which both material and structure become uniform is plainly visible wherever the formations are exposed.

Age and correlation.—Except petrified wood no fossils were found in the Chinle formation, and its correlation is therefore based chiefly on lithology and relations to known strata. Its position with reference to the Shinarump conglomerate and the general character of the beds leave little doubt that the series corresponds very closely to the Chinle formation of the Navajo country, which is considered to be Upper Triassic. The section on the Arrowhead road also has many points of resemblance to the Dolores formation of southwestern Colorado.

Conditions of deposition.—Aridity during Chinle time is suggested by the prevailing red color of the shales and sandstones and by the abundance of gypsum. All the sediments, however, show evidence of deposition in water, the thinly laminated shales, in places ripple marked, testifying to broad, shallow bodies of water, whereas the coarse, cross-bedded sandstones indicate streams or strong currents. The regional arrangement of the deposits, by which the texture grows finer and the thickness greater toward the north and west, suggests a highland source somewhere to the south and southeast, from which the sediments were distributed toward the Upper Triassic Californian sea as broad fans and deltas. Basin or lagoon conditions are indicated by the gypsum layers, particularly by the extensive layer of very regular thickness near the top of the formation. Some of the silicified trees may have grown beside the stream courses or lagoons near their present positions, whereas others were logs carried down by streams and buried in the accumulating sand and mud.

MEASURED SECTIONS

Section in the Valley of Fire, near the White Basin fault

Contact with cross-bedded Jurassic (?) sandstone conformable. Apparent unconformity caused by series of minor faults which cross the bedding (direction of faults approximately magnetic north). Faults offset contact 10 to 100 feet, giving steplike appearance to line of contact.

Chinle formation:	Feet
1. Brick-red to reddish-brown fine-grained sandstone, in beds a fraction of an inch to 12 inches thick, separated by thin layers of red gritty shale; small circular spots of bluish white near bottom of series	85
2. Heavy bed of medium to coarse grained sandstone; has lenses and streaks of bluish white; cross-bedding on small scale	12
3. Chiefly brick-red shale with interbedded red sandstone layers; gritty clay shale is predominant material in beds 10 to 30 feet thick, thinly laminated, micaceous, weathering to gritty red clay; contains seams and bunches of gypsum along bedding and in north-south joints; interbedded sandstones are fine to medium grained, beds 1 to 5 feet thick	400
4. Firmly cemented medium-grained red sandstone, single bed; gypsum in thin irregular seams	4
5. Chocolate-brown gypsiferous gritty shale, containing many round bluish-white spots, gypsum seams ⅛ of an inch to 1 inch thick along bedding, also crossing irregularly; shale shows thin lamination on unweathered edges; elsewhere bedding is indistinct and material has nodular form; seams of gypsum in the main are roughly parallel to strike of beds and dip at slightly greater angle; gypsum increases near base of horizon	270
6. Light-brown medium-grained sandstone, in part slightly cross-bedded, in the main thinly laminated, but some beds 12 inches thick	50
7. Gray conglomerate, pebbles mainly gray and pink chert, worn but not rounded; most pebbles are a fraction of an inch in diameter, a few as large as 2 inches; conglomerate contains many lime concretions which show concentric sections on weathered surface; cement is lime, very dense and firm	3
8. Purple limy clay or marl; weathers to loose, powdery soil	30
9. Chert, gray to pink, in part chalcedony, persistent layer	1
10. Clay shale, yellow to purplish	5
11. Coarse gray sandstone, firmly cemented; silicified logs 15 to 33 feet long lie on surface	5

	Feet
12. Medium to coarse brown sandstone, slightly cross-bedded, upper 10 feet shaly; true beds in lower portion are massive with some thin lamination; contains many round white spots	25
13. Purple and gray limy shale, similar to No. 8	25
14. Gray sandstone, coarse grained, in part conglomeratic with small chert pebbles; some cross-bedding; similar in composition to No. 11	20
15. Gray shale weathering to gritty clay	20
16. Coarse gray sandstone, conglomeratic, in beds 1 to 4 feet thick, slightly cross-bedded; contains pebbles of gray chert, partly rounded, as much as 1 inch in diameter	30
17. Gray sandy shale	30
18. Gray medium-grained sandstone weathering brown, cross-bedded on small scale, interbedded with layers of loose gray sandstone 2 to 5 feet thick, which weather back and are covered by talus of firmer sandstone layers; near base cross-bedding has thin lamination, giving slabs of sandstone ⅛ to ¼ of an inch thick	50
19. Coarse gray sandstone, heavy bedded and cross-bedded; in part has bands of greenish gray, apparently colored by solutions along bedding planes; contains small pebbles of chert and translucent quartz	25
20. Gray clay shale	10
21. Coarse gray sandstone, similar to No. 19, in part cross-bedded	35
22. Gray to brown shale, interbedded near top with cross-bedded brown sandstone which has thin lamination in cross-bedding	32
	1, 167
Shinarump conglomerate: White to gray massive cross-bedded sandstone; has layers and lenses of quartzite and chert pebbles; contains fragments of silicified wood; layer at base 4 to 10 feet thick contains many well-rounded quartzite pebbles up to 3 inches in diameter; slabs and small rounded fragments of wood plentiful among pebbles	41
Moenkopi formation: Brick-red gypsiferous shales ending at top as thin beds of chocolate-brown conglomeratic sandstone; contains many thin layers of gray and red fine-grained sandstone	300

Repetition of beds to south due to anticlinal structure.

Generalized section in Valley of Fire near head of Overton Wash

Jurassic (?) red sandstone, dipping 40°–50° E.

Chinle formation:	Feet
1. Brick-red gypsiferous shales, with many thin layers of red sandstone; bed of gypsum 25 feet thick 150 feet below top; many thin seams of gypsum fill irregular joints	1, 750

	Feet
2. Dark-red to brown gypsiferous shales, with many layers of brown sandstone; layer of gray sandy limestone near top; cut by many irregular seams of gypsum	1,000
3. Nearly all covered by waste, but evidently yellow to red gypsiferous shale and soft sandstone	300
	3,050
Shinarump conglomerate: Gray sandstone containing layers of coarse sand and small quartzite pebbles, shaly layer 100 feet below top, at base 20 feet of conglomerate, containing mainly quartzite pebbles, up to 2 inches in diameter; this portion weathers brown; near top a band several feet wide has green spots, similar to bed containing silicified wood opposite Logandale	250

Section in Horse Spring Valley

	Feet
Typical brick-red cross-bedded Jurassic (?) sandstone; largely weathered down and covered with waste	325
Chinle formation:	
1. Brick-red to deep-red clay shale, in part gritty, with a few thin beds of red and gray sandstone; in large part clay is gypsiferous and has irregular seams filled with secondary fibrous gypsum; largely covered with waste	230
2. Wash with no outcrops	250
3. Yellow clay shale, in part gritty	75
4. Purplish and gray marly shale, sandy near base; weathers to loose limy soil	40
5. Gray sandstone, heavy bed, coarse quartz sand loosely cemented with calcium carbonate; contains bunches of finer sand, brown to purple	5
6. Fine sandstone, gray and purplish brown; weathers to small angular pieces the size of peas	3
7. Gray sandstone, like No. 5, cross-bedded, with layers one-fourth to one-half inch thick in cross beds; ranges from fine to coarse grained; has brown splotches not related to bedding; contains considerable muscovite; browner near base	6–7
8. Brown gritty shale	8
9. Brown sandstone, quartz grains of various sizes, muscovitic; has small gray lenses; heavy bedded, loosely cemented and crumbles easily	18
10. Purplish-brown limy shale with gray splotches, in part gritty	12
11. Brown sandstone, similar to No. 9	7
12. Gray sandstone, similar to No. 5	1
13. Gray clay shale, calcareous, with yellow splotches	8
14. Brown, purple, and gray calcareous shale; weathers to loose clay	35
15. Gray and brown quartz sandstone, muscovitic, colors irregularly blended	12

	Feet
16. Purplish calcareous shale, containing considerable fine sand	30
	741
Shinarump conglomerate: Gray sandstone, slightly cross-bedded; has quartz grains of irregular size and contains chert and quartz pebbles, also some of quartzite, in rows and scattered irregularly; pebbles well worn, largest 1 inch long	3

Section in Sandstone Spring Valley

Chinle formation:	Ft.	In.
1. Deep-red sandstone, thin bedded, fine to medium grained; has sharp, conformable contact with the Jurassic sandstone; some of the thicker layers are slightly cross-bedded, near top some efflorescence of salts on edges of beds	30	
2. Deep-red gritty clay, same color as overlying sandstone, with many thin sand layers; shows gradation into overlying sandstone	60	
3. Deep-red sandstone with whitish spots, in beds 2 to 10 inches thick; some interbedded gritty shale in thin laminae	35	
4. Deep-red to pink clay shales with thin interbedded sandstone layers, gypsiferous near bottom	120	
5. Purplish-brown sandstone, poorly indurated, heavy bedded, grading downward into chocolate-colored gritty shale; cut by numerous irregular seams of white gypsum	65	
6. Brick-red to brown sandy clay, very gypsiferous; contains a few thin layers of brown sandstone	200	
7. Dense, hard gray limestone		5
8. Brick-red gritty gypsiferous clay	75	
9. Brown conglomerate; contains chert and quartz pebbles, well rounded to subangular, most of them one-fourth to one-half inch in diameter	1	
10. Brown conglomeratic sandstone, containing pebbles of chert one-fourth of an inch to 3 inches in diameter	5	
11. Brick-red gypsiferous clay	20	
12. Purple limy clay or marl	15	
13. Coarse gray sandstone, poorly cemented, layers half an inch to 2 inches thick	3	
14. Coarse brown sandstone, loose, here and there a gray layer; layers average half an inch in thickness	2	
15. Brick-red clay	3	
16. Coarse brown sandstone, poorly cemented, layers 1 to 2 inches thick	6	
17. Pink gypsiferous gritty clay with some thin layers of brown sandstone	28	
18. Green, pink, and gray sandstone, poorly cemented	5	

	Ft.	in.
19. Gray gritty clay; weathers to small hard lumps	12	
20. Covered with waste, gray and brown sandstone and pink gypsiferous gritty clay showing in a few outcrops	100	
	785	
Shinarump conglomerate:		
1. Coarse gray sandstone, loosely cemented, quartz grains	4	
2. Similar to above, color light green	3	6
3. Coarse gray sandstone, quartz grains, conglomeratic, quartz and chert pebbles the size of a pea in some beds	15	
4. Red to brown gritty clay	14	
5. Gray and green sandstone, quartz, medium to coarse grained; some layers weather to thin plates; cross-bedding in one layer 10 inches thick	21	
6. Green sandstone, coarse, heavy bedded, some cross-bedding	12	
7. Gray sandstone, platy	10	
8. Coarse quartz sandstone, gray to greenish, conglomeratic, with small black, gray, and yellow chert pebbles, cross-bedded	17	
9. Green conglomeratic sandstone	4	6
10. Brown conglomeratic sandstone, in regular layers 2 to 10 inches thick	4	
11. Green to gray fine-grained sandstone in very thin plates; some ripple marks	14	
12. Brown conglomeratic sandstone, similar to No. 10	3	6
Shale of Moenkopi formation.	122	6

Section in Valley of Fire immediately west of Logan Wash

Contact with Jurassic (?) red sandstone is conformable. Beds are practically vertical at contact, but in places they dip 80°–85° E.

	Feet
Chinle formation:	
1. Alternating red gritty shale and fine-grained red sandstone in beds 2 to 8 feet thick	40
2. Pink sandy shale with thin white gypsiferous layers; weathers to red sandy clay	60
3. Pure massive white gypsum	25
4. Brick-red gypsiferous sandy shale containing beds of nearly pure gypsum	200
5. Yellow to brick-red shale, in part sandy and containing many beds and thin layers of fine-grained red sandstone; contains many gypsiferous layers, and throughout there are numerous irregular joints filled with secondary gypsum; very weak formation, weathering to sandy clay; beds practically vertical	1,700

	Feet
6. Dark chocolate-colored sandstone and sandy shale, gradual transition in color between this and next higher bed; contains many layers of dense dark-gray limestone 2 to 5 inches thick; layers of sandstone are 1 to 12 inches thick	250
7. Brick-red sandy shale and argillaceous sandstone	200
8. Lavender limy clay or marl weathering to loose soil	50
9. Covered mainly by waste; some outcrops of red sandy shale	400
10. Variegated sandy shale, containing streaks or lenses of greenish, purple, and red	50
	2, 975

Shinarump conglomerate:	
1. Loose, coarse-grained greenish-gray sandstone, containing abundance of silicified logs 10 to 20 inches in diameter and 10 to 25 feet long; around logs sandstone has spots of bright yellow, brown, and red	30
2. Heavy-bedded gray coarse-grained sandstone, highly cross-bedded; contains lenses and rows of quartzite and chert pebbles, most of them ranging from one-eighth to three-fourths of an inch but some an inch in diameter; grows coarser and more conglomeratic toward base; contains many fragments of silicified wood and some large logs; with underlying conglomerate forms prominent ridge 10 to 50 feet high	200
3. Conglomerate, made up chiefly of well-rounded quartzite pebbles from a fraction of an inch to 2½ inches in diameter, cemented by brown iron-stained sand; some chert and quartz pebbles, also well smoothed; pebbles badly shattered	10
Shale of Moenkopi formation.	
	240

JURASSIC (?) SYSTEM

CROSS-BEDDED SANDSTONE

Distribution and general character.—The most striking rock formation in the Muddy Mountains is a massive sandstone which, because of its predominantly red color and the unusual forms produced by its dissection, stands out prominently in the setting of gray furnished by limestone masses and surface waste. The most prominent outcrop starts 6 miles southwest of St. Thomas and extends in a broad arc west and north almost to the Narrows, covering an area 18 miles long, with an average width of 2 miles. There are several smaller exposures of the sandstone in the southern part of the St. Thomas quadrangle in the valley of Bitter Creek, on the slope south of Muddy Peak, and near the head of Boulder Wash. East of Virgin River it is conspicuous in St. Thomas Gap and Horse Spring Valley.

In its principal physical features this sandstone is little different from red sandstones found in many other parts of the Southwest. The formation was classed by early geologists as Triassic, presumably because of lithologic features that resemble those of rocks known as Triassic elsewhere. It has a nearly uniform bright-red color; it is universally cross-bedded, usually on a large scale; and it is carved by the weather into spires, castlelike masses, doorways, and grotesque figures resembling animals. These are features common to heavy red sandstones in many Western States. In its distinctive lithology and its stratigraphic position the sandstone in southeastern Nevada evidently corresponds closely to the Wingate, Todilto, and Navajo formations farther east, which were formerly correlated with the La Plata sandstone of southwestern Colorado but which are now believed to be in large part older than the La Plata and are classified by the United States Geological Survey as Jurassic (?). In this report, therefore, the formation will be referred to as the Jurassic (?) sandstone, without any definite formation name.

Composition, texture, and structure.—The sandstone exhibits remarkable uniformity in texture and structure through great thicknesses. Typically it is a medium to fine grained quartz sand with minor amounts of feldspar and rare minerals, cemented with red oxide of iron and calcium carbonate. With magnification the grains of the typical massive sandstone have a frosted appearance and are seen to be dominantly rounded or bean-shaped. Weathered outcrops have a laminated appearance. No ripple marking is apparent. In many exposures cross-bedding is not tangential, but the false beds are straight and meet the true bedding planes at high angles. Tangential cross-bedding occurs, however, and is the rule in some sections. In Overton Wash, particularly in the lower half of the sandstone, the false beds appear as great sweeping arcs that converge along a common plane. Other examples of the tangential type of bedding may be found near the Valley of Fire immediately south of Overton Wash.

The general uniformity of the sandstone causes variations to stand out with startling prominence. Any change in color is visible at a long distance. In a number of sections there are large lenses and irregular bodies of white or pale-yellow sand within the red. As a rule these bodies are not different in other features from the typical red sandstone, and they finger and blend with the red without any apparent relation to bedding. The most conspicuous of these variations occur about midway in the formation, beginning near the headward branches of Little Bitter Wash and extending 2 or 3 miles to the northwest. Hills and ridges more than 200 feet high are formed partly or wholly of pale-yellow sandstone. There is no sharp line of demarkation from the sand of red color, and the two blend below, above, and along the strike of the formation. Near the top of the formation on both sides of the Arrowhead road there are smaller and equally irregular lenticular bodies of purple and variegated sandstone.

In two areas of considerable extent the lighter hues predominate over the red. Near the east end of Sawtooth Ridge an abrupt change occurs, the typical brick-red of the sandstone around Red Bluff Spring giving place to gray and almost white along the strike of the formation. Over an area of more than a square mile the only red color occurs in scattered thin layers or in irregular splotches, and yet the deposit is undoubtedly continuous both north and south, where brick-red is the universal color. In Muddy Peak Basin there is a similar occurrence on a large scale. (See pl. 7, *B*.) At least half of the sandstone exposed under the overthrust plate is gray or has a delicate purplish-pink tint. Within the light-colored areas the typical brick-red color appears locally, and on the north side of Muddy Peak the thin layers in the cross-bedding alternate between gray and red or pink. Abrupt changes from prevailing gray to brick-red occur both vertically and laterally. There is no reasonable doubt that this sandstone beneath the overthrust is the Jurassic (?), although there is no fossil evidence, and no older Mesozoic formations are exposed to assist in the correlation. The sandstone of Muddy Peak Basin has all the typical characteristics of the Jurassic (?) sandstone—the cross-bedding, locally tangential on a huge scale, the appearance of thin lamination in the false bedding, the abundance of "sandstone marbles," and a tendency to yield fantastic sculptured forms. From 700 to 800 feet of the sandstone is exposed under Muddy Peak, and no consistently cross-bedded sandstone in the region has this thickness except the Jurassic (?). Correspondence to the peculiar lithology of the Jurassic (?) sandstone is so exact that the correlation is made with entire confidence.

The most pronounced variation occurs nears Black Willow Tank, southwest of Overton, where beds of water-laid material reveal a definite anticlinal structure within the massive sandstone. The section at that place is as follows:

Section of Jurassic (?) sandstone near Black Willow Tank, southwest of Overton

	Feet
1. Typical cross-bedded red Jurassic (?) sandstone.	
2. Definitely and regularly stratified sandstone, with alternating thin layers of red and gray, fine grained and loosely cemented; grades upward into the ordinary cross-bedded red sandstone	20–30
3. Lenticular beds made up of remarkably round and uniform sand grains, resembling clover seed in size and shape, almost without cement	3–10

	Feet
4. Conglomerate, pebbles chiefly of quartzite, well rounded, average diameter 1 to 2 inches, maximum diameter 10 inches; contains a few pebbles of black chert and many of an older conglomerate which has subangular pebbles of red and gray chert one-half to three-fourths of an inch in diameter, very similar to pebbles from the Shinarump conglomerate	4–8
5. Cross-bedded white sandstone, medium to coarse grained, including lenses of conglomerate similar to overlying beds	5–20
6. Volcanic tuff, white with black particles, and tuffaceous gray sandstone	5–15
7. Gray clay, very hard, jointed, apparently siliceous; full thickness not exposed	5–30

These beds dip northwest and southeast in a truncated anticline that has a width of approximately a quarter of a mile. Near the center of the anticline the beds are almost vertical. The exact horizon of the beds within the Jurassic (?) sandstone is difficult to determine, for the structure in this section apparently consists of a series of north-south folds, which are obscure in the massive sandstone. However, less than 1,000 feet east of the tank the Overton fanglomerate rests unconformably on the red sandstone. The water-laid beds probably lie within the upper half of the formation. Prospects of carnotite have been located recently in these peculiar beds near Black Willow Tank.

Variations in the form of shale and argillaceous sandstone beds are conspicuous in their topographic expression, for they weather down easily. Near the old Arrowhead road red sandy shales interbedded with thin sandstone layers are persistent through a thickness of nearly 500 feet near the middle of the formation. Many of the fine-grained sandstone layers are ripple marked. Whatever may have been the origin of the formation as a whole these layers show clearly that they were laid down in water.

Thickness and topographic expression.—In its topographic expression the Jurassic (?) sandstone differs from place to place, owing to differences in thickness, structure, and composition. Commonly it is tilted at high angles, and the heavier sandstone forms ridges separated by valleys in the weaker layers or zones. The tops of the ridges are extremely irregular, parts of them being carved into spires and domes of fantastic shapes. The sides are pitted with cavities, many of which are caves of considerable size, and this feature gives the ridges a honeycombed appearance when viewed from a distance. Small detached buttes are shaped like beehives or coke ovens, and many are hollow, consisting of a mere shell with one or more openings. Approximately a mile north of the Arrowhead road the sandstone is invaded by the upper branches of Little Bitter Wash. Separate ridges become indistinct, and the entire surface is gashed to form a bewildering network of deep gorges. Grotesque forms, many of them resembling animals of various kinds, appear on every hand. Still farther north, in the vicinity of Overton Wash, the sandstone lies in a series of broad relatively low folds, and the topography again changes. There is no semblance of regular ridges, but broad, smooth domes, huge castle-like masses, and tall rounded buttes stand more or less isolated in sand-covered meadows that represent old erosion levels.

In outcrops farther south in the area rugged and grotesque topographic forms are the rule. The nearest approach to regularity is found in the vicinity of Sandstone Spring, near the head of Boulder Wash, where the entire thickness of the formation is exposed in a steep cliff capped by Tertiary beds.

The thickness of the Jurassic (?) sandstone differs greatly in different sections. No doubt this is due in part to irregularity in deposition, but subsequent erosion is largely responsible. Locally the deposit was almost or entirely removed before the younger formations now present were laid down. The thickest sections exposed are in the outcrop bordering the Valley of Fire, and the best opportunity for measurement is afforded 3 miles west of Logandale, where the beds dip steeply and consistently eastward. There the formation is 2,000 feet thick. Farther south, in the broader part of the outcrop, the folding is gentle and indistinct in the heavy cross-bedded layers, and exact measurements are difficult or impossible. In the southern part of the range the greatest thickness measured, 750 feet, is at Sandstone Spring. Between this locality and Muddy Peak the sandstone is absent from many sections, and the Tertiary deposits rest directly on shales of the Chinle formation.

Age and correlation.—Reference of the sandstone to the Jurassic (?) rests entirely on comparison with other Mesozoic sections in the Southwest. As the underlying rocks in this area correspond to the Chinle formation of Arizona and southeastern Utah, the sandstone occupies a horizon identical with that of the rocks in southeastern Utah that are now classified as Jurassic (?) and divided into the Wingate sandstone, Todilto formation, and Navajo sandstone. Lithologic similarity to the sandstones of southeastern Utah is also apparent, but subdivisions corresponding to Wingate, Todilto, and Navajo have not been recognized in Nevada, although there are variations in the sandstone which closer study may show to be more persistent laterally than the writer thinks and to supply a basis for valid divisions. Moreover, the sandstone has suffered erosion to an undetermined extent wherever it is exposed in the area mapped, and in its original state it may have included distinct members. With data now available it appears best merely to correlate the sandstone with the Wingate, Todilto, and Navajo as a whole. Even if the beds in the two regions are equivalent, it does not follow, of course, that the sandstone in Nevada is necessarily Jurassic, for the Wingate, Todilto, and Navajo have not yielded any faunal evidence and are now classified as Jurassic (?). However, it has been shown recently that the marine Sundance or its equivalent in southern Utah probably lies immediately above the Navajo sandstone.[38] As the Sundance is early Upper Jurassic, and as the Wingate, Todilto, and Navajo lie above beds of Upper Triassic age, it is probable that they and their assumed equivalents in Nevada belong to early Jurassic time. However, it is not inconceivable that at least a portion of the sandstone may belong in the late Triassic.

If marine Jurassic sedimentation reached into the St. Thomas region, the beds have been removed by erosion or concealed by more recent sediments. Beds belonging to the Upper Jurassic California invasion occur in western Nevada, and thin deposits of the Jurassic Logan sea are found near the southern boundary of Utah. No large extension of either shore line would be required to include the Muddy Mountain area.

Conditions of deposition.—Much has been said regarding the great cross-bedded sandstones of the Southwest without putting forth an explanation of their origin that has won general acceptance. The theory of eolian origin has much in its favor, especially with regard to those portions of the Jurassic sandstones that show a succession of truncated cross beds on a huge scale, an alternation of laminae made up of fine and coarse grains, and conspicuous frosting of the fine rounded grains. Although a considerable part of the Jurassic (?) sandstone has these indications of eolian deposition, some beds show definite evidence of deposition in water. The conglomerates and sandstones near Black Willow Tank are very probably stream deposits in part, for they show many local unconformities laterally and vertically, such as are common in the wash of swift, quickly shifting streams in an arid climate. Elsewhere red shale and thin sandstone layers are regularly interbedded and contain small regular ripple marks, indicating deposition in shallow water.

An explanation that will account for all peculiarities of the formation, including abrupt lateral changes of color from red to gray through large thicknesses, appears difficult indeed, and the difficulty is increased by the necessity of accounting for continuous distribution of the deposit over several States, its essential characteristics persisting with remarkable uniformity. The deposit is probably continental, and its great thickness and extent demand the existence of highlands to supply the material, although the high area must have been at a considerable distance to make possible the uniform

[38] Dake, C. L., The horizon of the marine Jurassic of Utah: Jour. Geology, vol. 27, p. 634, 1919.

size and well-worn surface of the sand grains. During early Jurassic time there were seas at no great distance to the north and northwest, and therefore the most probable location of mountains is south and southeast of the St. Thomas area. The Chinle deposits appear to have had their source on the south, and as sedimentation apparently continued without break into Jurassic time, it is suggested that the high areas that supplied materials maintained their general position and perhaps gained altitude by upwarp early in the Jurassic. In the area of sedimentation aridity became more pronounced than in Chinle time, a great desert, with shifting sand dunes and occasional intermittent streams, stretching from southern Nevada hundreds of miles to the east and northeast. In connection with this hypothesis it appears significant that the Upper Triassic California sea apparently maintained its general position into the Lower Jurassic. Therefore during the accumulation of the Chinle sediments and the Jurassic (?) sandstone the general slope of the southern Nevada surface may well have been toward the north and northwest.

CENOZOIC ROCKS

TERTIARY SYSTEM

OVERTON FANGLOMERATE

Definition and distribution.—The general structural conformity of sedimentary beds ends in the St. Thomas area with the Jurassic (?) sandstone. Breaks between lower adjacent formations are comparatively inconspicuous and are unattended by apparent angular divergence. The younger sediments, however, record a new order. A widespread surface of erosion was cut across the upturned edges of Mesozoic and Paleozoic beds, and on this surface the first record is found in a coarse, heavy alluvial-fan deposit that contains fragments of all the older local rocks. Exposures indicate that the deposit once covered practically every part of the area, although subsequent deformation and erosion have reduced its extent. Its thickness varies greatly, even more than is commonly expected in fan deposits. Near Bitter Spring it is 20 feet thick, whereas southwest of Overton it reaches a maximum of more than 3,000 feet. Adjacent to the Virgin Mountains it has a nearly uniform thickness, averaging 25 feet.

In seeking a lithologic term to apply to this deposit one has the feeling, as Lawson[39] had at Battle Mountain, that "conglomerate" is quite inappropriate. The rock fragments are not rounded, and many hardly show signs of wear by transportation. In all its features, large and small, the deposit is a series of cemented alluvial fans. It

[39] Lawson, A. C., The petrographic designation of alluvial-fan formations: California Univ. Dept. Geology Bull., vol. 7, pp. 325-334, 1913.

appears, therefore, that Lawson's term "fanglomerate" is the most convenient and appropriate to apply. The section of greatest thickness, near Overton, shows all typical features of its development, and the name Overton fanglomerate is proposed for the formation.

General character and topographic expression.—In every section the Overton fanglomerate consists in large part of coarse limestone fragments cemented by calcium carbonate, and not uncommonly this phase makes up the entire deposit. The writer proposes to use for this type of rock the term "limestone fanglomerate," just as "limestone conglomerate" is applied to conglomerates of a similar nature. Rock of this kind is very resistant to weathering in an arid climate, and the Overton formation invariably has a strong topographic expression. Where the strata are nearly horizontal it lies as a steep-edged capping on Mesozoic red beds or forms a prominent dark shelf beneath younger light-colored sediments. In ridges east of Red Bluff Spring and in some of the hills in the southern part of the Muddy Mountains the comparatively thin dark band of fanglomerate shows distinctly between white Tertiary limestone and the bright-red Jurassic (?) or Chinle beds. At these localities the rock is nearly uniform in character and forms beds of small or moderate thickness. In the valley of Muddy Creek it is more varied and much thicker and takes various expressions in the landscape. The following general sections show the nature of the variations from Weiser Gap to the southern limit of exposures in Muddy Valley, a distance of 15 miles.

Section in the Narrows, below Weiser Gap

	Feet
Volcanic ash and gravel beds at base of overlying limestone.	
Overton fanglomerate: Heavy beds and lenses of coarse limestone fanglomerate with a few lenses of sandstone. Base rests on beveled edges of Moenkopi formation; fanglomerate dips 10°–25° E., strikes N. 5° E.; forms steep bluffs on both sides of Muddy Creek	550

Section in Logan Wash

Top grades into overlying limestone.	
Overton fanglomerate: Heavy, irregular beds of extremely coarse limestone fanglomerate; contains slabs of Jurassic (?) sandstone near base; essentially uniform in character; strike is N. 5°–10° W.; dip is 10°–15° E., steepening near base to 20°, base unconformable on Jurassic (?) sandstone; deposit is dissected to form prominent rounded hills	975

Section in Wieber Wash

Top grades into limestone.	
Overton fanglomerate:	
Very coarse limestone fanglomerate, in thick layers and lenses forming essentially one thick bed	475

	Feet
Overton fanglomerate—Continued.	
Alternating beds of coarse limestone fanglomerate and red sandstone, individual beds from 10 to 100 feet thick, sandstones conglomeratic; contact with Jurassic (?) sandstone not seen; beds strike N. 7° W., dip 30° E.; resistant layers form sharp ridges; approximate measurement	1,000
	1,475

Section near Overton Wash

	Feet
Calcareous sandstones grading into magnesian beds.	
Overton fanglomerate:	
Very coarse limestone fanglomerate, essentially one heavy bed, exposed in high hogback ridge	215
White and red cross-bedded sandstones interfingering with fanglomerate lenses; near top fanglomerates have limestone pebbles; lower in section pebbles and boulders are of sandstone, silicified wood, and quartzite; edges of resistant layers form low, sharp ridges; approximate measurement	2,800
Jurassic (?) sandstone; little angular unconformity; series strikes N. 24° W., dips 25°–30° NE.	
	3,015

Section at Kaolin Wash

	Feet
Calcareous sandstones grading into magnesian beds.	
Overton fanglomerate:	
1. Coarse limestone fanglomerate, essentially uniform throughout, exposed as high hogback ridge	165
2. Cross-bedded red sandstone	250
3. Coarse limestone fanglomerate with lenses of sandstone	50
4. Cross-bedded white and red sandstone in very irregular lenticular beds, interfingering; local conglomerate lenses, conglomerate layers with sandstone boulders more conspicuous near base; sandstones poorly cemented, edges of conglomerate layers exposed in parallel ridges; series strikes N. 35° W., dips 30°–40° NE., approximately	2,700
	3,165

Details of composition, texture, and structure.—In the most characteristic sections of the fanglomerate a high percentage of the boulders and pebbles are of limestone. Intervening spaces are filled with sand, and the whole is held in a firm cement of calcium carbonate, the pink and gray sand and the cement forming a light-colored matrix in which the rock fragments are dark and distinct by contrast. Near Overton actual count on large surfaces showed 70 to 90 per cent of the fragments to be limestone, 5 to 20 per cent sandstone, and 0 to 10 per cent chert. Scattered pebbles of quartz and silicified wood also occur. The proportions differ from place to place, but limestone and sandstone everywhere predominate. Average and maximum sizes of fragments range between wide limits. East of Virgin River the average is less than 3 inches, and boulders 10 inches in diameter are exceptional. This is true also for exposures south of Bitter Spring Wash. In Kaolin Wash the average is approximately 5 inches, although in many lenses practically all pebbles are less than 3 inches in diameter, whereas in other layers boulders 12 inches through are common, and a maximum of 30 inches is reached. At Logan Wash large sizes are the rule. Heavy beds are made of fragments 4 to 24 inches in diameter, small pebbles occurring only in the interstices. Boulders 3 feet through are common, and one remarkable layer has numerous masses of Kaibab limestone 10 to 30 feet in greatest dimension. (See pl. 8, *A*.) A similar layer appears in the Narrows a short distance below Weiser Gap. These unusual boulders do not lie isolated in a great thickness of smaller fragments but are close together in a layer not much thicker than the diameter of the larger masses. At Logan Wash the horizon can be traced fully half a mile in the direction of dip and a like distance with the strike of the formation.

Among the smaller boulders and pebbles sharp angularity is not uncommon, but as a rule the fragments are subangular, and a small percentage of the pebbles are well rounded. With increase of size the surfaces generally show less effect of wear, but edges and corners even of some large masses have been more or less smoothed and blunted. In Logan Wash the lower 200 feet shows many flat slabs of sandstone that are certainly near their bedrock source. Some slabs are more than 3 feet across, and all are little affected by wear. (See pl. 8, *B*.)

Nowhere is there more than the slightest approach to sorting. Evidence of pulsation in deposition is general, the fragments in each thick layer or lens averaging coarser at the base than at the top, but in all beds pebbles and boulders of various sizes are jumbled together, their long axes trending in all directions, though they show a tendency to parallel the bedding. In places many large boulders are banked together, with little finer material between them, but as a rule the matrix of pebbles, sand, and cement envelops each boulder. Some boulders of the largest size occur isolated in a matrix of small pebbles and sand. In a large way the bedding planes are regular and parallel, but in detail irregularity is extreme, lenses everywhere interfingering. Thick narrow lenses of sand essentially free from pebbles occur, but they are exceptional in this phase of the formation. In the Narrows two irregular lenses are close together in the coarsest part of the fanglomerate. The sand in one is white and yellow, in the other bright red.

Local and unusual phases of the formation merit separate description. The most remarkable is the series of irregular beds below the limestone fanglomerate in the section southwest of Overton. Greater complexity in sediments can scarcely be imagined. Kind and size of material, color, and structure change repeatedly along the strike and from bed to bed. Fingers of limestone fanglomerate reaching from the northwest are longest near the top of the deposit and grow steadily shorter downward. Toward the southeast and deeper in the section pebbles of limestone decrease in number and finally disappear. Pebbles of quartzite, quartz, and chert are common, and fragments of silicified wood, more or less worn, are conspicuous. Most of the pebbles and boulders in the lenses, however, are of sandstone, apparently the Jurassic (?) sandstone. Thick lenses consisting almost entirely of sandstone fragments, comparatively soft and well rounded and ranging in size from the smallest pebbles to a diameter of 12 inches, grade within short distances into cross-bedded white and red sandstone that contains nests and long rows of well-worn pebbles, and this succession is repeated many times. Toward the southeast coarse lenses are progressively less abundant, and yellowish white becomes the prevailing color of the sandstone. Concretions and lenses of metallic iron and manganese oxide are numerous. Heavy bedding and extreme cross-bedding are general. Poor cementation is the rule, the sand grains separating easily on rubbing between the fingers. Near the base of the deposit red and yellow sandstones intermingle, pebbles are inconspicuous or absent, and inasmuch as the beds in this section have nearly the same inclination as the Jurassic (?) sandstone, the line between the formations is here rather ill defined.

Conditions of deposition.—The fanglomerate has all the features that are characteristic of a deposit in an arid country of high relief. This conclusion is reached quickly by comparing the formation with alluvial fans now forming adjacent to the steep mountain walls in the Muddy Mountains and neighboring ranges. The large average size and the angular to subangular shape of the included fragments; their remarkable freshness, although most of them are limestone; the almost total lack of sorting; the interfingering of lenses, recording repeated shifting of currents; the sporadic nests of pebbles and boulders through which the sand has streamed, leaving the interstices open; the presence of pebbles marked by desert etching before their burial; the occurrence of huge boulders set in a matrix of relatively fine fragments; the abrupt changes from enormously thick to relatively thin deposits—all these characteristics of the Overton taken together stamp it unmistakably as a formation built on a relatively steep grade adjacent to high scarps by swift intermittent desert streams.

The general physiographic conditions during Overton time are thus readily redrawn. An attempt will now be made to fill in some details of the picture. In every locality the general source of fragments in the fanglomerate can be identified. Thus a large part of the limestone boulders in the section at Logan Wash are recognized as Kaibab, and there is a smaller contribution from the older limestones. Toward the southeast fragments of Mississippian and Devonian limestones increase in number. The arrangement of boulders, banked against one another as they piled up in the swift waters, shows that the source of material was on the west and southwest. Therefore the present limestone masses of the Muddy Mountains must have been exposed when the great fan was made. In order to provide transportation for the materials the present topography would have to be altered considerably. The Valley of Fire would have to be filled, and to insure sufficient gradient for moving the materials deposited at the top of the fan it would be necessary to add hundreds of feet to the present altitude of Weiser Ridge. Subsequent folding, possibly accompanied by faulting, has so altered the attitude of all the strata, including the Overton, that a trustworthy calculation of original altitudes is practically impossible. However, on the assumption that relative altitudes have not been greatly altered by warping, it would be necessary to add 2,000 feet to the present height of Weiser Ridge to provide a grade as high as 5 per cent for the highest Overton deposits at Logan Wash, and the average size of the fragments probably made a steeper gradient necessary.

The exclusion of limestone fragments from the thick base of the fan in the Overton Wash section required a relatively high altitude in the Jurassic(?) sandstone on the west and south. Increasing abundance of quartzite pebbles, silicified wood, and Moenkopi limestone higher in this section, with the final predominance of Kaibab and older fragments, record successive stages of degradation through the Jurassic(?) to lower formations, just as would be expected. The extreme irregularity in this part of the fan, expressed in cross-bedding and many local unconformities with abundance of partly rounded boulders of soft sandstone, suggests a very rapid deposition of the thick lower beds, due no doubt both to relatively high relief and to the ease with which the formations above the Kaibab yielded to erosion. Proof that the limestones in the high nucleus of the range stood at a comparatively low altitude is found in the small and uniform thickness of the Overton deposits adjacent to the mass. Near Bitter Spring the fanglomerate is barely 25 feet thick within half a mile of the mountain front at its southeastern point. A similar thickness prevails in outcrops near the head of Callville Wash, immediately south of Muddy Peak. In White Basin and in Bitter Spring Valley on the south conglomerates and sandstones apparently of Overton age are hundreds of feet thick, but the materials are not extremely coarse, and it is probable that the basin was slowly subsiding along its present fault boundaries and supplied conditions for heavy accumulations with moderate relief. Thick fanglomerate below younger beds in

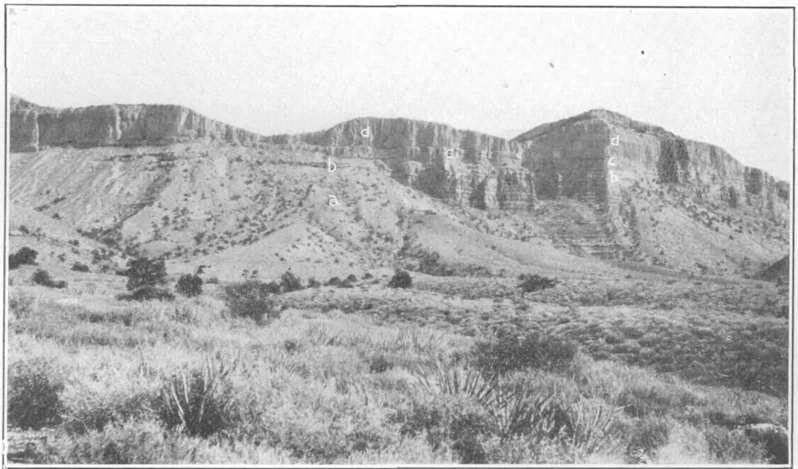
California Wash southwest of Muddy Peak may be explained in a similar way. The presence of comparatively thin Overton beds in association with all the present ridges adjacent to Bitter Spring Valley shows that these features of relief were not in existence in Overton time. The fanglomerate in these exposures contains fragments of Carboniferous and Devonian as well as Kaibab and Moenkopi limestones, indicating that relief features were built of the same formations as those now exposed. Around the rim of White Basin all the fragments came from the adjacent Carboniferous and Devonian limestones. Tongues of the Overton and overlying beds faulted into Callville Mountain prove that at least a part of that mass was practically buried at the end of the fan epoch.

With evident modification, therefore, the Muddy Mountains of Overton time corresponded well to the present range. The area was a desert; the same red sandstones and dark limestones were prominent in the landscape; centers of erosion and sedimentation were in general the same. The section of highest relief, however, was north of the present Arrowhead fault scarp. At the end of the fan stage the highest points had been reduced, some of them were practically buried in waste, and the deposition of finer sediments began in a basin region of subdued relief. The small and uniform thickness of the fanglomerate adjacent to the Virgin Mountains indicates an absence of high relief where that range now stands. As is shown in a later section, both Colorado and Virgin Rivers came into existence long after Overton time, and the exposures of the fanglomerate in and near St. Thomas Gap may therefore represent the thin deposits near the eastern margins of large Muddy Mountain fans that extended across the area of the present Virgin Valley.

HORSE SPRING FORMATION

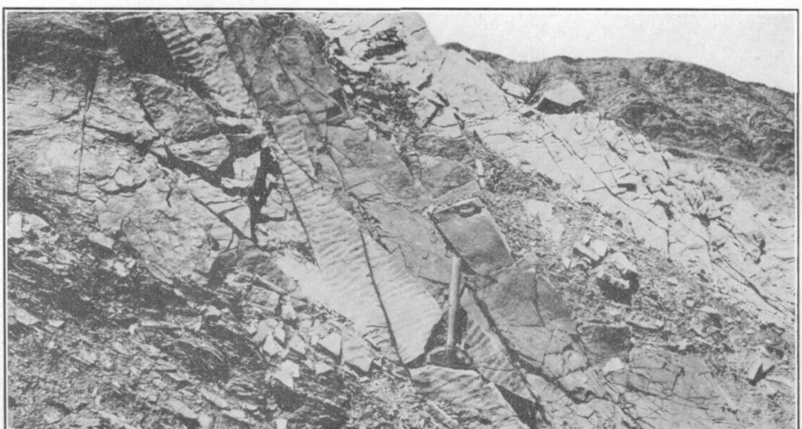
Distribution and general character.—The coarse Overton deposits are succeeded by a thick series of greatly varied beds, which were laid down under relatively quiet conditions of sedimentation. Limestone, compact clay, sandstone, gypsum, and volcanic tuff make up a total of hundreds or locally even thousands of feet. A light-colored limestone of varying thickness is the most persistent and characteristic horizon marker in the formation, but it also varies considerably in color and other physical properties, and as no fossils were found in any of the beds certain widely separated outcrops can be correlated only by a careful study of intervening gradations and the relations to other rocks. A large thickness of the limestone with smaller amounts of associated deposits is well exposed on the east side of Horse Spring Valley near St. Thomas Gap, and the name Horse Spring is proposed for the formation, without any lithologic designation.

In general the exposures of Horse Spring strata occupy altitudes intermediate between the older rocks and the more recent valley or



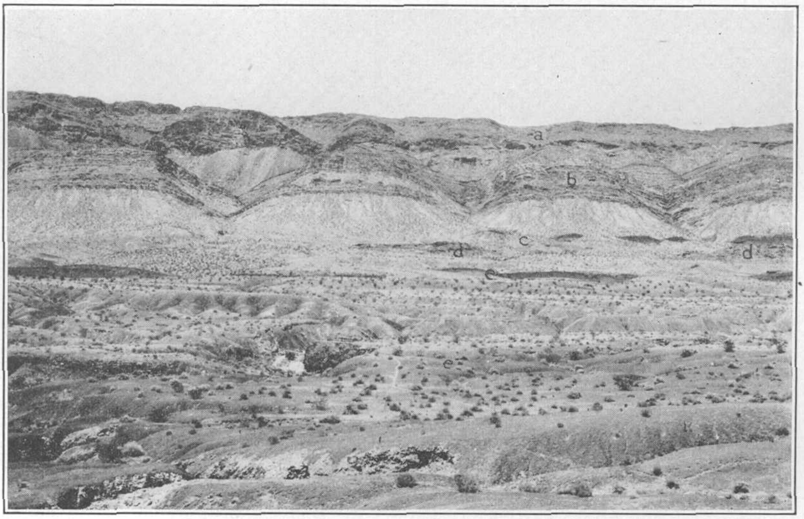
A. PORTION OF THE UPPER GRAND WASH CLIFF

a, Upper part of Supai formation; b, Coconino sandstone; c, interbedded limestone and sandstone member at base of Kaibab limestone; d, lower limestone member of the Kaibab, overlain on peak at right by upper limestone member, the bench below which is due to soft shale and sandstone



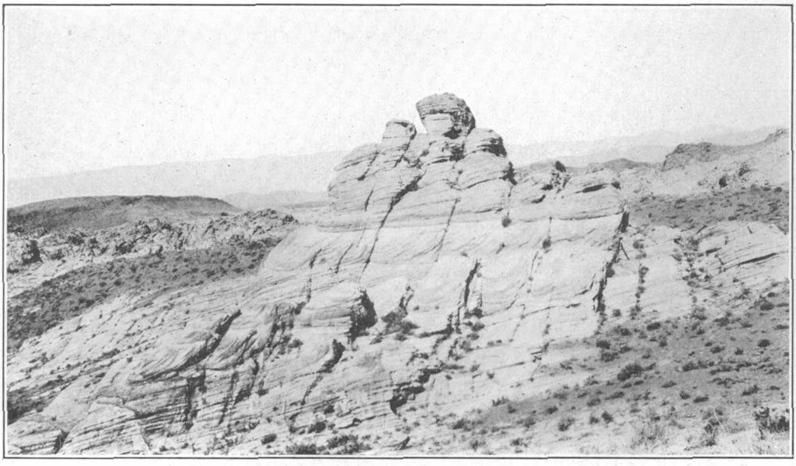
B. RIPPLE-MARKED SANDY LIMESTONE IN MOENKOPI FORMATION ON EAST SIDE OF WEISER RIDGE

The beds are practically vertical



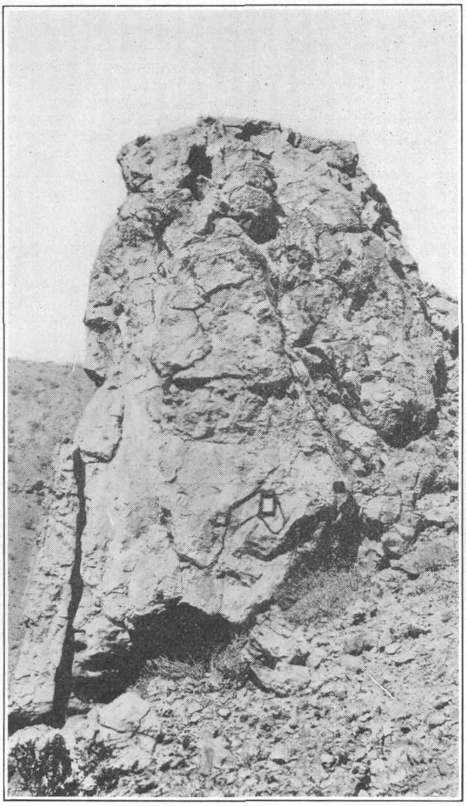
A. VIEW WEST ACROSS VALLEY OF FIRE

Strata in background dip steeply west; those on valley floor are practically vertical. a, Kaibab limestone, forming top of ridge; b, limestone of Moenkopi formation; c, shale and sandstone at top of Moenkopi formation; d, Shinarump conglomerate; e, Chinle formation. Gypsum bed near top of Chinle forms dissected ridge in immediate foreground



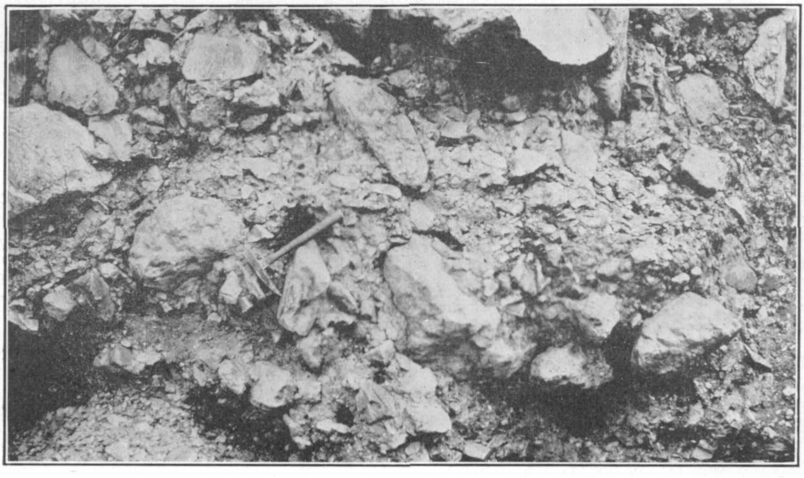
B. JURASSIC (?) SANDSTONE BENEATH OVERTHRUST IN MUDDY PEAK BASIN

Remnant of Paleozoic thrust plate in left background



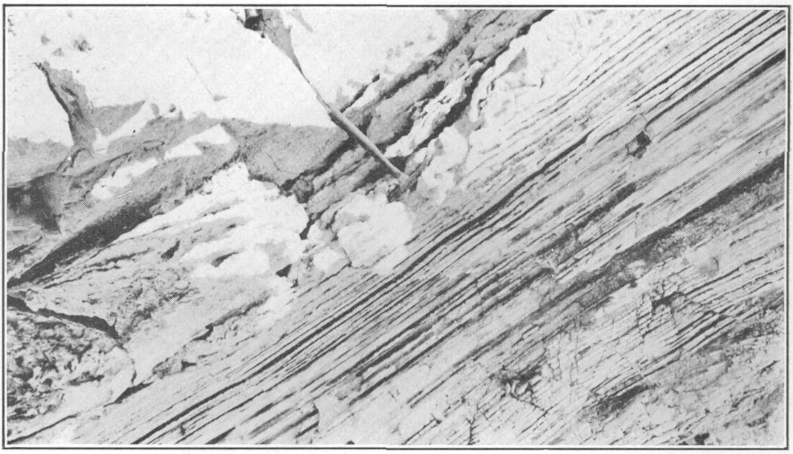
A. MASS OF KAIBAB LIMESTONE IN OVERTON FANGLOMERATE

Size indicated by camera case, which is nearly a foot long



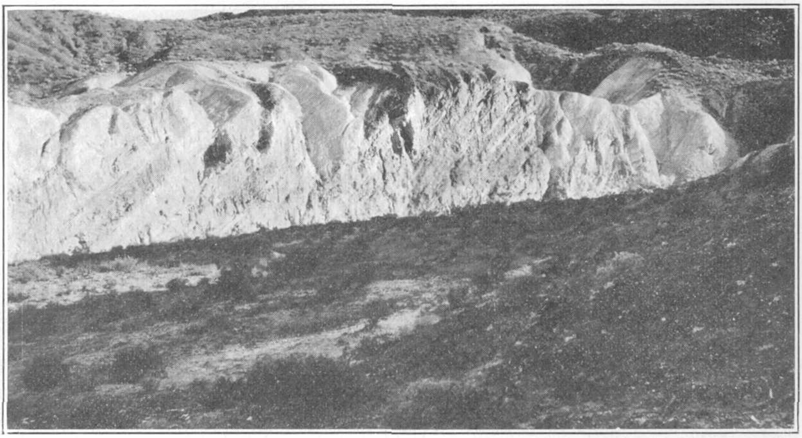
B. TYPICAL SECTION OF OVERTON FANGLOMERATE IN LOGAN WASH

Crude bedding dips about 15° NE. (to the right)



A. CLOSE VIEW

Massive layer at top; interlaminated "magnesite" and clay below



B. GENERAL VIEW

Thickness of nearly 300 feet shown. Beds dip 32° NE.

EXPOSURE OF "MAGNESITE" OF HORSE SPRING FORMATION IN KAOLIN WASH basin deposits, appearing on the flanks of upturned Mesozoic and Paleozoic masses or in comparatively low ridges produced by the latest periods of folding and faulting. North of Muddy Creek and east of Weiser Gap hills of this formation are 500 feet high, rising far above the low Kaibab knobs that extend from Weiser Ridge toward the Mormon Mountains. Three miles north of Muddy Creek the Horse Spring formation disappears beneath younger Tertiary beds, and no more of it was found farther north. Several small remnants lie just north and west of the Weiser ranch. South of the Narrows it forms many low hills, but shortly below Wieber Wash it disappears under more recent deposits and is seen only in deep cuts made by large washes.

In Logan Wash the heavy-bedded limestone of this formation is 500 feet thick, but at the base it grades directly into the Overton fan deposits. At the top, on an erosional unconformity, is a partial section of cemented coarse gravel, apparently a torrential deposit, containing a large percentage of fragments from the underlying limestone. Wieber Wash has an incomplete section of 350 feet, with a hardly appreciable change in the character of the rock. Toward the southeast successive outcrops show an abrupt and remarkable alteration, the limestone changing from a yellowish-gray or pink resistant formation to a soft snow-white substance very rich in magnesium carbonate. The first sections below Wieber Wash have at the top a sharply lessening thickness of the typical hard limestone, and a few resistant layers finger into the lower soft white beds. In Overton, Magnesite, and Kaolin Washes the transformation is complete and the sections are excellently exposed for study. Some of the soft white beds are almost pure magnesium carbonate, and the deposits are locally referred to as "magnesite." With interbedded thin dolomite layers and pink calcareous sandstones they are from 200 to 300 feet thick. In Overton Wash layers of pink and gray sandstone separate the "magnesite" from the coarse Overton beds beneath, and the top layers of the deposits are succeeded by pink sandstone volcanic tuff, and heavy fanglomerate. In Kaolin Wash the sandstone at the base has thickened, and the upper beds have become alternating compact gray and yellow clays and fine-grained sandstones with a few beds of volcanic ash, the entire series forming an exposed but incomplete thickness of 1,300 feet.

No other exposures occur in Muddy Creek valley, but the "magnesite" forms small outcrops on the west side of Virgin River Valley, in fault contact with Paleozoic rocks. Perhaps these outcrops are connected beneath the surface with the body in Kaolin Wash or at least have been separated from it only by deformation and erosion. An eastward-dipping section north of Bitter Spring contains, from the base upward, 125 feet of pink clay and white gypsum, 25 feet of resistant yellow limestone, with fine sandstones, clays, and gypsum beds amounting to more than 2,000 feet. Less than a mile to the west, across the White Basin fault, 300 feet of gypsiferous beds are succeeded by 600 feet of white porous limestone, above which lie at least 500 feet of white sandstone, thin-bedded "magnesite," volcanic tuff, and beds of calcareous clay which contain local deposits of colemanite, the principal mineral of borax. These are the strata with which White Basin is floored. The limestone outcrops continue in a narrow belt around the south and southwest sides of the Muddy Peak mass and widen to an undetermined extent in the broad California Wash, appearing through the waste in isolated outcrops along the west side of the range as far north as the Borax road. Narrow tongues are faulted into the mountain on this side and about the margin of White Basin. South of Muddy Peak the white beds contain a large deposit of colemanite, now being mined by the West End Chemical Co. Both at this place and in White Basin the mineral occurs associated with a peculiar knobby, concretionary form of limestone, known to prospectors as "goose-egg."

At Sandstone Spring the limestone is of the resistant type, but porphyries have been intruded into the higher beds so that their original character is difficult to determine. Near the mouth of Bitter Spring Wash highly tilted beds of the upper sandstones and clays are exposed, and other similar outcrops appear through the clays at a number of places along Virgin River. There are small exposures of the limestones along the west front of the southern Virgin Mountain block, and in St. Thomas Gap and Horse Spring Valley this phase of the formation is prominent. East of Red Bluff Spring it caps a prominent ridge, and it forms the essential part of a broken, hook-shaped ridge extending from a point near Mud Well across the Grand Gulch road and along the east side of Horse Spring Valley. Incomplete sections measured near Mud Well and above Horse Spring show respectively 600 and 800 feet of limestone, partly hard and heavy bedded, partly the soft white "magnesite," with all gradations. In St. Thomas Gap the "magnesite" shows through the waste in small isolated outcrops, of which the most easterly exposures observed lie immediately west of Pakoon Ridge.

Lithologic characteristics.—In detail as well as in a large way the formation is exceedingly varied. The limestones that make up the most distinctive portion grade from a very resistant, dense, gnarly rock in heavy beds to a soft, pure white magnesian substance, which commonly forms the thinnest laminae. All gradations occur, but three distinct phases are found in three type sections—in Logan Wash, Magnesite Wash, and Bitter Ridge.

The Logan Wash section is typical of the most northern exposures, but rock of the same character occurs in Bitter Spring Valley and near Mud Well. In Logan Wash the individual beds are from 2 inches to 20 feet thick and make up a total exposed thickness of about 500 feet. The bedding is not well defined throughout. Within a short distance a massive bed almost imperceptibly separates into thinner layers, and on badly weathered surfaces thick beds usually show subdivision into smaller units along irregular lines. At its base the limestone gradually develops from the underlying fanglomerate through a transitional zone 25 to 30 feet thick. In this transitional zone the pebbles become smaller and more widely spaced upward and are held in a firm matrix of limestone, which has a faintly pink color on weathered surfaces. Beds of this nature are separated by layers or lenses of pebbles, which become thinner and farther apart upward. The pebbles in the limestone matrix grow less numerous and smaller until only isolated pebbles are found. Through several feet more the rock contains some sand, and this phase grades into the typical limestone.

The rock is typically light gray with a pink tint that is locally very pronounced. In texture it is dense to moderately crystalline, and when fresh it is hard and resistant under the hammer. In the heavier beds the structure is porous or vuggy, and the vugs are almost invariably lined with drusy crystals of calcite. Between beds and in partings and joints within beds there is an abundance of comb structure with interlocking crystals, some of which are nearly an inch long. The porous beds alternate with layers, usually thin but not uncommonly several inches thick, of dense or finely crystalline material with a banded structure. On the upper bedding surfaces there are many concretionary bodies in the form of hollow branching stems or groups of small spherical knots that separate into concentric shells. Similar but larger concentric forms, some more than an inch in diameter, appear on weathered edges of the larger beds. The combination of bands, vugs, crystal-filled joints, and concretionary bodies, under the roughening influence of desert weathering, gives the limestone a remarkably gnarly and forbidding appearance. Typical material from this locality was analyzed and found to be almost pure calcium carbonate, with only a trace of magnesium.

Three beds of volcanic tuff appear in the section, one near the base and two about midway. The lower layer is greenish and quite firm and contains considerable calcium carbonate as cement. It is only 6 inches thick but is persistent on both sides of the canyon as far as its horizon is at the surface. One of the higher beds is more than 3 feet thick, the other little more than 1 foot. In both the ash is loose and crumbly, but all of it shows the effects of reworking and mixing with more or less calcium carbonate. The occurrence of tuff with the limestone is almost universal, thin layers appearing in every section studied. The most remarkable occurrences are those at the base of the limestone near the Narrows, where ash beds 3 to 25 feet thick alternate with lenses and layers of well-rounded gravel, and the series ranges in thickness from 50 to more than 150 feet. The ash is little cemented but well compacted and shows the effect of rapid deposition in water. It is gray, mixed with many black particles. Most of the pebbles are quartzite and quartz, with smaller amounts of limestone. Near the top of the series there are several thin layers of yellow clay with streaks of black carbonaceous matter. About a mile below Weiser Gap a cut along the railroad exposes a lenticular bed of limestone with a maximum thickness of 4 feet, lying within volcanic ash 30 feet below the base of the main limestone. The lens is hard and dense, is light gray, and in general resembles the limestone of the Logan Wash section.

In a straight line Kaolin and Logan Washes are barely 7 miles apart, and yet no observer who saw the two sections without studying intermediate exposures and the relations to other rocks would recognize them as cutting the same beds. The Kaolin Wash section begins with 12 to 20 inches of dense, hard pink limestone laid on a wavy surface of coarse Overton fanglomerate. The limestone grades almost imperceptibly into fine-grained pink sandstone with a rich lime cement and with small but conspicuous limestone and chert pebbles in small lenses and singly, scattered through a thickness of 6 to 8 feet. Above the pebble zone the sandstone is uniformly fine grained, and the prevailing pink color is varied by splotches of yellow that become increasingly larger upward, and in the upper 40 feet bright yellow is the general color. The total thickness of the sandstone is 110 feet; it is firmly cemented and indistinctly bedded throughout and has a massive appearance. At the top it grades into several inches of hard pink dolomite, the top surface of which makes a firm and well-defined base for the softer beds above.

The "magnesite" forms a very striking outcrop, the section in the canyon wall appearing from a distance like a huge snowbank. (See pl. 9, *B*.) Other colors, however, intersect the pure white, and it is evident even without detailed study that the section is far from homogeneous. Reference to the measured section indicates three chief interbedded materials—magnesite, occurring in massive beds or in thin laminae; hard gray dolomite, in thin layers; and pink gritty clay and argillaceous sandstone, in heavy beds. About 70 feet at the base of the section contains the best of the magnesite. (See pl. 9, *A*.) It is pure white to bluish white, is firm when fresh, has a massive, homogeneous appearance, and breaks with the conchoidal fracture typical of magnesite. In fact it differs in physical properties from the ordinary mineral only in having a slightly lower degree of hardness. It weathers easily to a formless claylike substance, and this fact probably explains why the term "kaolin" was applied to it for many years. The beds are regular and range in thickness from 1 to 10 feet. Higher in the section the material occurs chiefly in thin laminae, separated by other laminae containing

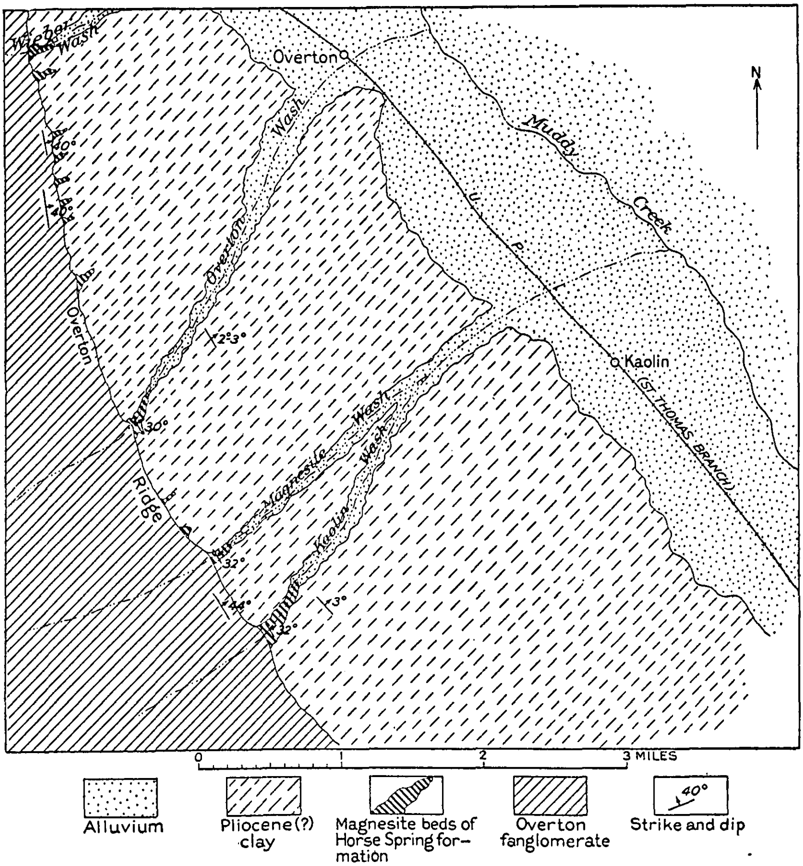


FIGURE 3.—Sketch map of "magnesite" outcrops

more or less clay. Ripple marks about 1 inch wide are numerous on these thin layers, and larger ripples are found on dolomite layers near the base. About midway in the section several thin beds contain volcanic ash and clay, and others appear conglomeratic from included small clay balls. Near the top white "magnesite" alternates with yellow and gray beds of compact clay, silt, and fine-grained sandstone, which gradually come to occupy the section.

A thicker section of the pure magnesite is found in Magnesite Wash, 1 mile farther north, where the outcrop forms a bluff more than 100 feet high. About 80 feet at the base consists almost entirely of the massive white material in beds from 6 inches to 10 feet thick. The top of the section contains many hard beds of dolomite, limestone, and sandstone, but magnesite is the chief constituent throughout the thickness of more than 200 feet. Thin layers in the upper part were greatly contorted during the disturbance that tilted the formation to its present attitude. Extreme contortion is also conspicuous in Overton Wash, where the white beds have a total thickness of 150 feet and contain a larger percentage of impurity than in Magnesite Wash.

The physical properties of the "magnesite" at different horizons are not constant, and this fact suggests a variation in chemical composition. Even the pure-white material varies considerably in hardness, and some layers effervesce much more freely in dilute hydrochloric acid than others. The occurrence of dolomite beds and others that resemble ordinary limestone suggests that both calcium and magnesium may be present in various proportions. The following analyses of Muddy Valley material were made by W. B. Hicks.[40] No. 1 represents cuttings from 10 feet of the best material in Magnesite Wash, and No. 2 combines similar cuttings from a thickness of 4 feet near the base in Kaolin Wash.

Analyses of magnesite

	Pure magnesite	1	2	Bissell, Calif.
SiO_2		11.12	11.82	9.64
Al_2O_3		.98	.94	2.46
CaO		5.36	5.90	4.25
MgO	47.6	36.72	36.40	37.19
CO_2	52.4	[a] 44.15	[a] 43.45	40.70
Undetermined				5.76
	100.0	98.33	98.51	100.00

[a] Determined by loss on ignition and therefore includes moisture.

The magnesite at Bissell, Calif., is a sedimentary deposit similar to the Muddy Valley magnesite but of much smaller extent and thickness.[41] The analysis included in the table above was made by J. G. Fairchild. Its similarity to the analyses of Muddy Valley material is striking, although the undetermined constituents might affect the proportion to some extent. Other analyses of Bissell materials show a smaller percentage of lime.[42] In the two analyses given for the Muddy Valley material the CO_2 is approximately sufficient to unite with both the MgO and the CaO to form the normal carbonates, provided no allowance is made for included moisture. It is possible,

[40] U. S. Geol. Survey Press Bull.

[41] Gale, H. S., Late developments of magnesite deposits in California and Nevada: U. S. Geol. Survey Bull. 540, pp. 512-516, 1914.

[42] Idem, p. 514.

however, that considerable water is included in the material lost on ignition, and if so some lime or magnesia or both must be accounted for otherwise than in the carbonate form. Gale notes that in the Bissell materials there is insufficient CO_2 to satisfy the lime and magnesia, and he suggests that part of the silica is combined to form calcium and magnesium silicates, whereas another portion of the silica is free. He also records F. W. Clarke's suggestion of the possible presence of basic carbonates, such as the hydromagnesite ($3MgCO_3.Mg(OH)_2.3H_2O$).

The limestone and related rocks in the Horse Spring formation in the southern part of the Muddy Mountains show decided differences from section to section, all including considerable magnesite, some dolomite, and heavy beds of limestone like those in Logan Wash. The most typical phase of the formation in this part of the area is found in the steep southern face of Bitter Ridge. The beds are thin, white, light gray, or pink, spongy when slightly weathered, and remarkably porous, open spaces as much as a quarter of an inch in diameter occupying nearly a third of the rock volume in some specimens. This texture suggests the composition of dolomite, but the rock effervesces freely in dilute hydrochloric acid. Along the sides of canyons the layers break off in huge slabs 5 to 12 feet across and only 2 to 6 inches thick. When such fragments are struck with the hammer they give out a clear ringing sound. At several horizons layers of dense limestone, fine sandstone, and conglomerate are interbedded with the porous limestone layers, and a number of heavy resistant limestone beds are also included. Rock of this character, but with the porous structure less pronounced, extends around Muddy Peak into California Wash, and long tongues of it are faulted into the mountain mass on the west. Shelly limestone concretions, some of them several inches in diameter, occur in many sections.

The beds higher than the limestone form a unique series in every section studied. North of the Narrows and in Logan Wash there is only a considerable thickness of coarse fanglomerate, apparently conformable with the limestone, but separated from it by an erosional unconformity. Probably it was formed much later than the limestone, for fragments of the limestone, some of them 3 feet in diameter, make up a large part of the fan. In Overton Wash a similar deposit is separated from the "magnesite" by beds of pink sandstone and shale and several layers of volcanic tuff; but here most of the fragments are of older limestones. In Kaolin Wash more than 800 feet of yellow and pink clay and sandstone in regular beds lie conformably on the "magnesite," and the series continues to an indeterminate distance beneath the younger horizontal deposits of gravel and clay. The longest and most varied section is found in Bitter Spring Wash, but even this one is not complete, although more than 2,700 feet was measured. The greater part of the section consists of tan and light-brown sandstone with fine and nearly uniform grain, laid in regular beds. Pink clay shale, much of it gritty, is also an abundant constituent. Beds of white gypsum and pink gypsiferous clay 10 to 20 feet thick are numerous, and two layers, each 5 feet thick, of bright-green fine-grained, thinly laminated sandstone are very conspicuous. Many layers of sandstone and clay show efflorescence of salts on exposed edges. The same or similar beds recur near the mouth of Bitter Spring Wash and on the east side of Virgin River, and here likewise the green sandstone beds show prominently. A notable feature of the series is its apparent lack of cross-bedding, ripple marking, and other signs of deposition in shallow water.

Adjacent to the Virgin Mountains beds higher than the limestones were not identified.

Conditions of deposition.—No fossils were found in any part of the Horse Spring formation, and therefore conclusions as to its origin must be drawn from its physical make-up. None of the evidence favors the idea of marine deposition, and much of it indicates unmistakably a continental origin. The several points of evidence will be enumerated and discussed separately.

1. Abrupt and extreme changes in lithologic character, such as occur throughout the formation vertically as well as laterally, favor the theory of deposition in a series of small interior basins. Such changes are especially marked in the limestone, a heavy calcareous deposit giving place within a mile to the remarkable "magnesite," not in one place only but in many. The occurrence of both types of rock in some sections, with here one and there the other at the base, indicates that the depositing solutions changed abruptly and radically and that the width of individual basins fluctuated considerably. Likewise the common appearance in the limestone of angular pebbles, singly or in lenses, may be explained by assuming that the basins were inclosed by low rocky land bodies in a dry climate, the influx of pebbles coming at times of rainfall, whereas during most of the year limestone might form adjacent to the land without inclusion of clastic materials except fine particles transported by the wind. It is also possible that the lakes shrank periodically from evaporation, and pebbles were washed out on the dry beds, to be buried by other sediments at the next spreading of lake waters.

2. The Horse Spring deposits follow closely the Overton alluvial fans—a normal sequence in an arid or semiarid basin country. In places the limestone rests on the fan deposits, succeeding the coarse formation without transition through sand and silt. Such a succession might well occur in basins in an arid land, where fine rock materials are commonly at a minimum and where a slight increase in rainfall could very quickly produce or enlarge semipermanent bodies

of water, causing them to spread beyond the playa limits and lap up on bajada slopes. A normal succession of arid basin sediments is suggested by the deposits along the northeast side of Overton Ridge. Fine calcareous sandstone lies beneath the "magnesite" in Kaolin, Magnesite, Overton, and other washes but thins uniformly toward the north, grading insensibly into coarse Overton fan materials before Wieber Wash is reached. Thus, interpreting both the Overton and the Horse Spring formations, we may trace the history of the basin through the building of the fan, the normal encroaching of the playa on the bajada, and finally, perhaps with some increase in humidity, the spreading of lake waters and deposits over both.

3. If the "magnesite" is of syngenetic origin, its nature appears to demand for its formation very peculiar conditions within closed basins. Nearly pure magnesium carbonate is unusual as a sedimentary deposit, and in the absence of parallel occurrences, present and past, it is difficult to picture the exact physical conditions that would permit the precipitation of such quantities as occur in the St. Thomas area. The fact that it is a rare occurrence, however, suggests its formation in isolated localities where the necessary conditions might exist. The common recurrence of ripple marks accompanied by sun cracks and the abundance of such objects as clay balls in some layers are further suggestions of deposition in shallow lakes. The borax deposits are also to be considered in attempting to outline the conditions of deposition. Boron

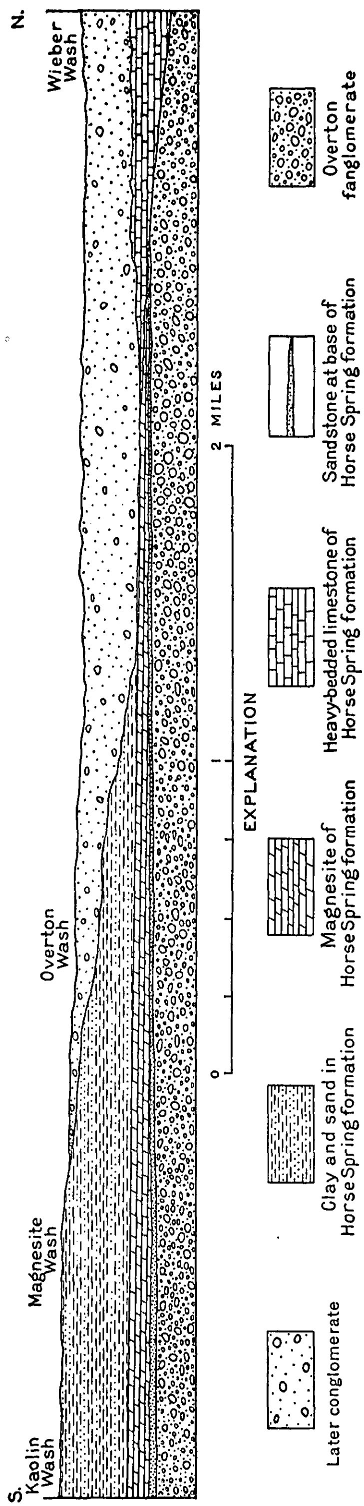


FIGURE 4.—Relations of Horse Spring and Overton deposits before deformation

in quantities required for large accumulations of colemanite suggests the agency of volcanoes or of hot springs with a deep source, and abundance of volcanic ash in the formation shows that volcanism was active in the region. The borax deposits found in this area are very similar to some of those in the Furnace Creek district of California, and closely similar conditions of deposition are suggested for the two areas. The origin of the borax has been discussed by Noble,[43] who suggests that ulexite (borate of sodium and calcium) was the original mineral from which the colemanite (calcium borate) was derived by subsequent alteration.

4. The peculiar spongy limestone layers in the formation, particularly in and near White Basin, resemble travertine deposits made by large springs. Perhaps a number of deep-seated springs supplied solutions of different composition to independent basins. The local interfingering of the limestone with the "magnesite" and the close lateral approach of large independent bodies of the two materials indicate a practically simultaneous development in neighboring basins. Alternate precipitation of calcium and magnesium salts might occur in the same basin, as a result of changes in degree of concentration of a solution, but some sections contain only "magnesite," whereas others near by have only the nearly pure limestone, a fact that apparently demands separate water bodies.

5. The local occurrences of gypsum and other saline deposits, of thick lenses of volcanic ash, and of clay and sand in great thickness and with various conspicuous colors are very strong indications that deposition took place in arid or semiarid basins of small extent, with recurrent volcanism in the neighborhood.

The Overton and Horse Spring formations taken together, therefore, appear to supply a clear history of a long arid cycle, which began in a stage of very high relief after or during the deformation of older rocks and proceeded through a fan stage to the development of comparatively low ridges and of shallow basins in which playa deposits built up and encroached upon the low fan slopes. An increase in rainfall or in the flow of deep-seated springs caused the formation of shallow lakes, or perhaps small basin lakes merely spread with the building up of playa deposits and the decrease of bajada slopes, finally forming widespread but discontinuous water bodies among low uplands. In these water bodies were laid down complex and interfingering deposits of lime and magnesium carbonates, colemanite (or ulexite), gypsum, and associated saline materials, and great thicknesses of sand and silt. Intermittent eruptions of volcanoes supplied quantities of ash, which was reworked and deposited by the shallow water, and emanations from the magma probably provided boron and other elements for the production of unusual compounds. The cycle was

[43] Noble, L. F., Colemanite in Clark County, Nev.: U. S. Geol. Survey Bull. 735, pp. 23-39, 1922.

completed by the coming of another fan stage, recorded in the coarse fanglomerate above the typical Horse Spring beds in Overton Wash and in other exposures reaching north of Muddy Creek. A deposit of this nature, made up in great part of large fragments of Horse Spring limestone, indicates the beginning of another deformation, probably the upheaval that folded the Horse Spring beds into their present steep attitudes and initiated the erosion that destroyed much of their original extent.

In this discussion the "magnesite" has been assumed to be a syngenetic deposit. An explanation of its origin as a replacement product of original calcium carbonate may be entertained, but the field evidence appears to favor the idea of direct precipitation of the beds with essentially their present composition. Layers of the "magnesite," of limestone, and of dolomite are interbedded in many places, and the beds of different materials are sharply defined. Moreover, the typical limestone sections contain little except calcium carbonate, and the many joints that cut the beds are lined with calcite crystals, unmixed with dolomite, indicating that magnesium was not present in the ground waters that have circulated in the formation. Gale suggests that the small California deposits resulted from the introduction of magnesium, probably as the sulphate, into a lake basin rich in sodium carbonate, which caused precipitation of magnesium carbonate. If this explanation is applied to the thick deposits of the Muddy Mountains, a large supply of magnesium-rich waters must be assumed, and conditions favorable to precipitation of the unusual carbonate must have continued without interruption for a considerable period. The thick dolomite beds in the Paleozoic section suggest a source for the large quantity of magnesium, but mineral matter derived from a formation that must have been near the surface and of general distribution would have affected all the basin deposits forming in the region; whereas it is evident that pure calcium carbonate was forming in adjacent basins simultaneously with the "magnesite" and colemanite. It is therefore probable that the magnesium and boron came from a deep source and reached only parts of the area receiving lake deposits. As the water bodies shifted, owing to erosion and sedimentation and possibly to fluctuations in rainfall, the composition and concentration of solutions changed at certain localities and precipitates of different kinds became interbedded. The mineral-bearing waters that laid down the magnesite may have been the source also of magnesium in the dolomite now found in the Paleozoic formations above the Muddy Mountain thrust. Much of this dolomite is obviously of secondary origin.

Measured sections.—Some of the sections of the Horse Spring formation that were measured in Horse Spring Valley and adjacent areas are given in the following pages.

Section of Horse Spring formation in Horse Spring Valley

[Thickness incomplete. Top eroded and covered with waste. Beds dip 25°-35° E.]

	Feet
Horse Spring formation:	
1. Limestone in beds 3 to 10 inches thick, light gray, dense, hard, surfaces deeply pitted; some beds are white and spongy, weathering easily to a soft white mass	25
2. Limestone beds weathering to a delicate pink color, white on fresh surfaces; dense, hard when fresh; disintegrates easily to chips and soft pebbles, forming talus; some beds contain pore spaces; others show small angular limestone fragments that resist weathering better than the matrix	35
3. Calcareous sandstone weathering with oolitic appearance, beds 4 to 12 inches thick, pink splotches on weathered surfaces	8
4. Soft limestone, similar to No. 2, forming talus	15
5. Hard, dense limestone in regular beds 12 to 20 inches thick; weathers into extremely jagged surface which has deep pits with knifelike edges; weathered surfaces are white, gray, and pinkish; a few layers of soft white limestone are interbedded; some beds have sandy or conglomeratic appearance when weathered	40
6. Calcareous sandstone, gray to brownish pink, heavy bed	5
7. Pure-white limestone in beds 2 to 20 inches thick, firm when fresh but weathers easily to soft white claylike mass; interbedded layers have vitreous, flinty appearance	220
8. Light-green conglomeratic sandstone and conglomerate; has small rounded pebbles of gray and dark chert; heavy bedded, with some cross-bedding; becomes gray downward	35
9. Hard, dense, brittle gray limestone in beds 2 to 10 inches thick, some layers with thin lamination; contains lenses and nodules of chert, parallel to bedding	12
10. Soft gritty gray limestone grading downward into calcareous sandstone, heavy bed	1⅓
	396⅓
Overton fanglomerate:	
1. Green conglomeratic sandstone, heavy bedded; grades into conglomerate near base, containing more or less rounded small pebbles (size of pea) of chert and quartz	30
2. Slope, showing gray and pink gritty soil, evidently weathered sandy shale	15
3. Red sandstone in thin lenticular beds	7
4. Fanglomerate; has red color due to large quantity of red sand in matrix; pebbles, angular and subangular, of dark and light limestone and chert; rests unconformably on slightly irregular surface of red Jurassic(?) sandstone	8
	60

Section of Horse Spring formation 2½ miles northeast of Mud Well

	Feet
Muddy Creek formation: Pink gypsiferous clay and gypsum beds, horizontal. Incomplete exposure, disappearing under waste	100–300
Large angular unconformity.	
Horse Spring formation:	
1. Dense, hard gray limestone in beds 1 foot to 4 feet thick, pink on weathered surfaces; has gnarly, banded appearance as in Logan Wash	25
2. Soft snow-white "magnesite," massive; grows harder at top, grading into hard limestone	30
3. Alternating beds of firm, dense limestone and softer white material resembling the "magnesite"; average beds are 1½ to 2 feet thick, and there are a few zones of thin-bedded, platy white limestone	50
4. Thin-bedded hard gray limestone with abundant thin lenses of gray chert; in places chert forms half the thickness	3
5. Soft "magnesite," heavy bedded, irregularly jointed	28
6. Alternating beds of firm limestone and soft "magnesite" 1 foot to 6 feet thick; most of the firm beds are snow-white on fresh surfaces and are somewhat spongy when slightly weathered; some beds have flinty appearance	95
7. Hard, resistant limestone in beds 3 to 8 feet thick containing abundant chert nodules; a few "magnesite" beds; soft layers form slopes; resistant beds stand out as continuous steps or bluffs	110
8. Soft white "magnesite" beds with a few harder white layers	50
9. Layers of brick-red and gray calcareous sandstone 6 inches to 2 feet thick, with many small dark chert pebbles; some beds loosely cemented, others have rich lime matrix; gray beds include some volcanic ash	25
10. Gray to yellowish-green volcanic ash with considerable clay, especially near top	15
11. Chert gravel, rounded, mixed with yellowish soil	4
12. Gray and pink clay containing considerable volcanic ash	55
13. Gray conglomeratic sandstone; consists of quartz sand, chert pebbles, and lime cement, making a firm bed	1½
14. Gray sandstone, fine, with a few chert pebbles, lime cement; sand becomes coarser downward	30

	Feet
15. Alternating greenish-gray sandstone and yellowish-green clay; contain some ash	50
16. Pink sandstone, fine, becoming conglomeratic downward, heavy bed at top 7 feet thick, well-defined beds near base 2 to 6 inches thick, deep red; grades downward into Overton fanglomerate	12
	583½
Overton fanglomerate in two 12-foot beds, separated by lens of cross-bedded pink sandstone 3 feet thick	27
Unconformity.	
Jurassic(?) sandstone.	

Section of "magnesite" facies of Horse Spring formation in Kaolin Wash

	Feet
1. Clay, silt, and sandstone in regular layers 3 inches to 5 feet thick, cut by irregular joints of gypsum; clay and silt are various tints of yellow; one bed of white volcanic tuff about midway in series; beds dip 30° N. 45° E	750
2. Thinly laminated white "magnesite," interlaminated with bluish-white calcareous clay; a few beds half an inch to 1½ inches thick of hard gray magnesian limestone	65
3. Pink clay and impure gray "magnesite"	14
4. Interlaminated white "magnesite" and bluish-white clay, including two beds each 1 foot thick of pink magnesian limestone; many bedding surfaces of "magnesite" show ripple marking	67
5. Heavy-bedded pink sandy clay	10
6. Thinly laminated white "magnesite" containing thin bluish claylike layers; ripple marks numerous	17
7. Thinly laminated white "magnesite" with thin claylike layers	18
8. Heavy bed of pink sandy clay	4
9. White, gray, and pink "magnesite," with interbedded thin layers of hard magnesian limestone; one bed of "magnesite" contains small clay balls and appears conglomeratic	7
10. Heavy-bedded pink sandy clay	46
11. Alternating thin layers of white "magnesite" and hard gray magnesian limestone	1
12. Heavy-bedded pink sandy clay and fine sandstone	16
13. Alternating thin layers of white "magnesite" and hard gray magnesian limestone	1
14. Heavy-bedded pink clay and calcareous sandstone	13
15. Alternating thin layers of "magnesite" and hard gray limestone	1
16. Heavy bed of pink calcareous fine-grained sandstone	6
17. White to pink "magnesite," chiefly soft and claylike, interbedded with beds of hard gray magnesian limestone from a fraction of an inch to 1 inch thick	23
18. White "magnesite," with a few thin layers of hard gray magnesian limestone	40

	Feet
19. White "magnesite," much of it soft and claylike, with many beds half an inch to 2 inches thick of hard gray magnesian limestone; one layer has strong ripple-marking	23
20. Alternating layers of soft "magnesite" and hard gray magnesian limestone, beds 3 to 5 inches thick	3
21. Pinkish-gray porous magnesian limestone	1
22. Bright-yellow sandstone, fine to medium grained, with calcareous cement; has pinkish spots and streaks; beds 6 to 12 inches thick	25
23. Sandstone with pink color predominant over yellow	35
24. Similar sandstone, pink to red; beds become heavier toward base; lower bed contains many pebbles of limestone and chert, from size of a pea to three-quarters of an inch in diameter, in small lenses or scattered	50
25. Dense hard limestone, pink on surface, weathering to a rough, gnarly form	1
Overton fanglomerate with slightly wavy upper surface.	
	1,237

AGE OF THE OVERTON AND HORSE SPRING DEPOSITS

The transition from the Overton fanglomerate to the finer Horse Spring deposits indicates that the two formations are merely different phases of a continuous sedimentary record. Moreover, in spite of the great thickness of the formations their deposition probably occupied only part of a geologic epoch, for many of the sediments are of kinds that are known to accumulate rapidly in present interior basins. As is shown farther on, sediments unconformable on the Horse Spring beds are probably not older than Pliocene. Neither the Overton nor the Horse Spring strata have yielded any fossils, and their dates are therefore speculative. Lithology and structure are the only means of comparing the deposits with known formations in adjoining regions, and this method of correlation can give only indefinite results, because in the Basin and Range province the orogenic history after Jurassic time is very complex, and interior-basin deposits are characteristic of a number of geologic epochs. It is very improbable, however, that the Overton and Horse Spring sediments belong to the Mesozoic era, for these formations have no resemblance to any Cretaceous deposits found in surrounding regions, whereas their general nature is characteristic of Tertiary sediments in many parts of the Great Basin and adjoining regions. Moreover, deformation of older beds before deposition of the Overton fanglomerate probably occurred in Tertiary time. There appears to be little doubt, therefore, that the Overton and Horse Spring formations are of Tertiary age.

Definite reference to an epoch must await the finding of fossils. For the present the deposits will be referred tentatively to the upper Miocene, for the following reasons:

1. Sediments of upper Miocene age have a wide distribution in south-central and southwestern Nevada and in eastern California. Examples are the "Siebert"[44] or Esmeralda[45] formation and the Barstow[46] formation. These deposits, like the Horse Spring formation, are largely lacustrine and contain an abundance of volcanic tuff.

2. The Overton and Horse Spring beds have apparently been subjected to only one period of severe folding. This is also true of the Esmeralda and Barstow sediments. Older Tertiary formations in the Great Basin may be expected to show more complex folding, as acute crustal movements occurred in Eocene and middle Miocene time.

3. The presence in the Horse Spring formation of unusual deposits, such as colemanite and magnesium carbonate, suggests correlation with upper Miocene beds containing similar deposits in eastern California. This feature taken alone has no value as a criterion in close correlation, for the California borax deposits may have a considerable range. However, it appears to be more than a coincidence that the Horse Spring formation should have a striking resemblance in lithology and degree of deformation to other borax-bearing sediments, all of upper Miocene age, in several separate localities.

MUDDY CREEK FORMATION

Distribution and general expression.—In all the large intermontane valleys adjacent to the Muddy Mountains and neighboring ranges there are thick clays or silts and associated deposits that have been relatively little disturbed by crustal deformation. As a rule they form belts from a fraction of a mile to several miles wide on each side of present stream valleys, above which the clay outcrops rise to a maximum height of approximately 600 feet. Adjacent to the highlands they feather out, lapping up on the older rocks. Between the Muddy and Virgin Mountains the area occupied by the clays is from 9 to 12 miles wide. South of St. Thomas this large area is divided into two nearly equal belts by Virgin River, and to the north the clays are cut by the converging Muddy and Virgin Valleys, each of which leaves a comparatively narrow strip of the deposits bordering the mountains. Between the streams the clays occupy a large triangular area extending more than 15 miles to the Mormon Mountains. In California Wash the clay exposures extend a maximum of more than 10 miles to the ranges on the west, and they form wide belts bordering

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[44] Spurr, J. E., Geology of the Tonopah mining district: U. S. Geol. Survey Prof. Paper 42, pp. 51–55, 69–70, 1905. Ball, S. H., A geologic reconnaissance in southwestern Nevada and eastern California: U. S. Geol. Survey Bull. 308, 1907 (many references).

[45] Turner, H. W., The Esmeralda formation: Am. Geologist, vol. 25, p. 168, 1900. Buwalda, J. P., Tertiary mammal beds of Stewart and Ione Valleys in west-central Nevada: California Univ. Dept. Geology Bull., vol. 8, pp. 335–363, 1914.

[46] Merriam, J. C., Tertiary mammalian faunas of the Mohave Desert: California Univ. Dept. Geology Bull., vol. 11, pp. 444–447, 1919. The Barstow section was described under Hershey's term "Rosamond series" by C. L. Baker in California Univ. Dept. Geology Bull., vol. 6, pp. 339–347, 1911.

Meadow Valley Wash and the upper part of Muddy Creek. They have invaded St. Thomas Gap in places, and in the broad Grand Wash Valley they are exposed wherever the surface waste has been sufficiently dissected. In a word, the intermontane areas occupied by clays are nearly equal to the areas of the mountain ranges. However, these broad belts do not show continuous clay outcrops, for the clays are largely covered by a veneer of varying thickness formed from more recent waste that was used in building aggradation levels at several altitudes. The clays are conspicuous beneath the waste in the sides of the large valleys and small washes and in extensive badland tracts where the later capping has been stripped away. (See pl. 11, *A*.)

Owing to many interbedded layers of sandstone more or less firmly cemented, the clays tend to stand in steep fronts along wash courses. The edges of the sandy layers are visible in all sections, standing out as narrow shelves or forming a horizontal banding almost concealed by clay carried from above and plastered on the slope by infrequent rains. In detail the carved surfaces have an intricate but typical pattern, many times repeated. Steep slopes are dissected into long parallel spurs, and these subdivide repeatedly into steep spurs of many orders, all with rounded upper surfaces and separated by V-shaped trenches. From a distance the spurs resemble irregular columns. In places they are interrupted by persistent shelves formed on sandstone layers of unusual resistance, below which the typical patterns reappear.

For this series of deposits Stock [47] has proposed the name Muddy Creek formation.

Details of composition, texture, and structure.—Although the deposits are referred to as clays, all sections contain other materials as abundant constituents, and in many localities there is practically no genuine clay. Sections have alternations of at least two types of deposit, showing a pulsating character in the sedimentation. In the area as a whole silt is much more abundant than clay, and sandy layers make up at least a fourth of the total thickness. Typically the fine deposits are yellow or buff, and the sands are gray, but locally both may be pink, and in areas of considerable extent the entire deposit is ash-gray or nearly white. This phase is common north of the Narrows, and farther south it occurs locally near Logandale and opposite Kaolin, on the east side of Muddy Creek. In all places the colors are light enough to make fresh surfaces good reflectors, and in summer anyone who attempts to work among the clay outcrops finds both the heat and the glare almost unbearable.

Around the margins, bordering the slopes of older rocks, an uneven thickness at the base of the sediments is made up of coarse sand and

[47] Stock, Chester, Later Cenozoic mammalian remains from the Meadow Valley region, southeastern Nevada: Geol. Soc. America Bull., vol. 32, p. 146, 1921.

gravel, partly consolidated but rarely entirely cemented. These deposits are everywhere very irregular in texture and structure. Near Overton Ridge 30 to 60 feet of interfingering sand and gravel lenses lie on the tilted and beveled Horse Spring beds. Lack of order is extreme, the pebbles and boulders reaching 12 inches in diameter and showing little approach to sorting. They are chiefly limestone, with some chert and sandstone, and many are practically unaffected by wear, the well-rounded specimens probably being an inheritance from older fans. Some lie isolated in masses of sand, others are collected in irregular groups, and still others form symmetrical lenses, representing cross sections of small stream channels. The materials are cemented sufficiently to stand in vertical cliffs 50 feet high, and the conglomerate lenses cause high falls in the small washes. At the top they are succeeded by many alternations of sand, silt, and clay in thin layers, of which the following partial section is typical:

Partial section of Muddy Creek formation near Overton Ridge

	Ft.	in.
Buff sand, medium grained		8
Gray sand		2
Gray silt, gritty		1
Gray sand, fine grained		½
Buff silt, gritty		½
Buff sand, medium grained		1
Yellow clay, with some silt		6
Gray sand, fine		½
Yellow silt	1	6
Buff sand, medium grained	1	6
Yellow silt		2
Buff sand, fine		½
Yellow silt		1
Buff sand, fine		½
Yellow clay		¼
Buff sand		½
Yellow clay		1
Yellow sand	1	½
Yellow clay and silt		6
Gray sand		1
Yellow silty clay		10
Gray sand		2

Above 30 to 50 feet of this succession the silt and clay layers are 6 to 20 inches thick, and the interbedded sand layers average 2 to 4 inches. The prevailing fineness of the sediments is notable in view of the fact that Overton Ridge is only 300 feet distant and rises steeply more than 200 feet above the base of the clay. In fact the silt and fine sand crop out almost in contact with the ridge. Each bed is massive. No ripple marks or sun cracks were found in the section. The silt and clay are well compacted but yield readily to water action. Although the sand layers are not entirely cemented they are sufficiently resistant to cause ledges and small falls in recent washes. Along this side of Muddy Creek the beds as a rule have a gentle dip toward the valley. Long washes, branches of Muddy Creek, expose excellent sections 100 to 200 feet high, in which the deposits differ little from those near the top of the formation close to Overton Ridge. The beds have an appearance of great regularity, although most of the sand layers are discontinuous within a few hundred feet. The clays are more or less gritty and lie in massive beds, few more than 2 feet thick. As a rule the thickness of the sand layers is less than 6 inches, although in a very few it exceeds a foot.

In the upper Muddy Valley saline beds in the clay are not common, but isolated gypsiferous layers occur in all sections, and along lower Muddy Creek and Virgin River saline deposits become very prominent. In St. Thomas and Little Bitter Washes layers of gypsum 1 inch to 6 inches thick are numerous, forming at least half the deposit through thicknesses of 50 to 100 feet. As a rule the gypsum is impure with clay, and gypsiferous clay is more abundant than gypsum alone. In Virgin Valley outcrops of rock salt are found in several localities. The best exposures are on the west side of the valley about 5 miles south of St. Thomas, where the clays are domed by moderate warping. A wash cuts through one large body of solid salt, exposing a thickness of 85 feet above the wash level. Another face, exposed below the mouth of the wash, has a height of more than 100 feet of salt, and the base is not visible. There are other outcrops in the vicinity, and all together mark out an area more than 1,600 feet long and 1,000 feet wide, all of which is probably underlain by salt. Possibly the extent is much greater, and the total thickness is nowhere evident. Some of the salt includes enough clay to discolor it, but most of it is nearly

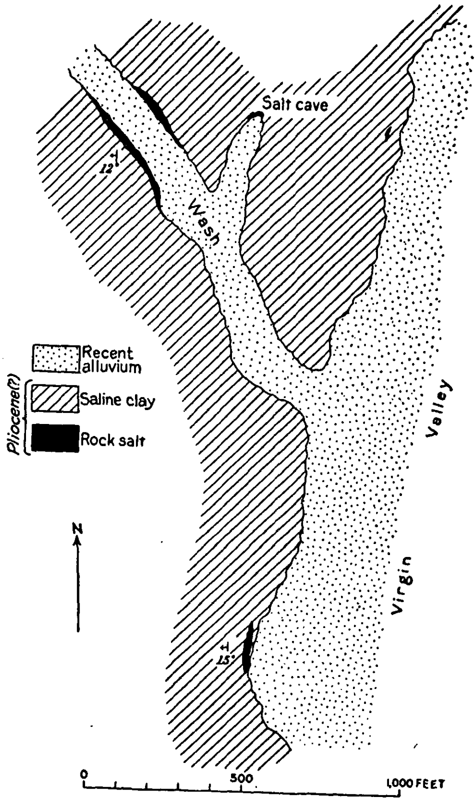


FIGURE 5.—Outcrops of rock salt at Virgin Valley salt mine

clear halite. The top surface is irregular, suggesting exposure and some solution before the overlying beds were deposited. Immediately above the salt lies an abundance of gypsum, much of it pure and crystalline, although the layers are thin and have considerable clay interbedded with them.

Farther south efflorescence of salt on the edges of the clay beds is common, and about a mile north of Bitter Spring Wash there are several outcrops, two or three of which have been worked slightly. Another large exposure, known as the "black salt," occurs on the east side of Virgin River about 10 miles above the mouth, and there are others nearer the Colorado. In general these lower outcrops contain more impurity than those near St. Thomas. That all are near the same horizon is indicated by a flow of basalt that lies in the clays at a nearly constant height above all the salt exposures. The lower Virgin River sections also show that the salt is near the base of the clays. The exposures near Bitter Spring Wash are less than 200 feet above the beveled beds of the Horse Spring formation, and the "black salt" is apparently about the same height above the unconformity, although an exact measurement was not obtained.

Except in partial sections it was not found practicable to obtain absolute thicknesses in the clay deposits. Near Bitter Spring Wash the beds are tilted toward the nor h, and although exposures are not altogether satisfactory a reasonably accurate estimate showed about 900 feet of sediments between the base and the included basalt flow. Near Little Bitter Wash the beds dip west, and at least 800 feet is exposed above the basalt flow. These estimates indicate a total of 1,700 feet, but the two partial sections were made nearly 8 miles apart. However, estimates made from disconnected outcrops above the basalt north of Bitter Spring Wash indicate that the order of magnitude is not too great for that locality. Furthermore, in view of the altitude which the highest beds reach against the mountain slopes and the amount of doming necessary to bring the salt to the surface near the level of Virgin River, 1,700 feet does not appear excessive for the thickness in the center of the basin. Within 500 feet of Overton Ridge the exposed thickness is 250 feet, and this is very near the feather edge of the sediments.

The clays in Grand Wash are similar in every way to those bordering the Muddy Mountains. Near the mountain slopes the deposits contain much sand and some gravel, but on the east side the sediments observed within a few hundred feet of the lower cliff are remarkably fine, suggesting a doubt that the cliffs had their present great altitude at the time the clays were deposited. Near the middle of the valley saline beds are conspicuous, and although no rock salt was identified gypsum is very abundant, especially in the dissected area known as the Gyp Hills.

Conditions of deposition.—Much of the material in the clay beds resembles a deposit in a playa lake. The abundance of silt, laid in massive beds and intercalated with thin lenses of fine sand, suggests the sudden spreading of fine materials at the end of a desert slope after infrequent heavy storms. However, a playa of the great extent represented by these intermontane deposits demands long bajada slopes adjacent, and the coarse sediments to be expected on such slopes are exposed very sparingly. In fact, except near the base of the series, the silt and fine sand extend without interruption to the slopes of high masses such as Overton Ridge. These relations, with the general horizontality of comparatively thin beds over a wide area, suggest deposition in a lake somewhat deeper than the ordinary playa. As the lake was undoubtedly in a dry country, very probably its depth varied considerably, decreasing at times until it approached the condition of a playa. In fact, the salt deposits, with marks of slight erosion on their surfaces, give evidence that the water completely disappeared for a time over at least a part of the lake bottom. Ripple marks at a higher horizon are a further indication that the water was shallow at times, at least locally. It also appears probable that the thin but widespread flow of basalt near the middle of the deposits was poured out at a time when the water had nearly or entirely disappeared, for the lava has no extraordinary structure such as would appear to be demanded if it were extruded under water. A level or gently sloping playa floor would supply the best conceivable surface for the wide flow of a thin, nearly uniform sheet of very fluid lava. Saline layers immediately below the flow give further support to this view; and the recurrence throughout the series of gypsum, probably associated with other salts, is evidence of continuing conditions that favored saline deposition. On the other hand, the fine sediments in contact with Overton Ridge at least 200 feet below its top must have been laid down in water of considerable depth, perhaps deep enough to submerge the ridge. It is probable that the relief during the Muddy Creek deposition was more subdued than at present. Although the clays are little deformed compared with older rocks, they have suffered considerably from broad warping, with local acute disturbances. Dips are everywhere away from the present highlands, suggesting broad uplifting of these areas, with possible sharp changes of relief due to faulting, after the deposition of the clays. (See pl. 10, *B*.)

During this time of sedimentation, therefore, the region was arid, with basin and hill topography corresponding in a general way to that of Horse Spring time but possibly with somewhat higher relief. Rainfall was insufficient to maintain permanent deep water bodies, but the basins alternately held playas and shallow lakes. At times of infrequent heavy rains the fine rock waste was rushed into the broad, flat-bottomed basins and deposited rapidly in massive layers of fairly regular thickness. Each silt or clay layer, possibly with the underlying sand lenses, represents the accumulation from a single storm. Washes entering from the highlands were short and had little ability to build deltas. The lake waters were strongly saline, and during stages of extreme aridity they shrank into the deeper depressions, where complete evaporation caused thick lens-shaped bodies of rock salt and gypsum to accumulate. The thick accumulations of salt near the base of the clays indicate that the conditions for depositing salts occurred early in the history of the basins. Then irregularities on the basin floors probably had not been greatly subdued by deposition of sediment, and the shrinking waters withdrew into deep pools of relatively small extent, in which were laid down the thick beds of salt now exposed.

The similarity of clay beds in the Grand Wash and other neighboring large intermontane valleys, including the great Detrital-Sacramento Valley south of Colorado River, suggests widespread aridity or semiaridity and nearly uniform conditions of sedimentation over southeastern Nevada and western Arizona.

Age.—Dr. Chester Stock, of the University of California, reports the finding of remains of camels in the Muddy Valley clays, but he does not consider these closely diagnostic. Near Panaca, 100 miles to the north, he found in similar deposits remains of horses that indicate Pliocene age, probably somewhat later than the date of the Muddy Creek deposits.[48] The writer saw the deposits at Panaca and similar sediments that are practically continuous in all the valleys between that region and northwestern Arizona. The close resemblance of the sediments in composition, texture, and structure, their apparently identical relation to older rocks, and the universal presence of a series of high terraces built on the clays by cut and fill give a strong implication that the clays wherever found are closely related in age. However, correlation merely by physical relations of typical desert deposits in a region known to have had a long history of aridity is not sufficient. The clays of southeastern Nevada are therefore only tentatively referred to the Pliocene as the best disposition with the data at present available.

QUATERNARY SYSTEM

DISTRIBUTION AND GENERAL NATURE

At present there seem to be no adequate data for delimiting the base of the Quaternary deposits in the Muddy Mountain region or for dividing the possible Pleistocene from the Recent. The saline clay

[48] Oral communication. See also op. cit.

series (Muddy Creek formation) has been tentatively referred to the Pliocene, and all younger deposits resting unconformably on that series will be grouped merely as Quaternary, with no attempt to separate them according to epochs. The following main groups of deposits are recognized:

Prevailingly coarse materials capping terraces and similar aggradational features; old alluvial-fan, talus, and travertine deposits adjacent to the mountain walls; alluvial fans still or until recently in process of building; recent talus cones and slope covers; valley fill; wind-blown sand.

COMPOSITION AND CONDITIONS OF DEPOSITION

Terrace cappings and related deposits.—Portions of terraces and mesas that have escaped stream attacks and now record former high base-levels show everywhere at least two unconformable components—a base, varying in height, of the Muddy Creek clays and a capping of coarse materials, uneven at the bottom to fit the irregularities of the clay surface but fashioned at the top into an almost smooth and even floor. (See pl. 11, *B.*) In thickness these coarse sediments range from a veneer of a few inches to fillings of more than 300 feet. On the broad Mormon Mesa, part of the highest level, such deposits stretch for miles, with a nearly level surface little interrupted by washes, sweeping up with a gradual but increasing curve to join the alluvial fans that border the Mormon Mountains. Parts of lower terraces, successive levels descending toward the larger streams, have similar surfaces. Where the remnants have not been isolated from the mountain walls it is not possible to draw a definite line between the old cappings and the alluvial fans still in process of building, nor is it worth while to attempt to do so. Evidently the same processes have been active throughout the terrace stages to the present time, disintegrating the mountain masses and moving the fragments outward. In inner portions of the broad intermontane troughs the process has been interrupted by lowering of base-level and cutting of new stream valleys, but adjacent to the mountain walls talus and fan slopes have slowly but continuously accumulated waste and are in part still protected by mesa remnants from direct effects of the lowered drainage.

Most of the material in the mesa and terrace cappings is gravel, with a relatively small amount of sand in the interpebble spaces. The composition of the gravel differs according to location with respect to large streams and mountain walls, some localities having fragments of one rock type only, others showing a large assortment of kinds, derived from widely separated areas. In the region as a whole, limestone naturally predominates in the pebbles, as all the local mountain ranges consist mainly of limestone. A broad belt bordering Virgin

River, however, has a great abundance of quartzite, chert, quartz, and various types of metamorphic and igneous rocks, commonly in well-worn pebbles from the smallest size to a maximum diameter of 10 inches, with an average of 2 inches or slightly greater. Possibly some of the quartzite and other hard pebbles have been transported from the Shinarump conglomerate of southwestern Utah, but some have come directly from the Cambrian quartzite overlying the schist in the neighboring Virgin Mountains. The many varieties of gneiss, schist, granite, and other rock types can be matched in the metamorphic core of the Virgin Mountain anticline, and the abundant angular fragments of these rocks on the mesas near St. Thomas evidently came from the metamorphic mass a few miles above the mouth of Muddy Creek. The portions of mesas and terraces that border Muddy Creek have large numbers and many varieties of porphyry pebbles, with kindred intrusive and extrusive rock fragments, all of which can be traced to their source in the volcanic region through which Meadow Valley Wash has cut its canyon. On the high surface represented by Mormon Mesa the zone occupied by these foreign pebbles is less restricted to the vicinity of the present stream courses, a wide expanse showing a considerable assortment of rock types. Toward the outer edges of the mesa and the borders of mountain slopes, however, the imported varieties decrease until they disappear, and the local limestone becomes almost universal.

The sizes of transported pebbles along Virgin River have been indicated, and pebbles of these sizes predominate in most of the cappings, but among them are scattered boulders 1 or 2 feet through or even larger. Toward the mountain walls the larger pebbles naturally become more numerous. Most of the fragments show evidence of considerable wear, and more than half are well rounded, except near the local mountain sources. At the top of the high mesas calcium carbonate or locally gypsum forms a firm cement, in many places becoming a solid matrix in which are embedded relatively few rock fragments. Below a depth of 5 or 6 feet, however, cementation is negligible, although the gravel deposits interlock so that they are self-supporting in bluffs 25 to 40 feet high where capped by the firm layer. There is little sorting or bedded arrangement of the fragments, although in part they lie in rude lenses. Evidently the gravel has been spread over the wide intermontane areas in part by streams and in part by sheet floods.

Old fan, talus, and travertine deposits.—Remnants of well-cemented deposits of pebbles and boulders occur at many places around the edges of the high Muddy Mountain mass, clinging to the steep mountain sides or partly filling small narrow canyons. On the Rogers Spring fault scarp 4 miles north of Bitter Spring a narrow, steep canyon descends through the limestone to the mountain front, and is continued as a wash, which cuts down 20 to 30 feet into the slope of waste. At the mouth of the canyon the walls and floor are not entirely of solid limestone but are made up in part of a coarse clastic deposit, which consists of large angular boulders and smaller fragments of limestone firmly held in a hard pink matrix of calcium carbonate containing some sand. The deposit is roughly stratified and dips 15° E. In places it forms the entire canyon bottom, but elsewhere parts of the uneven limestone beneath are exposed. On the steep walls at the mouth of the canyon masses of the fragmental material extend to a height of 150 feet, showing that the deposit once had at least that thickness. About 20 feet above the base a layer of white lime travertine 12 inches thick is included, having the same dip as the beds of coarse material. Patches of the deposit were traced up the canyon for a distance of 700 or 800 feet. Other canyons along this mountain front contain similar deposits.

Along the Arrowhead scarp, about a mile west of the White Basin fault, parts of the present steep cliff are formed on masses of cemented limestone fragments. These masses cling to a steep and uneven solid rock surface. The apparent base of this deposit is 500 feet above the floor of the Valley of Fire, or about 2,800 feet above sea level, and the thickness of the remnants is more than 200 feet. The presence of the deposit on the mountain front is apparently confined to a slight reentrant near the mouth of a canyon that is continued upward into the limestone as a wash of considerable width and low grade. Remnants of the fragmental deposit are present in this valley several hundred feet back of the mountain front. The materials are rudely bedded, and the bedding planes dip 1°–3° N., approximating the grade of the wash above the falls near the fault front. The materials in the deposit are derived from the Paleozoic limestones and included chert forming the local bedrock. The average fragments are from 1 inch to 2 inches in diameter and have very sharp angles and edges. Scattered blocks a foot or two in diameter are included. The interpebble spaces contain sufficient red sand to give a pink color to the firm lime cement. It is very clear that the materials were deposited by a small stream that was rapidly aggrading its valley.

Farther west along the same front, near the east end of Summit Canyon, a small valley enters the Valley of Fire from the south. The lower part of its course is a canyon cut nearly to grade with the larger valley floor. On the sides of this canyon, extending beneath its present stream bed and fingering back into tributary canyons, is a deposit of coarse limestone fragments with a firm matrix of calcium carbonate, which contains many thick lenses of red sand with weaker cement. Red sand is also abundant in the spaces between the coarse fragments, giving the cement a pink or red color. The fragments are very angular and are poorly assorted. The bedding is rude and lenticular, and the indistinct bedding surfaces dip gently downstream on the canyon floor and steeply toward the middle of the canyon along its sides and in small tributaries with high gradient. The base of the deposit rests on an uneven bedrock surface, which has a slope less steep than the present canyon sides.

Probably the three occurrences just described represent a stage or stages in the Quaternary history of the region. The deposit near the intersection of the White Basin and Arrowhead faults is at a higher level than the other two and was laid down with a gentler gradient. Observations in the field suggest that this deposit originally sloped down to connect with the gravel at the top of Mormon Mesa, and it is very probable that the materials are a remnant of the Muddy Mountain border of that high level. Although the present base map does not permit close comparison in altitude of widely separated points, the deposits near Summit Canyon and on the Rogers Spring scarp appear to be in approximately the same plane at an altitude of about 2,000 feet and probably represent rapid fan growth during one of the stages of aggradation.

Present alluvial fans.—Typical alluvial fans are found either at intervals or in continuous succession at the base of all steep mountain slopes. Temporary swift streams have dropped their loads of coarse material with decrease of gradient, in the manner common in arid lands of steep relief, their channels braiding and frequently changing to produce a complex lenticular structure of poorly assorted fragments. Practically all the fans adjacent to the mountain walls have ceased to aggrade and are cut by narrow trenches 20 to 70 feet deep in which the present loads, including contributions from the fans themselves, are carried out to be spread on gentler slopes at a distance from the steep fronts.

Talus deposits.—Along cliffs and steep slopes between washes or canyons loose blocks accumulate as talus débris and encroach on the fans, the two types of deposit blending without sharp lines of separation. Whether fans or talus slopes predominate is determined by the steepness of the cliff and the interval between adjacent canyons, and these conditions are in turn largely determined by the age of the cliff and the structure of the block that it bounds. Fault fronts on dipping blocks of Kaibab limestone capping Supai sandstone are especially favorable for the formation of long steep talus slopes unbroken by fans. Broad-topped blocks like those making up the high nucleus of the Muddy Mountains develop many stream courses, and except where the upper surface dips away from a recent scarp fan material at the base equals or exceeds the talus débris. Thus the eastward dip of the strata favors the formation of many canyons along the Rogers Spring fault scarp, and the waste deposited on the slope to the east is largely alluvial-fan material. Along the Arrowhead scarp east of the White Basin fault the southeast dip of the rocks and tilt of the block surface have retarded the formation of stream courses toward the north, and therefore an unbroken talus slope borders the cliff. (See pl. 13, *B*.)

Both talus and fans are practically absent from the Jurassic (?) sandstone areas, except where that formation has a capping of Overton fanglomerate or some other resistant rock. The loose sandstone is disintegrated and carried away by water and wind as fast as blocks are dislodged.

Valley fill.—The present valleys of Virgin River and Muddy Creek are floored with silt and sand to an undetermined depth. Sections exposed in the banks of the Virgin River channel do not exceed 20 feet in height. Recent incising by Muddy Creek has formed a narrow inner valley with steep banks from 30 to more than 50 feet high, in which the exposed sediment is chiefly sandy silt, with lenses of fine sand and thin layers of clay. Thin lamination is common; layers of yellow, gray, pink, and green are arranged in various combinations, giving the vertical banks a banded appearance. The wide flood channel of Virgin River is entirely floored with sand, though considerable silt is included where eddies and quiet stretches have favored its deposition. Fresh pockets of the finer materials that have not settled and drained sufficiently are very treacherous, acting like quicksand. Even when it becomes firmer the surface of such a pocket trembles and bends like "rubber ice" under the weight of horse or man. The old flood plain, from 10 to 40 feet higher than the flood channel, is underlain by sandy silt and forms good farm land except where included alkaline salts are concentrated. These salts form a white efflorescence on flat surfaces after every rain.

Wind-blown sand.—Sand dunes and wide sheets of wind-blown sand are numerous on the floors of Muddy and Virgin Valleys, on portions of the lower terraces, and on the north and east slopes of ridges. West of St. Thomas deposits of this kind cover large areas of the partly dissected mesas. Much of the material moves with every high wind, but part of it is held in position by the sparse desert vegetation. Sand dunes are most conspicuous in or near the areas underlain by Jurassic (?) sandstone.

IGNEOUS ROCKS

The northern part of the Black Mountains consists principally of porphyry, basalt, and other kinds of igneous rock, both intrusive and extrusive. Around the southern border of the Sandstone Spring anticline bodies of the porphyry are intruded into Horse Spring and other formations. Near Virgin River thick sills and other intrusive bodies cut the Muddy Creek formation and lava flows are intercalated with the same sediments. Hence if the Muddy Creek clays are Pliocene, the buried lava flows are also of that age, whereas the intrusive rocks may be younger. No study was made of the area occupied by these rocks.

Two miles north of Bitter Spring Wash, west of Virgin River, the edge of a basalt flow buried in the clays is exposed as a low ridge. The beds dip north, and consequently the outcrop of basalt extends generally east. The flow is approximately 100 feet thick. Near the base the rock is decomposed, for water admitted along joints finds its descent interrupted by impervious clay at the base. In a large part of its thickness, however, the basalt is little altered. The outcrops appear black in the setting of yellow clays. On fresh surfaces light is reflected from crystal faces, for the rock is entirely crystalline, although the texture is fine. In thin section the basalt is seen to be very basic, consisting essentially of labradorite and augite with an abundance of small olivine phenocrysts. Toward the top the rock becomes increasingly vesicular, and amygdules of pectolite, some of them half an inch in diameter, are abundant. The surface of the flow is rough and slaggy. The overlying sands and silts contain fragments of the lava through a thickness of 2 or 3 feet.

Several outcrops of the same flow occur farther north. Near the salt mine 4 miles south of St. Thomas the black lava sheet forms a prominent capping of clay bluffs on the west side of the Virgin Valley. There is a less conspicuous exposure directly east, on the opposite side of the river. In this locality the thickness of the flow ranges from 40 to 50 feet. In St. Thomas Wash it is only 20 feet thick, and at the most northern exposure, 2 miles southwest of St. Thomas, the thickness is less than 15 feet. There is no doubt that the several outcrops are parts of the same flow, for they lie at approximately the same horizon, 800 to 900 feet above the base of the clays, and specimens from all outcrops are identical in petrographic character.

Its continuous thinning toward the north indicates that the flow originated in the Black Mountain volcanic center. The flow is unusually thin for its extent, and the thickness decreases so gradually as to suggest an intrusive sheet rather than a surface flow. Evidently the molten lava was very fluid, and its extremely basic character allowed it to spread as a wide, thin sheet before it solidified.

On the west side of Grand Wash Valley two flows of dark basalt form conspicuous outcrops. Near Buckhorn Spring the lower flow is 20 to 25 feet thick, and its base rests on an eroded surface of the Muddy Creek formation. The rock is black, and microscopic analysis shows that its essential constituents are labradorite, augite, and olivine. The flow is separated by 70 feet of gravel from a younger extrusive sheet 75 feet thick. The upper flow has a lighter color than the lower and contains an abundance of olivine crystals as large as coarse sand grains. Gravel has buried the younger flow to a depth of 50 feet or more, but wide surfaces have been stripped by later erosion. Both flows are probably of Quaternary age.

STRUCTURE

GENERAL CONSIDERATIONS

A desert country of high relief offers exceptional advantages in the study of structure. As a rule the rocks are remarkably well exposed, and structural features commonly have a strong topographic expression. Where there is such complex shattering as is found in southeastern Nevada, however, the wealth of detail exposed is at first confusing rather than helpful. Minor faults and folds partly or entirely conceal more essential features, and structural forms of widely different nature produce topographic features that are remarkably similar.

In the area of this report four main groups of structural features are recognized—great intermontane faults or fault zones that bound individual ranges; intersecting faults that divide each range into a mosaic of blocks; folds, both moderate and intense; and overthrusts of a major character. (See pl. 1.) The intermontane faults will be considered first, and the other features will be described in connection with the structure of the individual ranges. Finally, an attempt will be made to outline the structural history, assigning dates so far as possible. (See pls. 12–15.)

INTERMONTANE FAULTS

The rock floors of the large intermontane valleys are buried under thick covers of waste that prevent any accurate determination of structure. It is certain, however, that Grand Wash Valley is a zone of profound faulting. Edges of fault blocks appear above the waste, and portions of separate faults are exposed, demonstrating that displacement has occurred on a series of westward-dipping faults with a general north-south trend. Pakoon Ridge is a tilted block bounded on the west by a fault extending almost due north. An apparently similar block is exposed northwest of Pierces Ferry, near the mouth of Grand Wash, but the actual position of the fault bounding it was not determined. Without doubt other fault blocks are entirely buried under the valley deposits. It is evident, however, that the principal throw occurred along a line or zone that lies somewhere in front of the high scarp at the western edge of Shivwits Plateau. If the upper cliff were projected to the edge of the lower, the scarp would stand 4,000 feet above the valley floor. The total measure of the throw is greater than this, for the eastern edge of the downthrown block is covered by a large thickness of later deposits. An approximation of the throw may be obtained by considering the tilted Kaibab and Supai block northwest of Pierces Ferry as a part of the thrown mass adjacent to the main fault. It will be assumed that the position of the fault is 1 mile west of the top of the lower cliff. This estimate seems reasonable, because the recession of this resistant limestone cliff must have been many times slower than that of the upper cliff with its high altitude and its weak base of Supai sandstone. An average dip of 20° E. on the Kaibab limestone of the tilted block will place the top of that formation 3,200 feet below the 2,000-foot contour at the assumed position of the fault. Adding the height of the scarp makes the vertical displacement on the main Grand Wash fault approximately 7,000 feet. Dutton[49] estimated the throw to be between 6,000 and 7,000 feet. It is apparent that the amount of displacement decreases gradually toward the north.

The age of the fault and the possible recurrence of movement are problems whose solution requires detailed field work. The ragged appearance of both cliffs and the recession of the upper cliff 2 to 6 miles from the edge of the lower give the impression that a long time has elapsed since the principal movement occurred. However, the presence of the very thick and weak Supai sandstone beneath the Kaibab would undoubtedly cause the stripping of those formations to proceed at a relatively rapid rate. Moreover, the lower cliff owes its ragged outline chiefly to canyons of considerable length heading on Shivwits Plateau, 6,000 feet above sea level, where precipitation is considerably greater than in the lower country on the west. It does not appear necessary, therefore, to rate the fault as extremely old merely because the scarp is considerably modified. The writer saw no direct evidence of recent faulting in Grand Wash Valley, but the area was not examined thoroughly. Local warping has affected the saline clays and associated deposits, and there is a noticeable lack of coarse materials in these sediments adjacent to the lower cliff. Deformation of Quaternary deposits is indicated by considerable differences in the altitude of thin basalt flows, and although these differences may be due to moderate warping, they suggest a possibility of recent recurrence of faulting. A large amount of movement in pre-Pliocene(?) time is indicated by the unconformable relation of the saline clays to the tilted blocks of Kaibab and Supai strata.

The mountain walls on both sides of the Virgin Valley are fault scarps that represent great displacement, and the downthrown block is on the valley side of each fault. This relation in itself accounts for depression of the valley floor, but in view of the close repetition of faults in the highlands it is improbable that the bedrock beneath the valley lies in one or two blocks dropped as grabens. It is more plausible to picture the floor as a mosaic of irregular blocks, with the

[49] Dutton, C.E., The physical geology of the Grand Canyon district: U. S. Geol. Survey Second Ann. Rept., p. 126, 1882.

longer axes trending generally north, parallel to the prevailing exposed fault lines. The possibility of a major fault located near the stream course is seen in the abrupt ending of the crystalline rocks near the Gentry ranch. Southwest of Muddy Creek the thick Mesozoic and Miocene(?) rocks dip directly toward the schist ridge, and the intervening wide belt of late Tertiary and Quaternary detritus suggests a concealed fault block rather than a fold. It is possible that some displacement on this Virgin River fault has occurred in post-Pliocene time, as the beds of the Pliocene(?) Muddy Creek formation dip strongly east at the point of the mesa directly north of St. Thomas. The Pliocene(?) deposits were not seen closely adjacent to any of the large faults along the mountain borders, and therefore these faults can be dated only as post-Miocene(?).

Evidence of major faults following the course of California Wash is less convincing. General anticlinal structure on each side implies that the valley may be a great synclinal trough, but the fold is probably modified by faulting, as is suggested by the steep scarps on the west front of the Muddy Mountains.

STRUCTURE OF THE MUDDY MOUNTAINS

Both faulting and folding have contributed to the structure of the Muddy Range, the relative importance of the processes differing in different parts of the area. The mountains are not a structural unit, and in a strict sense the term "range" is not descriptive of the area as a whole. There are three well-defined structural divisions, separated by lines running roughly east. The northern division, between the Arrowhead fault and Muddy Creek, shows chiefly close folding, though it has also been faulted to some extent. Everywhere the surface bevels steeply dipping strata that strike generally north, except in the southern part of the division, where a large cross fold turns the structure lines toward the east, giving the outcrops of certain formations the shape of an L. The central division is an irregular remnant of an overthrust block bounded as well as cut by steep faults. Doming and warping have affected parts of the mass, but faulting was the outstanding process in its construction. The southern division exhibits folds with axes trending approximately northeast, cut and greatly modified by a number of normal faults. (See fig. 6.) These folds continue into the Black Mountains, and hence there is no sharp structural division between the two mountain groups.

NORTHERN DIVISION

WEISER ANTICLINE AND RELATED STRUCTURAL FEATURES

South of the Narrows of Muddy Creek the surface cuts steeply inclined beds exposing from west to east a complete succession of sedimentary formations from the Supai to the Horse Spring. In

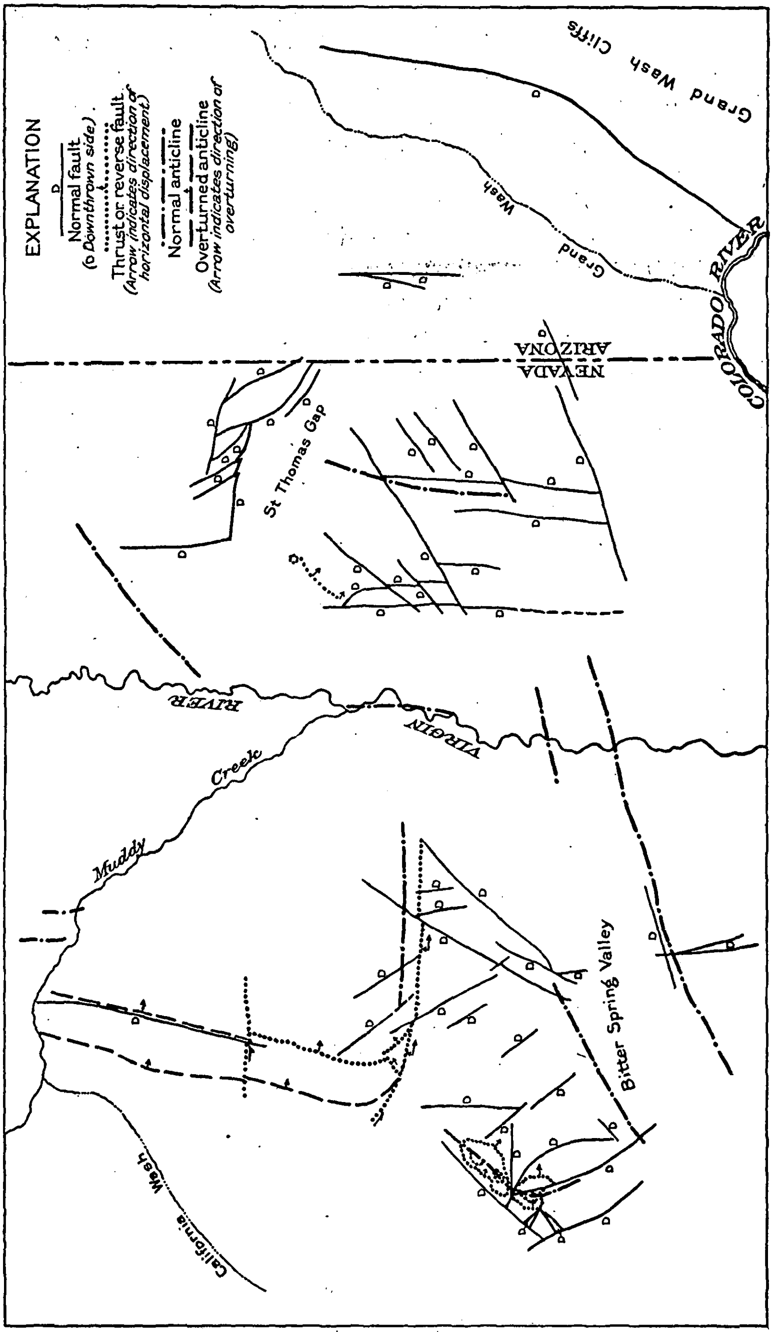
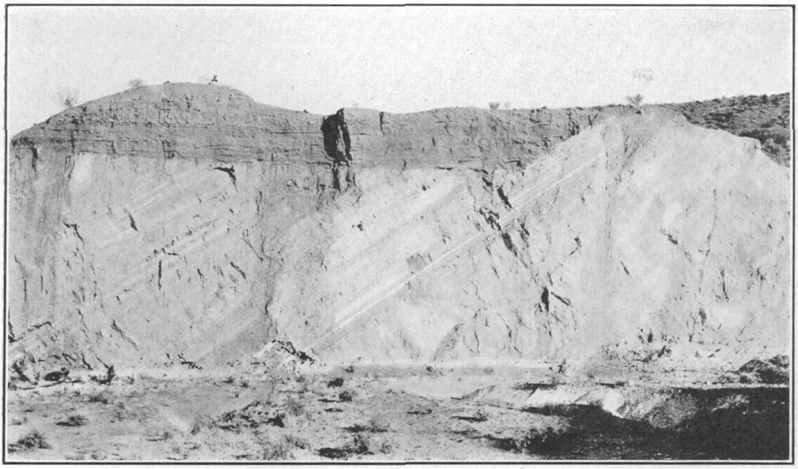
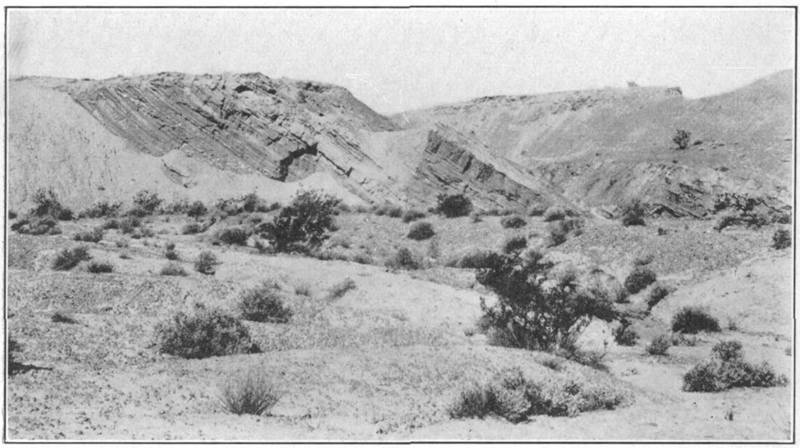


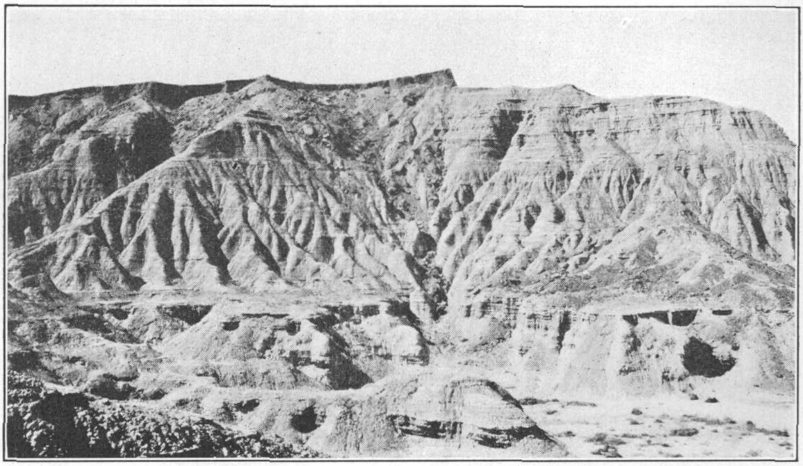
FIGURE 6.—Structure diagram of the Muddy Mountain region



A. UNCONFORMABLE CONTACT BETWEEN PLIOCENE (?) BEDS (MUDDY CREEK FORMATION) AND HORSE SPRING FORMATION IN KAOLIN WASH

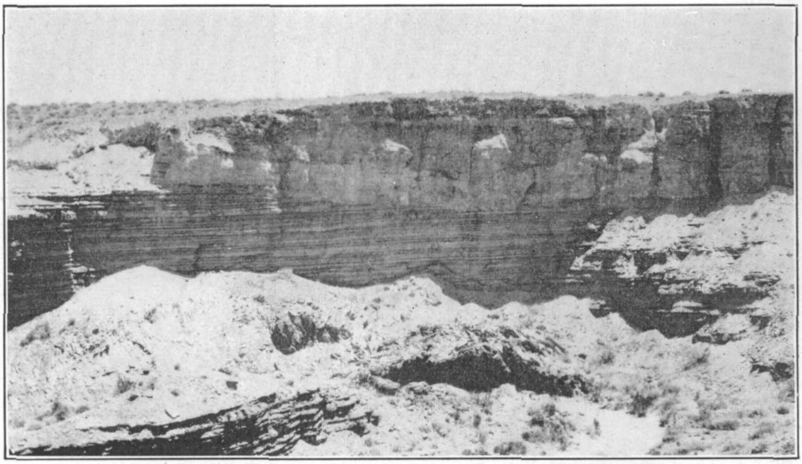


B. TILTED MUDDY CREEK CLAYS SOUTHWEST OF ST. THOMAS

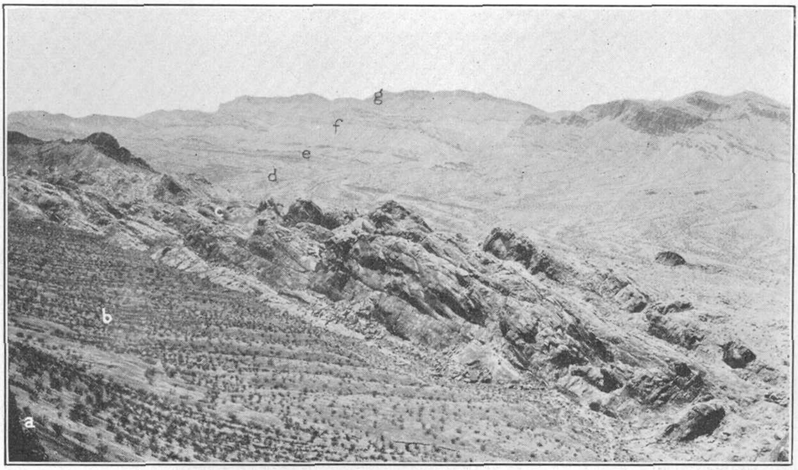


A. TYPICAL SECTION OF MUDDY CREEK FORMATION

Gravel capping at top. Height of section about 200 feet

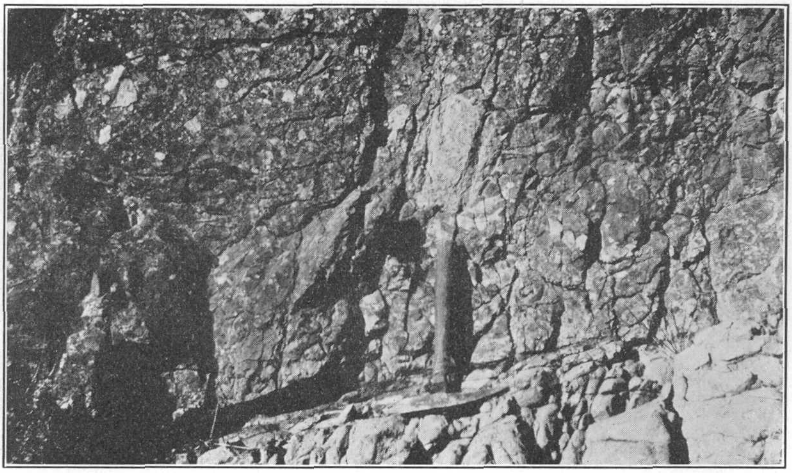


B. TERRACE CAPPING OF GRAVEL RESTING ON MUDDY CREEK BEDS



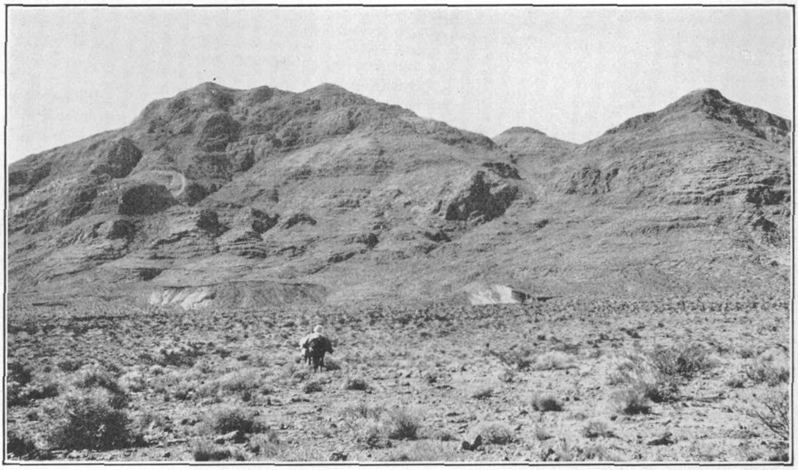
A. VIEW SOUTHWEST ACROSS WEISER VALLEY

a, Kaibab limestone on west side of Weiser Ridge; b, gypsiferous shale at top of Supai formation; c, sandstone in Supai formation; d, Moenkopi formation; e, Chinle formation and Shinarump conglomerate; f, Moenkopi formation; g, Kaibab limestone. All beds dip west in overturned position. Weiser Valley fault between c and d



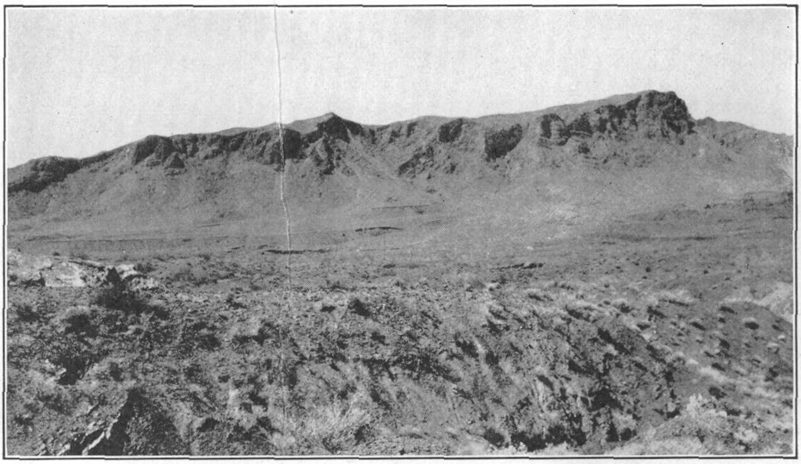
B. CLOSE VIEW OF GREAT THRUST CONTACT IN MUDDY PEAK BASIN

The hammer-head rests on Jurassic (?) sandstone; thick fault breccia above



A. PART OF ROGERS SPRING FAULT SCARP

The white rocks near the base are in the Horse Spring formation, faulted down against the Paleozoic rocks in the scarp



B. PART OF THE ARROWHEAD SCARP NEAR THE EAST END OF THE VALLEY OF FIRE

Highest point, at right, at an altitude of 3,600 feet; valley floor, 1,800 feet. Note the tilted erosion surface cut across the dipping Paleozoic limestones in the high block

Weiser Ridge the strata are overturned. Their strike is nearly north, and their average dip is 60° W. Toward the east the dip gradually becomes steeper until near the middle of the Valley of Fire the beds are vertical; and the inclination then becomes eastward, steadily decreasing through the Jurassic(?) sandstone. These relations continue uniformly for several miles south of Muddy Creek, and in the Valley of Fire the general structure, with local modifications, remains the same almost as far south as the Arrowhead fault scarp. All the Paleozoic and Mesozoic formations, beginning with the Supai at the west base of Weiser Ridge, apparently lie in the east limb of a closely compressed anticline whose axial plane is overturned to the east and the beds on whose eastern flank gradually resume their normal stratigraphic positions with increasing distance from the axis.

Immediately south of Weiser Gap the overturned anticline is exposed in continuous section. The dips are essentially isoclinal toward the west; but the Kaibab limestone is duplicated, and west of the ridge the Moenkopi formation lies in normal position above the Kaibab. Slightly more than a mile south of the gap the lower Moenkopi beds disappear, the Kaibab is no longer of double thickness, and Supai sandstone appears at the core of the fold. It is evident from the stratigraphic relations that a large normal strike fault cuts the anticline west of the axis, but the stream course in Weiser Valley follows the fault and conceals it except in a few places. The Moenkopi shales are in contact with the Supai to a point 9 miles south of Muddy Valley. Near this point Weiser Valley terminates abruptly against a wall of Kaibab limestone, which extends continuously between Weiser and California Ridges, marking the position of an east-west fault. South of this fault the Weiser anticline passes into a thrust, the Kaibab limestone riding eastward over the Moenkopi. The thrust surface and the overlying beds have a low dip to the west, and the overridden Moenkopi strata are doubled over to the east. Near the Arrowhead fault the thrust steepens to a maximum dip of 60°. Immediately north of the old Arrowhead road all the formations in the overthrust block are overturned, and limestones of the Moenkopi formation lie on the thrust surface, which cuts across Jurassic (?) sandstone. In this vicinity the structural lines are bent and displaced strongly to the east. Evidently this deflection is closely related to movement on the Arrowhead fault and merits further mention in connection with that feature.

The overturned fold in Weiser Ridge will be referred to as the Weiser anticline, and its broken continuation to the south as the Weiser thrust. The later normal fault, displacing the western limb of the anticline, will be called the Weiser Valley fault. West of this fault the formations have a synclinal structure, the Kaibab limestone turning up sharply in California Ridge, a close duplicate of Weiser

Ridge. (See pls. 1 and 12, *A*.) On its western flank the full thickness of the Supai formation lies in an inverted position, and a low, discontinuous ridge is made by upturned beds of Callville limestone. At several points these Pennsylvanian strata have been turned through an angle of 160° and now dip at a low angle away from the younger formations. This extreme overturning, which was accompanied by considerable crumpling, suggests that these beds were overridden by a thrust. The alternate assumption is an essentially recumbent anticline, the upper part of which has been removed by erosion. Whether the structure is that of a thrust or a fold, probably its continuation to the west has been concealed by displacement on a north-south fault paralleling the west border of the range. As no part of such a fault was seen, it is not represented on the geologic map.

ARROWHEAD ANTICLINE

The axis of the Arrowhead anticline trends nearly east, practically at right angles to the Weiser anticline. It is a broad, open fold, in which the steepest dips range from 25° to 35°. At the east end of the Valley of Fire the fold plunges abruptly beneath the Pliocene (?) clays, and toward the west it becomes obscure on meeting the stronger anticline from the north. A large northeasterly fault extends across the eastern part of the fold and causes offsets of several hundred feet in all formations. Many minor faults with the same general trend make conspicuous jogs in the contact between the Jurassic (?) sandstone and Chinle shale. Farther west two faults with northwest trend cause displacements of several hundred feet, bringing the Jurassic (?) sandstone against beds low in the Chinle formation. Other small faults affect the anticline, causing minor irregularities in the structure.

The relation of the Arrowhead anticline to the Arrowhead fault presents an important question. By reference to section D–D′, Plate 1, it is seen that the south limb of the anticline contains the old Paleozoic formations in the main overthrust mass, and that the Arrowhead fault separates these older formations from the Mesozoic rocks in the crest of the north limb of the fold. Is there a genetic connection between the fault and the fold? This problem can be considered to best advantage after the principal thrust and the Arrowhead fault have been discussed. (See p. 111.)

FOLDING AND TILTING OF OVERTON AND HORSE SPRING BEDS

Near the Narrows of Muddy Creek the Overton fanglomerate dips 10°–15° E. and thus lies almost at right angles to the overturned and beveled strata in the Weiser anticline. (See fig. 7 and pl. 15.) Therefore these earliest Tertiary deposits are considerably younger than the major folding and thrusting. However, both the Overton and Horse Spring beds have been strongly deformed. North of Muddy

Creek the outcrops of Horse Spring limestone show two parallel anticlines with crests about a mile apart, in which the limbs dip 25° at a maximum. South of the creek the smaller outcrops of this formation and the entire section of Overton deposits have a monoclinal dip to the east-northeast. From an average of 15° near the Narrows this

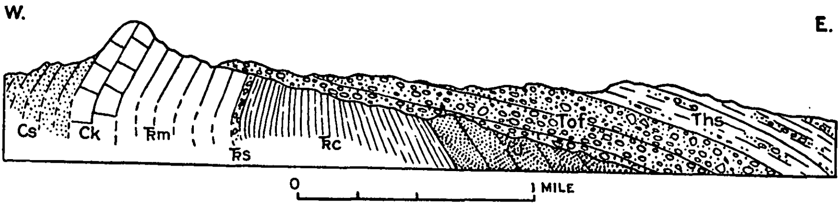


FIGURE 7.—Cross section showing structural relations near Muddy Creek. Cs, Supai formation; Ck, Kaibab limestone; Ꞧm, Moenkopi formation; Ꞧs, Shinarump conglomerate; Ꞧc, Chinle formation; J, Jurassic (?) sandstone; Tof, Overton fanglomerate; Ths, Horse Spring formation.

dip increases steadily toward the outheast to a maximum of 35° in Kaolin Wash. As the strike does not conform to any definite axis of folding, it is suggested that this steep tilting is related to post-Miocene (?) faulting along the general course of Muddy Valley.

CENTRAL DIVISION

MUDDY MOUNTAIN THRUST AND ARROWHEAD FAULT

Complex normal faulting in the high central division obscures an older structure that is relatively simple, although it is a product of intense compression. The Paleozoic limestones and dolomites in this area form a unit thrust plate of large dimensions. In Muddy Peak Basin the Jurassic (?) sandstone is exposed beneath the Paleozoic beds over an area measuring 6 miles from north to south and 2 miles from east to west. In this typical window remnants of the dark Paleozoic dolomite and limestone remain as cappings on sandstone hills, and the younger formation passes beneath the older around the rim of the basin. Thrust relations are clear at all points, the surface of thrusting practically paralleling the bedding both below and above. In the underlying sandstone most of the original laminated structure has been destroyed to a depth of several feet, and in this zone the sand is more firmly cemented than in the normal rock. The principal surface of movement is sharply defined, and the rocks on each side are smoothly polished. Above it is a zone of breccia, 25 feet or more thick, made up of angular limestone fragments, some rounded pieces of sandstone, and considerable sand in a firm limy matrix. Above the typical breccia the Muddy Peak strata are intensely shattered through a thickness ranging from 100 to 500 feet, and there has been pronounced slipping between beds. (See pls. 5, 7, *B*, and 12, *B*.)

Minor thrust faulting and crumpling indicate that the thrusting force acted almost directly from the west. The thrust surface is visible only in the eroded dome that forms Muddy Peak Basin; but the presence of corresponding Paleozoic formations throughout this part of the range shows clearly that it is a unit block, and undoubtedly it was continuous across the area of White Basin before normal faulting produced that depression. Therefore it is clear that the thrust was at least as extensive as the area that includes outcrops of the Callville limestone and older Paleozoic formations. In an east-west direction this area has a length of 15 to 18 miles, and this distance may be taken as a minimum measure of horizontal displacement on the fault. The full extent of horizontal movement can only be conjectured, as the thrust plate disappears to the west under recent deposits in California Wash. The vertical displacement of the Paleozoic strata in Muddy Peak Basin is approximately 11,000 feet, and yet the thrust surface is almost parallel to the bedding. Therefore the thrusting was certainly initiated far to the southwest. Moreover, the plate is now bounded on the east by a later normal fault, and the downthrown portion may extend considerably farther beneath younger sediments in Virgin Valley.

Evidence as to the original extent of the thrust plate in a north-south direction is not altogether satisfactory. South of White Basin the older formations are hidden by Tertiary and later deposits, and the continuation of the thrust appears to be effectively concealed. On the north the visible part of the thrust block terminates abruptly at the Arrowhead fault. (See pl. 13, *B*.) Fortunately, the nature of this fault is easily determined, and the relation of the major thrust to the formations and the structure in the northern division of the range may be inferred. From Bluepoint westward the Arrowhead scarp is interrupted only by minor offsets on later intersecting faults and by small canyons in which exposures of the fault surface may be studied. This surface dips steeply to the south, and striations on it are nearly horizontal. These facts together with the strong eastward bending of structure lines north of the fault indicate that the block south of the Arrowhead fault moved eastward. The possible implications of this conclusion will now be considered.

It is evident that movement on the Arrowhead fault resulted from strong compression with a large west to east component. It is an obvious suggestion, therefore, that this fault was contemporaneous with the major thrust and served to accommodate differential movement between the two parts of an overriding block. It is pointed out on page 108 that the Weiser anticline and Weiser thrust reflect strong compression from the west, and that the overturned strata in and west of California Ridge suggest overriding by a thrust plate. It may be assumed, therefore, that these structural features are expressions of a single large thrust, which affected the entire range but became more intense south of the Arrowhead cross fracture. Under this interpretation the part of the thrust plate north of the Arrowhead fault probably never reached far to the east, and this part has been completely removed by erosion. The Arrowhead fault may represent a cross fracture contemporaneous with some stage of movement on this principal thrust, or it may have developed at a distinctly later date. In any case the present steep fault front is not to be interpreted as a direct effect of movement on the fault. The superior resistance of rock formations in the high thrust block as compared with Mesozoic rocks to the north, together with the southward dip of the fault, serve to maintain a high scarp so long as active erosion of the region is in progress. Further discussion of the fault scarp will be reserved for the section on physiography. (See pp. 135–137.)

It appears significant that the axis of the Arrowhead anticline is practically parallel to the Arrowhead fault. There is strong implication that the two features are genetically connected. With this relationship assumed, evidence of a large southerly component in the compression that produced the fault is seen in the presence of the fold, in the southward dip of the fault, and in the sharp flexing at the south end of the Weiser thrust. The compression that produced the Weiser and Muddy Mountain thrusts apparently acted more nearly from west to east. This discrepancy may be taken to indicate that the latest movement on the Arrowhead fault is of somewhat later date than the general thrusting.

On the south the relations of the thrust block are more obscure than on the north. From Muddy Peak the thick Paleozoic limestones dip steeply southward and pass under Horse Spring deposits. A short distance southeast of the Muddy Peak mass lies an isolated block of Callville limestone whose relations appear significant. The strata in this block dip northwest, and on the south side the block is in contact with Jurassic (?) sandstone along a fault that dips steeply northwest. Another large outcrop of Callville limestone lies in the midst of the Horse Spring formation south of White Basin and several miles east of Muddy Peak. Finally, northwest of Bitter Spring, near the south point of the Paleozoic block, a large outcrop of Jurassic (?) sandstone is unconformable below the Tertiary beds and apparently is separated from the thrust block by a fault. The presence of Jurassic (?) sandstone at this point and south of Muddy Peak gives reason to suspect that a fault similar to the Arrowhead fault bounds the thrust block on the south. Such a fault, concealed in large part under the later Tertiary deposits, may extend from the outcrop southeast of Muddy Peak to the point of the mountain northwest of Bitter Spring. If this interpretation is correct, the Paleozoic rocks in this high division of the range represent a great wedge-shaped block driven eastward between two steep faults. This action must have occurred in a late stage of the thrusting, after the development of the flat

Muddy Mountain thrust and of the Weiser anticline and thrust. This possibility is further considered on page 123.

DATE OF THRUSTING

In the Muddy Mountain thrust, as in the Weiser anticline, the youngest formation involved is the Jurassic(?) sandstone. On the north and south sides of White Basin and west of Muddy Peak the Tertiary deposits are unconformable on strata in the thrust block and were certainly laid down after the principal movement. Hence the thrusting occurred between the Jurassic(?) ~~and the~~ Miocene(?). Considerations bearing on a more definite date are discussed in a section following the descriptions of structural features (pp. 121–126).

NORMAL FAULTS

General features.—Several large normal faults have displaced parts of the Muddy Mountain thrust block. There are also many fractures with small displacement, but no attempt is made to show these on the map. Most of the faults are disclosed by direct evidence, such as exposure of actual fault surfaces, intensely brecciated zones, lateral contact of different formations with the edges of beds bent and dragged along the plane of movement, and steep scarps almost unaffected by erosion. The fresh appearance of several scarps is especially striking. Surfaces hundreds of feet high retain essentially the original dip of the fault, and large slickensided surfaces are common. Undoubtedly the freshness of most of these features is due to recent uncovering and not to extreme recency of movement. Most of the faults range in inclination from 45° to 60°, and some are as steep as 70° or 80°. Striations found on some surfaces indicate important lateral as well as vertical components in the movement.

Not all the faults can be assigned to definite sets, but at least three general trends are recognized—N. 30°–40° E., N. 25°–40° W., and north to N. 5° W. Each of these sets is represented by several large faults and many smaller ones. At least one large fault runs nearly east and another is decidedly curved. Many minor fractures appear to have erratic trends.

Rogers Spring fault.—The large fault bounding the thrust block on the east will be referred to as the Rogers Spring fault, from the name of the large warm spring that issues at the base of the scarp. (See pl. 13, *A*.) A number of canyons cut through this mountain front, but the base has a remarkably regular course. Recent dissection has exposed Horse Spring limestone in plain fault contact with the older formations of the thrust block. The weak Tertiary beds in the hanging wall are bent sharply upward to a position almost parallel with the fault, which dips 60° SE. There is also conspicuous downward drag of the heavy limestones in the footwall.

The scarp curves somewhat to the east, toward Bluepoint. No indication was found that the fault continues northeast of Bluepoint, but the soft formations and the covering of recent débris may account for its apparent disappearance. Undoubtedly it is a structural feature of great magnitude. The maximum height of the footwall block, more than 1,500 feet, is only a partial measure of the throw, as the Carboniferous limestones in the thrown block are buried to an unknown depth under other formations. Possibly the movement was of a hinge nature, decreasing toward the northeast, as the strata in the footwall dip more steeply eastward in that direction and the visible throw becomes correspondingly less. Subsidiary faults in the footwall block parallel the general front, indicating movement in a zone of considerable width. Displacement on these "sympathetic" planes is comparatively small.

The Rogers Spring fault curves westward north of Bitter Spring and apparently ends against another fault with northeasterly trend.

White Basin fault.—The Paleozoic ridge east of White Basin is an excellent example of a narrow horst. It is bounded on the east by the Rogers Spring fault and on the west by a fault of corresponding magnitude, here called the White Basin fault. (See pl. 14.) This feature is marked by the best-preserved scarp in the region. It can not be certainly traced southward through the soft formations and the waste cover of Bitter Spring Valley, but on the east side of White Basin the footwall stands as a steep, regular cliff, averaging several hundred feet in height. The course of the fault northward through the Paleozoic limestones is marked by a valley, on the east side of which the footwall continues as a cliff with decreasing height and regularity. At its intersection with the Arrowhead fault the mountain front on the east is offset to the north several hundred feet. This abrupt jog corresponds in direction and amount to a straight offset, previously mentioned, in the Jurassic(?) sandstone outcrop north of the Valley of Fire. In the valley itself there are similar offsets in contacts of formations, but the fault can not be traced continuously in the soft shales partly concealed by débris. It is reasonably certain, however, that the White Basin fault extends across the valley, as indicated on the geologic map. It was not traced far north of the Valley of Fire, and its possible continuation in that direction would be very difficult to follow in the massive Jurassic(?) sandstone and the soft Tertiary formations.

In a distant view the scarp east of White Basin appears as regular and smooth as an artificial wall. Closer inspection shows minor irregularities due to erosion, especially in the upper part of the cliff. Near the base large polished surfaces have an average dip of 48° W., and readings on the slope of the entire scarp give almost exactly the same inclination to a height of several hundred feet. The slickensided surfaces near the base are marked with deep, regular striae and flutings inclined 65° S. Fresh slickensides are restricted to the lower 75 feet of the face. Fainter surfaces higher on the cliff probably represent auxiliary planes of slipping, parallel to the chief plane but beneath it and exposed recently by slabbing off of the original footwall. In the upper portion of the scarp large blocks have fallen away, leaving niches and narrow benches.

In the direction of strike the fault scarp is slightly sinuous; the average trend is N. 30° E. Its base is followed by a long wash that has taken advantage of the zone of weakness. At several places along its course the wash reveals the edges of Horse Spring limestone in fault contact with the Devonian, the white Tertiary beds turning up steeply nearly parallel to the fault, thus indicating considerable movement under a light overburden. The throw indicated by the scarp is at least 1,500 feet, but probably this is many hundreds of feet less than the entire movement, as the thrown block of Carboniferous strata is covered by a great thickness of Horse Spring beds, probably with Overton deposits beneath. An approximation of the vertical displacement may be obtained by considering the strike slip, which the offset in the Arrowhead front records as about 1,200 feet. As the striations on the fault near the southeast corner of White Basin incline 65° S., the measure of the vertical movement should be 1,200 ÷ tan 25°, or about 2,570 feet. In view of the thickness of Horse Spring beds in the basin, this figure appears to be of the right order of magnitude. This method of computation can not be relied on for accurate results, however, as the throw was apparently a hinge movement, greatest toward the south and decreasing northward.

Other faults around White Basin.—Some faulting marks the long north boundary of White Basin, but none of the displacements appear to be great. The Carboniferous strata on the north incline southward at steep angles which carry them beneath the Horse Spring beds on a line with a general east course, but with many deviations due in part to minor faults and in part to irregularities in the dip. It is evident that White Basin has resulted from southward tilting of a large block bounded by the White Basin fault on the east and by faults of the same general direction on the west, the northwest portion of the block suffering little vertical displacement. The northwest corner of the basin is made irregular by intersecting faults, one trending nearly north, another nearly east, and another nearly northwest. None of these faults was traced beyond its entrance into the Tertiary deposits, and the amount of displacement was not determined for any of them. The north-south fault extends northward into the limestones and is probably the cause of the abrupt change in dip, which is approximately east on the west side of the fault and southeast or south in the block north of White Basin. The east-west fault continues westward, invading Muddy Peak Basin and apparently continuing across to California Wash. Assisted by another large fault on the south, it drops into the dome structure a long, narrow tongue of Horse Spring limestone hundreds of feet in thickness, the beds bending sharply upward along each fault and forming a narrow structural trough with the axis pitching toward White Basin. The fault on the south side of the faulted tongue turns continuously to the south in approaching White Basin. Directly east of the Muddy Peak mass this fault runs practically north and cuts obliquely across the Devonian and Carboniferous strata, which dip steeply to the southeast. The scarp is high and steep and represents large displacement. At its base washes cut through the waste and reveal Horse Spring beds turning up along the fault surface.

West boundary of the Paleozoic thrust block.—From Piute Point a steep scarp facing westward extends toward the south and cuts obliquely across the Paleozoic limestones. Probably this scarp represents a fault with downthrow on the west; but no direct evidence of faulting was seen. Several miles farther south the direction of the mountain front changes to northeast. The Paleozoic limestone and dolomite overlying the Muddy Mountain thrust dip steeply under the slope débris, but the base of the mountain front keeps an approximately straight course, and farther southwest outcrops of Horse Spring limestone appear on the west, faulted down against the older formation. It is probable, therefore, that this portion of the west boundary is marked by a continuous fault with northeast trend. Whether this same fault swerves to the north or is intersected by a north-south fault passing Piute Point was not determined.

Northwest of Muddy Peak the mountain front turns southeastward, and Horse Spring limestones follow the base closely, although the contact was not seen. The mountain slope west and southwest of Muddy Peak is very high and abrupt, and probably the Tertiary beds are thrown down along a northwesterly fault; but this relation was not determined positively.

Northwest of Muddy Peak two narrow tongues of Horse Spring limestone are faulted into the Paleozoic rocks. One of these tongues is bounded by a pair of faults running northwest, the other by two northeasterly faults. In each of these narrow strips the beds are flexed strongly upward along the fault boundaries, forming a strucural trough plunging toward the outer mountain border. Several hundred feet of thin-bedded porous limestone is included in each of the faulted tongues. Although these Horse Spring remnants have been dropped considerably by faulting, they lie several hundred feet above outcrops of the same formation west of the mountain mass and in White Basin. It is therefore certain that the Horse Spring beds were originally laid down at a high altitude with relation to the

Paleozoic thrust block and probably covered much of it before normal faulting and later erosion occurred. This obvious fact strengthens the probability that the Horse Spring deposits southwest of the Muddy Peak mass are faulted down against it.

MUDDY PEAK DOME

Muddy Peak Basin marks the top of an elongated dome whose long axis appears to bend from a course due north to northeast. In the northern part of the basin this axis is nearly parallel to the fault along the western border of the range. From the flat attitude of the Jurassic(?) strata on the floor of the basin the dips steepen outward in all directions, and in the Paleozoic beds around the rim of the basin they average 30°. The general regularity of the dome is modified considerably by faulting, particularly on the east side. Probably to this faulting is largely due the apparent bend of the long axis.

SOUTHERN DIVISION

In Bitter Spring Valley the general structure is broadly anticlinal on an axis trending northeast. The Horse Spring strata dip northwestward into White Basin, at angles as great as 25°, and southeastward, toward Bitter Spring Valley, at smaller angles. West of Bitter Spring much of the valley floor is covered with waste, and the structure was not determined in detail. Steep tilting and tight compression of the beds southwest of Bitter Spring are probably related to obscure faulting. Many faults in addition to those shown on the map affect the Tertiary beds both in White Basin and in Bitter Spring Valley. Small faults with northwest trend are especially numerous. Northwest of Bitter Spring a north-south fault drops Horse Spring beds to the west against Jurassic (?) sandstone, and a larger fault parallel to the White Basin fault, with the displacement decreasing toward the northeast, extends from the area of Horse Spring deposits into the Paleozoic thrust block.

Several miles south of Bitter Spring all formations from Kaibab to Horse Spring inclusive are arched sharply into an elongate dome, which is here called the Sandstone Spring anticline. The axis trends about N. 65° E., essentially parallel to the anticlinal axis south of White Basin. On its north side the Sandstone Spring anticline is considerably modified by faulting, but the south limb is fairly regular, with dips ranging from 35° to 50°. A fault trending slightly west of north cuts across the entire fold just east of Sandstone Spring and causes offsetting of all formation contacts. This fault forks toward the south, and a narrow wedge-shaped block has dropped between the two branches. The fold is about 10 miles long, and at each end it plunges steeply. At the southwest end the outcrops of formations turn around the axis farther than is shown on the map, but the structure was not studied in detail in that vicinity. The faulting on the north is obscure, and perhaps it is not indicated correctly on the map.

West of the Sandstone Spring anticline and south of Muddy Peak, in the unmapped area reaching southwest to Las Vegas Wash, the dominant trend of structure lines, as reflected in the topography, is generally northeast, approximately parallel to the Sandstone Spring anticline.

DEFORMATION OF INTERMONTANE DEPOSITS

On the west side of Muddy Creek Valley the Muddy Creek beds show little disturbance but have a general inclination toward the valley ranging from 100 to 200 feet to the mile. In the Virgin River Valley, however, these beds have been considerably folded. A zone of disturbed strata follows the direction of the Rogers Spring fault northeast of Bluepoint, the net result being a monoclinal dip east by southeast, although strong dips to the northeast occur locally. Near the line of greatest disturbance dips of 20° are common and some as high as 40° were observed. Faulting has occurred locally, but it may have been the result of slumping caused by solution of saline beds. It is quite possible that general faulting accompanied the bending, but the soft clays do not preserve evidence of the break. This line of disturbance passes just west of St. Thomas and appears to good advantage in the bluffs north of Muddy Creek, where the clays dip 15°–20° E. and disappear under an unusual thickness of terrace gravel that extends below the present stream grade. An exposure showing similar relations occurs in the west bluff of Virgin River immediately below the Gentry ranch. Possibly this disturbance is an effect of recurrent faulting along Virgin River Valley in post-Pliocene time.

An anticlinal fold of considerable prominence follows the course of Virgin River near the Virgin Valley salt mine and for several miles to the south. West of the river the saline beds, clays, and an included basalt flow dip with a maximum inclination of 30° W., and more than a mile distant on the east side the same beds dip eastward at a similar angle. Evidently the crest of the anticline lies near the present channel of the stream. At the salt mine near Little Bitter Wash a broad, gentle swell with its axis trending nearly east intersects the steeper fold. A more pronounced east-west anticline affects the clays on both sides of the river near the mouth of Bitter Spring Wash. On each limb of the anticline the maximum dip is 20°, and the crest has been eroded until the underlying Horse Spring beds are exposed. The clays have a gentle dip eastward from the Rogers Spring fault, continuing the monoclinal structure farther north, and this inclination, combined with the anticlinal folds referred to, results in a basin-like structure in the clays over a considerable area between Bluepoint and Virgin River.

STRUCTURE OF THE VIRGIN MOUNTAINS

Only a small part of the Virgin Range was studied in connection with the work on the Muddy Mountains, and therefore the major framework can not be fully described. Northeast of St. Thomas the end of the principal range is a great anticline with a metamorphic core, the thick Paleozoic sediments dipping northwest and southeast from the axis, which trends generally northeast. East of St. Thomas the rocks are broken and lowered abruptly by a complex group of large faults, and within the structural gap thus formed the rocks are tilted by both faulting and folding. Between the gap and Colorado River lies another mass of metamorphic rock, flanked on the north and east by Paleozoic sediments. On the east side of this southern division of the Virgin Mountains the sedimentary beds form a continuous stratigraphic series dipping steeply toward Grand Wash. On the north side the sedimentary beds also dip to the east but are affected by large faults, some of which parallel the strike and with the aid of differential erosion have produced long finger-like ridges that make an irregular boundary on the south side of St. Thomas Gap.

FAULTS NORTH AND SOUTH OF ST. THOMAS GAP

The map shows that the general fault pattern around St. Thomas Gap differs from that of the Muddy Mountains, although some fault sets have corresponding directions on both sides of Virgin River. A set trending approximately north is conspicuous in both ranges. The east and southeast sets of the Muddy Mountain area are each represented by at least one major displacement near St. Thomas Gap. A very prominent set in the Virgin Mountains has a direction approximately N. 60° E., conforming closely to the axes of folds about Bitter Spring Valley and nearly paralleling the Virgin Mountain anticline. Minor faults trend in many directions.

The floor of St. Thomas Gap may be considered an irregular downthrown block bounded by faults of different trends. Without doubt many faults cross the block and subdivide it into smaller units, and the adjacent mountain masses are affected by numerous displacements. Most of these faults were studied in a general way only and will be described briefly.

A fault on the west side of the high Virgin Mountain block, northeast of St. Thomas, has an average direction slightly west of north and has a throw to the west measured certainly in thousands of feet. Its eroded scarp cuts almost squarely across the strike of steeply dipping limestones thousands of feet thick. Apparently a large block between this face and the schist ridge on the west has dropped either with movement as around a hinge on the north or as a simple graben and is now entirely buried by waste. The steepness of the scarp may be due to recent exhuming of the fault rather than to recent movement. Evidently the fault either ends or is offset on the north side of St. Thomas Gap, as it does not visibly affect formation contacts northeast of Sawtooth Ridge.

The long fault bounding the same mountain block on the south is clearly defined and evidently has large displacement, bringing Jurassic (?) sandstone against Kaibab limestone. North of the fault line the Kaibab dips 30°–45° S. and forms hills with curved summits separated by V-shaped canyons. On the south the Jurassic (?) sandstone, which in St. Thomas Gap has a general dip to the east, has been dragged upward along the fault and pitches steeply south. The average strike of the fault is N. 80° W.

Another fault farther east is essentially parallel to the last, but the downthrow is on the north. Movement has occurred on a series of closely spaced fractures. One of these, exposed in an old shaft, dips 69° N. Pre-Cambrian gneiss on both sides is crushed, stained with copper, and cut by stringers of quartz. About 200 feet farther north Paleozoic limestone is dropped against the pre-Cambrian, with undetermined but apparently large displacement.

The fault bounding Whitney Ridge on the west strikes generally northwest, but its course is prominently curved, convex toward the southwest. Displacement on this fault is very large, as upper Paleozoic formations are dropped against pre-Cambrian. Toward the southeast the fault scarp cuts almost exactly across the strike of thick Paleozoic formations in Whitney Ridge. (See pl. 4, *B*.) Smaller faults with similar trends make offsets in the large east-west fault. Another large northwesterly fault passes through the Whitney ranch and follows the northeast side of Whitney Ridge.

South of St. Thomas Gap a large north-south fault is represented by a steep scarp of Callville limestone rising hundreds of feet above the dissected terraces of Virgin Valley. South of Red Bluff Wash the front is offset by smaller intersecting faults, and on the north all trace of the large fault is lost beneath the gravel west of Sawtooth Ridge. Moenkopi shale and limestone appear west of the fault near its northern outcrop, and several miles to the south Jurassic (?) sandstone is exposed against the scarp. Along the entire front the displacement is measured in thousands of feet. Callville limestone in the footwall block dips 20°–30° E.

Another fault farther east roughly parallels the last, but the throw is in the opposite sense, leaving the intervening ridge as a narrow horst. Along the east side Moenkopi and Chinle beds are turned up steeply at the base of the fresh-looking scarp, the throw measuring at least several hundred feet. Offsets are caused by intersecting faults. Toward the north the fault curves to the northwest around the end of the horst. The fault appears to die out toward the south.

A fault that trends generally northeast offsets the two faults last described and causes jogs in formation boundaries. As the strata dip eastward the observed offsetting may be explained as due to simple normal faulting and erosion, without lateral movement. The displacement is moderate and apparently decreases toward the northeast. The last indication of the fault in that direction is a short jog in the ridge of Horse Spring limestone east of Red Bluff Spring.

A larger fault marks the ends of several high ridges that approach St. Thomas Gap from the south and terminate abruptly on a common line trending N. 60° E. North of the fault outcrops of formations ranging from the Moenkopi to the Horse Spring appear through the dissected cover of waste. At the north end of the Tramp Range the throw is at least 2,000 feet, and probably the displacement increases toward the southwest. Southeast of Mud Well offsetting due to this fault is small, and to the northeast the fracture passes into bending. No observations were made on faults extending south from this northeasterly fault.

A fault crosses Horse Spring Valley and is marked by large offsets in all formations. It makes a conspicuous break in the ridge of Horse Spring limestone near Horse Spring. The trend of this fault is north of east. North of Horse Spring smaller faults in the same set break the ridge east of Horse Spring Valley but produce no visible effect on the Kaibab ridge west of the valley. In all these faults the downthrow is on the north.

South of Horse Spring all formations are thrown down against the pre-Cambrian rocks on a fault whose trend is N. 70° E. The throw is at least 12,000 feet, but all direct topographic expression has disappeared.

STRUCTURE WITHIN ST. THOMAS GAP

Sawtooth Ridge.—Sawtooth Ridge consists of an overturned and overthrust block of Kaibab limestone. At the south end the strata are simply overturned, the Kaibab dipping 30°–60° NW. with Moenkopi limestone beneath it. Toward the east, along Red Bluff Wash, the Moenkopi and Chinle beds pass through the vertical attitude to southeast and east dips, which are continued at decreasing angles in younger formations. Northeastward in Sawtooth Ridge the overturned attitude becomes more pronounced and finally develops into an overthrust in which the Kaibab has ridden over the upturned shales and lies directly on the Jurassic (?) sandstone. In a small isolated hill northeast of the ridge a remnant of Kaibab limestone caps the sandstone, suggesting that the thrust once had a greater extent than at present.

On the northwest side of the ridge the Kaibab dips under intermontane waste, and its relations farther northwest are obscure. The thrusting and overturning reflect intense compression, but directly south of Red Bluff Wash the same formations show disturbance by normal faulting alone. If the thrust was once more extensive, the evidence has been concealed by later faulting and erosion.

Folding in St. Thomas Gap.—Quaternary waste covers much of the surface in St. Thomas Gap, and in places beneath the waste the hard bedrock is covered also by clay similar to the saline deposits of the Virgin Valley and Grand Wash. Except the Kaibab limestone of Sawtooth Ridge, Horse Spring limestone is the most resistant rock exposed, and it forms practically all the hard-rock ridges in the gap. All exposures show folding of the strata with varying degrees of intensity. East of Sawtooth Ridge the Jurassic (?) sandstone and the Overton and Horse Spring formations dip 10°–20° E., and their upturned edges form a low continuous ridge. In view of the intensity of compression implied by the structure of Sawtooth Ridge the dips become surprisingly gentle and regular within a short distance. Stronger deformation is shown near Mud Well, where all formations from the Moenkopi to the Horse Spring are arranged in anticlinal structure plunging northward. Clearly the fold included also the Pennsylvanian and Permian formations in the ridges on the south and was formed before the time of normal faulting at this locality.

SEQUENCE AND PROBABLE DATES OF STRUCTURAL EVENTS

The first intense crustal movement recorded in the Muddy Mountains consisted of folding and thrusting along axes running nearly north. The Weiser anticline and thrust and the principal Muddy Mountain thrust are products of this disturbance. Probably the Sawtooth thrust also belongs to this period, but certain facts favor a later date for this feature. The Arrowhead fault was probably formed in a late phase of the general thrusting movement as a transcurrent fracture to accommodate differential lateral movement. Clearly the block south of this fault rode eastward with relation to rocks on the north, and the flat thrust exposed beneath the Paleozoic plate was probably of wide extent, although only the portion preserved in this block is now available for study.

Assigning a date to this intense disturbance is a difficult problem. The youngest formation involved in the thrusting is the Jurassic (?) sandstone, and the oldest deposits subsequent to the disturbance are the Overton and Horse Spring formations, probably not older than Miocene. The thrusting occurred sometime in the long interval that is not represented by sediments, embracing all of the Cretaceous and the early Tertiary.

Two well-known regional disturbances with which the Nevada thrusts may be correlated are naturally suggested. These are the Jurassic folding of the Sierra Nevada and Humboldt Range, and the late Cretaceous-early Tertiary thrusting in the northern Rocky Mountains. In an early stage of the study the writer favored correlating the Nevada structure with the older movement.[50] Evidence for that correlation is altogether indirect. The Jurassic disturbance was intense and far-reaching, and its axis is not far distant from southern Nevada. During the Cretaceous period Nevada as a whole was a persistently high area, shedding an abundance of débris both eastward and westward and receiving no permanent sedimentary deposits. It is reasonable but not necessary to suppose that the post-Jurassic uplift was attended or preceded by strong crustal deformation. Furthermore, by reasoning from the common history of geosynclines, the theoretical argument may be advanced that the first severe disturbance in this area of thick Paleozoic and Mesozoic deposits would be expected soon after sedimentation had ceased, rather than after a long period of vertical uplift and erosion. There is another possible argument in the present distribution of the thick Jurassic (?) sandstone, the youngest formation involved in the thrusting. If there was broad, simple uplift of the region, attended by profound erosion, through the Cretaceous and Eocene, it appears that these uppermost rocks should have been largely removed. As a matter of fact, however, some of the Jurassic (?) outcrops, in folds or beneath thrusts, extend for miles with great and essentially uniform thickness. This fact is readily understood on the assumption that the rocks now exposed were protected in the deeper parts of a folded and faulted complex developed soon after the Jurassic (?) sediments were deposited.

The possibility that the thrusting occurred in late Cretaceous or early Tertiary time must be recognized, and after further study of the problem the writer has come to favor this later date as the more probable. Arguments for this view also are indirect. Perhaps the strongest point is found in the sedimentary and structural history of the area after the thrusting. Clearly considerable erosion preceded the deposition of the Overton fanglomerate, but this formation is extremely coarse and locally very thick, giving evidence of high relief and vigorous erosion. The heaviest deposits are found east of the Weiser anticline and north of the Arrowhead fault, and these are the only visible structural features capable of forming the high relief required. It is logical, therefore, to consider the Overton fanglom-

[50] Longwell, C. R., Geology of the Muddy Mountains, Nev.: Am. Jour. Sci., 4th ser., vol. 50, p. 61, 1921; The Muddy Mountain overthrust in southeastern Nevada: Jour. Geology, vol. 30, p. 63, 1922.

erate as a coarse fan deposit derived from scarps newly formed by the general thrusting movement. An alternative possibility is movement on the Arrowhead fault in the Tertiary and at a much later date than the Weiser anticline and the Muddy Mountain thrust. In the belt of Overton fanglomerate west of Muddy Creek the deposits thicken greatly toward the south, in the direction of the Arrowhead fault, and have the least thickness near the Narrows. On the other hand, at the north end of this belt the deposits are still very thick, their coarseness reaches a maximum, and their source was at the west instead of the south, as indicated by the positions of overlapping boulders and slabs. It is also significant that fragments derived from the older formations exposed south of the Arrowhead fault are restricted to the southern part of the belt of fanglomerate, whereas in the northern part the fragments are derived only from formations exposed in the Weiser anticline and largely from the Kaibab limestone. It appears, therefore, that during the Overton epoch high relief existed throughout the area of thrusting and folding, and the most logical inference, on the basis of present information, is that the deformation, including movement on the Arrowhead fault, occurred only a short time before the fanglomerate was deposited. If the Horse Spring and Overton formations belong in the upper Miocene, the thrusting may have occurred even as late as lower Miocene time, and a date older than Eocene seems very improbable.

Other considerations favor a post-Cretaceous date for the disturbance. The great thrusts of the northern Rocky Mountains, described by Mansfield, Richards, Blackwelder, and others, extend from Idaho into northern Utah. It is not to be expected that these large structural features, representing tens of miles in horizontal displacement, should end abruptly in the Wasatch Mountains. Ranges farther south, directly west of the Colorado Plateau, have been incompletely studied, but some of them appear to contain overfolds and thrusts directed from the west.[51] The Muddy Mountain thrust corresponds in direction to the thrusts of northern Utah and southern Idaho and compares with them in character and amount of displacement. There is much probability, therefore, that future field studies will demonstrate a continuation of the structure typical of the northern Rocky Mountains toward the south, along the western border of the plateau.

The later structural history in this part of Nevada accords with the supposed Tertiary date for the first major disturbance. Normal faulting would naturally follow extensive thrusting, to facilitate isostatic adjustments. Most of the larger normal faults affecting the

[51] See Gilbert, G. K., Report on the geology of portions of Nevada, Utah, California, and Arizona: U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 59, 1875; Davis, W. M., The Wasatch, Canyon, and House Ranges, Utah: Harvard Coll. Mus. Comp. Zoology Bull., vol. 49, pp. 15–56, 1905.

Muddy Mountain thrust block cut the Horse Spring and Overton formations and therefore may be considered post-Miocene (?). However, there was undoubtedly considerable displacement, perhaps on some of these same fault lines, before or during the accumulation of the earliest Tertiary deposits. Such an early movement on or near the White Basin fault is especially evident. Northwest of Bitter Spring the Tertiary section exposed above the Jurassic (?) sandstone has barely 30 feet of Overton fanglomerate, followed by 125 feet of gypseous clay and gypsum, only 25 feet of thin-bedded limestone, and a great thickness of silt, sandstone, and clay beds. Directly to the west, in Bitter Spring Valley and White Basin, the fanglomerate is hundreds of feet thick and is succeeded by at least 1,000 feet of limy beds, above which lie the borax-bearing clays. This abrupt change in thickness and character of deposits suggests that the down faulting of the White Basin area, at least along its eastern margin, may have begun shortly after the thrusting was completed.

Folding of the Overton and Horse Spring formations is irregular but locally very strong. The axis of the Sandstone Spring anticline runs nearly northeast; the less distinct fold immediately south of White Basin has essentially the same direction, and this trend is dominant in the area between Bitter Spring Valley and Las Vegas Wash. In this part of the region, therefore, the force that produced the folding acted consistently. Minor folds with north-south axes occur in the Horse Spring formation north of Muddy Creek. The Mud Well anticline and smaller folds in St. Thomas Gap also trend generally north. Possibly the Sawtooth thrust was formed contemporaneously with these folds, as the Overton and Horse Spring beds exposed east of Sawtooth Ridge are not noticeably discordant with the Jurassic (?) sandstone but dip eastward as if they were disturbed with the first notable tilting of the older strata. In the Mud Well anticline also the angular discordance between the Tertiary and older strata is slight, whereas all the formations are strongly affected by the folding. Strong compression in a general east-west direction is indicated by this folding; but the Sawtooth thrust and the large anticlinal fold of the Virgin Mountains near the Key West mine strike parallel to the folds in the southern part of the Muddy Mountains, reflecting compression from northwest to southeast.

Two possible explanations are suggested for the diverse trends in these Tertiary folds. The folds may represent a recurrence of regional compressive stress, directed generally in this area from northwest to southeast but diverted and resolved locally by differential movements of blocks in a crust previously shattered; or some of them may be the result of local adjustments during large-scale movement on the major intermontane normal faults. The first suggestion is favored by the intensity of the folding, particularly in St.

Thomas Gap and in the southern part of the Muddy Mountain area This movement preceded the deposition of the Pliocene (?) Muddy Creek beds, as shown by their unconformable relation to the folded Horse Spring formation, and therefore probably occurred not later than the early Pliocene. The anticlinal structure of the northern Virgin Mountains is correlated with these late Tertiary folds because the Overton fanglomerate of the Virgin Mountain area is uniformly thin and shows little angular discordance with older formations, thus indicating that no serious disturbance of the strata east of Virgin River occurred before Overton time.

Probably a large part of the normal faulting also occurred before the Muddy Creek deposits were complete. These deposits lie horizontally against tilted fault blocks in Grand Wash Valley. In no part of the area were these intermontane Muddy Creek sediments seen to be affected by major faults; but this evidence is entirely negative, as the Muddy Creek formation was not found exposed close to the larger fault scarps. Strong local deformation appears in the Pliocene (?) strata, and the anticlinal fold along Virgin Valley is particularly suggestive, as it may have resulted from lateral crowding of these soft beds incidental to sinking of the valley block between marginal faults that converge downward. However, it is probable that the Pliocene (?) clays accumulated during the period of normal faulting and that since their accumulation they have suffered only moderate displacement in the final stages of movement. The deposits were certainly formed in intermontane basins; they are uniformly of fine or moderate texture, suggesting accumulation during slow and nearly uniform subsidence; and in general their original attitude has not been greatly disturbed. Therefore the general normal faulting that followed folding of the Horse Spring formation probably occurred during the Pliocene in a long series of recurrent movements. There is no direct evidence of any large displacement after Pliocene time.

The time relation of normal faults in different sets can not be stated in definite terms, although in some localities one set is clearly later than another. South of St. Thomas Gap the faults with northeast trend consistently offset the north-south faults and therefore are later, but there is nothing to indicate how much later. Similarly the large fault trending nearly east on the north side of the gap is older than the northwest set of fractures. This east-west fault possibly caused offset in the large fracture that extends southward from the Key West mine. This evidence, so far as it goes, indicates that the north-south set in the Virgin Mountains is the oldest. This relation is to be expected, as probably the earliest and principal displacements occurred on the north-south faults, and later sets with various trends were induced by strains set up during the movement of the larger mountain blocks. There is considerable difference even in the directions of the intermontane fractures, however, as shown by the irregular course of the main Grand Wash fault, and therefore the exact trend of any fault can not be made the sole criterion for its place in the structural history of the region.

Aside from the uplifting of the Virgin Valley anticline the most pronounced deformation of the Muddy Creek deposits was subsidence, due either to faulting or to warping, along Virgin River northeast of St. Thomas. Coarse gravel to a depth of several hundred feet was deposited in the depression, probably in Quaternary time. Tilting of a high gravel remnant north of Sawtooth Ridge may be an effect of the same movement.

Keeping in mind the uncertainties indicated in the preceding discussion, we may summarize the possible sequence of structural events as follows:

1. Intense folding and thrusting of all formations up to and including the Jurassic (?) sandstone in pre-Miocene (?) time.
2. Earliest normal faulting, probably accompanying deposition of Miocene (?) formations.
3. Recurrence of compressive deformation, at the end of the Miocene or in early Pliocene time.
4. Extensive and profound normal faulting, blocking out the present ranges and intermontane valleys probably during the Pliocene epoch. Probably recurrent movement during a long time, with thick basin deposits accumulating simultaneously.
5. Moderate warping and faulting in Quaternary time.

PHYSIOGRAPHY

Land forms in southern Nevada contrast sharply with those of the closely adjacent plateaus. The region differs also from the typical basin country farther north. As Gilbert[52] says, it is part of "an orographic province which has its type in the Great Basin but is not coincident with it." The typical desert basin with its playa has no place in the landscape around the Muddy and Virgin Mountains. The explanation is found in the through-flowing Colorado River and its tributary, the Virgin, which have tapped the basins that formerly existed in the intermontane troughs and interrupted the normal desert erosion cycle. Every part of the area is reached by drainage channels, which receive from infrequent heavy downpours sufficient run-off to maintain connection with the master stream and keep up the process of valley growth. However, remnants of old basin deposits show that the dominance of the present river system has been of comparatively short duration and that the region was formerly an integral part of the Great Basin.

[52] Gilbert, G. K., op. cit., p. 22.

FACTORS GOVERNING EROSION

Relief.—The lowest altitudes in the region, about 700 feet, are on Colorado River below Callville. In the Muddy Mountains the highest point is Muddy Peak, approximately 5,800 feet above sea level. These extremes mark a difference in altitude of more than 5,000 feet in a horizontal distance of 14 miles, and most of the descent is found in a much shorter distance adjacent to the peak. The average altitude of the high Paleozoic thrust block is above 3,000 feet, whereas that of its base is about 2,000 feet. North and south of this high mass the country has an average altitude of less than 2,000 feet, though sharp peaks and ridges rise several hundred feet higher. In the Virgin Mountains the highest point is nearly 8,000 feet above the sea, from which the descent toward Virgin Valley averages 1,000 feet to the mile for 5 miles. Elsewhere the degree of relief is similar to that in the Muddy Mountains, the altitude ranging from 2,000 to 5,000 feet with many abrupt changes.

Thus the general altitude above the Colorado is considerable, and local prominences help further to give high gradients to drainage channels. The fall of the Colorado itself is relatively slight in this region, probably averaging less than 5 feet to the mile. The Virgin has a fall of nearly 15 feet to the mile below the mouth of Muddy Creek and of nearly 20 feet in the lower 10 miles of its course, where the stream has cut a gorge through the hard igneous rock south of Bitter Spring Wash. Below Moapa the grade of Muddy Creek ranges from 16 to 20 feet to the mile. Bitter Spring Wash drops 1,300 feet in 16 miles, and the rate of fall in the lower part of its course probably exceeds 50 feet to the mile, whereas Callville Wash has an average gradient at least twice as steep. The minimum grade of washes in the northern part of the range is 50 feet to the mile, and this increases to hundreds of feet in the headward reaches of small branch washes, especially those heading among the higher peaks and ridges. The relief therefore favors erosion, and there is ample evidence that erosion is taking place at a rapid rate. During floods the streams move large quantities of silt, sand, and gravel, and all channels show recent cutting below former levels.

Climate and vegetation.—The rainfall of the region is deficient, but most of it is concentrated in comparatively few hard showers, with a resulting high percentage of run-off. Usually the hardest downpours are local, but probably most parts of the area are visited by at least one hard rain in the course of the year. In the summer of 1919 there were several times when parts of the branch railroad line in Muddy Valley were washed out, and an especially heavy rain near the end of July either undermined or buried a large part of the lower 5 miles of track. Water poured out of the short washes south of Muddy Creek and spread over the valley in sheets, in places burying good land under thick deposits of sand and gravel, in other places digging deep trenches. In the streets of St. Thomas water ran waist deep. Boulders many feet in diameter were moved by washes intersecting Overton Ridge, and in the Jurassic (?) sandstone areas the waste deposited in depressions by smaller floods was removed, making room for large pools of water.

Frost work is limited to the higher altitudes and to about three months of the year, and even then there is not always sufficient moisture for much effect. However, when snow lies at the higher levels there is always some thawing by day and hard freezing at night, and at such times the ice must be a powerful factor in breaking up the rocks. Its work is favored by the closely spaced joints that give excellent opportunities for the moisture to enter. Insolation is a very efficient weathering agent, operating through a large part of the year and at all altitudes. Although most of the rocks are sedimentary and fairly homogeneous, small slabs and chips are broken from their surfaces by rapid and unequal heating and cooling. When the thermometer reads 110° to 120° in the shade the temperature on rock surfaces in the sun is probably 40° or 50° higher, and during the nights that follow these hottest days there is sometimes a drop to 60°, giving a range of approximately 100° in surface rock temperature during the 24 hours. Early in the morning and again near sundown the variation is especially rapid.

The desert vegetation has a negligible effect in hindering erosion, because the plants stand too far apart to form a mat of roots or branches. An exception is found in Muddy Peak Basin, where parts of the floor have a fairly dense covering of grass. Locally the transportation of sand by wind is hindered by sand grass and by Mormon tea and other shrubs, but the work of water proceeds practically unhampered by vegetable cover.

Rock composition and structure.—The sedimentary formations differ greatly in resistance to erosion, and this difference is everywhere expressed in the topography. Hard rocks are the mountain makers, whereas areas underlain by softer formations are valleys. The prominence of the central Muddy Mountain mass is due to the great thickness and resistance of the limestone and dolomite that form it. Heavy limestones also form the highest parts of the Virgin Mountains, reaching far above the associated crystalline rocks. Weiser and California ridges, the core of the Sandstone Spring anticline, and many of the ridges east of Virgin River are expressions of the Kaibab limestone. In fact, the Paleozoic limestones are the dominant rocks topographically throughout southeastern Nevada, forming the conspicuous portions of the Virgin, Muddy, Mormon, Las Vegas, Sheep, and neighboring ranges. Lower ridges connected with the Muddy and Virgin Mountains consist of Moenkopi limestone, Jurassic (?)

sandstone, Overton fanglomerate, and Horse Spring limestone. The Triassic shales are conspicuously weak, flooring depressions between ridges of older and younger rocks.

Structure is closely associated with rock composition as an influence in shaping the landscape. Its effect appears most conspicuously in the contrast between the high, regular plateau east of Grand Wash and the broken basin ranges on the west. The positions and general form of these ranges and of their component ridges are due primarily to the structure, whereas details of sculpture and the preservation of the main relief depend chiefly on differences in rock composition. The high Muddy Mountain block exists because of the overthrust that pushed the hard Paleozoic rocks above softer formations, and its general plan was established by the faults that bound it. The peaks on its summit reflect faithfully the attitude of the beds, standing out sharp and asymmetric where the dip is strong and rising in regular pyramids on horizontal strata. Asymmetric forms of peaks and ridges predominate in both the Virgin and the Muddy Mountains, long slopes following the dip of beds and shorter and steeper slopes marking the upturned edges. In the Jurassic (?) sandstone even the details of sculpture are influenced by the attitude of beds, grotesque forms appearing in greatest number where the dip is high.

VALLEYS

Regional considerations.—Two main classes of valleys are easily recognized in southeastern Nevada—The great intermontane troughs, such as California and Meadow Valley Washes and the Virgin Valley, and the smaller tributaries that head in adjacent mountains. Gilbert[53] had in mind the first class when he wrote: "In the region of the Basin ranges the valleys are residual; the mountains were uplifted in parallel lines, and the intervening troughs remain as valleys."

Some of the smaller valleys have had a similar origin and history; but most of them are ordinary erosional features. Only the Virgin and the Muddy Valleys are occupied by permanent streams. The others, large and small, are entirely dry during most of the year or at best contain only small streams from springs in parts of their courses. In the large valleys the stream beds are cut for the most part in soft clays and sands where adjustments of grade by cutting or building are easy, and the grades are practically established for present conditions. The tributaries are at grade only in the lower parts of their courses, their headward portions reaching into the hard rocks of the ranges, where stream profiles are steep and broken by falls. V-shaped canyons with boxed heads are common at these higher altitudes where the bedrock is hard, but in the weaker materials bordering the mountains the stream beds are wide and flat-bottomed. The life history

[53] Gilbert, G. K., Report on the geology of portions of Nevada, Utah, California, and Arizona: U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 63, 1875.

of the larger valleys has been somewhat abnormal, for the streams found little hard rock in the wide waste-filled troughs and basins inherited from the earlier desert cycle, and hence they cut laterally with unusual rapidity.

Virgin Valley.—For most of its course in the St. Thomas quadrangle Virgin River occupies a wide, flat-bottomed inner valley cut in soft materials. The modern valley ranges in width from a few hundred feet to more than half a mile, and at flood stage the river spreads over the entire width, but at ordinary stages the narrow stream meanders with a tortuous course on the sandy bed, cutting against vertical banks of silt on the outer sides of curves. Above the banks, which are 10 to 20 feet high, is the old flood plain, in places stretching half a mile from the river on each side. Its surface is generally even but has minor irregularities made by sand dunes and abandoned channels. Salt grass, arrow weed, and shrubs form a cover on much of the plain, but elsewhere the surface consists of bare sand or has a white coating of efflorescent salts. At its outer boundary it meets the edge of the first large terrace, and the floor of the intermontane valley continues to broaden and rise by a series of steps with steep front and wide tread, the total width between mountain walls reaching a maximum of 12 miles.

The gorgelike character of the inner valley below the Gentry ranch is due to a thick deposit of gravel that was laid down after downwarping of the Muddy Creek beds, at a time when the local base-level stood several hundred feet higher than at present. During subsequent lowering of the stream channel the gravel has stood in steep valley walls and has limited the lateral cutting by the river. (See pl. 16, *A*.)

Hard bedrock is exposed in the Virgin River channel for several miles below the mouth of Bitter Spring Wash, where the stream has cut a narrow gorge through the porphyry and basalt that form the northeastern limit of the Black Mountains. The cliffs adjacent to the river in few places exceed 100 feet in height, but here and there they are almost vertical, and the valley narrows to less than 300 feet. In a distance of 4 miles there are several rapids, and the average gradient exceeds 30 feet to the mile.

Muddy Valley.—In the greater part of its course the valley of Muddy Creek resembles that of Virgin River in cross section, consisting of an inner, recent trench, an old flood plain, and a number of terraces bordering both sides. South of the Narrows the maximum width between Overton Ridge and the edge of Mormon Mesa is about 6 miles. Above the Narrows the terraces merge with those of Meadow Valley and California Wash, covering a wide expanse. The old stream-cut valley ranges in width from a few hundred feet to 2 miles, and has an average width of nearly a mile south of the Narrows. Its borders meet the clay of the terraces in ragged lines, the plain jutting back as coves between long points or headlands of the higher ground. The surface is comparatively even, but its regularity is broken by washes cutting through to the main stream, by abandoned channels of the creek itself, and by heaps of wind-blown sand. There is a gradual rise toward the high ground, due to wash from the valley sides.

The present stream course is deeply incised through most of its length, and old settlers state that practically all the cutting has been done since 1880, starting during a time of unusual floods. Formerly the channel was of slight or moderate depth, and much of the bottom was set with grass. At rare times of high water the stream overflowed its banks and spread over parts of the flood plain. Now it is confined between banks that are in most places vertical and from 10 to 40 feet high. The recency of the trenching is evident in the steepness of the loose silt banks and in the absence of effects of lateral cutting, the width of the channel barely accommodating the stream. Undercutting and caving of the banks are in progress, however, and will in time make inroads on ranch lands bordering the creek.

Directly below the Weiser ranch, where the stream cuts through the Kaibab limestone of Weiser Ridge, the valley narrows abruptly to a gap about 250 feet wide. The walls are vertical or very steep to a height ranging from 50 to nearly 200 feet. The horizontal distance through the ridge is about 1,000 feet, and the valley widens slightly where it enters the younger formations on the east, but the Overton fanglomerate and Horse Spring limestone stand in steep bluffs and confine the gorge to a width of a few hundred feet for a distance of 2 miles, the stream flowing in a deep trench cut into a narrow strip of alluvium. Above the gap the old flood plain has a maximum width of about half a mile. Meadow Valley Wash, which joins Muddy Creek above the Weiser ranch, is comparable in dimensions and in cross section to the valley below the Narrows.

California Wash.—No measurements or detailed observations were made in California Wash, but in general aspect it resembles the other wide intermontane valleys without permanent streams. Opposite Piute Point it is more than 10 miles wide, and in a general view its floor appears to be a smooth carpet of waste, sloping gradually but perceptibly from the mountain walls toward the middle. The bottom is dissected by many dry washes, however, and near the margins remnants of aggradation surfaces with gravel capping appear through the waste as low, flat-topped hills. Lateral washes are deeply intrenched and apparently have recently begun a vigorous attack on the long slopes of débris from the mountains.

Grand Wash.—Grand Wash and its tributaries occupy a structural valley nearly 50 miles long, with a maximum width of 15 miles.

Long branches enter from the Virgin Mountains on one side, and others have cut deep canyons far back into Shivwits Plateau. The trunk wash has a flat bottom 400 feet wide in the lower 6 or 7 miles of its course, and its sides rise steeply 50 to 200 feet. The gradient is regular and at the rate of 50 to 60 feet to the mile. All tributaries are deeply incised and are rapidly removing the old filling of waste. In the lower 10 miles of the valley all the large tributaries have cut through the Quaternary gravel into the underlying saline clay, and east of the trunk wash large areas of the clay have been stripped and dissected. Between the washes wide stretches of the old valley levels are preserved as flat mesas or terraces. (See pl. 4, *A*.) On the west side the basalt flows buried in the gravel tend to preserve the mesas and make the washes steep sided. East of the junction with Colorado River a tilted block of Paleozoic rocks projects above the waste and shuts off from the Grand Wash a portion of the valley which is drained by a short independent channel joining the Colorado at Pierces Ferry.

Minor fault valleys.—The wide lowland shown on the map as Bitter Spring Valley is greatly out of proportion to the stream channel that occupies it. This valley and White Basin, which belong to the same drainage area, are primarily structural features. They resulted from the dropping of blocks in fault zones and hence are similar, though on a smaller scale, to the great intermontane valleys. The larger faults around the borders of the lowland are clearly expressed in the topography, and probably other displacements that were instrumental in directing the present drainage are obscured by the softness of the bedrock and by the recent cover of waste. Both the valley and the basin have had comparatively smooth surfaces of aggradation, which are now greatly dissected by deeply incised washes. Along the margins recent talus slopes and alluvial fans have accumulated, and these too have been deeply trenched. In the lower half of its course Bitter Spring Wash flows between vertical or steeply sloping banks 20 to 50 feet high, and its tributaries enter it by deep V-shaped valleys. The channel is flat bottomed and ranges in width from 50 to 300 feet. A short distance above the spring a fall supported by recent conglomerate marks the headward limit of the latest cutting. Above the fall the channel is shallower and less confined.

St. Thomas Gap, which cuts directly through the Virgin Mountains, is a wide fault zone similar to the large intermontane valleys. Remnants of former surfaces of aggradation in and near the gap testify to the fact that within comparatively recent time the rock ridges and buttes that now project above the general level were nearly or entirely buried, giving an almost even floor of waste with little grade in an east-west direction. Erosion of the cover has exposed the edges of faulted and folded bedrock layers and has trenched the remaining waste with deep channels, producing a surface that is very irregular in detail. The main drainage divide between Grand Wash and Virgin River lies a short distance east of Mud Well. Red Bluff Wash runs westward, cutting through a sharp ridge on a minor fault line, its channel growing wider and deeper until, after passing the point of Sawtooth Ridge, it becomes a deep gorge in recent coarse gravel. There the walls are practically vertical to a height of 50 to 75 feet, and in places the gorge is barely wide enough for a wagon to pass. As it approaches Virgin River the channel widens and the walls become higher but less precipitous. Another large wash leaves the gap north of Sawtooth Ridge and also joins Virgin River. On the east side of the divide the drainage becomes united in one large wash that enters Grand Wash Valley through a somber gorge known as Black Canyon, which has been cut through basalt sheets.

Minor valleys due to structure and differences in hardness of rocks.—The conditions that produced the Valley of Fire are repeated with some modifications in other parts of the region, and everywhere with very similar results. These conditions are high tilting and beveling of the strata with exposure of the upturned edges of all formations from the Kaibab limestone to the Jurassic (?) sandstone. The long north-south arm of the valley is an expression of the relatively slight resistance of the Moenkopi and Chinle shales, the Kaibab and Moenkopi limestones rising sharply on one side and the Jurassic (?) sandstone on the other. An east-west anticlinal fold intercepting the prevailing north-south structure lines completes the peculiar L-shaped plan of the Valley of Fire, and on the south side of the shorter arm the limestones in the Arrowhead scarp take the place normally occupied by Moenkopi and Kaibab limestones.

In width the valley ranges from less than half a mile to slightly more than 2 miles; it narrows toward the north end, where the dips are steepest and where the Overton fanglomerate overlaps the Triassic shales. The sides are straight and sharply defined in the north half of the longer arm but become more ragged in the zone of cross faulting and near the elbow. There are gentle slopes northward and eastward from the bend, and the floor is comparatively even as a whole, but with many small irregularities caused by projecting edges of resistant sandstone layers and by recent trenching of washes. Recent waste formerly covered the floor and still remains in and near the elbow, but near the outer ends of the arms drainage channels have stripped off most of the loose materials and exposed the edges of weak bedrock. The east arm has much the more uneven surface, because sandstone layers are more numerous in this section and the outcrops are duplicated by anticlinal structure, forming a number of hogback ridges and buttes 20 to 60 feet high. In this part of the valley there are also several large Jurassic (?) sandstone buttes, remnants that have not yet been eroded from the top of the anticline.

Sandstone Spring Valley is formed on the south side of an eroded anticline and has a strong resemblance to the north end of the Valley of Fire, but the strata dip uniformly south and are not overturned as they are in the larger valley. The sides are high and well defined. On the south the edge of the Jurassic (?) sandstone, capped by Overton fanglomerate, rises in a steeply sloping wall 300 to 600 feet high. Near the middle point of this side Boulder Wash breaks through toward the Colorado, receiving a long branch from the western half of the valley and a shorter branch from the east. Recently renewed activity in the washes is shown by deep trenching of the shales. The valley floor is made still more irregular by low hogbacks formed on beveled edges of sandstone layers, which are as numerous in this section as in the east end of the Valley of Fire. East of the spring there is a distinct jog in the valley corresponding to an offset in the strata along a north-south fault. At each end of the plunging anticline the valley terminates abruptly as the strata curve toward the north.

Horse Spring Valley is of the same type as Sandstone Spring Valley but here the high ridge opposite the Kaibab wall is formed by thick Horse Spring limestone, and most of the Jurassic (?) sandstone is worn down to make part of the valley floor. The east wall is broken and offset by a number of minor faults, and through one of these openings the main wash escapes from the valley to join the Grand Wash drainage system, leaving the lower part of the trough a part of the Virgin River basin. Not one of the valleys of this type is occupied by a unit drainage channel. A trough of the same general character lies east of Sawtooth Ridge, and another in the Callville Wash drainage basin directly south of Muddy Peak, but both are much modified by faulting. Weiser Valley is also a modification of the type, for although it is floored by the same Triassic shales it is bounded on both sides by Kaibab limestone ridges that rise abruptly several hundred feet above the valley bottom. In width and in the general nature of the floor, it compares well with the Valley of Fire. Ridges and spires of Supai sandstone skirt the base of the east wall, and large spurs of Kaibab and Moenkopi limestone, probably irregular blocks dragged along a fault, project westward into the valley.

Superimposed valleys.—A number of washes have courses that are inconsistent with the present topography and were evidently inherited from a previous stage. Overton Wash cuts indiscriminately across the low Valley of Fire, the highlands formed by Jurassic (?) sandstone and Overton fanglomerate, and the Muddy Valley terraces. Its bed is well graded throughout except for falls with a total drop of 60 feet in the narrow gorge cut through the resistant upper member of the Overton fanglomerate. In the weak Triassic shales the channel is in a V-shaped trench with a maximum depth of 40 feet. In the Jurassic (?) sandstone the valley walls are irregular and have a maximum height of nearly 100 feet near the wash, but the general altitude of the sandstone is nearly 100 feet higher. In the Overton formation the weak materials at the base form low walls and permit the wash to widen by lateral cutting to an average width of more than 100 feet, but the high hogback at the top of the fanglomerate confines the channel to a gorge 10 feet wide at the bottom, gradually flaring to a width of 20 feet at a height of 75 feet from the floor, and above this point the walls diverge at an increasing rate to the top of the ridge, more than 200 feet above the wash. The wash continues narrow through the tilted Horse Spring beds, but in the Tertiary clays it broadens until at its junction with Muddy Creek Valley it is several hundred yards wide. The banks are vertical or steeply sloping throughout.

Magnesite and Kaolin Washes head in the Jurassic (?) sandstone, and in greater part their drainage basins lie in the weak lower Overton beds. Otherwise they are very similar to Overton Wash. Both cut through the resistant Overton hogback in narrow gorges in which they fall 65 feet, cross the Horse Spring beds on grade but in deep narrow valleys, and grow constantly wider in the Tertiary clays. Wieber and Logan Washes have similar relations, but their gorges are longer because in them the Overton formation is coarse and resistant in its entire thickness. Moreover, the Horse Spring limestone is much thicker and harder than in the sections farther south, and in Logan Wash both formations have a low dip, increasing the horizontal distance across the beds. Logan Wash near its head in the sandstone has a comparatively shallow and open valley, but on entering the more resistant fanglomerate it becomes a narrow gorge with steeply sloping sides 200 feet high, and this character is maintained for more than 2 miles, the walls becoming even more precipitous in the Horse Spring limestone.

Another superimposed wash drains the upper end of Weiser Valley into California Wash, passing through the Kaibab limestone of California Ridge as a V-shaped gorge more than 200 feet deep. Weiser Gap has been cut through Weiser Ridge by Muddy Creek in lowering its bed, and there are other less conspicuous examples in the area.

Hanging valleys.—Many small valleys on the high blocks bounded by the Arrowhead and Rogers Spring faults have relations of sharp topographic unconformity. At 600 to 700 feet above the base of the mountain some of the stream courses are at grade for a distance of a mile or more, but near the edge of the mountain block they plunge abruptly by a series of high falls. One such valley south of the

Arrowhead fault has already been mentioned in connection with remnants of high-level Quaternary deposits. A number of the valleys have been widened in their upper reaches beyond the canyon stage, and the stream courses are bordered at some localities by remnants of deposits in the form of low terraces. It is evident that these valleys were developed at a time when the local base-level was much higher than at present. The graded profiles and wide cross sections show that the higher base-level persisted for a considerable period, and the location of the fall line, only a few hundred feet back of the mountain walls, indicates that the lowering of the streams outside the mountain front has occurred within comparatively recent time. Without doubt the level of the valleys corresponds to the highest aggradation surface in the intermontane troughs. Old stream notches at the top of Weiser Ridge probably represent valleys developed during the same period.

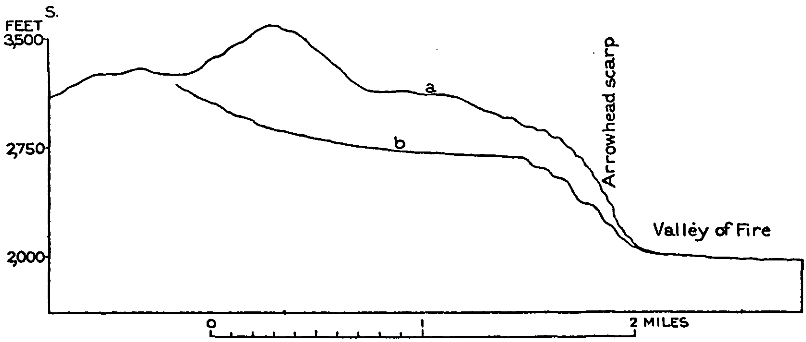


FIGURE 8.—Profile of hanging valley south of Arrowhead fault. a, Generalized surface profile of mountain south of Valley of Fire. b, Profile of typical hanging valley. Datum, mean sea level

In striking contrast with the hanging valleys, a few of the larger canyons crossing the Arrowhead and Rogers Spring faults are graded, or nearly so, for almost half a mile within the mountain front, and at least two of these canyons have on their sides and floors the consolidated fan or talus deposits mentioned in a preceding section. Thus the mountain shows a record of oscillating base-levels. Evidently the large canyons at the lower altitude were first developed when the principal streams of the region were near their present level. The canyons were then partly filled by coarse deposits during a long period of aggradation, and the present hanging valleys had their growth during this period. In later lowering of the regional base-level, with development of high relief due to differing resistance of formations, most of the coarse filling has been removed from the older mountain valleys, but sufficient time has not elapsed to destroy the high-level grades developed in solid rock.

There is a natural tendency to attempt correlation of the hanging valleys with movement on the Arrowhead fault and other large faults, but there is no direct relation of these features to faulting. The valleys were developed at a time when the base-level of the region was much higher than at present, as testified by a high aggradation surface represented by mesas in the intermontane valleys and by remnants of gravel deposits clinging against the mountain walls. The aggradation surface corresponds in altitude to the graded portions of the hanging valleys. Therefore the hanging character of the valleys is a result of recent rapid differential erosion and not of displacement on faults. The complex nature of the erosional history is discussed in later paragraphs.

OLD SURFACES OF AGGRADATION

Distribution and general relations.—The ascent of several hundred feet from the recent flood plains in intermontane valleys to the base of mountain walls is made by a series of wide steps with abrupt risers and nearly flat treads. Although the continuity of these features has been interrupted by dissection, the remnants are sufficient for interpretation of their former extent and relations. They border Virgin River, Muddy Creek, Meadow Valley and California Washes, and the Grand Wash, so far as those valleys were studied, and are present also in the larger tributary washes. In places one or more of the levels can be traced for a mile or more parallel to the valley without breaks in their surfaces except trenches made by a few washes, and in a few localities the entire ascent from stream channel to mountain wall can be made on an uninterrupted succession of the steps. Elsewhere, however, only fragments of the surfaces stand as islands or peninsulas in large areas of badlands. Without considering recent flood plains bordering partly incised channels, four principal surfaces are recognized, and they will be referred to from the highest downward as Nos. 1, 2, 3, and 4. The two lower surfaces are restricted to narrow belts bordering streams and may be considered ordinary stream terraces. Surfaces Nos. 1 and 2 are of much wider extent and are not terraces in the ordinary sense of the term. (See pl. 16, *A*.)

All the surfaces slope in general with present drainage grades but at different rates, and therefore it is not possible to specify for any surface a definite height above sea level or above an adjacent stream. Existing stream grades are the best datum lines to which the altitudes may be referred, but the recent flood plains will be used instead, because they have about the same grades as the streams, are practically level from side to side, and lie adjacent to the lower terrace. On this basis approximate average altitudes of the aggradation surfaces in Muddy Valley are as follows: No. 1, 700 feet; No. 2, 250 feet; No. 3, 100 feet; and No. 4, 40 feet.

The age of the surfaces increases from the lowest to the highest, and the original extent increases in the same order. Surface No. 1

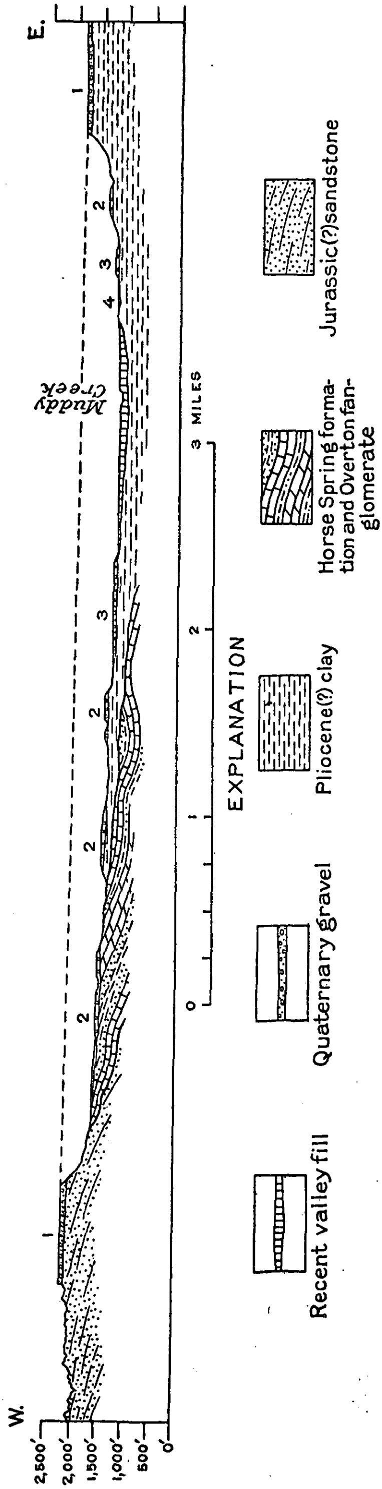
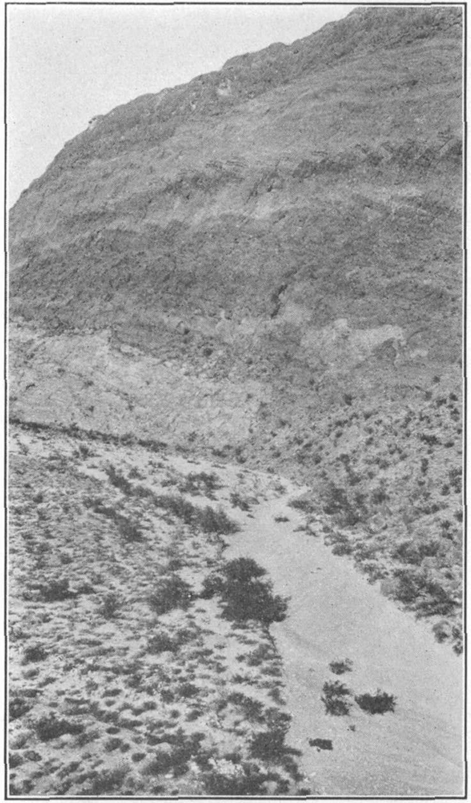


FIGURE 9.—Section of Muddy Creek Valley, showing aggradation levels (1 to 4)

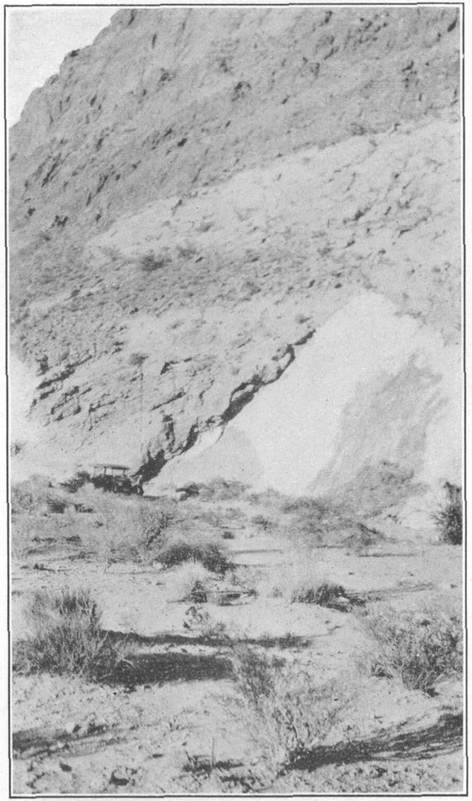
formerly spread over all the intermontane lowlands and the rock-cut benches around the borders of the mountains. Small but conspicuous remnants on the Jurassic (?) sandstone south and west of Muddy Creek indicate that the surface extended to the Arrowhead fault scarp at a present altitude of about 2,800 feet, and that only one small area of the Jurassic (?) sandstone escaped burial in the waste. The Kaibab limestone, forming the summit of Weiser and California Ridges, was hidden except for a few of the higher peaks. Along Virgin River south of Muddy Creek nearly all traces of the actual surface have been removed by erosion. In the angle between the Virgin and Muddy Valleys, however, a large and almost undissected portion of this oldest level is preserved as Mormon Mesa. This is the largest single remnant of any surface. An unbroken expanse of surface No. 2 about 4 miles wide lies east of Virgin River immediately north of Red Bluff Wash. The later surfaces were formed by partial destruction of the earlier. Washes cutting remnants of the higher surfaces are bordered by terraces continuous with surfaces Nos. 3 and 4.

Slopes of the surfaces.—The lower terrace (surface No. 4) is seen to best advantage on the east side of Muddy Creek between Overton and Logandale, where its surface, though considerably dissected, can be recognized over a width of half a mile. In tributary washes its slope toward Muddy Creek is about 70 feet to the mile, whereas the



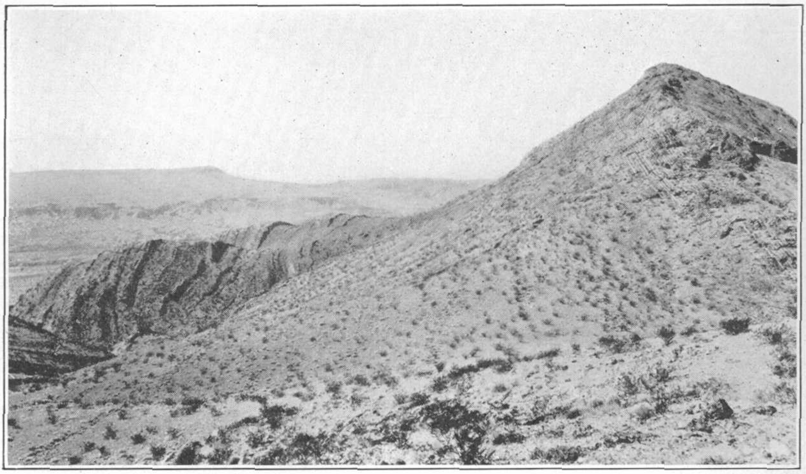
A. PART OF WHITE BASIN FAULT SCARP, 900 FEET HIGH

Strata are mainly Mississippian limestone. The wash is on the Horse Spring formation



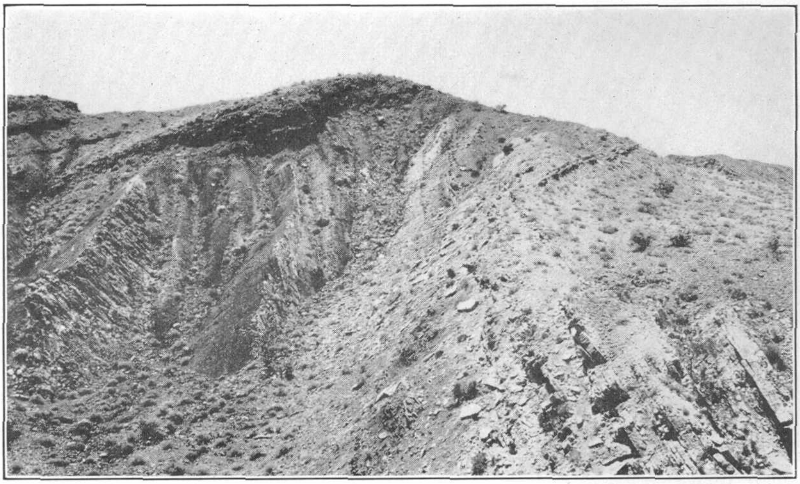
B. DETAIL AT BASE OF WHITE BASIN FAULT SCARP

Large polished fault surface in right center. Directly back of the car are Horse Spring strata, bent up nearly parallel to the fault



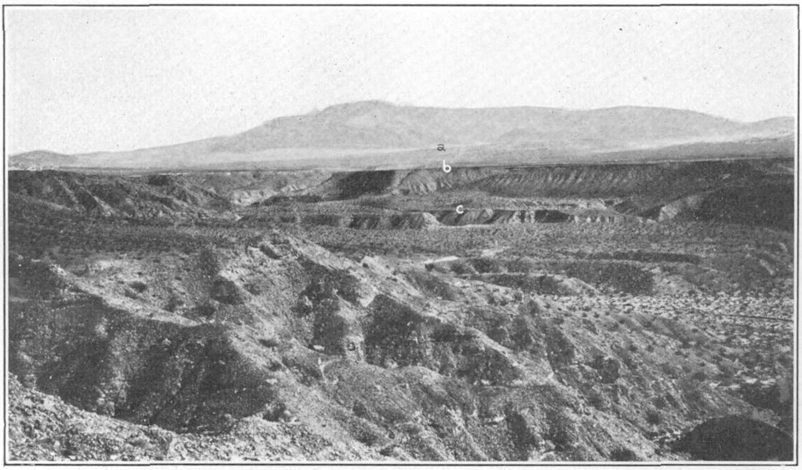
A. VIEW SOUTHEAST ACROSS VALLEY OF FIRE FROM TOP OF WEISER RIDGE

Strata overturned to the east. At right, Kaibab limestone; in order toward the left, Moenkopi formation, Chinle formation and Shinarump conglomerate in valley, Jurassic sandstone forming distant badlands. High mesa in distance on Overton fanglomerate, which is unconformable on the Jurassic sandstone



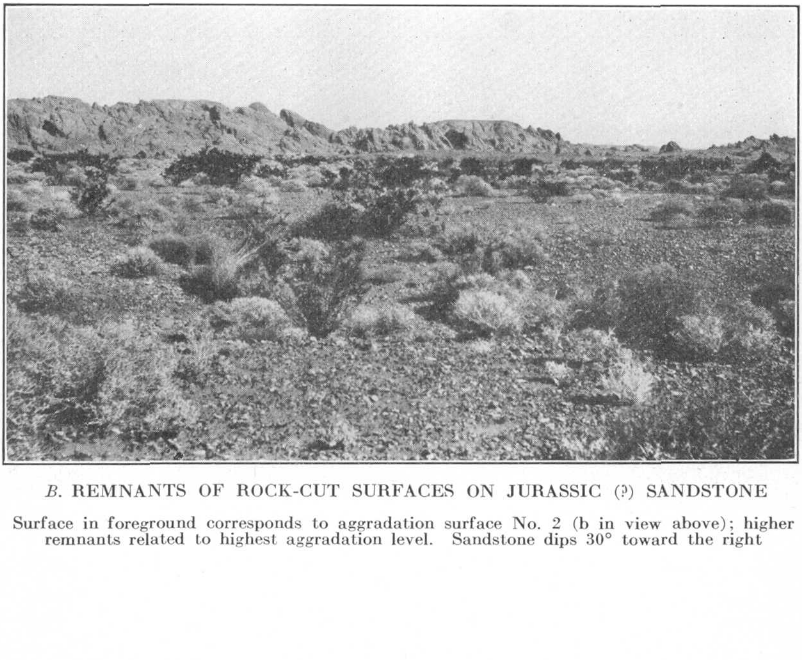
B. OVERTON FANGLOMERATE UNCONFORMABLE ON MOENKOPI FORMATION SOUTH OF THE NARROWS OF *MUDDY CREEK*

Overton beds dip 15° E. (to left); Moenkopi beds, in overturned position, dip 65°–70° W. (to right)



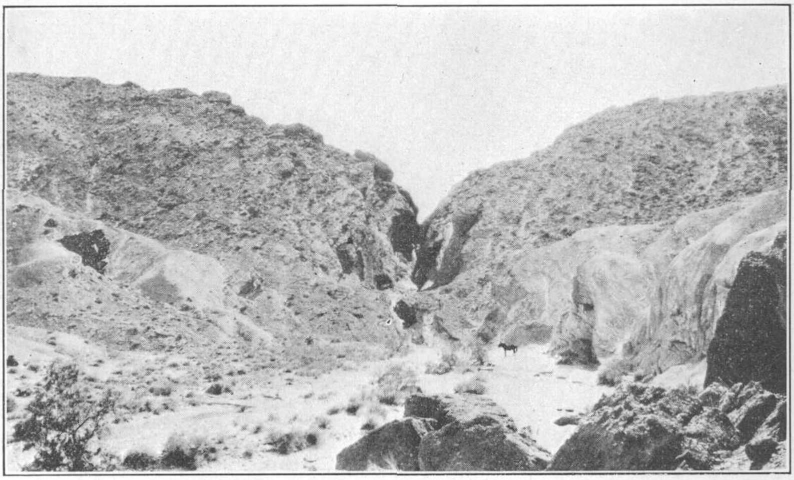
A. VIEW NORTHEAST ACROSS VIRGIN VALLEY FROM POINT NEAR ST. THOMAS

a, b, c, Aggradation surfaces. Lower terrace does not appear in view



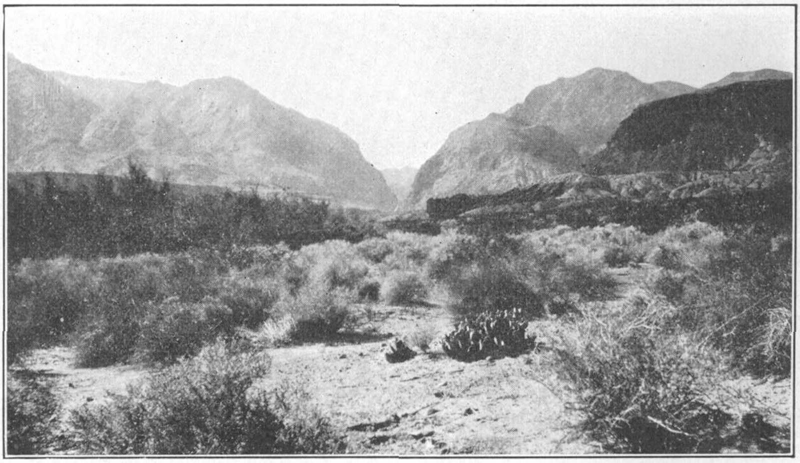
B. REMNANTS OF ROCK-CUT SURFACES ON JURASSIC (?) SANDSTONE

Surface in foreground corresponds to aggradation surface No. 2 (b in view above); higher remnants related to highest aggradation level. Sandstone dips 30° toward the right



A. GORGE WITH COMPOSITE SLOPES CUT THROUGH OVERTON RIDGE BY OVERTON WASH

Ridge consists of limestone conglomerate, dipping 40° toward observer. Light-colored beds in foreground are Horse Spring "magnesite"



B. COMPOSITE SLOPES AT HEAD OF BOULDER CANYON, COLORADO RIVER

Highest points are 2,000 feet above the stream grade parallel to the stream is less than 20 feet to the mile. Parts of the next higher terrace are preserved on both sides of the valley. A long remnant of this surface bordering Overton Wash slopes toward Muddy Creek at the rate of 70 feet to the mile. Overton Mesa, a remnant of surface No. 2 in the same locality, has a slope of 66 feet to the mile, whereas the gradient of Overton Wash in the same direction is 77 feet to the mile. It appears, therefore, that the old surfaces have more gentle slopes toward the middle of the valley than the graded beds of the largest tributary washes. Furthermore, the higher surfaces appear to have the gentler slopes. Observations on remnants of the highest surface indicate a slope out from the mountain wall of not more than 50 feet to the mile. Slopes parallel to the courses of Muddy Creek and Virgin River can not be stated exactly but are comparable to present stream gradients.

Surfaces in other valleys.—Surface No. 1 extends without appreciable break around the south end of the Mormon Range and up Meadow Valley Wash. Lower surfaces are interrupted at the Narrows but reappear above Weiser Gap and continue up Muddy Valley and into California and Meadow Valley Washes. Meadow Valley Wash contracts repeatedly to canyon width, but wherever it widens one or more terraces similar to those farther south are present. In the wide valley near Panaca, nearly 100 miles north of Muddy Creek, there is a series of wide surfaces strikingly similar to those in Muddy and Virgin Valleys. In Grand Wash at least three levels are present, and it appears certain that surface No. 1 in Virgin Valley formerly extended entirely through St. Thomas Gap. Exact correlations of surfaces in separate valleys, however, must await more exact data than are now available.

Construction and origin.—In general the features are of similar construction, having as caps irregular sheets of gravel and sand that lie unconformably on the Muddy Creek clays. This relation is modified near the outer margins, especially in the highest level, where the gravel capping in places lies on a very even, sloping surface of bedrock. In the central parts of the valleys, however, the underlying clay is everywhere present, except near Virgin River northeast of St. Thomas, where deformation of the beds prior to the completion of surface No. 2 carried the clays below the present stream level and gave rise to an unusual thickness of the gravel filling. The cappings of detritus range in thickness from a few feet to at least 300 feet. As a rule the contact between gravel and clay in any terrace has many minor irregularities but general uniformity of slope. In general the clay beneath the gravel capping reflects the step relation of the terrace surfaces; thus clay is exposed in the edge of almost every mesa or similar remnant at a higher altitude than that of the next lower surface.

The general correspondence of slopes to those of the existing stream channels indicates the development of at least the three lower surfaces after the present open drainage system was established. Moreover, there are among the materials in all cappings many foreign pebbles like those now brought in from the north by Virgin River and Muddy Creek. Evidently each surface represents a considerable period of nearly stationary grade in the stream channels, during which the general tendency was downward but at a rate so slow that relatively great lateral cutting was permitted at the expense of the next higher level. During this period slow aggradation of the valleys was dominant at intervals, producing a nearly even surface of fill above the more irregular clay floors that resulted from stream cutting. The end stage in constructing the unusually wide and smooth upper level must have been a relatively long period of aggradation, during which waste accumulated to a considerable depth in the valley interiors and spread over much of the rock-cut slope around the margins. Remnants of this surface preserved on the Jurassic (?) sandstone west of St. Thomas (pl. 16, *B*) consist of a thin capping of coarse waste that rests on remarkably even surfaces of the bedrock. The rock-cut floors slope toward the valley at the rate of 100 feet or more to the mile; whereas the smooth surface of waste has a slope about half as great, the capping of waste thinning toward the mountain wall. Before destruction of this widespread surface began relief in the Muddy and Virgin Mountains was certainly much less than at present, and areas of waste-filled lowlands greatly exceeded the areas of rock outcrops.

OLD EROSION SURFACES

Remnants of former erosion levels are easily recognized in even rock-cut surfaces that form flat tops on ridges of tilted rock or abut against the higher peaks as sharp benches. Because of the high inclination of beds, however, the older surfaces have escaped destruction only on edges of the hard limestone layers, and therefore their remnants are necessarily small and scattered, and their correlation is uncertain. Suggestions of badly dissected surfaces are found in the high part of the range, but they can have their counterparts only in neighboring high ranges, and extensive discussion of these surfaces will not be attempted in this report.

The highest recognized surface is represented by remnants in the high block south of the Arrowhead fault. One of these remnants several acres in extent has a thin veneer of conglomerate and caliche on the evenly beveled limestones. It lies at an altitude of 3,200 feet or more than 1,000 feet above the present mountain base. East of the White Basin fault a similar surface, at about the same altitude, has a steep eastward slope, probably due to tilting of the block by faulting. (See pl. 13, *B*.) Clearly this surface represents an advanced stage of erosion, and if the tilting occurred during the Pliocene faulting, the surface may have been developed in early Pliocene time.

A surface several hundred feet higher than the present streams is clearly recorded on Weiser and California Ridges, where it makes long stretches of nearly even skyline and has a gentle slope toward Muddy Creek. A few peaks that rise higher have well-defined shoulders at the old level. The best example is a peak on California Ridge rising sharply 300 feet above a nearly continuous platform several hundred feet in width, the surface of which slopes gradually from the peak in all directions and ends abruptly at the steep sides of the ridge on the east and west. Small rounded knobs and shallow channels make the surface slightly irregular, and in some of the depressions there are remnants of caliche containing coarse pebbles, resembling the veneer of deposits beneath aggradation surfaces. From a flat part of the platform a nearly vertical hole, roughly circular and several feet in diameter, descends to an unknown depth into the solid rock. This feature may have originated as a pothole but is more probably a solution cavity developed during the period of high base-level. The alidade shows that the shoulder exactly corresponds in altitude to the even top of Weiser Ridge directly opposite, and both surfaces are approximately on a level with the top of aggradation surface No. 1 near the south end of the Mormon Mountains. Evidently the rock-cut shoulders were made during the stage of waste accumulation that produced the high surface. Near the end of the stage only isolated points and buttes of Kaibab limestone projected above the floor of waste and marked the trend of the present ridges. Shallow notches in the tops of the ridges show the positions of washes during the building of the old surface or in the early stages of its destruction.

A pronounced bench is developed on the upturned edges of Moenkopi limestone that flanks the east side of Weiser Ridge, the surface running evenly across the tops of spurs, with a gradual descent in the direction of the Narrows. (See pl. 15, *A*.) If this bench is projected across the Valley of Fire with a gentle eastward inclination, it connects naturally with large patches of planed surface on the Jurassic (?) sandstone, and these in turn may be projected, with a similar eastward slope, to connect with remnants of surface No. 2 in the Overton fanglomerate area. Field observations made in several places indicate that this correlation is correct. During the development of the level considerable areas of the softer rocks were planed, but no appreciable effect was produced on the hard Paleozoic limestones. Subsequent erosion has not been sufficient to destroy all traces of the rock-cut bench on the Jurassic (?) sandstone and Moenkopi limestone, but the weak shales between have been reduced to a lower level. Remnants of rock-cut surfaces on the Jurassic (?) sandstone at a higher level have been mentioned previously. (See pl. 16, *B*.)

CANYONS WITH COMPOSITE SLOPES

Where superimposed streams cut through hard ridges there is commonly a record of stationary or slowly degrading stages, separated by pulses of quickened incising. The record consists of a series of abrupt breaks in the profile of the canyon side, the angle of slope becoming smaller upward. Nearly all such breaks in profile can be connected with gravel-covered terraces, some represented by remnants only a few feet wide, developed on clays or other soft materials in the sides of the valley. In Overton Ridge (pl. 17, *A*) wide rock-cut benches with gentle slopes correspond to distinct stream terraces, whereas the shorter and steeper rock slopes can not be connected certainly with any other features of the stream. In Kaolin Wash five distinct stages are recognized between the level of aggradation surface No. 2 and the present stream grade. Most of these features occur in pairs, fairly symmetrical on opposite sides of the gorge, but some are distinct on one side only. That these broken slopes do not result from unequal rock hardness is evident after considering the nature of ridges in which the gorges are cut. Overton Ridge is a hogback made of massive homogeneous beds that are tilted 40° in the direction of stream flow. The benches are therefore developed diagonally across the bedding. Moreover, corresponding composite profiles are found in all the washes that parallel Kaolin Wash, and similar features occur wherever washes cut tilted blocks of Kaibab limestone. Slopes of the same nature but on a larger scale are conspicuous at the head of Boulder Canyon. (See pl. 17, *B*.)

The term "composite slope" used to designate these features is in accordance with Barrell's usage. Canyons in which one or two breaks occur as definite steps have been referred to by Matthes as "two-story" or "three-story" canyons.

HISTORY OF THE PRESENT DRAINAGE SYSTEM

Fundamental events in the development of Virgin River and its tributaries must be read in the history of the Colorado, and the area studied in detail for this report does not include any part of that stream. Some general observations, however, are worthy of note. Between Virgin and Boulder Canyons the Colorado flows in a relatively open valley cut in weak materials, and on both sides are terraces that apparently correspond to those of Virgin Valley and of the Detrital-Sacramento Valley. Stream gravel similar to that now abundant in the river bed lies on the terraces hundreds of feet above the present grade. The head of Boulder Canyon contracts abruptly to a narrow gorge cutting the Black Mountains, which rise at least 2,000 feet above the average level of the Virgin and Detrital Valleys.

Lee [54] considers these valleys as a unit "old débris-filled valley," and the writer thoroughly agrees with this view. Clearly the saline clay deposits of the Virgin Valley, tentatively referred in this report to the Pliocene, continue southward into the Detrital Valley with no interruption except that caused by the Colorado, and coarse deposits overlying the clay certainly correspond on the north and south sides of the river. In fact it is very probable that the coarse filling beneath the highest aggradation surface in the Muddy and Virgin Valleys is equivalent to the Temple Bar conglomerate south of the river. This material was deposited by streams and may well be connected with the early drainage history in this region, but the clays beneath are typical basin deposits, containing thick beds of salt and gypsum with a wide distribution. The basin in which they were deposited was continuous across the present course of the Colorado and extended far to the north and south. Precise dating of the clays, therefore, will place a maximum time limit on the existence of the Colorado and the Virgin in their present positions, for these streams could not have had their present courses until some time after deposition in the basin had ceased. It is probable that the Black Mountain barrier grew in large part contemporaneously with the formation of the saline clays, and perhaps in part at a later date, for some of the porphyries and basalts at the north end of the range are lava flows interbedded with the clays, and others are intrusive bodies in the same sediments. The deep and narrow Boulder Canyon bas been cut since these igneous rocks came into position, and the age of the canyon may be only a small fraction of the time that has elapsed since the stage of volcanism. Lee [55] considers that the Colorado formerly occupied the Detrital-Sacramento Valley and was diverted to its present course, presumably by some deformation of the crust. If this view is correct, it appears that Boulder Canyon and other canyons farther down the present course must be very recent. If the clays are Pliocene, the Colorado could not have occupied its present course until after the Pliocene epoch, and the canyon cycle, which is still in progress, almost certainly began in Quaternary time.

"BASIN-RANGE STRUCTURE"

Any consideration of structural relations in the Nevada ranges inevitably raises the question of "basin-range structure." Gilbert's famous generalization, based, as he himself intimated, "on a larger collection of impressions than of facts," [56] has been the subject of

[54] Lee, W. T., Geologic reconnaissance of a part of western Arizona: U. S. Geol. Survey Bull. 352, p. 36, 1908.

[55] Idem, p. 61.

[56] Prefatory note inserted in privately distributed copies of U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, 1875.

much discussion. He postulated that the present regional pattern of alternating ranges and valleys is due in the main to dislocation on steep faults. It is known that Gilbert modified his views somewhat after further study,[57] and even in his original statement he was careful to mention important exceptions to the application of his hypothesis. Furthermore, he recognized more than one period of deformation in some parts of the region. It is true that he overlooked, in his necessarily hurried reconnaissance, structural features that were later recognized as important. For example, he did not suspect the presence of large thrusts in southern Nevada but thought the strata were in normal sequence and essentially undeformed except by normal faults. Discovery of the great thrusts, however, does not of necessity affect Gilbert's main thesis. There is opportunity for misconception in analyzing regional structure which is the final product of successive disturbances. Whatever the actual date of the first major thrusting in Nevada may be, doubtless time enough has elapsed to permit obliteration of topography resulting directly from that movement. Normal faulting on a large scale is clearly much later than the thrusting, but even the effects of this faulting have been greatly modified by erosion. To what extent are the present ranges and valleys the direct result of "block faulting," and to what extent are they the product of differential erosion guided by structure lines? As a complete answer to these questions involves physiographic as well as structural considerations, the subject has been reserved until detailed evidence of both kinds has been presented.

It is evident that the Virgin and Muddy Mountains are fortunately situated for the study of marginal features, because the present drainage is exterior, and the intermontane waste is undergoing rapid dissection. Remnants of conglomerate clinging high on the mountain walls show that the depth of Quaternary débris recently removed was several hundred feet, and underlying Tertiary sediments have also been deeply eroded. Before this stripping began, each of these ranges evidently showed only as groups of peaks and ridges nearly or quite isolated by waste that reached far back into wide valleys or embayments and effectually concealed the borders of the mountain blocks. Now the ranges stand high, and precipitous fault scarps face each other across the wide Virgin Valley. These faults were probably formed in large part during the Pliocene epoch, with some recurrent movement in Quaternary time. So long as interior drainage prevailed, the intermontane basins were kept nearly filled with débris, the fault scarps were effectively hidden, and the separate ranges were low. It is improbable, however, that the relief due to the major

[57] Gilbert, G. K., Studies of basin-range structure: U. S. Geol. Survey Prof. Paper 153, 1928.

normal faults was ever entirely obliterated, and therefore the rapid removal of intermontane waste by the present drainage system has merely increased the height of the "fault-block mountains." Perhaps the present relief is greater than that existing at any time during the period of active faulting.

In this part of the Basin and Range province, therefore, there is a definite "basin-range structure," superimposed on an earlier "Appalachian structure" of thrusts and folds. Strong influence of the earlier structure lines is seen in details of the present topography, and erosion has modified greatly the effect of the "basin range" faults. Nevertheless, highland and intermontane valleys owe their location and general form in large part to normal faulting.

SUMMARY OF GEOLOGIC HISTORY

In the Virgin Mountains the geologic record extends backward into pre-Cambrian time, but in the metamorphosed rocks older than the Paleozoic the record is complicated and very obscure. Apparently the clastic Cambrian sediments were deposited on a nearly even surface that cut across the structure planes of the crystalline rocks. This old erosion surface probably represents a period of peneplanation in early Cambrian time. During much of the Paleozoic era southeastern Nevada was a part of the Cordilleran geosyncline, although it was somewhat east of the area that received the thickest deposits. Further study will be required to determine the amounts and kinds of sediments deposited prior to the Devonian period. The Upper Devonian sea shallowed steadily eastward and deepened toward the west and north. Early Devonian invasions may have covered this region, but faunal evidence is not available.

The intermediate position of the Muddy Mountain area between the eastern shores and the greatest depths of the Cordilleran seas is especially well shown by the Mississippi sediments. Strata of this age are many times thicker in southeastern Nevada than in the Grand Canyon region, but the formations of the Muddy Mountain region are in turn greatly exceeded in thickness by rocks of corresponding age at Eureka. Faunas of lower and upper Mississippian and of Pennsylvanian age are sharply defined in the Muddy Mountains, indicating possible withdrawal of the epeiric seas for long intervals. The extent and direction of the upper Mississippian marine invasion are uncertain, for rocks of that age are known in few western localities. The large thickness of Pennsylvanian rocks in the Muddy Mountains probably represents continuous sedimentation through the Pennsylvanian epoch. The highest beds containing Pennsylvanian fossils in the Grand Wash Cliffs indicate an oscillation between shallow sea and delta or continental conditions. These beds are probably equivalent to Noble's basal Supai in the Grand Canyon region.[58]

The earliest deposits of possible Permian age record widespread continental and probably near-shore conditions with effective dry seasons. These deposits may include a portion of the typical red sandstone and gypsiferous shale of the Supai formation. The Coconino delta and dune deposits succeeded, heralding the invasion of the Kaibab sea. The distributing centers of the Coconino sand were probably northeast of the Muddy Mountains, for in the Virgin Mountains the deposit feathers out, and in the Grand Canyon district the foresetting of the delta beds indicates that the source was on the north and northwest.[59] The Kaibab sea was widespread but shallow and oscillating, as shown by the presence of sandy beds in all known sections. General aridity is also indicated by the thick gypsum layers near the middle and at the top of the formation in southeastern Nevada. The uniformity of the Kaibab formation in thickness and lithologic character over thousands of square miles is truly remarkable. Evidently during this stage of the Permian epoch the region of the southwestern United States was at a generally low altitude. The flat-bottomed Kaibab sea was bordered by featureless lands, and the deposition of thick limestone beds was permitted over wide areas covered by shallow water. Temporary shrinking of the sea caused fine sand and silt carried by old and sluggish streams to be spread over nearly all of the epeiric sea bottom. Broad bodies of water were practically isolated and became sufficiently saturated to deposit thick layers of gypsum. By a later depression of the land the original extent and depth of the Kaibab sea was restored, the mouths of the rivers were pushed back long distances, and the deposition of the thick upper limestone member followed. Abundance of clastic sediments in the formation in southern Utah suggests that land lay north or northeast of the Grand Canyon district.

The unconformity above the Kaibab limestone represents the erosion interval separating the Paleozoic and Mesozoic eras. Reports of an unconformity at this horizon come from widely separated parts of the plateau, and it now appears certain that the break is a regional feature of great extent in the Southwestern States. Dake[60] has suggested the possibility that the break is an unconformity of considerable stratigraphic magnitude in the San Juan oil field of southeastern Utah. His suggestion, however, was based on an uncertain correlation of the Goodridge formation and on erroneous inclusion in the

[58] Schuchert, Charles, On the Carboniferous of the Grand Canyon of Arizona: Am. Jour. Sci., 4th ser., vol. 45, pp. 358-359, 1918. Noble, L. F., A section of the Paleozoic formations of the Grand Canyon at the Bass trail: U. S. Geol. Survey Prof. Paper 131, pp. 60-63, 1922.

[59] Schuchert, Charles, op. cit., p. 349.

[60] Dake, C. L., The horizon of the marine Jurassic of Utah: Jour. Geology, vol. 27, p. 634, 1919.

Moenkopi of rocks now known to be older than the Kaibab limestone. The Muddy Mountains are 300 miles from the Circle Cliffs, in southern Utah, and in the intervening region the base of the Moenkopi and equivalent Lower Triassic beds rests on Kaibab limestone at every locality where the horizon has been studied. This relation is especially significant, as the age of the Moenkopi formation has been determined to be Lower Triassic. Evidently the end of the Paleozoic era was not marked by mountain making in the southwestern United States but by a broad emergence attended by little local deformation. Apparently the elevation of this pre-Triassic plain was slight, for the Kaibab limestone was not cut through in a wide region. It is possible that higher Permian beds were stripped away, leaving a plain capped by the Kaibab as the end stage of long-continued erosion, but we have no evidence to support this possibility.

In later field work the writer has found that the Kaibab was removed by pre-Triassic erosion in part of the Spring Mountain area, west of the Muddy Mountains.[61] Apparently this was due to local upwarping at the time of general post-Kaibab emergence.

The Lower Triassic sea advanced from the west and apparently covered much of the region west of the Rocky Mountains. The sediments deposited in southeastern Nevada indicate that the sea was shallow and oscillating, and there were low lands at no great distance to the southeast. Emergence was gradual, allowing the marine deposits to pass into fine-grained continental sediments, which give evidence of a dry climate. After the Lower Triassic epoch upwarping began south of the Muddy Mountain region, probably in central and southern Arizona, and the coarse Shinarump conglomerate was formed over a wide area, probably in a desert land of moderate relief. During the Upper Triassic the high ground on the south persisted and furnished materials for the thick Chinle formation of Nevada and Arizona. Possibly these southern uplands also continued into the Jurassic period and served as the source for the great amount of sand in the Wingate, Todilto, Navajo and equivalent formations. There is evidence of widespread aridity in the Southwestern States throughout Upper Triassic and Lower Jurassic (?) time. The presence of a high mountain range southwest and south of the region may have been the cause of this general aridity, for the highlands would be a barrier to the moisture-bearing winds from the Pacific.

Details of Mesozoic history later than the Lower Jurassic (?) are not revealed in the Muddy Mountains. The Jurassic (?) sandstone is the youngest formation affected by the intense thrusting which is the first definitely recorded mountain-making movement in southeastern

[61] Longwell, C. R., The pre-Triassic unconformity in southern Nevada: Am. Jour. Sci., 5th ser., vol. 10, pp. 93-106, 1925.

Nevada. So far as sedimentary records show, this deformation may have occurred at any time between the Jurassic and the middle Tertiary. Certain general considerations favor the earlier part of this interval as the time of the disturbance, making it contemporaneous with the post-Jurassic folding recorded in the Sierra Nevada and Humboldt Ranges; but good arguments can be advanced for a Tertiary date, making the thrusting the initiatory cause for the coarse Overton fanglomerate at the base of the Tertiary sediments. This problem affects the whole history of the region during Cretaceous and early Tertiary time. If the thrusting occurred at the end of the Jurassic period, we may logically assign it to the movement that resulted in great uplift of the whole Basin and Range region, making this region an important source of Cretaceous and Eocene sediments. On the other hand, if the thrusting occurred in Tertiary time, the pre-Cretaceous uplift was of a broad, plateau-forming nature, for the thrusting marks the first serious disturbance of the Jurassic and older sediments.

In any case the region did not receive permanent sediments during Cretaceous and early Tertiary time. A change in conditions came abruptly, probably during the Miocene epoch. If the thrust movement did not initiate this change, we must seek the cause in profound faulting that converted the region into a country of block mountains, with interior basins in which lakes were formed. In western and southwestern Nevada and eastern California the Esmeralda ("Siebert") and Barstow beds were deposited in basins, volcanism was widespread, and volcanic ash formed a considerable part of the water-laid formations. In southeastern Nevada the coarse Overton fanglomerate was formed during or soon after faulting, and the finer Horse Spring sediments were laid down after the relief became more subdued. The nature of the materials deposited indicates deficient rainfall, but the climate was certainly much more humid than it is in that region at present, as the widespread lacustral deposits required large water bodies for their formation. There is evidence of continuous or recurrent movement on large faults during the lake stage, maintaining depressions in which unusual thicknesses of the lake beds were formed. Probably the lacustral deposits are of late Miocene age, although this assignment is tentative.

Not long after their deposition the lake beds were highly folded in a crustal movement that probably initiated the Virgin Mountains. The folding was followed by intense normal faulting that divided the older structural units into a mosaic of blocks. Certainly large displacement occurred on the Grand Wash and Virgin River faults, but possibly some of these features had their beginning in an earlier stage of normal faulting, and the later movement was of a recurrent nature. The later faulting probably occurred during the Pliocene. Some of the large faults that separate the plateau blocks on the east may belong to this stage.

Basin conditions succeeded and probably attended the later faulting. Thick playa and lake deposits were formed in the intermontane areas. Salt and gypsum deposits in the clays indicate aridity during this stage, which probably belongs in the upper Pliocene epoch. Lavas were extruded on an extensive scale. Colorado and Virgin Rivers were not in existence, for their present channels are cut in the typical basin deposits.

After the deposition of the intermontane clays (Muddy Creek formation) disturbances of considerable magnitude occurred, probably in Quaternary time. These movements affected the clays by local folding and faulting, and probably the last notable elevation of the plateau country occurred at this time. During recent years evidence has been accumulating to prove that the elevation which led to the cutting of the Grand Canyon took place in the Quaternary period, and quite possibly large displacement occurred on the Grand Wash fault after the deposition of the intermontane clays. However, there is as yet no definite field evidence to demonstrate such a movement.

During Quaternary time southeastern Nevada has been affected by repeated lowering of base-level, which is recorded in a series of high surfaces of aggradation. These features have been observed in a large region adjacent to Colorado River.

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