Geology and Geography of the Zion Park Region Utah and Arizona

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A comprehensive report on a scenic and historic region of the southwest

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GEOLOGY AND GEOGRAPHY OF THE ZION PARK REGION, UTAH AND ARIZONA

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ABSTRACT

The Zion Park region comprises about 2000 square miles of plateau and canyon lands in southwestern Utah and northwestern Arizona within and bordering the Zion National Park. It is a region of scenic beauty, recently made accessible by the construction of Federal highways. Within it are preserved the records of the prehistoric Basket Makers and Pueblos, of the once-numerous Piute clans, and of the early white settlements. The exploration of this region by the Spaniards, fur traders, government scientific and military expeditions, and scouts of the Mormon Church and its subsequent colonization constitute an important part of the history of southwestern United States.

Most of the rocks exposed in the Zion Park region are sedimentary; they constitute the general surface and are revealed beneath the lava flows by stream trenching. Sandstone predominates in thick and thin beds widely variable in composition and texture; shale, limestone, coal, and gypsum are restricted to narrow belts in persistent stratigraphic positions.

The consolidated sedimentary rocks belong to the Permian, Triassic, Jurassic, Cretaceous, and Tertiary systems; the unconsolidated sediments to the Quaternary (Pleistocene and Recent series). They include marine, brackish-water, and fresh-water deposits. The Permian system is represented by the Kaibab limestone; the Lower Triassic by the Moenkopi formation; the Upper Triassic by the Shinarump conglomerate and the Chinle formation; the Lower (?) and Middle (?) Jurassic by the Wingate sandstone, the Kayenta formation, and the Navajo sandstone; the Upper Jurassic by the Carmel, Entrada, Curtis, and Winsor formations; the Cretaceous by the Dakota (?) Tropic, Straight Cliffs, Wahweap and Kaiparowits formations; and the Tertiary by the Wasatch formation. Of these the Kaibab, Shinarump, Navajo, Carmel, Kaiparowits, and Wasatch correspond substantially at their type localities; the others differ considerably.

Igneous rocks are represented by several volcanic cones, which retain much of their original form; by lava flows from existing craters, most of them little modified; and by an isolated dike. The rock in cones, flows, and the dike is basalt, which varies from place to place in proportionate amounts of olivine, augite, magnetite, and mica.

The chief structural features of the region are the prevailing northeast dip and two great normal faults, which, trending a little east of north, have broken the continuity of all the strata exposed and have exerted a profound influence in the development of the topography. The Hurricane fault, with an upthrow on the east of 1,000 to more than 5,000 feet, marks the base of the Hurricane Cliffs, and the Sevier fault, with an upthrow also on the east of 100 to more than 2,000 feet, marks the base of the Elkheart Cliffs continued northward as the Sunset Cliffs. Faults of less length and throw have determined the position of Johnson Canyon, and probably Kanab Canyons and have disturbed the strata at Cougar Mountain, Grafton, and a few other places. Folds are represented by very low waves and wrinkles, generally parallel with the major faults.

The dominant topographic features of the Zion Park region are two extensive platforms. The lower one consists of the Uinkaret and Kanab plateaus of northern Arizona, the higher one of the Markagunt and Paunsaugunt Plateaus of central Utah. Between the platforms, in a vertical interval of about a mile, the rocks have been cut into broad, long terraces outlined by almost continuous cliffs of commanding height. The plateaus and terraces are intricately dissected by deep, narrow meandering canyons. The regional topography is remarkably angular; flat surfaces and vertical walls are common, curved outlines and gentle slopes rare.

The present topography is the result of a combination of conditions present in few other regions—general horizontality of strata, alternation of thin resistant hard beds with thick massive friable beds and thin soft beds, a climate characterized by spasmodic rainfall and consequent sharply fluctuating runoff, and altitudes that give streams steep gradients. The physiographic history includes the precanyon cycle and the canyon cycle, as outlined in previous publications, and a subdivision of the canyon cycle into the gorge epicycle, two inner-canyon epicycles, and the terrace epicycle. Interesting physiographic features are the valley fill of Pleistocene and Recent time, well-developed erosion surfaces, cliff caves, rock arches, landslides of large dimensions, and active sand dunes.

The rocks of the Zion Park region are but slightly mineralized. The minerals of demonstrated economic value are bituminous coal, which is abundant near the base of the Cretaceous, in the Tropic formation; gypsum; and oil, which has been recovered in small amounts from strata in the Moenkopi formation.

Note.—Since the submission of this paper for publication (1939) studies in adjacent areas that apply also to the Zion Park region have led to a revised interpretation of post-Eocene stratigraphy and certain features of faulting. See Gregory, H. E., Post-Wasatch tertiary formations in southwestern Utah: Jour. Geology, vol. 53. pp. 105–115, 1945; also, Colorado drainage basin: Am. Jour. Sci., vol. 245, pp. 694–705, 1947.

INTRODUCTION

For more than a century the Colorado Plateau province has been known to scouts of the Church, traders, prospectors, and pioneer stockmen and farmers. Scientific knowledge of this vast region is the result of Federal surveys by Sitgreaves (1851–52), Whipple (1853–54), and Ives (1857–58) in north-central and western Arizona; McComb (1859) and Hayden (1874–76) in southwestern Colorado and extreme eastern Utah; Fremont (1842–1844), Gunnison (1853), and King (1868–79) in central and northern Utah; and Powell (1869–75) and Wheeler (1869–79) in southern Utah and northern Arizona. The reports of these early surveys outline the geography and geology of the canyons and borderlands of the Colorado River and the cliffs and plateaus of southern Utah.

After a lapse of a quarter of a century the pioneer work of Wheeler and Powell was continued by the Geological Survey in explorations of the least-known parts of the Colorado Plateaus—the Navajo country (1909–13), the Kaiparowits region (1918–27), the San Rafael Swell (1924–26), the San Juan country (1925–29), and the Moab district (1926–27). The study of these regions involved observations on agricultural and mineral resources and mapping of geologic formations in at least sufficient detail to serve as a basis for comparative regional studies in stratigraphy, physiography, and structure. The present paper is a continuation of those studies and has the same scope and purpose, except that to meet the wishes of the National Park Service, human geography and the interpretation of scenery have been treated more fully than is customary in geologic reports. Also for this reason parts of manuscripts that relate to adjacent regions have been incorporated without much rewording. The fieldwork has been intermittent. Traverses in 1900 and 1922 were followed by "vacation studies" in 1928–29, 1932, 1934–35. Systematic mapping was carried on during the field seasons of 1936, 1937, and 1938 and the present report was prepared in 1939. The fieldwork is appropriately classed as detailed reconnaissance. The stratigraphic record is believed to be reasonably accurate, and for Zion National Park, the excellent topographic map permitted satisfactory delineation of formation boundaries. For the large areas where base maps are much less complete and reliable, the mapping is merely a close approximation. (See p. 3.)

In this and previous studies of plateau country, inspiration has come from friendly chats in Washington with Alvin H. Thompson, G. K. Gilbert, C. D. Walcott, and W. H. Holmes, who recalled their pioneer experiences and generously pointed out the "inadequacy" of their early work, and also from the friendly Mormon residents eager to find a meaning in the story of the rocks about them. The value of my investigations has been enhanced by the facts from the study of existing literature and by conferences in the field and office with W. C. Mendenhall, H. D. Miser, G. R. Mansfield, D. F. Hewett, J. B. Reeside, Jr., and L. F. Noble, of the United States Geological Survey. Also, I owe much to my field assistants, A. M. Woodbury, V. W. Vandiver, J. C. Anderson, Bronson Stringham, and F. W. Christiansen, who shared the inconveniences of camp life and made observations in places I was unable to reach. I am indebted to Mr. Anderson for photographs taken at designated places. Throughout the years of field work I have enjoyed the most generous cooperation of the National Park Service and the Utah Parks Co., acting for the Union Pacific R.R.

This report is by no means exhaustive. Much more can be learned from the rocks and the fossils, the canyons, plateaus, and cliffs, and the geologic interpretations are surely open to revision. In a sense the work recorded is an extension of the pioneer investigations of Thompson, Gilbert, Howell, and Dutton, and the purpose of this report will have been served if it opens the way to fuller enjoyment of a region that has few peers in scientific and artistic meaning.

GEOGRAPHY

LOCATION, EXTENT, AND ACCESSIBILITY

The Zion Park region lies mostly in Kane County and Washington County, Utah, but includes small parts of Iron County, Utah, and of Mohave County and Coconino County, Ariz. (See pl. 1; fig. 1.) It is approximately included between parallels 36° 50′ and 37° 30′ and meridians 112° 20′ and 113° 30′. As thus outlined the region has an approximate length of 50 miles and a width of 35 miles. All but about 450 square miles of its area is in Utah. It is primarily a grazing district, utilized by the sparse population that cluster in settlements where water is available for the irrigation of small farms and orchards.

Parts of the region, including areas of attractive scenery, are readily accessible. Automobile highways lead to Zion National Park from the west through Cedar City and St. George, from the north through Panguitch, Hatch, Glendale, and Mt. Carmel, and from the south through Fredonia and Kanab. Secondary roads connect Virgin and Hurricane with Short Creek, Pipe Spring, Moccasin, and Fredonia; Kanab with Johnson, Skutumpah, Alton, and Paria; and Springdale with Navajo Lake on the Markagunt Plateau. When in repair the steep tortuous roads from

Rockville to Big Plain, from Virgin up North Creek and across the Kolob Terrace to Cedar City, from Glendale to Kanab Valley and Alton, and from Hurricane to Antelope Springs, may be traversed by automobile, and a recently constructed road makes the grazing land on the Uinkaret Plateau accessible to trucks.

The villages in Virgin Valley, Parunuweap Valley, Fortunately, the diversity, beauty and grandeur of the scenery along the highways is a counterpart of that viewed by the scientific explorer whose routine duties lead him to places difficult of access. However, for those intent on adventure the way is still open along unmarked trails to unique geologic features, areas of unusual vegetation, and prehistoric ruins so far undisturbed.

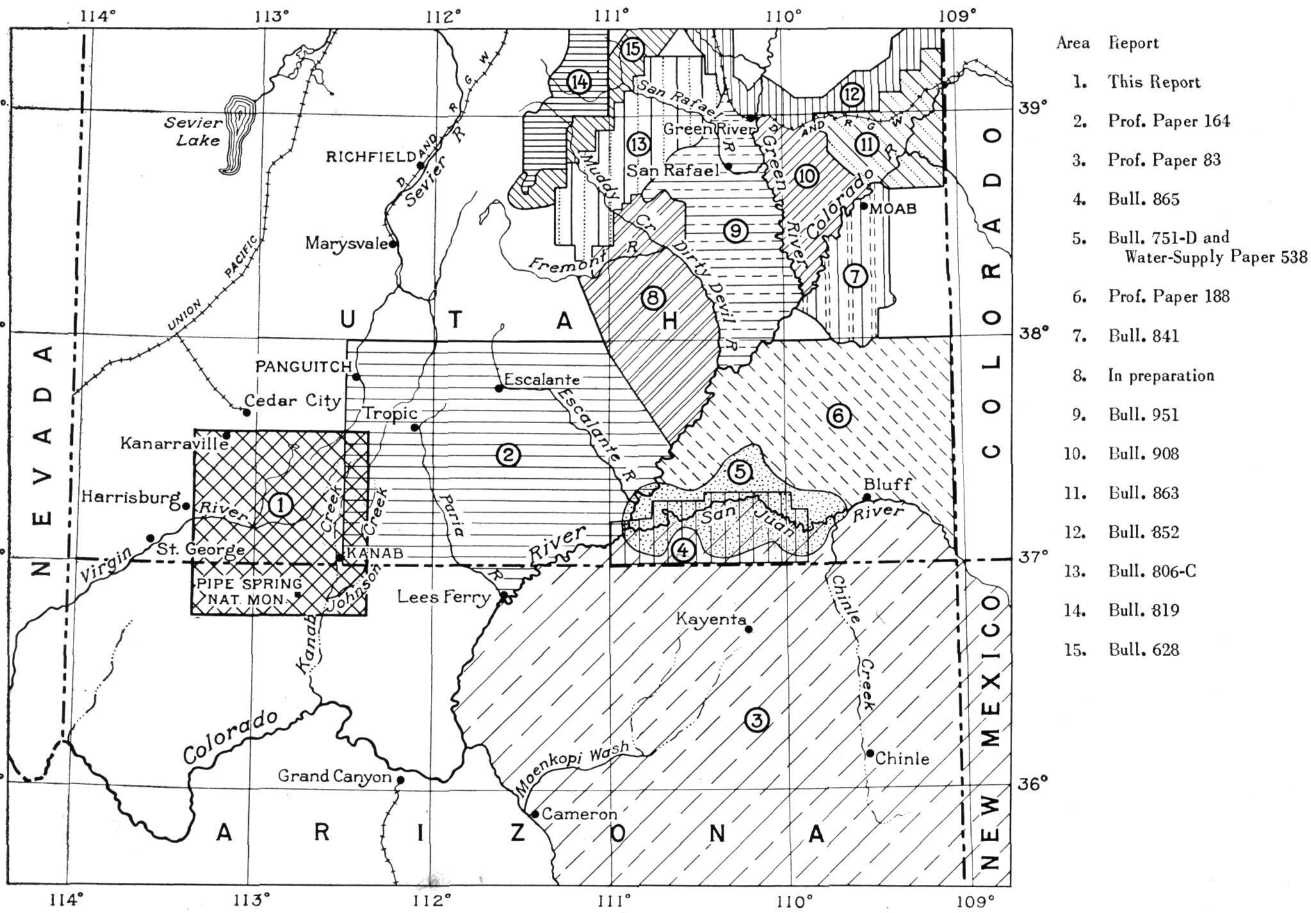


FIGURE 1.—Map showing location of Zion Park region (shaded area) and areas in adjoining regions for which reports have been published by the Geological Survey.

and Kanab Valley maintain stores, postoffices, and tourist cabins, and in Zion Park accommodation for travelers are available throughout the year. The larger commercial centers of Cedar City and St. George are reached by Federal highways at distances from the Zion National Park of respectively 60 and 40 miles.

However, most parts of the region are still "horseback country" and to reach such scenic areas as the face of the White Cliffs and the Pink Cliffs, the Block Mesas, Moccasin Terrace, the eastern part of the Kolob, and such outlooks as Heaton Point, Dutton Pass, and the crest of Vermilion Cliffs calls for the use of strong horses and intelligent guides. Many spectacular features are accessible only on foot. Climbing canyon walls and traversing canyon floors up "dry waterfalls," and around huge talus boulders is the everyday task of the field worker.

THE MAP

The base map that accompanies this report was compiled from maps issued by the Powell and Wheeler surveys (1872–73), the Geological Survey, the Forest Service, from unpublished charts of the Land Office, and from surveys made for the present purpose. The topographic map of the Powell Survey (scale: 1 inch = 4 miles; contour interval 250 feet) and the hachure map of the Wheeler Survey (scale: 1 inch = 8 miles) picture in generalized form the plateaus, the lines of great cliffs, and the approximate courses of the major streams. For part of the Zion Park region the map compiled by the Forest Service, which incorporates the work of the Land Office (1860–1935), gives the position of the main streams and many of their tributaries and the settlements and political boundaries. Of the maps prepared by the Geological Survey, that issued in 1909 by G. B. Richardson (scale: 1 inch = 4 miles; contour interval 500 feet) covers the Kolob-Kanab coal field; the unpublished map by C. E. Dobbin (scale: 1 inch = 2 miles; structure contour interval 500 feet) shows the "oil reserve" in the lower Virgin River Valley, and that by L. S. Gardner records the position of the Hurricane Cliffs. The Survey topographic map of Zion Park, prepared by R. T. Evans in 1929–32 and issued in 1936 (scale: 1 inch = ½ mile; contour interval 50 feet) is fully adequate for geologic studies, but unfortunately it covers but a small part of the area here treated, and most of the major geological structures in southwestern Utah are outside its boundaries.

In preparing the present report it was at first thought that in some way the existing regional maps and local maps that show relief might be combined to form a topographic base. However, superposition of the various maps showed not only a range in contour intervals of 50 to 500 feet, but also considerable difference in the altitude of prominent cliffs and plateaus and differences in latitude and longitude. In fact until 1928 the altitude and geographic position of no topographic feature in southern Utah had been determined with the accuracy expected in modern maps. In view of these inadequate and confusing topographic data it was decided, in conference, to omit contour lines, represent prominent features by hachures, and use the township plates of the Land Office in recording the position of such features as streams and settlements. The alternative involved the large expense and long delay incident to the construction of a satisfactory base. For areas not covered by the Land Office net, the township lines, in places also the section lines, were interpolated, and to show the boundaries of the geological formations in their proper relations plane-table maps were made in certain key areas. Thus the strip along the highway from the east entrance of Zion Park to the Elkheart Cliffs at Mt. Carmel was surveyed by D. K. Mackay of the National Parks Service, and with the assistance of Bronson Stringham, Instructor in Geology, University of Utah, and V. W. Vandiver of the Park Service, topographic maps were made of a strip 12 miles wide along the Utah-Arizona boundary from Hurricane Cliffs to Johnson Canyon, of the Block Mesas eastward to Kanab Valley, and of the White Cliffs region east of Heaton Point. At a number of points, particularly where stratigraphic sections were measured, relative altitudes were determined by aneroid. The base map that accompanies this report is thus a composite in which the various parts are of unequal accuracy and inconsistent to an undetermined degree. It is believed, however, that it records the noteworthy geographic features in their proper setting. The names on the map include the 19 on the Powell map, the 21 on the Wheeler map, and, with some revision, those on the map of the Forest Service. Many new names have been added, both those locally in common use and those needed to facilitate the description of geographic districts and prominent topographic features.

The geologic mapping, like the topographic mapping, may be classed as detailed reconnaissance. For parts of the region knowledge of the stratigraphy and structure is insufficient for precise mapping; for other parts more of the geology is known than is practicable to represent on the base map. Though the geologic map does not attain a high degree of accuracy, it probably records fairly well the significant features of the geology of the Zion Park region.

TOPOGRAPHIC OUTLINE

In its general relations the Zion Park region is part of the Colorado Plateaus, a geographic province comprising 100,000 square miles of strongly carved tabular relief here and there modified by volcanic masses. Its dominant topographic features are plateaus, cliffs, and canyons strongly contrasted in magnitude, form, and color, which so completely dominate the landscape that features unnoticed here would be picturesque landmarks in different surroundings. On large and small scale the topography is angular—terraces and vertical walls are common and curved outlines and gentle slopes are rare. Few regions are more rugged or more difficult to traverse. Unlike the eastern parts of the Colorado Plateaus, where generally flat surfaces are broken by such ridges of folded rocks as the Echo Cliffs, Comb Ridge, Waterpocket Fold, and San Rafael Swell and reach their highest altitudes in such piles of igneous rock as the Abajo, Navajo, and Henry Mountains, the pattern of the Zion Park region is relatively simple. The rocks are displayed as a series of platforms at various altitudes, bordered by cliffs of commanding height and so continuous that canyons which pass through them appear in distant views as insignificant breaks in a horizontal sky line. The landscape of all southern Utah might be described in terms of platform and cliff—plateaus hundreds of square miles in area and cliffs 1,000 to 2,000 feet high; terraces narrow or wide, short or miles long, outlined by escarpments a few hundred feet high; and long sharply cut benches outlined by the eroded edges of individual strata. Innumerable low benches stand on the terraces and cling to the cliffs and canyon walls, and even isolated buttes and mesas are outlined by vertical and horizontal lines. In crossing plateaus, climbing cliffs, or scaling canyon walls, altitude is attained by ascending steps.

In a regional sense the dominant topographic features of the Zion Park region are two platforms each thousands of square miles in area. (See fig. 2.) The lower platform consists of the Uinkaret and Kanab Plateaus, which border the Colorado River in Arizona. A mile above it stand the Markagunt and

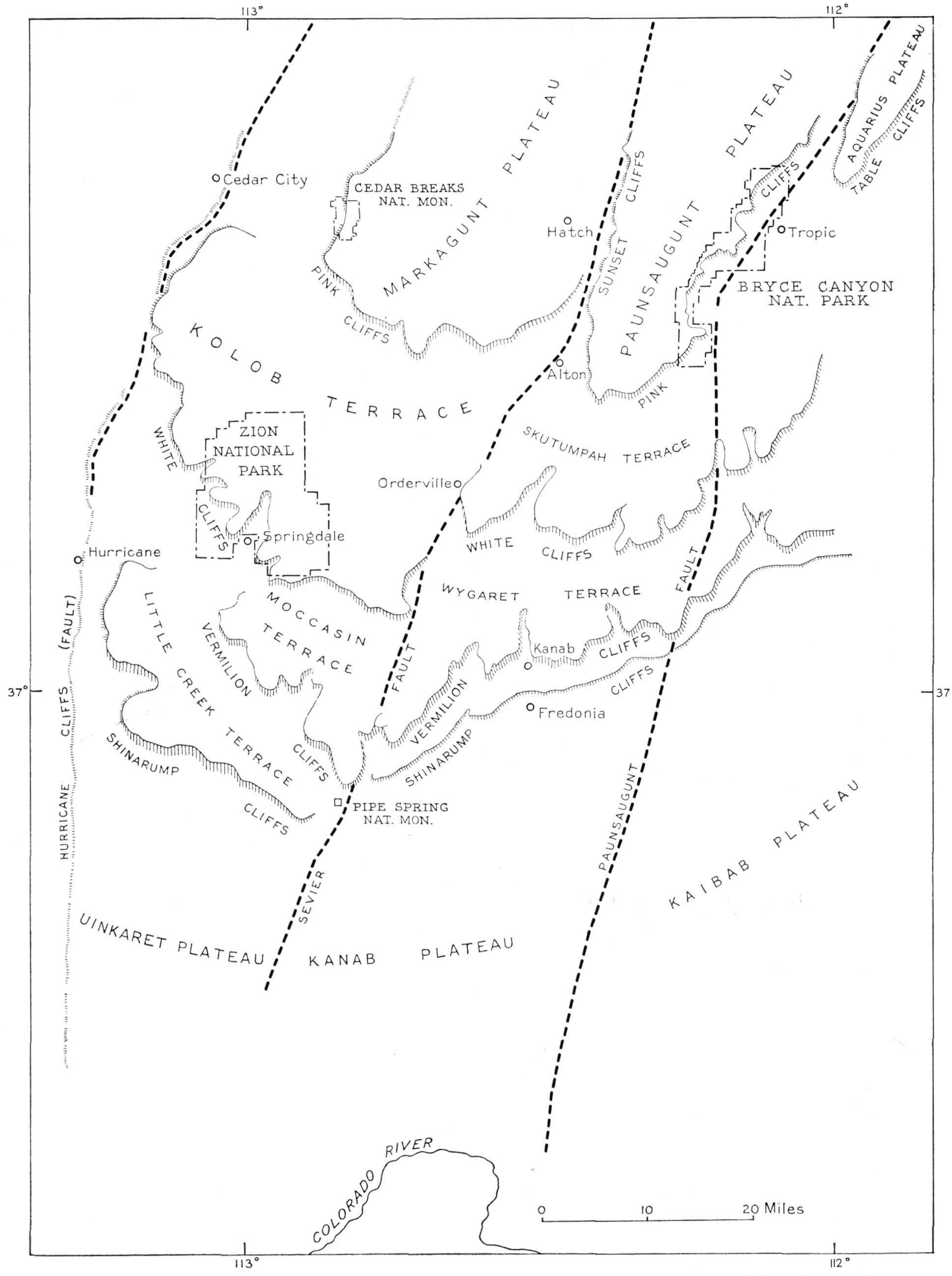


FIGURE 2.—Sketch map showing position of major plateaus, terraces, and lines of cliff in Zion Park region.

Paunsaugunt Plateaus, which extend far northward into central Utah. In the face of the higher plateaus terraces hundreds of square miles in area have been cut. The result is a gigantic stairway of uneven treads that leads from the flat surface of Lost Spring Mountain, near the Utah-Arizona line, to the equally flat top of the Pink Cliffs, some 40 miles distant. A north-south profile through Zion Canyon National Park shows three high steps magnificently carved on their tops and edges. The lowermost step is the Uinkaret Plateau, which in northern Arizona extends eastward from the Hurricane Cliffs to Kanab Canyon and southward from the base of the Vermilion Cliffs to the rim of Grand Canyon at a general altitude of 5,000 feet. Near the Hurricane Cliffs in southern Utah the surface of this plateau is incised by broad valleys that outline Lost Spring, Little Creek, and Gooseberry Mountains whose flat tops may be considered as parts of a once-continuous subordinate platform, here called the Little Creek Terrace. The middle step is the Kolob Terrace, whose tilted surface lies at altitudes of 7,000 to 9,000 feet. On the south and west it is sharply bounded by walls along Virgin River and Hurricane Cliffs. On the north it terminates in the Gray Cliffs, which here stand as foothills below the Pink Cliffs, and on the east it merges with other highlands along the line of the Elkheart Cliffs. The highest step, reached by ascending the Pink Cliffs, is the Markagunt Plateau, whose general surface lies about 10,000 feet above sea level—the highest land in southwestern Utah. Each of these three great platforms is distinctive in erosion forms, in drainage, in coloring, in vegetation, and in fitness for human occupation.

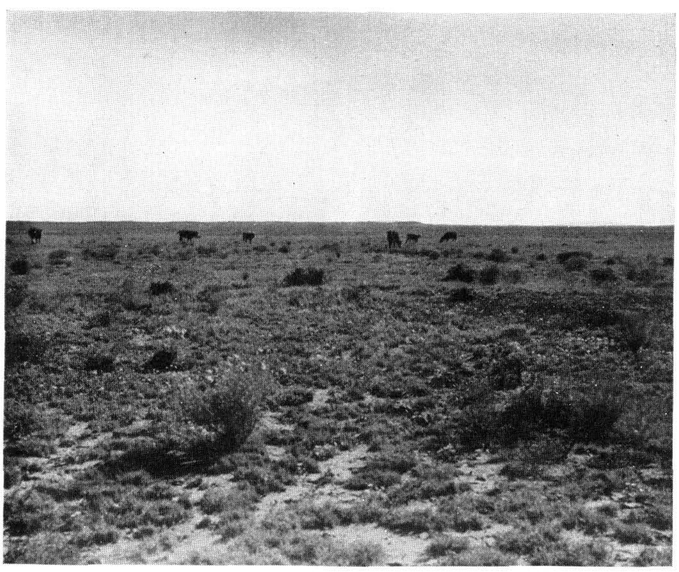


FIGURE 3.—Surface of Uinkaret Plateau. View southward from Pipe Spring-Short Creek road west of Cedar Ridge. Dominant vegetation, sagebrush.

The Uinkaret Plateau is an open country of broad flats and wide, shallow valleys, isolated low, highly colored mesas, and flat ridges of rock and gravel. Its high points are volcanic masses of the Uinkaret Mountains, which rise 2,000 feet above the regional surface. On this plateau most of the streamways hold water only after rains, and vegetation is sparse and specialized. It is a cattle country with few inhabitants. (See pl. 3; figs. 3, 4.)

The Kolob Terrace, cut into the south flank of Markagunt Plateau, is an area of swales, low rounded ridges, and gentle slopes interrupted by escarpments and volcanic cones. In places a prominent line of cliffs separates the area into two uneven plateaus, known locally as "the Kolob" and "the Lower Kolob." Its surface is further roughened by scores of canyons tributary to the Virgin River, canyons so narrow, deep, and closely spaced as to preclude traverse of the region except by roundabout routes. (See figs. 5, 6.) Because of their scenic beauty parts of the Kolob have been set aside as the Zion National Park and Zion National Monument. Outstanding features are East Temple and West Temple. (See pls. 10, 10a, 11.) Unlike the Uinkaret Plateau, the Kolob Terrace is well watered by springs and streams, and its abundant grasses and shrubs provide excellent forage for sheep and cattle. The Markagunt Plateau (fig. 10) has a surface of low relief, particularly the areas of lava and the broad valleys through which wind slow meandering streams. In contrast with its surface the south and west faces of the plateau are deeply trenched by box-headed canyons leading southward to the Virgin River and westward to the desert flats of the Great Basin. The surface of the plateau descends northeastward for some 30 miles from the top of the Pink Cliffs 10,000 feet in altitude, to bench lands along the Sevier River at 7,000 feet. The highest points are igneous masses poured out by ancient and recent volcanoes. As viewed from Little Creek Mountain, South Mountain, or Smithsonian Butte, the Uinkaret Plateau, the Kolob Terrace, and the Markagunt Plateau, each with its distinctive color and style of erosion, rising from a flat, arid foreland to the forested cloud-capped High Plateaus, compose a scene of unusual grandeur. Similar in form to the steps measured in miles and more beautiful in color and carving are the rock terraces along the Virgin River below Springdale, in Little Creek and Short Creek Valleys, and on the face of the Vermilion Cliffs.

Along the line of Kanab Creek four platforms constitute a series. The lowest is the Kanab Plateau, at an average altitude of 5,000 feet. From Kanab Canyon it extends eastward toward the Paria River and from the base of the Vermilion Cliffs southward to Grand Canyon. It is an area of broad, flat valleys crossed by flat ridges of east-west trend and isolated mesas outlined by steep cliffs. Where they emerge from the Vermilion Cliffs Johnson, Cottonwood, and Sand Creeks and other tributaries to the Kanab that cross the plateau flow in shallow trenches that make possible the recovery of water for irrigation at Johnson, Kanab, and Fredonia. Like the Uinkaret, the Kanab Plateau is but sparsely coated with vegetation and has few perennial streams and springs. It is essentially a grazing ground for stock. The next higher step in this series is the Wygaret Terrace, 6,000 feet above sea level—the area that extends from Sand Canyon eastward beyond Johnson Canyon, bounded northward by the White Cliffs and terminated southward at the crest of the Vermilion Cliffs. Its surface is roughly even except for rounded knobs that rise above it and short canyons sunk a few hundred feet below. On it grows a pygmy forest of pinon, juniper, and sage and some shrubs and herbs suitable for the sheep and cattle that find water at the few springs and ephemeral ponds. Except on the floors of Kanab and Johnson Canyons, where water for a few ranches is available, the Wygaret Terrace is not used for agriculture. The third step in this eastern series of platforms and cliffs is the Skutumpah Terrace—a broad belt of nearly flat land crossed by southward flowing streams that head in canyons and end in canyons. (See fig. 12.) This terrace extends from the Parunuweap Valley northeastward to the Paria River, a distance of 40 miles. Its southern edge is sharply outlined by the White Cliffs (fig. 11), its western edge by the Elkheart Cliffs. Northwards its general surface at an altitude of 7,000 feet merges into the low benches and escarpments, the foothills of the Paunsaugunt Plateau, the highest bench in the series, 9,000 feet above sea level. The Skutumpah Terrace and adjoining highlands is a grazing country, the site of a few ranches occupied during the summer by stockmen who make their homes in Alton, Glendale, and Kanab.

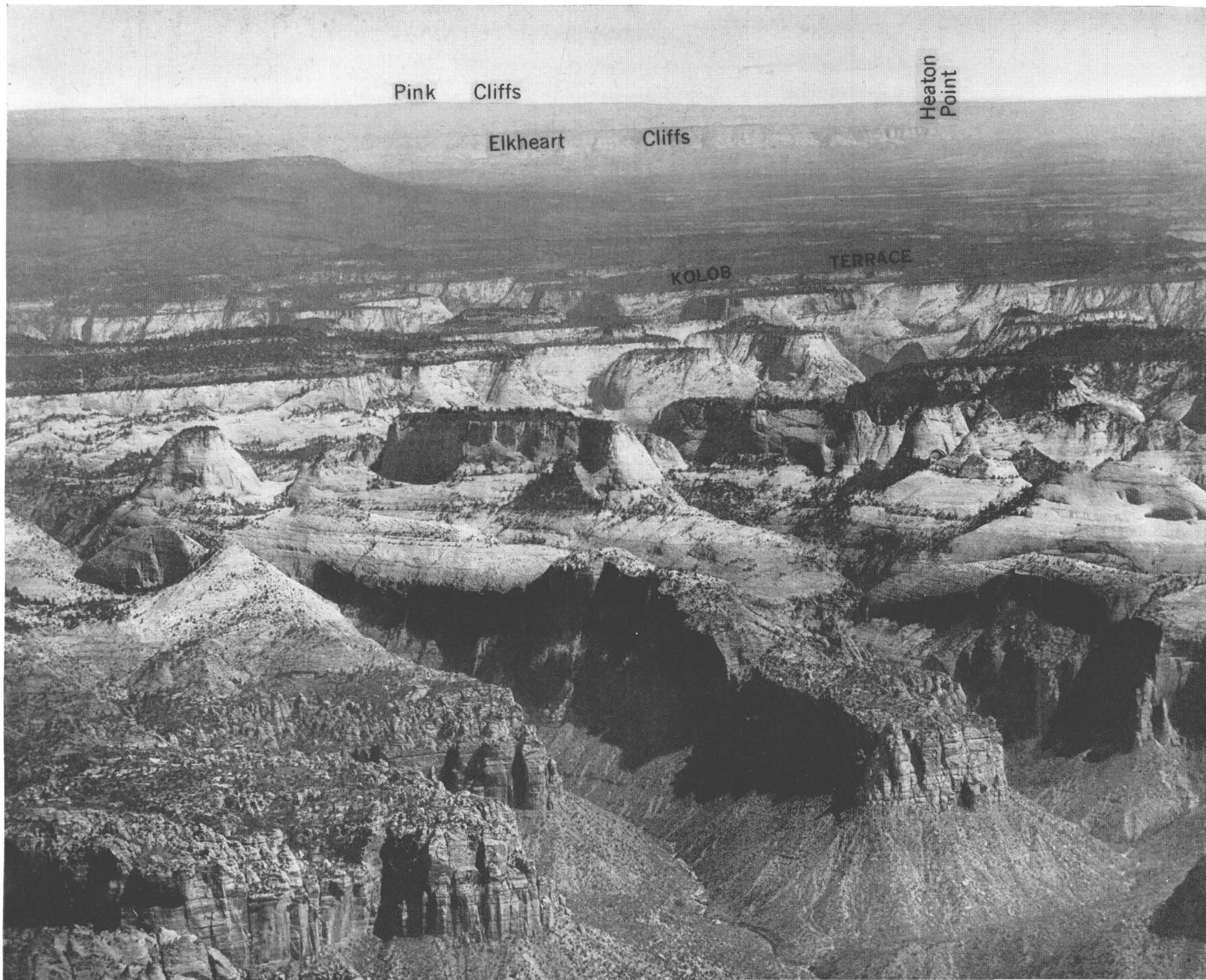
FIGURE 4.—Kaibab Indian School at north edge of Uinkaret Plateau near Moccasin, Ariz. Alluvial plain (foreground), Vermilion Cliffs (upper left and center sky line), typical exposure of Shinarump conglomerate and Moenkopi shales on ridge (upper right).

From the highway east of Fredonia, particularly where it ascends the slope of the Kaibab Plateau, this eastern stairway is revealed in all its magnificence. From the floor of Kanab Plateau, here almost bare of vegetation and painted in tones of chocolate and gray, rises abruptly the red wall of the Vermilion Cliffs, and behind it in turn the White Cliffs, the Gray Cliffs, the shining Pink Cliffs that rim the Paunsaugunt Plateau, and the towering Table Cliffs of Aquarius Plateau beyond. (See fig. 2.) At no place in the Plateau province are the characteristic rock benches better displayed. Here may be had an uninterrupted view of a vertical mile of rock arranged in orderly layers, which seem to compete with each other in attaining brightness of color and variety of decorative form.

The boundary between the Zion Park and Kanab Valley series of platforms is the line of a great earth crack, the Sevier fault, which begins in central Utah and extends southwestward across southern Utah into Arizona. (See p. 144; pl. 2.) At Glendale, Orderville, and Mt. Carmel, in Yellow Jacket Valley, in Sand Canyon, and at Pipe Spring the position of the fault is marked by cliffs that border terraces. In consequence of the faulting, land surfaces once continuous were broken into blocks which during the process of later erosion have been cut into smaller blocks, each with a new position in altitude, longitude, and latitude but without change in their regional relation. Thus in a sense the Uinkaret and Kanab Plateaus are parts of one general surface, as are the Kolob and Skutumpah Terraces and the Markagunt and Paunsaugunt Plateaus. The Moccasin Terrace, which extends northward from the crest of the Vermilion Cliffs at Moccasin, Pipe Spring, Cane Beds, and Short Creek, is the offset extension of the Wygaret Terrace, to which it corresponds in height, in style of erosion, in vegetation, and in fitness for human settlement. Topographically it belongs in the series that includes the Uinkaret, Kolob, and Markagunt platforms, but west of South Mountain the rocks that compose it have been removed by erosion, leaving as its representative such lower lands as Lost Spring Mountain, Little Creek Mountain, and Big Plain. (See fig. 14.)

The break in alinement of corresponding sets of plateaus and terraces, which in other respects are similar, is well shown by the cliffs that mark their limits. Along the line of the Sevier fault, the Vermilion Cliffs, the White Cliffs, and the Pink Cliffs, otherwise nearly continuous for some 50 miles, are offset 3 to 6 miles. (See pl. 2.)

The borders of the Zion Park region are not everywhere marked by prominent topographic features. The south, north, and east boundary lines are on surfaces that extend beyond the area with little modification. The west border is sharply outlined by Hurricane Cliffs—the longest and the best-defined escarpment in the Colorado Plateau province and the dividing line between two strongly contrasted geographic districts. (See p. 143.) East of the cliffs the rocks are nearly horizontal and are arranged in an orderly succession of low benches. On the lowland



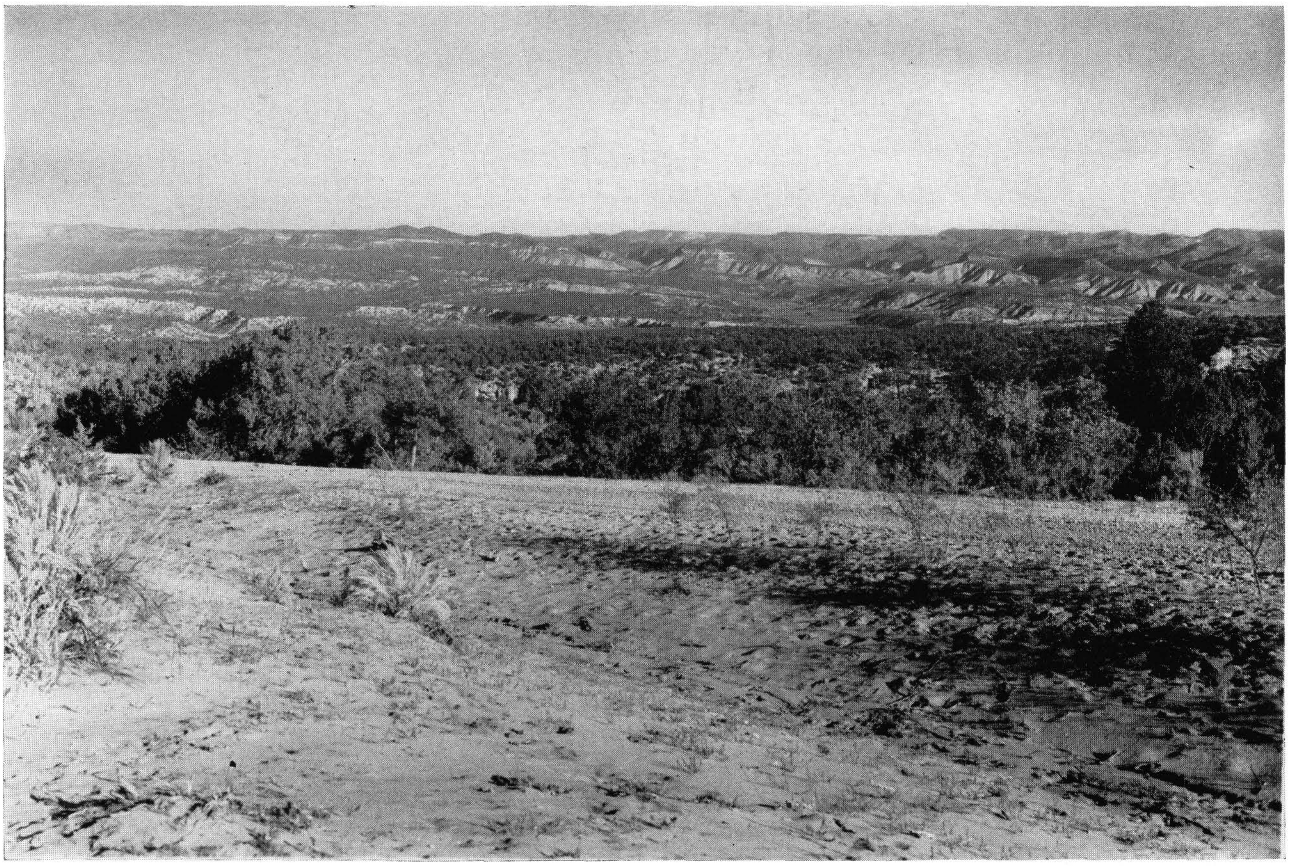


FIGURE 6.—Kolob Terrace (upper and middle left). View northwest from base of Elkheart Cliffs southwest of Mount Carmel. Surface eroded on tilted Upper Jurassic strata. Cretaceous beds (upper left and top). Parunuweap River flowing to left (beyond trees) joined by Muddy Creek (center).

west of the cliffs the rocks are arched in domes and dikelike ridges, streaked with lava and made even rougher by the drifting red sands. From the crest of the cliffs eastward, streams supply insufficient water to permit permanent settlement; westward, irrigation ditches from the Virgin, the La Verkin, and Ash Creek make large-scale horticulture possible. The view from the crest of the Hurricane Cliffs across desert lands westward to hayfields and orchards grouped about prosperous villages, then eastward across uninhabited grazing lands in much their original condition, makes clear the twofold interests of the people of southern Utah—agriculture in the canyoned valleys and grazing on the plateaus. (See fig. 13.)

The characteristic streamways of the Zion Park region are meandering canyons which maintain their pattern regardless of their length, breadth, or depth. Valleys with broad flood plains and with sides that slope gradually from the edge of a stream to the adjoining uplands are lacking. The flat floors meet the steep walls nearly at right angles, and the tops of the walls are truncated at the level of interstream surfaces. (See fig. 15.) Such trenches, especially those sunk into broad rock terraces, may be discovered only when their rims are reached; canyons as much as 20 miles long and 1,000 feet deep are not shown on reconnaissance maps. Some of the canyon floors are wide enough for fields and village sites, but generally there is room only for the streams that occupy them. A few canyons are narrow, deep trenches throughout their length; most of them show "narrows" and "wides," but these are not proportionate to depth. Some canyons have so few tributary canyons that their rims may be traversed for miles. Others are so abundantly provided with interlaced branches that the only feasible trail in some square miles of country is the floor of the master canyon. Kanab, Cottonwood, and Short Creek canyons, which cut through the Vermilion Cliffs, and Parunuweap, La Verkin, and North Creek canyons, and Orderville Gulch, which break through the Kolob Terrace, are features of beauty and commanding proportions, but the glory of the region is Zion Canyon of the Virgin River—a trench 1,000 to 2,000 feet deep, which branches headwards into gashes equally profound but less than 50 feet wide. (See p. 161.)

Down the steep cliffs and across the broad terraces

EXPLANATION OF FIGURE 5

Part of Kolob Terrace (center) bounded on west (foreground) by White Cliffs and now broken by branches of Zion Canyon; bounded on east by Elkheart Cliffs, the part of White Cliffs raised by Sevier fault at Mount Carmel. Pink Cliffs of Paunsaugunt Plateau on dim sky line, Gray Cliffs upper left. Photograph by Army Air Corps.

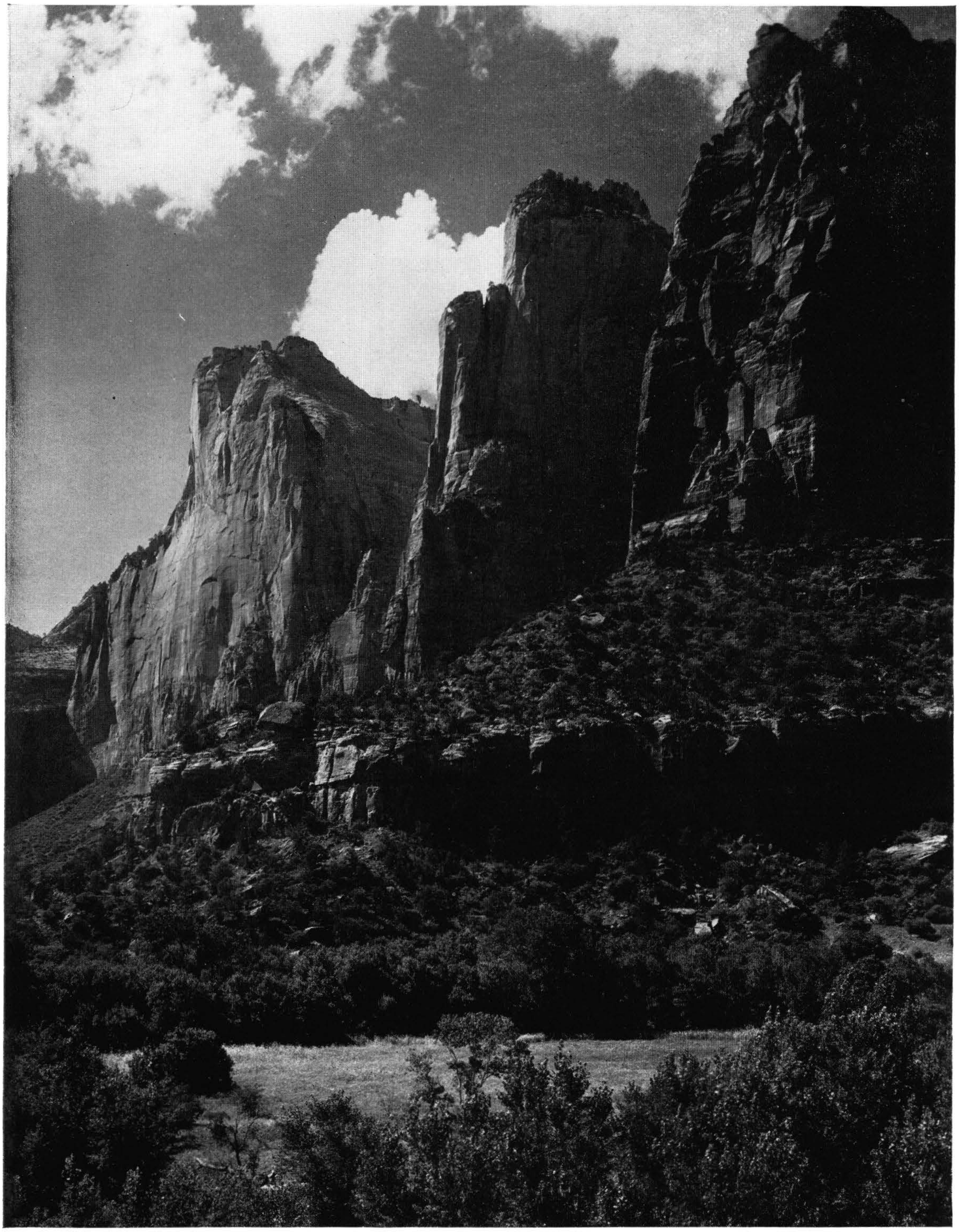


FIGURE 7.—The Three Patriarchs in Zion Canyon National Park. Parts of the White Cliffs (Navajo sandstone) separated by tributaries to the Virgin River. Tops of monuments are at level of Kolob Terrace. Height above river in trench at their base is 2,200 feet.

scores of streams carry surface water southward and southwestward to the Kanab and the Virgin and on to the Colorado Rivers. From the rim of the Paunsaugunt Plateau (9,000 feet) the Kanab descends southward through canyons in the White and the Vermilion Cliffs to the flatland at Fredonia (4,500 feet), then through a profound canyon to its mouth in the Grand Canyon (1,850 feet). Within the Zion Park region the Kanab and its few short tributaries drain 734 square miles. The Virgin River has its source in the edge of the Markagunt Plateau; there its tiny, swift tributaries bring surface water and big springs contribute much. From Kolob Terrace the river receives water through the Parunuweap

River and North and La Verkin Creeks, and south of the Vermilion Cliffs through Little and Short Creeks. In its roundabout course it descends swiftly from the Pink Cliffs (10,000 feet) to the floor of Zion Canyon (4,000 feet) and with less gradient into Timpoweap Canyon (3,200 feet) and on through flatlands and canyons to the Colorado (740 feet). The main Virgin River and its long eastern branch, the Parunuweap, drain 1,010 square miles east of the Hurricane Cliffs, 513 square miles of it above 7,000 feet. Except for the few lakes and small pools in the meadow lands about springs, the water from rain passes readily along a well-marked course on its way to the sea. It is interesting to note that although the major streams flow southward, the regional slope of the rocks is northeastward. (See pp. 141–142.)

The Kanab, the Virgin, and many of their tributaries that head in the High Plateaus have permanent water at their heads, and during most of the year water flows continuously in the larger channels. Many canyons normally present alternating stretches of stream and of dry bed. On both sides of Zion and Kanab Canyons, on Moccasin and Wygaret Terraces, and on the Uinkaret and Kanab Plateaus, nearly all the drainage is ephemeral, the streams flowing only in immediate response to rain.

The topographic features of the Zion Park region are developed in both sedimentary and igneous rock. The plateaus and terraces are built mainly of sandstone in thick and thin layers, slightly tilted. Crater Hill, on Coalpits Wash; Gray Knoll, on Little Creek Mountain; Corral Crater, on Skutumpah Terrace; and Spendlove Knoll and Fire Pit, on Kolob Terrace are craters little modified by erosion. Their symmetrical form and the freshness of the lava flows about them date the eruptions as of relatively recent time.

FIGURE 8.—East Temple in Zion National Park. Bridge Mountain (right). Temple of the Sun (left). Sketch by W. H. Holmes, 1872.

As shown by the behavior of streams, by soil, and by vegetation, the climate of the region, particularly that of the areas below 7,000 feet, is semiarid. Deserts in the sense of large salt pans, alkali flats, and pavements of wind-worn stones are lacking, but areas of shifting sand dunes mark the heads of Cottonwood Canyon and Three Lakes Canyons and Short Creek, and sand is piled here and there at the bases of cliffs and canyon walls.

Talus so deep as to conceal the rocks lies against the cliffs at Springdale and elsewhere along the Virgin River. In much smaller amounts it appears at the heads of some gulches and at the bases of many cliffs. Likewise the jumbled material of landslides is prominent in Zion Canyon and is noticeable at a few other places. However, talus and landslide debris are not conspicuous regional features. Over many square miles of cliff faces, mesas, buttes, lava flows, craters, and terrace flats the bedrock seems naked.

Soil has been swept away by rain and wind, and vegetation is sparse and scattered. In place of the green and subdued tones due to plant covering are conspicuous reds, browns, yellows, and white—the colors of the rocks themselves.

As scenery, the topographic features of the Zion Canyon region are unexcelled by any other part of the Plateau province, and as illustrations of the work of erosion they are of exceptional interest to students of land forms.

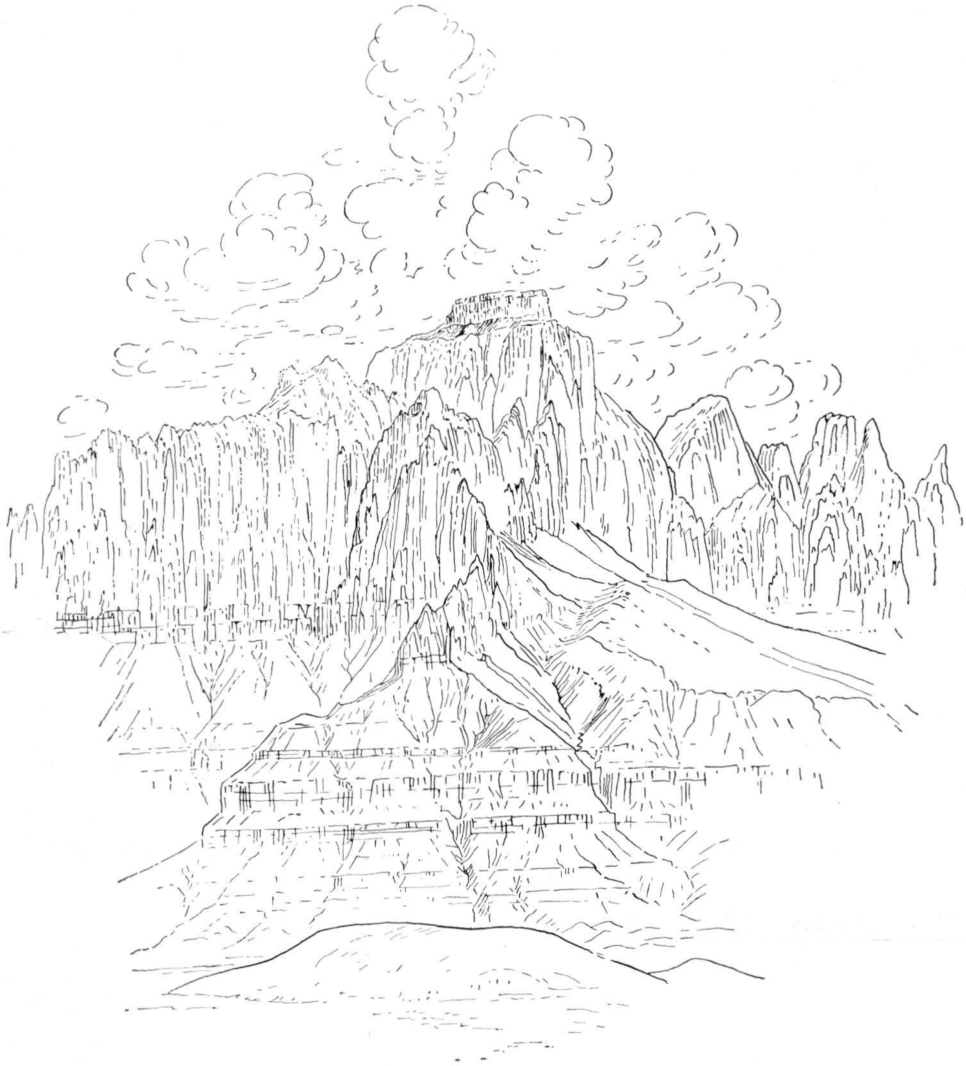


FIGURE 9.—West Temple in Zion National Park. Sketch by W. H. Holmes, 1872.

HISTORICAL SKETCH OF SOUTHWESTERN UTAH

MISSIONARIES AND TRADERS

The first white men in southwestern Utah and probably the first within the state were members of the Dominguez-Escalante expedition, so far as known the only one of the famous Spanish entradas of the period 1540–1800 to reach lands beyond the canyons of the Colorado. The general course of this pioneer traverse is recorded in the Diario by Escalante and on the map prepared by Miera.[1] Starting from Santa Fé, July 29, 1776, Escalante with his party of priests and soldiers entered Utah near Jenson, crossed the plateaus to "Timpanagos" (Utah Lake) and "Rio Santa Isabel" (lower Sevier River). On the flatlands near the mouth of "Lost River" (Beaver River), "the meadow of the gateway," he was deserted by his Indian guide and, realizing the risk of travel in a "veritable wilderness" and across mountains in winter time, he abandoned his plan of reaching Cali-

[1] Escalante, S. V. de, Diario, in Documentos para la historia de Mexico, ser. 2, vol. 1, p. 37. Of the many translations of this Spanish manuscript that by Dr. W. R. Harris in The Catholic Church in Utah, pp. 126–242, though geographically inaccurate, seems to preserve best the ecclesiastical flavor. The parts of this translation that refer to Utah are reproduced with comments by J. Cecil Alter (Father Escalante and the Utah Indians, Utah Hist. Quart., vol. 1, pp. 75–86, 106–113, 1928; vol. 2, pp. 18–25, 46–54, 1929). Bolton, H., Escalante in Dixie and the Arizona Strip, New Mexico Hist. Rev., vol. 3, no. 1, 1928; Gregory, H. E., Spanish entradas, in The Kaiparowits Region, U.S. Geol. Survey, Prof. Paper 164, pp. 5–6, 1931. The map of the route of the Dominquez-Escalante expedition drawn by Bernardo de Miera y Pachero in 1777 (?) is, so far as known, reproduced for the first time in the Utah Historical Quarterly, vol 9, 1941, where it is described and interpreted by J. Cecil Alter and Herbert S. Auerbach.

FIGURE 10.—Top of Markagunt Plateau back of Pink Cliffs. Parklike areas of well-watered meadowlands, chiefly grasses and annuals bordered by forests of aspen, spruce, and fir. Photograph by J. C. Anderson.

FIGURE 11.—White Cliffs in Johnson Valley; Navajo sandstone, 1.400 feet thick, capped by limestone of Carmel formation; cliffs continuous for about 40 miles. Alluvial terrace formed by trenching of valley fill.

fornia and redirected his course southward with the intention of crossing the "Rio Grande" (Colorado) to the Hopi villages he previously had visited. On this new route he descended "Rio Pillar" (Ash Creek) through "San Hugolino" (Toquerville) to "Rio de les Piramides Sulfurio" (Virgin River, near the La Verkin Hot Springs. From the crossing of the Virgin he continued southward along the base of Hurricane Cliffs to San Donulo and Arroyo del Tarai (Fort Pearce Wash), Ariz. Here for a second time his course was changed; the plan to reach the Pueblo villages by continuing southward was abandoned. The Parusis (Virgin River Indians) "told us . . . that we could not go by the way we had wished, because it had no watering places, nor would we be able to cross the river [Colorado], for the banks were very high, the river very deep, and the sides were rocky and dangerous." Reluctantly Escalante led his party eastward up the Hurricane Cliffs and across the Uinkaret Plateau (Este la Mesa y sin Agua), camping at "San Samuel" (Coopers Pockets?), Wild Band Pockets, and probably at Pipe Spring. Continuing on Piute trails past Fredonia, Navajo Wells, and House Rock Valley, he crossed the Paria River and, skirting the base of Kaiparowits Plateau, reached the Colorado at the Indian ford, since known as the "Crossing of the Fathers." From the crossing Navajo and Hopi trails were followed to Oraibi and on to Santa Fé. So far as known, the eight members of Escalante's party were the only white men to enter Glen Canyon before Powell's memorable traverse nearly a century later.

Though available descriptions of Spanish visits to the Utah tribes after the return of Escalante (1777) are few and indefinite, it seems reasonable to assume that the adventurous traders and priests of New Mexico did not neglect this promising field. It is known that Manuel Mestas, who "reduced the Utes to Peace," visited Utah Lake in 1805, that in 1813 Mauricis Arze and Lagos Gracia traded with the Indians at Timpanagos (Utah Lake) and San Sebro (Sevier) River, and there is plenty of evidence that during the first decades of the nineteenth century Mexicans from Santa Fé made frequent trips to Utah to purchase Piute children.

FIGURE 12.—Skutumpah Terrace. View southeast from Kanab-Parunuweap divide across Kanab Canyon. Top of White Cliffs (upper right). Piñon, juniper, sage, and oak.

The Utes have stories of white men on the Paunsaugunt Plateau following Arze and Garcia, and it may well be that stray hunters of furs and slaves, perhaps also prospectors, passed the rim of the High Plateaus, but no records of such travels are known, and the Piutes at Moccasin Springs have no traditions of them. It seems probable that after 1776 (Escalente) no white men visited the valleys of the Virgin, the Kanab, or the Paria until 1826, when the search for beaver pelts was extended to southern Utah.

To the fur traders northern Utah was familiar ground. Between 1820 and 1840 such traders as William Ashley, Peter Ogden, Etienne Provost (Provot, Provo), William Sublette, William Henry, and Jedediah Smith, in association with Indian guides and such veteran scouts as Jim Bridger and Kit Carson,

EXPLANATION OF FIGURE 13

Valley of Virgin River viewed from crest of Hurricane Cliffs (Kaibab limestone) near mouth of Gould Canyon; village of Hurricane on alluvial plain at west base of fault scarp. Volcanic cones (center); just beyond, sunk into the surface, are the canyon of Virgin River and its tributaries, Ash Creek, and La Verkin Creek. Pine Valley Mountain is in distance. Photograph by National Park Service.

had established "forts" and systems of land trails and water routes in Green River and Cache Valleys, the Uinta and the northern Wasatch Mountains, Salt Lake Valley, Utah Lake, and the lower Sevier River valleys. Fort Uintah (Uinty, Uwintey) (1832) and Fort David Crockett (Fort Misery) on the Green River in the present Daggett County were the first white settlements in Utah.

When the Rocky Mountain Fur Co., organized by Ashley and Henry in 1822, passed to the control of Smith, Jackson, and Sublette in 1826, plans were made to extend operations southward. In this search for new beaver country Jedediah Strong Smith was chosen leader. In 1827 he wrote[2]:

> I started about the 22d of August 1826 from the Great Salt Lake with a party of 15 men for the purpose of exploring the country S. W., which was entirely unknown to me and of which I could collect no satisfactory information from the Indians * * *

The general course of Smith's traverse is known—Great Salt Lake to the Colorado River at the mouth of the Virgin River, down the Colorado some distance, thence westward across the Mojave Desert, through Cajon Pass, and on to San Diego—but attempts to map the route in detail have yielded unconvincing and inconsistent results.[3]

[2] Letter to William Clark, Superintendent of Indian Affairs, dated July 12, 1827, quoted by Woodbury, A. M., Utah Hist. Quart., vol. 4, pp. 43–46, 1917.

In Smith's original account[4] the only places in Utah and Nevada that can be identified with confidence are Great Salt Lake, Little "Uta Lake" (Utah Lake), some part of "Ashley River" (Sevier River), "Adams River" (Virgin River), "Seeds Keeden River" (Colorado River), and the salt cave below the mouth of the Muddy River, Nev. The diary of Rogers,[5] a member of Smith's company, gives no more specific information. A recently discovered manuscript[6] permits charting a route in southern Utah from the Sevier River near Joseph through Clear Creek Valley to the site of Cove Fort, thence south past Beaver, Parowan, and Cedar City, down Ash Creek and the Virgin River.

[3] Bancroft, H. H., History of Utah, pp. 22–23, 1884–86. Cleland, R. G., History of California: The American period, 1922. Dale, H. C., The Ashley-Smith explorations, 1917. Farish, T. E., History of Arizona, 1915. Gallatin, A., Synopsis of Indian tribes, map, p. 265, 1836. Hanna, P. T., California's debt to Jedediah Strong Smith, Touring Topics (Los Angeles), September, 1926. Merriam, C. H., Earliest crossing of the deserts of Utah and Nevada to southern California; route of Jedediah S. Smith in 1826: California Hist. Soc. Quart., vol. 2, pp. 228–237, 1923. Chittenden, H. M., The American fur trade of the Far West, 1902. Woodbury, A. M., The route of Jedediah S. Smith in 1826 from the Great Salt Lake to the Colorado River: Utah Hist. Quart., vol. 4, pp. 35–46, 1931. Sullivan, Maurice, The travels of Jedediah Smith: A documentary outline including the journal of the great American pathfinder, Santa Ana, Calif., 1934.

[4] Letter to Gen. William Clark, Superintendent of Indian Affairs, dated Little Lake of Bear River, July 12, 1827; reproduced by Woodbury, A. M., The route of Jedediah S. Smith in 1826: Utah Hist. Quart., vol. 4, pp. 35–46, 1931.

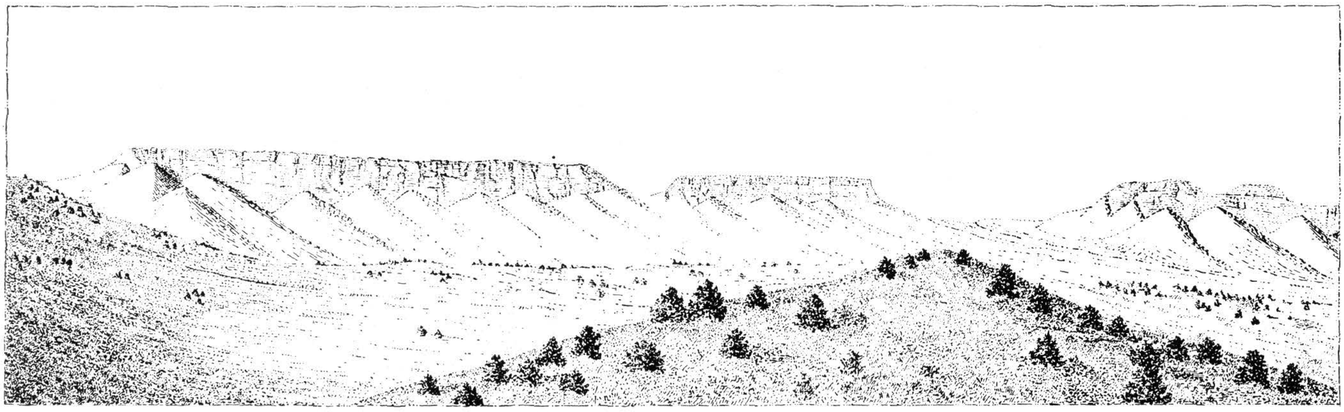
[5] Rogers, H. G., Journal, in Dale, H. C., The Ashley-Smith explorations, 1917.

[6] Sullivan, Maurice, The travels of Jedediah Smith, Santa Ana, Calif., 1934.

So far as known, Smith was the first American to explore Utah south of Lake Sevier and the first to write a description of any part of the State. Like his predecessor, Escalante, he seems to have mingled love of adventure and search for financial profit with missionary zeal. He is described as preaching to the Indians with a Bible in one hand and a rifle in the other and conducting Methodist service in camp. Doubtless his kindly treatment of the Utes and Piutes—he was the first white man whom most of them had seen—made easier the friendly understanding established by the eventual settlers of western and southern Utah. As an explorer his high rank rests on his discovery of a feasible southern route between Salt Lake and California.

A man of importance in the early history of Utah was William Wolfskill (1798–1866), a Kentucky-born trader and trapper of large experience. With a party of volunteer adventurers who had become "inflamed by the stories of Jedediah Smith," Wolfskill left Taos, New Mex., in September 1830 on his memorable trip to California. Through eastern Utah he marked out a new path, probably the route through Green River, Fruita, and Salina Canyon, now used as a Federal highway. From the Sevier River[7] southward trails previously known were followed, probably to the site of Parowan; thence a new route was chosen through Mountain Meadows, down the Santa Clara, and over the Beaver Dam Mountains to the lower Virgin River, where Jedediah Smith had previously been. From the mouth of the Muddy River to the Mojave River a new route (through present Las Vegas) was explored.

Wolfskill's name is closely associated with the history of the "Old Spanish Trail" from Salt Lake Valley to Los Angeles and San Diego, though, as Hill[8] points out, this trail was originally a route established during the development of trade between the Spaniards



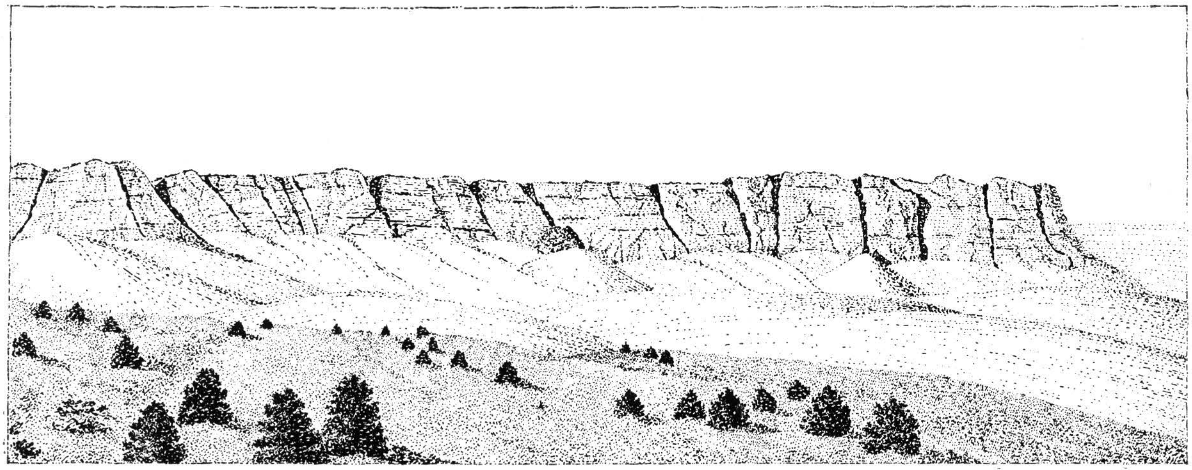


FIGURE 14.—White Cliffs, along the south face of Block Mesas. Sketches by Elinor Stromberg.

[7] In a manuscript history of Enterprise, Utah, Joseph Fish states that "it is claimed that when Wolfskill came to the Sevier River he gave it the present name in honor of Gen. John Sevier, of Kentucky, an early Indian fighter." The river, or parts of it, has thus been christened several times—Rio Santa Isabel by Escalante; San Sebro by Arze and Garcia; Rio Sebero by Spanish traders; Lost River by Bonneville (map); Ashley River by Smith; Sevier River by Wolfskill. To the Piutes the stream was known as Avapah, "big quiet water."

[8] Hill, J. J., Spanish and Mexican exploration and trade from New Mexico to the Great Basin: Utah Hist. Quart., vol. 3, pp. 3–23, 1930.

EXPLANATION OF FIGURE 15

Valley of Virgin River near abandoned settlement of Duncan. River in canyon (center), mesas south of river, Moenkopi shales capped by Shinarump conglomerates. Smithsonian Butte and South Mountain (Navajo sandstone) upper left. Cottonwood trees. Photograph by National Park Service.

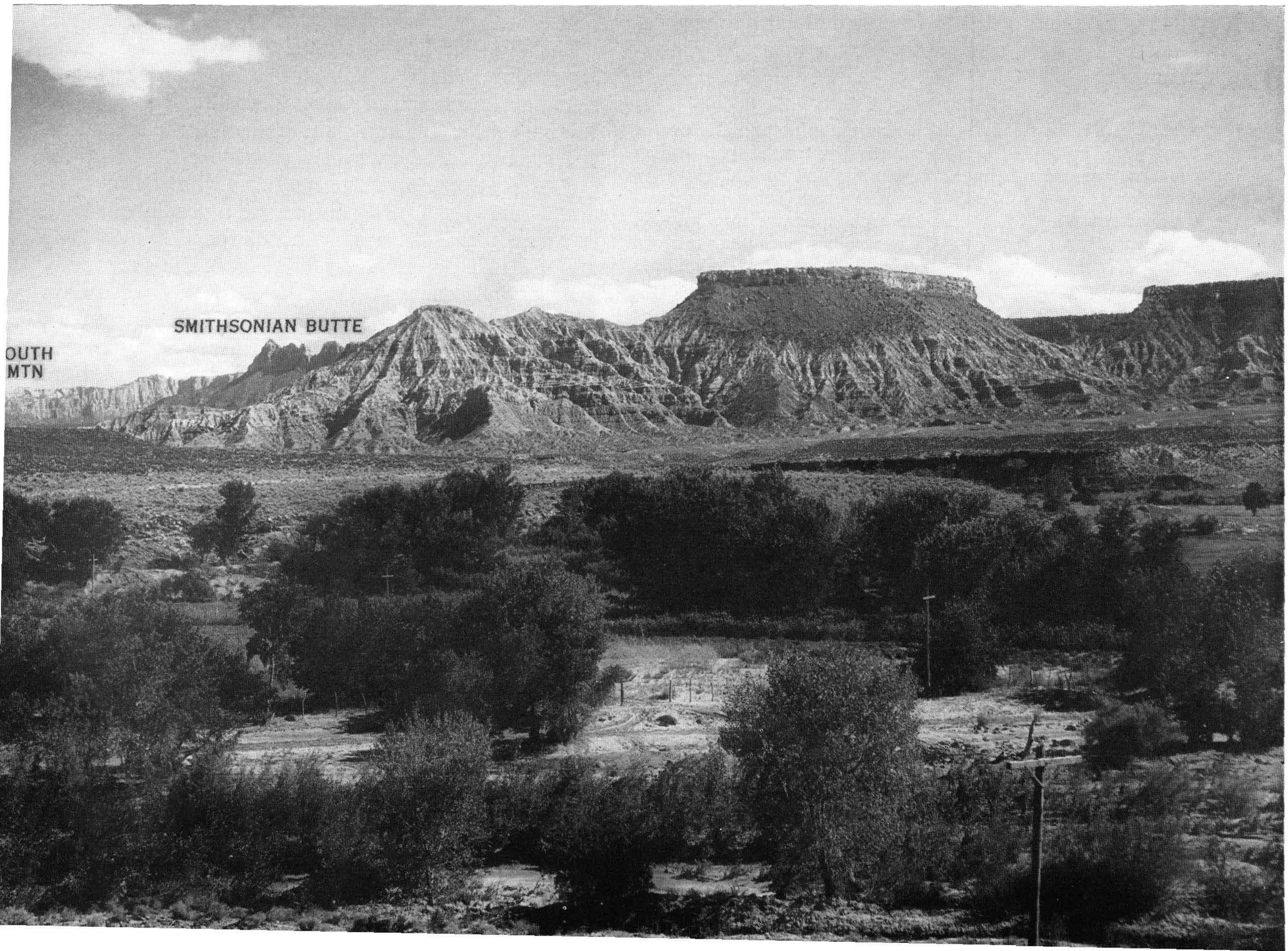
of New Mexico and the Indians of Colorado in the seventeenth and eighteenth centuries. The stretches of the trail in Colorado were extended into Utah by the Dominguez-Escalante expedition of 1776, which, though failing of its objective, outlined a feasible route to Salt Lake Valley and to southwestern Utah. This road between the southern Rocky Mountains and the Great Basin, with cut-offs and changes of alinement, seems to have been in frequent use until Santa Fé lost its position as a source of supplies for Utah and western Colorado. The trail was extended to California by Smith in 1826, but the route of this daring pioneer included long stretches of desert in Nevada and California and two crossings of the Colorado. It was circuitous and difficult, in places dangerous, and suitable only for small bodies of horsemen equipped for speed. It remained for Wolfskill to mark out a route along which forage and water were sufficient and where the ascents and descents, the fields of sand, and the barrancos and arroyos did not seriously impede the movement of large pack trains, and a small amount of road work would have permitted the passage of wagon caravans.

For 30 years the Old Spanish Trail was a main artery of trade between California and the Missouri River, and between the settlements on the Rio Grande and those later established in Colorado, Utah, and southeastern Nevada. Many California gold hunters passed this way. Because it was traveled frequently by the Mormons in their religious and commercial contacts with Nevada and California and extended through the site of the Mountain Meadows massacre, it is locally known as the "Old Mormon Trail." With an alternate route between Cedar City and the Santa Clara, the road first traversed by Wolfskill is substantially the present Arrowhead Highway from Provo to Los Angeles.

Yount,[9] a companion of Wolfskill, thus describes the Virgin River Valley in the winter of 1830–31:

> To their utter astonishment, they were ushered into another of those enchanting valleys * * * There the earth was bare of snow, and the evergreens waved in gentleness and calm serenity. The elk, deer, and antelope, driven from the mountains by the snow and piercing cold, were basking, with their frolicsome fawns, unaware and unintimidated by the sight of man. They would flock around like domestic sheep or goats, and would almost feed from the hand * * * Flocks of their young, of every age and size, would bound and glide gracefully from hillock to hillock and approach like lambs in the farmer's farmyard * * * There, at evening, our adventurers encamped in a perfect Elysium. Instead of the howling and tempestuous winds of the mountains, calm zephyrs

[9] Camp, C. L., The *chronicles of George C. Yount*: California Hist. Soc. Quart., vol. 2, no. 1, p. 40, April, 1923 (based on a manuscript by Rev. Orange Clark, 1851).



played around them * * * Our travelers lingered here, reluctant to again resume the toils of travel which lay before them.

SCIENTIFIC EXPLORATION

FRÉMONT EXPEDITION

The first scientific observations of the geography and geology of the plateau country were made by officers of the United States Army during the course of military surveys and the search for feasible railroad routes from the Missouri River to the Pacific. Recognizing the Colorado canyons as impassable barriers, most of the Army expeditions passed through central Arizona or northern Utah. Only General John C. Frémont[10] and Lt. George M. Wheeler conducted operations in southwestern Utah and in Arizona north of Grand Canyon.

On his second expedition to California Frémont[11] spent 2 months (August-September 1843) in northern Utah. His return route from San Diego followed substantially the "Old Spanish Trail" along the Virgin and Santa Clara Rivers and the base of the Wasatch to Timpanagos Lake, renamed by him Utah Lake. In passing over the Beaver Dam Mountains and up the Santa Clara River and Magotsu Wash to Las Vegas de Santa Clara (Mountain Meadows) in the present Washington County, Utah (May 10–16, 1844), Frémont noted the marked change in vegetation, topography, and geologic structure: the mountains

> here began to be wooded with cedar and pine and clusters of trees gave shelter to birds—a new and welcome sight—which could not have lived in the desert we had passed * * * The stream [Santa Clara] is prettily wooded with sweet cottonwood trees * * * a different species from any in Michaux's Sylva * * * the snowy mountains on our right [Pine Valley Mountains] showed out handsomely—high and rugged with precipices, and covered with snow for about two thousand feet from their summits down.

In crossing the low divide at the head of Mountain Meadows, Frémont realized that he had left the Colorado drainage system and entered a region of interior drainage, the southern edge of the great region that includes Sevier Lake, Salt Lake and innumerable salinas, playas, and rugged mountain masses between the Wasatch and the Sierra Nevadas. "We considered ourselves as crossing the rim of a basin." For this vast area he adopted the term "Great Basin," which has become fixed in geographic literature.

The widely distributed reports of Frémont's second expedition (1843–44) and also of his third (1845–47) aroused the interest of government officials, scientists, and laymen and had no small influence in the controversies that led to the war with Mexico. Favorable accounts of the natural resources of Utah and the possibility of their successful exploitation are known to have influenced the Mormons in their choice of a field for colonization.

In his journeys in Utah previous to 1850 Frémont followed few trails not previously traversed by trappers and Santa Fé traders but on his fifth expedition (1853–54), undertaken to locate "a central route" for a railroad to the Pacific, new country was traversed. The expedition crossed Green River near the mouth of the San Rafael, south of previously known crossings, and made its way along rough trails to an unknown river (Fremont River) and up the river through Rabbit Valley to the Awapa Plateau, south of Fish Lake. The route then led down Otter Creek (Grass Valley), down the East Fork of Sevier River, up the Sevier to Circle Valley, and westward across the Tushar Mountains to the Salt Lake-California road.

The brief account of this traverse by Frémont[12] supplemented by Carvalho,[13] artist to the expedition, and by Bigelow,[14] is a story of endurance and resource.

WHEELER SURVEY

The Wheeler Survey (officially the United States Geographic Surveys West of the One Hundredth Meridian in charge of Capt. Geo. M. Wheeler) was the most extensive and elaborate scientific investigation ever undertaken by the Engineer Corps of the United States Army. Though not organized on a regional scale until 1872, the Survey was in reality a continuation of the exploratory expeditions in 1869 and 1871. As described by Wheeler,[15] the survey authorized by Congress (June 10, 1872) "was a plan substantially for a complete, connected, continuous, detailed topographic survey (with associated natural-history observations) of the territory of the United States west of the 100th meridian, with primarily a resultant topographic map, scale 1 inch to 8 miles, to be in the main an aid to military administration and operations, to occupy about 15 years and to cost in all not exceeding $2,500,000."

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10 For a supplementary account of the expedition led by Frémont, Wheeler, and Powell see Gregory, H. E., Scientific explorations in southern Utah (manuscript report in files of U. S. Geol. Survey).

11 Frémont, Captain J. C., Report of the Exploring Expedition to the Rocky Mountains in the year 1842 and to Oregon and North Carolina in the years 1843–44. Printed by order of the Senate of the United States, Gales & Seaton, Printers, Washington, 1845.

12 Frémont, J. C., Some general results of a recent winter expedition across the Rocky Mountains for the survey of a route for a railroad to the Pacific: National Intelligencer, submitted to the editor June 13, 1854; published also as 33d Cong., 2d sess., H. Misc. Doc. 8, Dec. 27, 1854.

13 Carvalho, S. N., Incidents of travel and adventure in the Far West with Colonel Frémont's last expedition, 1857.

14 Bigelow, John, Memoir of the life and public services of John Charles Fremont, New York, 1856.

15 Wheeler, G. M., Preliminary report upon a reconnaissance through southern and southeastern Nevada [in 1869], Washington, 1875; Preliminary report concerning explorations and surveys, principally in Nevada and Nevada and Arizona [in 1871], Washington, 1872; Geographic Report: U. S. Geog. Surveys W. 100th Mer. Rept., vol. 1, p. 46, 1886.

This ambitious project for detailed mapping of 1,443,360 square miles was not completed, but before field work ended (1879) and the compilation of maps and reports was discontinued (1884) the Wheeler Survey had made an invaluable contribution. The 50 published sheets of the Wheeler topographic atlas cover 326,891 square miles and manuscript sheets an additional 32,174 square miles—areas that embrace 66 percent of New Mexico, 54 percent of Arizona, 32 percent of Colorado, 46 percent of Utah, 60 percent of Nevada, 41 percent of California, and considerable areas in Idaho and Oregon. The large illustrated volumes on geology, paleontology, zoology, botany, and archeology are introductions to fields of great interest, the 9 annual progress reports, 18 special reports, and the final report give information about mineral deposits, timber, arable lands, grazing areas, water supply, routes of travel, and native races that must have been welcomed by the host of immigrants who sought homes west of the Rockies during the decades 1870–1890. The reports and recommendations served also as guides in legislation.

In the Zion Park region studies were made by the Wheeler Survey in 1871 and 1872. In 1871 the lower Virgin River Valley was mapped. In 1872 the Survey staff of 25 scientists and engineers, 6 officers, 50 privates, 2 guides, and a score of packers, herders, and laborers mapped the region northward from the Grand Canyon well onto the High Plateaus and eastward from Nevada to the Crossing of the Fathers in Glen Canyon. During August, Wheeler made traverses of the Kolob Terrace, the Markagunt Plateaus, and the Parunuweap Valley. He writes:[16]

Usually volcanic material appears on the surface of the Colob plateau, with occasional limestone, sandstone, and shale. There is a fine growth of grass and groves of quaking aspen * * * The cooperative Mormon herd of Cedar grazed in this vicinity a distance of 9 miles from the settlement. [Southward] the ground still continues volcanic, with here and there points of sandstone, limestone, and shale, the latter profuse with marine shells * * * Skirting the rim of the plateau a break in the wall is finally found, and the train taken down into a box canyon along a descent having an angle of fully 55° at the head of Le Verken Creek.

The summit of the southern rim [of the Markagunt Plateau], at an altitude of over 10,000 feet, affords one of the finest panoramic views then witnessed (1872)—the Virgin River lying at our feet, the Colorado Canyon in the distance, plateaus, canyons, and mountains to the east, mountains high and frowning to the north, and the mountains and desert to the west and southwest, the ranges bordering the Colorado, especially the Virgin. Below us lay the brown and black bristling ridges of the eroded mesas that for grandeur of beauty and desolation of appearance far surpass all that words can express. Clambering along the cliff, and while securing a large haul of fossils, the crisp edge of coal crops was noticed, and prospecting which a 12-foot vein of dense bituminous coal, having both above and below a bed of shale 15 to 18 inches thick, was found, with petrified wood strewn in many directions. Fossils were found in sandstone * * *

[16] Wheeler, G. M., op. cit. (1886), Geological report, pp. 49–51.

For part of the route along the Parunuweap River a primitive wagon road was followed, but the canyon of the Parunuweap was found impassable for horses; the pack train was taken over the rough bare ledges along the south side of the river, where lack of water forced the party to descend the canyon wall.

Regardless of the roughness, and threading the way among rock and débris, the descent is begun, soon a narrow shelf of 10 to 12 inches wide is reached, overlooking a deep and dangerous gorge, leading to an abyss of darkness, which was passed after dusk. For a distance of 1½ to 2 miles the trail, or rather the want of a trail, followed the upturned strata edges, winding in and out of projecting ledges, which could only be skirted in the darkness on hands and knees. It was near 10 o'clock when the small party reached a little trickling stream that soon joins the main river, which was quickly followed after quenching our thirst, on a prospecting tour for the first settlement down the river, which proving to be a few houses (Schoonesburg, elevation 3,920.5 feet) was reached about 11 p.m., where terms were soon made with the presiding elder, who, besides promising immediately a cup of coffee, invited us to the soft side of a haystack for the night, and into a little vineyard near at hand, wherein the moon acted as a most fascinating guide in pointing out the plump, full-grown, well-ripe clusters of grapes, of the finest cultivated varieties, including the Tokay. Our coming created a sensation, as no party, except on foot, had ever been known to pass this route, unless it were an adventurous mail rider with a trusty led mule, in case of great emergency. Nothing short of considerable blasting could render the trail passable even for pack animals.

The situation of Schoonesburg is exceedingly romantic. Mesa-locked as it is by the huge, steep escarpment of the semiplateau forms at either hand, it lies ensconced in a little opening, a sparkling gem, dropped as it were through the mountains upon the desert. The elevation of the plateau or summit of the Wriggle Trail is approximately 2,100 feet above the valley of Virgin River, or approximately 6,020 feet above the sea.

A drawing of the "Wriggle Trail" at Shunesburg—reproduced in this report as figure 107—is the first known illustration of the great rock walls of Navajo sandstone that dominate the landscape of southwestern Utah.

The geologic work of the Wheeler Survey was done chiefly by G. K. Gilbert and Edwin E. Howell. Of his 3 years' service with the Wheeler Survey (1871-73), Gilbert spent the first in Nevada and western Arizona, the second in southwestern Utah and northwestern Arizona, and the third in New Mexico and eastern Arizona. His work in Utah (1872) included the plateaus and canyons of the Zion Park region. He spent some days on the summit rim of Markagunt Plateau, traversed for the first time the canyon of the Virgin River from its source in the Pink Cliffs below Navajo Lake to the mouth of Zion Canyon; followed the Vermilion Cliffs through Cane Beds, Pipe Spring, and Kanab and eastward to the Paria; made special studies of the stratigraphic effect of the Kaibab fold, of the Sevier fault at Mt. Carmel and Pipe Spring, and of the Hurricane fault at Toquerville. One of his few geographic descriptions applies to Zion Canyon:

> The North Fork [of the Virgin River] has opened a valley in the Cretaceous, but too narrow for cultivation. From the foot of this valley to the hamlet of Little Zion the stream traverses, in the most wonderful defile it has been my fortune to behold, the massive sandstones of the Gray and Vermilion Cliffs, here combined in a single undistinguishable body, certainly not less than 2,000 feet in depth. At the head of "The Narrows" the top of this bed is at the water's edge; and, as the strata rise and the stream descends southward, the height of the canyon walls gradually increases, until it includes the entire mass of sandstone [Navajo sandstone]. At the water's edge the walls are perpendicular, but in the deeper parts they open out toward the top. As we entered and found our outlook of sky contracted as we had never before seen it between canyon cliffs I measured the aperture above, and found it 35°. We had thought this a minimum, but soon discovered our error. Nearer and nearer the walls approached, and our strip of blue narrowed down to 20°, then 10°, and at last was even intercepted by the overhanging rocks. * * * For a number of miles the bottom of the cleft averages 30 feet in width, contracting frequently to 20, and in many places is entirely occupied by the stream, even at its low stage. [See fig. 102.]

Howell, who served 2 years with the Wheeler Survey (1872, 1873) and another (1874) with the Powell Survey, likewise "traversed portions of the Sierra region of western Utah and adjoining Nevada" and the lower Virgin Valley. His reconnaisance included geographic and geologic studies of central Utah, of the Aquarius and Paunsaugunt Plateaus and of the region about the head of the Paria River.

The work of the Wheeler Survey was done under conditions unfavorable for systematic or detailed studies. Thus Gilbert[17] writes:

> The observations which form the basis of these reports were hurried in the extreme * * * in a country almost unmapped the demand for geographical information was more urgent than that for geological, and all plans and routes were accordingly, and with propriety, shaped to give the topographer the best opportunities consistent with rapidity of movement, while the geologist gleaned what he could by the way. To study the structure of a region under such circumstances was to read a book while its pages were quickly turned by another, and the result was a larger collection of impressions than facts.

Despite these handicaps the geologic descriptions and interpretations and especially the colored geologic maps prepared for publication by Gilbert and Howell constitute material of permanent value. Most of the conclusions have stood the test of later investigations.

POWELL SURVEY

The Spaniards in their search for converts and trade and the Americans in their search for beaver hides became acquainted with the Green River and its tributaries but gave a wide berth to the "inaccessible and worthless country" below the mouth of the Price River. Likewise the military expeditions in search for routes for transcontinental railways avoided the Green and Colorado Rivers below Gunnison Crossing (village of Green River, Utah). They doubtless recalled the remark of Captain Macomb[18] (1859) on the country at the mouth of Indian Creek, "I cannot conceive of a more worthless and impracticable region," and Lieutenant Ives' comment[19] (1857), "It seems intended by nature that the Colorado River, along the greater part of its lonely and majestic way, shall be forever unvisited and undisturbed." The Army engineers met fewer obstacles in constructing roads through mountain ranges than in crossing the relatively flat but intricately dissected plateaus bordering the Colorado canyons. It remained for Maj. J. W. Powell to explode the myths of "sucking whirlpools," "underground passages," and "plunging, roaring waterfalls" in the mysterious river by safely navigating its canyons to their mouth.

Powell first came to the plateau country in 1867 as a free-lance collector of museum specimens in northwestern Colorado and adjoining parts of Utah. He quickly became fascinated with this little-explored region of canyons and brightly colored rocks and was eager to visit the even less known lands farther south. During his second field season (1868), while collecting along the Green River canyons, his nebulous wishes seem to have taken definite form in the audacious plan of descending the Green-Colorado by boat. The opportunity came the next year. Thus began the series of expeditions that made known not only the Colorado River but also the High Plateaus, which make of southern Utah a region of scenic grandeur.

Though done under various auspices the geographic, geologic, and ethnologic work under the direction of Powell during the decade 1869–79 and appropriately termed the "Powell Survey," had a continuity of purpose and program. In the words of Powell:[20] "Begun originally as an exploration the work has finally developed into a survey embracing the geography, geology, ethnography, and natural history of the country * * *."

The first traverse of the Colorado River by Powell (1869) was essentially the adventurous task of propelling boats, procuring supplies, and following a stream whose channel and bordering lands were unknown. It ranks high among feats of daring exploration. Gilbert[21] remarks:

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[17] Gilbert, G. K., U.S. Geog. Surveys W. 100th Mer. Rept., vol. 3, "Prefatory note" in copies personally distributed by Mr. Gilbert, 1876.

[18] Macomb, J. N., Report of the exploring expedition from Santa Fé, N. Mex. to the juncture of the Grand and Green Rivers [in 1859], U. S. Army Engineer Dept., 1876.

[19] Ives, J. C., Report upon the Colorado River of the West: 36th Cong., 1st sess., H. Ex. Doc. 90, 1861.

[20] Powell, J. W., Exploration of the Colorado River of the West, preface, 1873.

[21] Gilbert, G. K., John Wesley Powell (1834–1902): Smithsonian Inst. Ann. Rept. for 1902, p. 634, 1903.

The undertaking was * * * of phenomenal boldness and its successful accomplishment a dramatic triumph. It produced a strong impression on the public mind and gave Powell a national reputation, which was afterward of great service, although based on an adventurous episode by no means essential to his career as an investigator.

Naturally the scientific results of this pioneer traverse were meager. The difficulties of navigation through 539 miles of canyon at the rate of 23 miles a day left little time for scientific observations beyond the recording of approximate distances and directions. To those of us who knew Powell, it is not surprising to find him "not satisfied with the results obtained" and "determined to continue the explorations of the canyon of the Colorado * * * to once more attempt to pass through the canyon in boats, devoting 2 or 3 years to the trip."

In preparation for this proposed second voyage, Powell returned to Utah in 1870 and selected places where supplies might be brought to the river by pack train. (See footnote 46, p. 25.) In September, with a party of Mormons en route from Parowan to the Paria River and Kanab, he visited the Indians on the Uinkaret and Shivwits Plateaus to investigate the death of three members of his expedition of 1869 who had left the river party near Toroweap Canyon. His return trip was made through Pipe Spring and Kanab and eastward to Fort Defiance, Ariz., by way of the Lees Ferry-Echo Cliffs-Tuba route explored the preceding year by Hamblin. Partly because of his strong interest in native races and partly, no doubt, to explain the peaceful purpose of scientific expeditions, Powell spent some time with the Hopis at Moenkopi and Tusayan, and with the Navajos at Fort Defiance. (See p. 26.)

While visiting the Uinkarets, Powell took occasion to descend the old trail from the Toroweap (Tuweap) Valley to the Colorado and to examine the most prominent peaks of the Uinkaret volcanic fields. Two of these he named Mount Trumbull and Mount Logan (for senators from his home State, Illinois) and a third Mount Emma (for Emma Dean, Powell's wife). On the Toroweap road south of Pipe Spring, Powell first noted the gloriously banded wall along the south face of Moccasin Terrace.

Starting, we leave behind a long line of cliffs, many hundred feet high, composed of orange and vermilion sandstones. I have named them "Vermilion Cliffs." When we are out a few miles, I look back and see the morning sun shining in splendor on their painted faces; the salient angles are on fire, and the retreating angles are buried in shade, and I gaze on them until my vision dreams, and the cliffs appear a long bank of purple clouds, piled from the horizon high into the heavens.

In 1871, on the second traverse of the Green and the Colorado, Powell was in charge of the boat party as far as the Crossing of the Fathers (May 22–October 10). Here he left the river and returned to Washington by way of Paria, Kanab, and Salt Lake City.

Powell's most active season in southern Utah was that of 1872, when he directed the river party on its cruise from Lees Ferry to the mouth of the Kanab (August 17–September 7) and made traverses of Kanab and Virgin Valleys and of the Vermilion Cliffs from Smithsonion Butte eastward through Short Creek, Pipe Spring, and Kanab. From a camp in a "beautiful meadow at the head of the Kanab" he ascended the wall of the Pink Cliffs of Paunsaugunt Plateau and explored the broken country "where the Rio Virgin and the Sevier rivers are dovetailed together." From here his route led south and west, presumably along the road down Long Valley.

Below Mount Carmel, Powell and his companions, S. V. Jones and Joseph W. Young, followed the Parunuweap to the Mormon settlement of Shunesburg. This traverse of the formidable Parunuweap Canyon, one of the few that ever have been made, he describes in detail:[22]

After spending a night at the Shunesburg ranch, Powell and his companions followed the Virgin River northward into the present Zion Canyon.

The Indians call the canyon through which it runs "Mukoon'-tu-weap" or Straight Canyon. Entering this, we have to wade upstream; often the water fills the entire channel, and although we travel many miles, we find no flood plain, talus, or broken piles of rock at the foot of the cliff. The walls have smooth, plain faces and are everywhere very regular and vertical for a thousand feet or more, where they seem to break back in shelving slopes to higher altitudes; and everywhere as we go along we find springs bursting out at the foot of the walls, and, passing these, the river above becomes steadily smaller; the great body of water, which runs below, bursts out from beneath this great bed of red sandstone; as we go up the canyon, it comes to be but a creek, and then a brook. On the western wall of the canyon stand some buttes, towers, and high pinnacled rocks. Going up the canyon, we gain glimpses of them, here and there * * * These tower rocks are known as the Temples of the Virgin.[23]

Powell's account of his explorations (1869–72)[24] is surprisingly brief, especially as regards the geography of southern Utah. Of its 203 pages, only 13 are descriptive of overland trips, and of the space allotted to the river traverses, about half is given to the Green River Valley. Fortunately Powell's meager account is supplemented by his associates, Almon H. Thompson,[25] Frederick C. Dellenbaugh,[26] and Stephen V. Jones,[27] who were members of river and land parties during 1871 and 1872. Their day-by-day account is further supplemented by records of the Mormon

[22] Powell, J. W., Exploration of the Colorado River of the West, pp. 109–110, 1873.

[23] Powell, J. W., op. cit., p. 111.

[24] Powell, J. W., Exploration of the Colorado River of the west and its tributaries explored in 1869, 1870, 1871, and 1872 under the direction of the secretary of the Smithsonian Institution, Washington, Government Printing Office, 1875.

[25] Thompson, A. H., Diary * * * with introduction and notes by Herbert E. Gregory, Utah Hist. Soc. Quart., vol. 7, nos. 1, 2, 3, 1939.

[26] Dellenbaugh, F. S., A canyon voyage, Yale Univ. Press, 1926.

[27] Jones, S. V., Diary, April 21 to July 25, 1871; August 1 to December 14, 1872; manuscript in the library of the U. S. Geol. Survey.

church and by diaries of farmers and stockmen from whom the explorers obtained supplies and information.

In comparing the available documents some inconsistencies appear. For example, the boat trips down the Colorado River are described by Powell as of 1869; no mention is made of a second traverse (1871-1872) during which nearly all the scientific records were made. Likewise the traverse of the Parunuweap Canyon is dated by Powell as September 10-11, 1870; by Dellenbaugh as September, 1872; and by Jones, who accompanied Powell, as September 10-11, 1872. The chronology of Powell's itinerary is further confused by certain of Little's[28] statements, which are out of accord with those of Thompson, Dellenbaugh, and Jones and with the records of the Mormon Church.

The geographic maps of the Powell surveys are the work of A. H. Thompson and his associates, particularly F. S. Dellenbaugh, W. H. Graves, J. H. Renshawe, and J. K. Hillers. After mapping the Green and the Colorado to the mouth of the Paria (May 22-October 26, 1871), Thompson established field headquarters at Kanab and during the next 6 years completed a topographic survey of Arizona north of the Grand Canyon and of southern and north-central Utah. This reconnaissance map, issued in sections, is the first made for a considerable part of Utah and is still in use. It is the base on which are recorded the geologic observations of Powell, Dutton, Howell, Gilbert, and later students of Utah geology, botany, and zoology. In making this map Thompson must have become familiar not only with the topographic relief but also with the areal extent of lava flows and stratigraphic units and with suitable camp sites and sources of supply. The geologists of the Survey drew heavily on this fund of information and acknowledge their debt in highly commendatory terms. Of particular value was Thompson's pioneer traverse of a route from Kanab to the mouth of Trachyte Creek (May 29 to July 7, 1872), which resulted in differentiating the drainage of the Paria, the Escalante, and the Frémont Rivers and sketching the features of the Aquarius Plateau, the Waterpocket fold, and the Henry Mountains.

During the first 4 years (1869-73) of the Powell Survey geologic investigation was almost incidental. Except in the Uinta Mountains Powell himself gave little attention to geologic details. His outstanding contribution to geologic knowledge was his epochal analysis of the processes and results of land sculpture, gained from a regional reconnaissance. His reports are rich in generalizations. Geologic work in southern Utah assumed prominence with the appointment of Howell in 1874 and that of Gilbert and Dutton in 1875.

[28] Little, J. C., Jacob Hamblin; Deseret News, Salt Lake City, 1909.

Dutton,[29] who became a member of the Powell Survey in 1875, gave chief attention during three field seasons to the structure and igneous history of the High Plateaus, which he considered "about as difficult an undertaking as ever falls to the lot of a geologist." Fortunately he had available the topographic base map of Thompson, the copious notes and geological sections of Howell (1874), and many valuable suggestions from Gilbert.

Dutton outlined the "District of the High Plateaus of Utah" and recognized that "The plateaus are not a part either structurally or topographically of the Wasatch, but belong to another age and are totally different in their forms and geological relations. The extension of the name 'Wasatch Mountains' south of [Mount] Nebo is a misnomer."[30] In Dutton's terminology the High Plateaus, outlined by faults, canyons, or lines of Cliffs, comprise three ranges—a western range that comprises the Pahvant, Tushar, and Markagunt Plateaus; a middle range, the Sevier and the Paunsaugunt; and an eastern range, the Wasatch, Fish Lake, Awapa, and Aquarius Plateaus.

Because of his primary interest in igneous rocks, Dutton centered his field work in the High Plateaus, where lavas and agglomerates are widespread and their history complex. For the Zion Park region he accepted the work of Gilbert and especially of Howell, to whom he ascribes the authorship of that part of his geologic map south of the Markagunt and Paunsaugunt Plateaus. However the belt between the rim of the High Plateaus and the Colorado canyons was not entirely neglected. Dutton states:

> When the early snows and biting winds of autumn drove us out of the lofty volcanic regions of the north, the remaining weeks of each year were spent in rapid excursions through the milder regions which lie beyond the foot of the great stairway of terraces which leads down from the heights of the Markagunt.

Seemingly these preliminary traverses of the Kanab and Paria Valleys and of the Uinkaret and Kanab Plateaus led Dutton to believe that except for the volcanic rocks, the "District of the High Plateau" and the "Grand Canyon District" have a common geologic history. As a result of later field work[31] (1880) this preliminary view became a fixed idea as applied not only to the regions studied but to the whole Colorado Plateaus province. It is doubtless for this reason that the maps, descriptions, and conclusions in the two reports by Dutton so freely overlap. The report on the High Plateaus stresses volcanism and structure, the Grand Canyon report is chiefly devoted to a description of the methods and results of erosion

[29] Dutton, C. E., Report on the geology of the High Plateau of Utah with atlas, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1880.

[30] Dutton, C. E., op. cit., p. 2

[31] Dutton, C. E., Tertiary history of the Grand Canyon district, with atlas: U. S. Geol. Survey Mon. 2, 1882.

upon a grand scale, but both deal briefly with other geologic processes. For the Zion Park region, the Grand Canyon report rather than that on the High Plateaus is of direct importance. It deals more fully with the Hurricane and Sevier faults, the Vermilion Cliffs, the Virgin River canyons, and the great beds of colored sandstone; in fact, the vivid text by Dutton and the incomparable drawings by W. H. Holmes were from the date of their publication accepted as descriptive of a region of marvelous landscapes, in which may be read with exceptional ease the story of geologic time.

Supplementing the work of Dutton, Walcott[32] measured sections in Kanab Valley, examined the Kaibab structure near the village of Paria, and gave particular attention to the fossiliferous beds a few miles south of Fredonia, Ariz. For the upper Kanab Valley Walcott's manuscript notes and unidentified fossils, supplemented by other material, were studied by Stanton.[33]

The Powell Survey marks an epoch in the history of geology in America. It established some new geologic principles, revised old ones, and provided unique illustrations of processes, structure, and topographic forms. Modifications of the conclusions reached as the result of more recent studies relate chiefly to the date and repetition of faulting and to the source and mode of deposition of the Triassic, Jurassic, and Tertiary strata. Partly because of revised terminology but largely because of more detailed areal surveys, the geologic map in the present report differs considerably from those compiled by Dutton.

Unfortunately the Wheeler Survey (War Department, 1869–79) and the Powell Surveys (Smithsonian Institution, 1869–1872; Department of the Interior, 1874–79) were not areally distinct. The geographic and geologic work covered the same areas, and the generalized reports were issued the same year (1875). Along the Grand Canyon and northward into central Utah the overlapping was complete. In 1872 topographic parties of the two surveys were at work along the Virgin River, in Kanab Valley, on the Uinkaret Plateau, and eastward to the Paria, and geologists of both surveys were making parallel traverses and studying some of the same outcrops. As a result the topography of southern Utah is represented on hachure maps by Lts. R. L. Hoxie, W. L. Marshall, W. A. Dinwiddie, and Wallace Mott, and five civilian engineers of the Wheeler Survey and on much less detailed contour maps by A. H. Thompson, F. S. Dellenbaugh, S. V. Jones, and J. H. Renshawe of the Powell Survey. Likewise the geologic maps issued in 1874 by Gilbert and Howell, of the Wheeler Survey, are duplicated by those of Dutton, issued by the Powell Survey in 1879. On these reconnaissance maps the main stratigraphic units are shown, though with considerable difference in areal extent, but the position in the time scale assigned to strata shows such little significant difference as to suggest consultation while the maps were being prepared in Washington, D. C. Interchange of field data and interpretation between Powell and Gilbert in Salt Lake City is on record, and the intimate relation between these two comrades in science is well known.

In 1879 the Wheeler and Powell Surveys, also the related King Survey (War Department) and the Hayden Survey (Department of the Interior), were replaced by the Geological Survey under the directorship first of King (1879) and then of Powell (1880–94). Appropriately enough the first published monograph of the newly organized Geological Survey was Gilbert's report on Lake Bonneville, a continuation of studies by the Wheeler Survey; the second, Dutton's report on the Grand Canyon, an outgrowth of the Powell Survey; and the third, G. F. Becker's report on the Comstock Lode, the first important product of the King Survey.

MORE RECENT SURVEYS

The maps and memoirs of the Wheeler and Powell surveys constituted the essential literature on the canyons and plateaus of southwestern Utah until the publication by Davis[34] of the results of a reconnaissance in 1900 by a party consisting of Tempest Anderson, R. L. Barrett, William M. Davis, and Herbert E. Gregory, who, under the leadership of Richard E. Dodge made a pack-train traverse across the Colorado at Lees Ferry, over the Kaibab Plateau to Fredonia, Pipe Spring, the Uinkaret Mountains, the Hurricane Cliffs, Toquerville, Cedar City, and on to the railroad at Milford. In 1902 this reconnaissance was supplemented by Davis and a group of geological students, who crossed the High Plateaus and the Uinkaret Plateau and spent some days in the Kanab and Virgin River Valleys. Two members of the Davis party of 1902, Huntington and Goldthwait,[35] spent 3 weeks in a general survey of the Hurricane fault.

Though no regional reports nor geologic maps of the Zion Park region have been made since the publication of Dutton's monograph on the Grand Canyon (1882), several papers on special subjects have been

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32 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; Study of a line of displacement in the Grand Canyon of the Colorado in northern Arizona: Geol. Soc. American Bull., vol. 1, pp. 63–64, 1890.

33 Stanton, T. W., The Colorado formation and its invertebrate fauna: U. S. Geol. Survey Bull. 106, pp. 34–35, 1893.

34 Davis, W. M., An excursion to the Grand Canyon of the Colorado; Harvard Coll. Mus. Comp. Zoology, Geol. ser., vol. 5, no. 4, pp. 107–198, 1901.
Anderson, Tempest, the Grand Canyon of the Colorado River: Alpine Jour., vol. 20, pp. 360–368, 1901. Dodge, R. E., Life on the Colorado Plateaus; Jour. School Geography, vol. 4, pp. 45–51, 1900. Gregory, H. E., North of Grand Canyon (unpublished address, Yale Univ. Geol. Club, 1901).

35 Huntington, Ellsworth, and Goldthwait, J. W., The Hurricane fault in the Toquerville district, Utah: Harvard Coll. Mus. Comp. Zoology Bull., vol. 42, 1904; The Hurricane fault in southwestern Utah; Jour. Geology, vol. 11, pp. 46–63, 1905.

issued,[36] also compilations that include southwestern Utah.[37] The scenery of the region has been described by Dellenbaugh[38] and by Lee.[39] This pioneer exploration, which led to the founding of settlements in Virgin, Kanab, and Johnson Valleys, is a fascinating story as yet incompletely told.[40]

MORMON EXPLORATION AND SETTLEMENT

By the middle of the nineteenth century northern Utah was fairly well known. Salt Lake was found by James Bridger in 1826, and during the decades 1830–50 the Green River, the Uinta Mountains, and the valleys of the Wasatch Mountains were explored by trappers and prospectors, trading posts and military stations were established, and the Old Spanish Trail, the northern route from Santa Fé to California, became a much-used highway. For parts of this region maps and geographic descriptions had been prepared by Bonneville (1832–33), Frémont (1843, 1845), Stansbury (1849–50), Gunnison (1853), and others.

Likewise for regions south of the Grand Canyon of the Colorado information had been recorded by Diaz (1540), Gardenas (1540), Onate (1604), Garces (1775), Fout (1777), and other Spanish priests and adventurers while traveling back and forth between Santa Fé and southern California in search of adequate sites for missions, and this knowledge had been greatly increased by the military and geographic explorations of Emory (1847), Derby (1850), Sitgreaves (1851–52), the United States and Mexican Boundary Commission (1849–55), Whipple (1854), Parke (1855), and Ives (1857–58).

In contrast the geographic knowledge of southern Utah, of the High Plateaus, and of the adjoining "Arizona Strip" came late: the region was practically unknown in 1850. The Mormon pioneers who extended their settlements southward along the base of the plateaus and into the valleys tributary to the Colorado were unacquainted with the journeys of Escalante, Smith, and Wolfskill, and had nothing to guide them except the little knowledge gleaned from the Piutes, old-time trappers, and prospectors. They had no usable information regarding soil, forage, timber, predatory animals, noxious plants, kind of winters, rainfall, length of growing season, or the size and regularity of streams available for irrigation. When the first settlements were established (1851), the southwestern region was an undefined part of that vast "California" recently taken from Mexico. It lay within the "State of Deseret," the predecessor of the Territory of Utah that, until 1861, included not only Utah but also Nevada, most of Arizona, southern California, half of Colorado, and parts of New Mexico, Wyoming, Idaho, and Oregon.

Systematic exploration of southern Utah resulted from the policy of the Mormon Church to occupy strategic points in Deseret before the tide of general immigration reached lands west of the Rocky Mountains. The Church leaders planned an independent state with a distinctive religious control and social organization, sufficiently isolated and sufficiently strong to withstand persecution by its neighbors. They recognized that the building of such an economically independent community involved the possession of arable lands on which grain, vegetables, fruit, and cotton could be raised, of grasslands for stock raising, and forests that could provide lumber and fuel. Obviously the first step was to obtain general information regarding natural resources and specific information for areas suitable for agriculture.

Beginning in 1849, only 2 years after the Mormons had reached Utah, a party led by Parley P. Pratt[41] systematically explored the west base of the Wasatch and the High Plateaus from Utah Lake to the "Little Muddy" (Coal Creek) and sent scouts into the valley of Ash Creek and Santa Clara Valley. Encouraged by Pratt's optimistic report, a party of 118 men, 30 of them with families, were sent to southwest Utah (1850–51) prepared to stay. A result of this expedition was the settlement in 1851 of Parowan on Center Creek and Cedar City on Coal Creek.

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36 Richardson, G. B., The Harmony, Colob, and Kanab coal fields, Utah: U. S. Geol. Survey Bull. 341, pp. 379–400, 1909; The Upper Cretaceous section in the Colob Plateau, southwest Utah: Washington Acad. Sci. Jour., vol. 7, pp. 464–475, 1927. Shimer, H. W., Permo-Triassic of northwestern Arizona: Geol. Soc. America Bull., vol. 30, pp. 471–494, 1919. Reeside, J. B., Jr., and Bassler, Harvey, Stratigraphic sections in southwestern Utah and northwestern Arizona: U. S. Geol. Survey Prof. Paper 129, pp. 53–73, 1922. Bassler, Harvey, and Reeside, J. B., Jr., Oil prospects in Washington Co., Utah: U. S. Geol. Survey Bull. 726, pp. 85–107, 1921. Gregory, H. E., and Noble, L. F., Notes on a geological traverse from Mohave, Calif. to the mouth of the San Juan: Am. Jour. Sci., 5th ser., vol. 5, pp. 229–238, 1923. Gregory, H. E., Zion and Bryce Canyon National Parks, Nat. Park Service, 1935. Gregory, H. E., and Evans, R. T., Zion National Park (on back of topographic map), 1936. Gregory, H. E., Geology of Zion National Park, Nat. Park Service, 1938.

37 Butler, B. S., and Loughlin, G. F., Heikes, V. C., and others, Ore deposits of Utah: U. S. Geol. Survey Prof. Paper 111, 1920. Gregory, H. E., The Colorado Plateau region: 16th Internat. Geol. Cong. Guidebook 18, 1932. Baker, A. A., Dane, C. H., and Reeside, J. B., Jr., Correlation of the Jurassic formations of parts of Utah, Arizona, New Mexico, and Colorado: U. S. Geol. Survey Prof. Paper 183, 1936.

38 Dellenbaugh, F. S., New Valley of Wonders: Scribner's Mag., vol. 35, pp. 13–14, 1904.

39 Lee, W. T., The Zion Canyon and Painted Cliffs of Zion National Monument and the story of their origin (unpublished manuscript, Nat. Park Service, 1918).

40 Among general histories that deal in part with southwestern Utah and adjacent parts of Arizona are Young, L. E., The founding of Utah, Charles Scribnèr & Son, 1924; Alter, J. C., History of Utah, Chicago and New York, 1932; Warrum, Noble, History of Utah since Statehood, Chicago and Salt Lake, S. J. Clark Publishing Co., 1919; Young, Brigham, Journal and discourses; Skidmore, C. H., and others, Utah, its resources and activities, Salt Lake City Dept. Public Instruction, 1933. Publications and manuscripts of particular reference to the Zion Park region include Little, J. A., Jacob Hamblin, Deseret News, 1909; The diary of Alvin H. Thompson, Utah State Hist. Soc., 1939; Diary of Stephen V. Jones (assistant topographer, Powell Survey), 1872, manuscript; Dellenbaugh, F. D., A canyon voyage, Yale Univ. Press, 1926; McClintoch, James, Mormon settlements in Arizona, Phoenix, Ariz. Manufacturing Stationers, Inc., 1921; and Woodbury, A. M., Colonization of southwestern Utah (manuscript). Articles by W. R. Palmer relating chiefly to the Piutes have appeared in the Utah Historical Quarterly for April 1928, April 1929, and April, 1933. The unpublished history of the Church of Latter Day Saints—a comprehensive record, based on annual, at times monthly, reports of the various stakes and missions—is rich in pertinent details.

41 Pratt, P. P., Report of the southern exploring expedition, dated January 31, 1851 (manuscript on file, Office of the Historian, Church of Latter Day Saints).

In 1852, lands south and east of these outpost villages were investigated in detail. Early in that year a party of 12 men, led by the geographically minded John D. Lee, explored Ash Creek Valley and the country to southwest through the present Leeds, Washington, St. George, and Santa Clara—a region of "rich soil and abundant streams of pure water * * * where we can raise cotton, flax, hemp, grapes, figs, sweetpotatoes, fruits of almost every kind * * *." In June, Lee, in company with others, starting from Parowan, visited Panguitch Lake (Piute, "big fish lake"), the headwaters of the Sevier, traversed Long Valley (Parunuweap Valley), made their way over the plateau between Mount Carmel and "Virgin Bottoms" (Cane Beds, Ariz.), and thence westward along Vermilion Cliffs to their former "camp at the jerks [junction] of the Virgin, Levier Skin [La Verkin] and Ash Creek."[42] Lee[43] remarks: "I have been gathering all the information that I could from the Spaniards * * * and have taken a map from them."

Frémont[44] reports that in 1854 the knowledge of southwest Utah possessed by the Mormon pioneers was so complete as to make unnecessary his proposed investigations of the region about Pine Valley Mountains, Beaver Dam Mountains, and Hurricane Cliffs, permitting him to select an alternate exploring route to California—from Cedar City west across Nevada.

Scouting in regions south of Fort Harmony (New Harmony, founded in 1852 on Ash Creek) showed Santa Clara Valley the most promising field for missionary "labor among the Indians"—a prominent feature of the Mormon Church program. The Santa Clara Mission was organized in 1854 and a vanguard of some 50 families began the construction of irrigation dams and ditches and erected a lumber mill at Pine Valley in 1855. With accretions of new immigrants Santa Clara grew in strength and influence and became the "granary of the south" and the center from which expeditions were dispatched to found other Indian missions and to search for promising agricultural and grazing lands in neighboring regions.

While the farmers and ranchers were forming settlements along the Santa Clara River, others occupied favorable sites on lower Ash Creek at Toquerville (1858) and in the Virgin River Valley at Virgin, Grafton, and Adventure (Rockville) (1859). All these early settlements were small. There was much regrouping and relocation of families. In 1860 the population of the present Iron, Washington, and Kane Counties was reported as 1701 persons, distributed in groups on irrigated lands along the rivers and at springs on adjoining "herd grounds."

Large-scale permanent settlement in southwest Utah dates from the founding of St. George in 1861–62. The primary motive back of this colonizing scheme seems to have been the belief that the cotton industry of the Southern States would be disrupted or even ruined by the Civil War and that Utah's "Dixie" might become the source of cotton for the western United States, perhaps even for the whole nation. All the power and influence of the Mormon Church were back of the project. Brigham Young impressed upon those chosen as settlers "that God expected them to go into that region and conquer it and make it blossom as a rose." He prophesied that "there will yet be built between those volcanic ridges a city with spires, towers and steeples, with homes containing many inhabitants." The "call" was issued to 309 Utah families in addition to 26 families newly arrived from Switzerland—in all, perhaps 1,500 men, women, and children. The men were carefully selected to include only those possessing energy, skill, endurance, and "unfaltering faith in the leadership of the Church." They included farmers, stockmen, masons, carpenters, weavers, blacksmiths, painters, shoemakers, and millwrights. Though the hope of developing a "cotton-raising empire" was frustrated by unfavorable soil, climate, and economic conditions, St. George and the other villages in "Dixie" have grown in size and influence. The population of the present Washington County has increased from 691 in 1860 to 3064 in 1870 and 9269 in 1940.

After the founding of villages in the lower Virgin Valley, the exploration of southern Utah was extended eastward and southward. In 1866 Captain Andrus[45] located favorable sites for irrigation farming on the Paria River and in Escalante Valley, and in 1867–68 ranches were established along the base of the Vermilion Cliffs.

To extend the area of prospective colonization the "lands of the Moqui and Navajo" were visited by no less than seven expeditions prior to 1872, and feasible crossings of the Colorado River between Black Canyon and the Henry Mountains were examined—so thoroughly that later surveys have found no other routes.[46]

Within 5 years after the establishment of St. George the agricultural and grazing lands in southwestern Utah, southeastern Nevada, and northwestern Arizona were fairly well known. Villages were founded along the Virgin River above and below the "capital," on the Parunuweap, on Kanab, Johnson,

[42] Deseret News, April 3 and August 7, 1852.

[43] Letter to Brigham Young, March 17, 1852.

[44] Frémont, J. C., Some general results of a recent expedition across the Rocky Mountains, for the survey of a route for a railroad to the Pacific: 33d Cong., 2d sess., H. Misc. Doc. 8, Dec. 27, 1854.

[45] Andrus, James, manuscript report made available by Mr. A. B. Andrus, St. George, Utah.

[46] For additional details and references see Gregory, H. E., Crossings of the Colorado, in The Kaiparowits region: U. S. Geol. Survey Prof. Paper, 164, pp. 10–12, 1931; White settlements, in The San Juan Country, U. S. Geol. Survey Prof. Paper 188, pp. 31–33. 1938.

and Paria Creeks, and ranch sites were occupied along Vermilion Cliffs. Rockville was settled in 1862; Kanab and Springdale in 1863; Berryville (Glendale) and Winsor (Mount Carmel) in 1864; Graham (Ranch P. O:), Upper Kanab and Paria in 1865; Yellow Springs (Pipe Spring) and Quitchumpah (Short Creek) in 1866. Except for the ranch sites at Johnson and Skutumpah and the villages of Orderville, Alton, La Verkin, Hurricane, and Fredonia, founded in response to special circumstances, the permanent settlements in the valleys of Markagunt and Paunsaugunt Plateaus and southward to Grand Canyon were established before 1871. Of these early villages Duncan, Dalton, Shunesburg, Mountain Dell, Northrup, Upper Kanab, and Paria have been abandoned.

In their search for new fields, grasslands, and centers for missionary enterprises, the Mormon pioneers did not restrict their activities to Utah. Colonization of the Little Colorado began with the founding of Tuba City on the Moenkopi Wash (1876). In Nevada settlements were made on the Virgin River at Beaverdam (renamed Littlefield), Mesquite, Bunkerville, on the Muddy Creek at St. Thomas, at Overton and St. Joseph (1865), and on the meadows east of Spring Valley Mountain at Las Vegas (1875). In California, San Bernardino was developed as a center of Mormon influence, a source for special foods, and an outfitting point for oversea projects. Though these new enterprises involved serious hardships and no little danger, the "call of the Church" was insistent. In the words of President Brigham Young "our people will want all the choice places where there is water and grass."

INDIAN RELATIONS

A perplexing problem for the southern Utah pioneers was the adjustment of relations with the Navajos, Utes, and Piutes. To the Mormons the Indians were Lamanites, descendants of Laman, son of Lehi, who led a company of Israelites from Palestine about 600 B. C. They were potential converts to the Mormon faith, also neighbors, and in some degree associates in community activities. They therefore should not be "exterminated" or driven from their lands, even if the colonists found it possible.

Undoubtedly the hoped-for cooperation of the Indian population with the whites in farming, grazing, and religious enterprises lessened the chance of repeating in Utah the disastrous wars and massacres that had characterized Indian relations east of the Rocky Mountains, but it did not at once bring peace. The interests of the Indians and those of the colonists were sharply opposed. The coming of a few peaceful whites was not objectionable, but the uninvited occupation of lands with herds and flocks by an increasing number of families was vigorously resented. As the colonists were determined to deprive the Indians of the unrestricted use of their hereditary fields and hunting grounds, resort to force seemed necessary. In northern and central Utah the Walker (Wah Ka Ar) war (1853–55), the Gunnison massacre (1853), the battle of Bear River in which some 400 Indians were killed (1863), and the Black Hawk war for the possession of the Sevier River Valley (1865–67) were episodes of bitter struggles with the Utes.

The Navajos were especially troublesome, and though they claimed no land north of the Colorado River, Utah to them had long been a hunting ground for elk, deer, antelope, and mountain sheep, and a place where corn and children might be purchased or taken from the Piutes. After Mormon settlement the animals hunted included the horses, cattle, and sheep of the pioneers. In the winter of 1865–66, during one of these infrequent raids two white men and several Indians were killed near Pipe Spring. In 1869 some 1,200 head of cattle and horses were stolen on the plateaus, and during the spring and summer of 1870 herds were attacked at several places. But though no systematic warfare was waged with the Navajos, the pioneers in the Virgin, Kanab, and Johnson Valleys, at Short Creek and Pipe Spring, were constantly on guard, and riflemen kept watch at the crossings of the Colorado. Each settlement had its fort large enough to house the population in time of siege. The settlements were a string of forts—stockades of upright logs and adobe or stone structures like Winsor Castle at Pipe Spring. Fear of the Navajos made life in the frontier villages and outlying ranches precarious. Several villages in Kane County were abandoned between 1865 and 1870, and the occupants of others lived close to the forts. In desperation a mission under the leadership of Jacob Hamblin and accompanied by Major Powell was sent into the Navajo country: "we traveled at night most of the way, to preserve our animals from the Indians." At Fort Defiance, where about 6,000 Navajos "were gathered to receive the annuities * * * the blessings of the Lord were over us in our efforts for peace." In his closing speech at the council of the chiefs, November 2, 1870, Hamblin[47] asked:

> What shall I tell my people the "Mormons" when I return home? That we may expect to live in peace, live as friends, and trade with one another? Or shall we look for you to come prowling around our weak settlements, like wolves in the night? I hope we may live in peace in time to come. I have now gray hairs on my head, and from my boyhood I have been on the frontiers doing all I could to preserve peace between white men and Indians. I despise this killing, this shedding of blood. I hope you will stop this and come and visit and trade with our people. We would like to hear what you have got to say before we go home.

Some days later Barbenceta, "chief of the chiefs," gave his reply:[48]

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[47] Little, J. A., Jacob Hamblin, p. 108, 1909.
[48] Little, J. A., op. cit., p. 110.

We have some bad men among us, but if some do wrong, the wise ones must not act foolishly, like children, but let it be settled according to the spirit of your talk at Fort Defiance. . . . We hope we may be able to eat at one table, warm by one fire, smoke one pipe, and sleep under one blanket.

With this historic interview the Navajo "wars" came to an end. To remove misunderstandings that might arise in the future, Hastele was given authority to act for the Navajos and Hamblin for the Mormons. Thereafter the Navajos came to the settlements as traders, not as thieves and marauders, and the pioneers returned to their fields and herd grounds in safety.

Unlike the Utes and Navajos, the Piutes caused little trouble. Within a few years after settlement their active hostility ceased; in fact, for a decade the Piutes joined with the whites in guarding river crossings, passes, and water holes on the trails traveled by the Navajos. The treatment of the Piutes by the Mormons is a bright page in western history. Though at times suspicion, fear, and cupidity led to misunderstanding and even persecution, the attitude of the president and other officers of the Church—unfortunately not fully shared by Church members—was consistently friendly. In a public address (October 1853) Brigham Young said:

Any man who cheats an Indian should be dealt with more severely than for cheating a white man. You brethren must lay aside your angry feelings toward them and cease wishing to kill them.

At the annual conference in 1856 Young's views were further expressed:

Let the millions of acres of land now lying waste be given to the Indian for cultivation and use. Let the poor Indians be taught the arts of civilization, * * * instead of pursuing the uncertain chances of war and game for a livelihood. I have often said, and I say it now, let them be surrounded by a peaceful and friendly influence and a humane and benevolent policy.

Though the pioneers responded cordially to the "call of the Church" to occupy Utah land, they recognized the disastrous consequences to the Piute. As Jacob Hamblin[49] expresses it,

The great numbers of animals brought into the country by the settlers soon devoured most of the vegetation that had produced nutritious seeds, on which the Indians had been accustomed to subsist. When, at the proper season of the year, the natives resorted to these places to gather seeds, they found they had been destroyed by cattle. With, perhaps, their children crying for food, only the poor consolation was left them of gathering around their camp fires and talking over their grievances.

Those who have caused these troubles have not realized the situation. I have many times been sorely grieved to see the Indians with their little ones glaring upon a table spread with food and trying to get our people to understand their circumstances without being able to do so. Lank hunger and other influences have caused them to commit many depredations.

[49] Little, J. A., Jacob Hamblin, a narration of personal experience, 2d ed., pp. 94–95, Salt Lake City, Deseret News, 1909.

The faith of the Piutes in the good will of the Mormons was expressed by the chief of the Shivwits in that inspiring conference with Hamblin and Powell on the bleak lava fields near Mount Trumbull, September 19, 1870.[50]

When you are hungry you may have our game. You may gather our sweet fruits. We will give you food when you come to our land. We will show you springs, and you may drink; the water is good. We will be friends, and when you come we will be glad. * * * We are very poor. Look at our women and children: they are naked. We have no horses; we climb the rocks, and our feet are sore. We live among rocks, and they yield little food and many thorns. When the cold moon comes our children are hungry. We have not much to give; you must not think us mean. You are wise; we have heard you tell strange things. We are ignorant. Last year we killed three white men. Bad men said they were our enemies. They told us great lies. We thought them true. We were mad; it made us big fools. We are very sorry. Do not think of them; it is done; let us be friends. We are ignorant, like little children in understanding compared with you. When we do wrong do not get mad and be like children too * * *

When white men kill our people we kill them. Then they kill more of us. It is not good. We hear that the white men are a great number. When they stop killing us, there will be no Indian left to bury the dead * * * We are very poor; we are very ignorant, but we are very honest. You have horses and many things. You are very wise; you have a good heart. We will be friends. Nothing more have I to say.

In stamping out Indian slavery the Utah pioneers were confronted with a particularly embarrassing task. There is abundant evidence to show that the purchase and capture of Indian children for slaves was a widespread and continuous practice during the first half of the nineteenth century, not only by outsiders but among the Indian tribes as well. It created antagonism and fear and gave rise to intertribal wars. The Piutes especially suffered. Their continuous impoverished state tempted some to sell their children, and they were unable to resist raids by Utes and Navajos who captured children for their own use or for sale to white men.

Farnham[51] writes that in 1839 the purchase of slaves was common, "particularly young girls, who were valued at $30 to $40. These poor creatures were hunted in the spring, when they were weak and helpless."

Jones[52] noted that in 1851 "the people of New Mexico * * * were making annual trips through Utah to California * * * Their used-up horses were traded to the poorer Indians for children. Children bought on the down trip would be traded to Mexican Californians; children bought on the return trip would be taken back to New Mexico."

Writing in 1860, Hunt[53] says:

[50] Recorded in Powell, J. W., Exploration of the Colorado River of the West, pp. 129–130, 1874.

[51] Farnham, T. J., Travels in the great western prairies, May 21–Oct. 16, 1839, in Thwaites, Early western travels, vol. 28, p. 249, 1906.

[52] Jones, D. W., Forty years among the Indians, pp. 49–50, 1890.

[53] Hunt, Garland, Indians of Utah, in Simpson, J. H., Report of explorations across the Great Basin of Utah for a wagon route from Camp Floyd to Genoa in Carson Valley in 1859, pp. 461–462, 1876.

So abject and degraded are the Pyeeds [Piutes] that they will sell their children to the Utahs for a few trinkets or bits of clothing. The Utahs carry these children to New Mexico where they find a profitable market among the Navajos * * * to supply themselves with blankets from the Navajos, who manufacture a superior article * * * the trade has become almost indispensable.

The barter in human flesh was legally stopped in 1852 by the vigorous action of the Mormon leaders and the Territorial Legislature; the Mexican slave traders were prosecuted without mercy, and the Navajo traders were hunted down wherever found. To the Piutes the elimination of slavery was but another act of oppression; an important source of income had been cut off. The heroic response of the Mormons was to pay the purchase price and adopt the children into their families.

CLIMATE OF SOUTHWESTERN UTAH

GENERAL CONDITIONS

The climate of the Zion Park region is much like that of east-central and southeastern Utah, which has elsewhere been discussed in detail.[54] In a broad sense the northwesterly winds of winter and the southwesterly winds of summer control the precipitation, and differences in altitude control the temperature, but the influence of these factors is so greatly modified by topography that each deep canyon, wide valley, broad slope, and plateau top seem to have a climate of its own. Thus with respect to the distribution of rainfall and temperature, southwestern Utah has a group of local climates sufficiently unlike to determine types of native vegetation and the kind of crop that can be profitably raised. (See pp. 34–37.)

In the Zion Park region a characteristic feature of both precipitation and temperature is wide annual, seasonal, monthly, and daily variations. In yearly rainfall the departures range from about half to nearly twice normal, and very dry years follow or precede wet years. The precipitation is so irregular that the annual and even the seasonal and monthly means have little significance. Temperature, like rainfall, follows no regular procedure. The coldest months and the warmest months are not the same each year; the coldest day and the hottest day in a year may be in any one of 3 months, and the date of killing frosts varies widely. In the Virgin River Valley west of the Hurricane Cliffs subtropical warmth is experienced. At progressively higher altitudes the days with freezing temperature increase in number, and on the Markagunt Plateau frosts may come during any month.

The snow that falls each year over all of southwestern Utah and adjoining parts of Arizona varies much in amount, in place, and in time. On the High Plateaus, where a short summer is followed by a long winter, the precipitation of months is in the form of snow that covers the valley flats and the lower hills and forms high banks at the base of volcanic craters and cliff-faced ridges. During the winter season snow plows are busy on the main highways, secondary roads are abandoned, and generally over the broad terraces above the 6,000-foot contour line travel is by ski and snowshoes.

Alton receives on the average 75.6 inches of snow each year, Kanab 22.3 inches, and even on the lowlands about St. George the average annual snowfall is 7.3 inches, half of it in January. These snowfalls are perhaps the most valuable natural asset of southern Utah. Unlike the rainfalls which are quickly carried away by torrential streams, they supply most of the water that percolates into the soil and feed the numerous springs, which in turn supply the rivers. Because of the snow, the tributaries of the Virgin and the Kanab provide those streams with water sufficient for irrigation as late as June—the critical month for agriculture. Also because of the snow the herbage on the plateaus and high terraces is rejuvenated each year. The best pasture lands are those that receive the most snow.

Ever since the pioneers came to southern Utah, droughts, floods, winds, the time of killing frosts, snowfall, and ice in streams have been recorded in reports to the Church of Jesus Christ of Latter Day Saints. Diaries and interviews with men who have spent a lifetime in the Zion Park region, and incidental references in reports of the Wheeler and Powell surveys, supply additional information. (See p. 21.) From these sources it appears that the settlers in the Virgin and Kanab Valleys, on the Parunuweap, and on the streams that issue from the Vermilion Cliffs experienced years of heavy rains, excessive snowfalls, and drought—variations of the first importance in the life of pioneers. Diaries record that in 1870 "no water flowed on canyon floors," and the usual "pools at the base of waterfalls were dry." In the winter of 1883–84 the snow lasted so long and buried the grasslands so deep that "most of the livestock perished for lack of food." In 1896 the water was insufficient to fill the irrigation ditches and "hot dry winds destroyed the crops." At Mount Carmel in 1894 "50 percent of the stock died" on account of the drought. At Kanab, July 1896 was a time of rejoicing: "a dry spell of 2 years was broken by showers nearly every day in the month." Residents in the Virgin River Valley speak of 1900, 1901, and 1910 as "hot years" and 1916 and 1917 as "cold years."

Instrumental records, for some years lacking or incomplete, have been kept by volunteer observers since 1876 at St. George, 1899 at Kanab, 1904 at Springdale, and 1902 at Alton. These four meteorologic stations have been chosen as suitably placed and long

[54] Gregory, H. E., and Moore, R. C., The Kaiparowits region: U. S. Geol. Survey Prof. Paper 164, pp. 14–23, 1931. Gregory, H. E., The San Juan country: U. S. Geol. Survey Prof. Paper 188, pp. 15–20, 1938.

enough established to furnish a representative record of the climate in the Zion Park region. St. George (altitude 2,880 feet, years of record 47) lies at the edge of the broad Virgin River flood plain, bordered on the west by highlands; Kanab (altitude 4,925 feet, years of record 34) abuts against the south base of the Vermilion Cliffs and overlooks the broad Kanab Plateau; Springdale (altitude 4,048 feet, years of record 33) is in the narrow, deep entrance to Zion Canyon; Alton (altitude 7,000 feet, years of record 35) lies at the western end of Skutumpah Terrace, bordered on the west by hills and on the northeast by the high cliffs of the Paunsaugunt Plateau. In nearby regions Hurricane (altitude 3,800 feet) and Cedar City (altitude 5,805 feet), at the base of the Hurricane Cliffs, and Leeds (altitude 3,800 feet), at the base of Pine Valley Mountain, present climatic records in general accord with those at stations in the Zion Park region.

In part due to altitude but more to topography, unusual climatic conditions prevail in the Virgin Valley from Springdale downstream to St. George. Though the latitude of St. George is that of central Kentucky and the altitude much higher, the mean annual temperature at this station is that of the cotton lands of southern Alabama. St. George has the highest mean annual temperature (59.4°) and the highest absolute temperature (116°) of all the stations in Utah. During nearly half a century the temperature reached zero only in January 1901 and December 1936. The climate of Springdale likewise exhibits interesting anomalies. Here a moist, cool winter and early spring become progressively drier and warmer to a dry, hot June; and moist, hot weather of July and August becomes drier and colder toward winter. There are thus two wet cycles: winter-early spring and late summer; and two dry cycles: late spring-early summer and late fall. To this cyclical arrangement the plant growth is adjusted. (See p. 34.)

PRECIPITATION

As shown in the accompanying tables, published by the United States Weather Bureau, the precipitation in the Zion Park region is small and is characterized by great annual and seasonal variations in place and in time. The general influence of altitude is plainly expressed, though not consistent. St. George (altitude 2,880 feet) receives 8.75 inches of rain each year and Alton (altitude 7,000 feet) 19.25 inches; but because of its topographic setting Springdale (altitude 4,048 feet) receives considerably more rain than Kanab (altitude 4,925 feet) or Cedar City (altitude 5,805 feet). From year to year the range in precipitation is remarkably great, at times even in successive years. (See fig. 16.) Thus the range at Alton is 10.77 to 34.85 inches; at Kanab 7.29 to 20.70; at Springdale 7.98 to 20.78; and at St. George 3.55 to 18.71. When Alton received its maximum annual rainfall (1909), the highest ever registered for Kane County, the precipitation at Springdale and St. George was likewise above normal, and during the driest years at St. George (1903) and at Alton (1917), Kanab received about its normal rainfall. At Alton one of the wettest years (1916, 28.40 inches) was followed by one of the driest years (12.22 inches). In Zion Canyon 19.67 inches of rain fell in 1927 and but 9.75 inches in 1928. The average annual number of days with as much as 0.01 inch of rain at St. George, Kanab, Springdale, and Alton is respectively 54, 53, 66 and 72. The precipitation at these stations represents the deficient rainfall of Utah. For the State as a whole, which receives an annual rainfall of 13 inches, 50 out of 169 stations record less than 10 inches of rain a year, only 16 more than 20 inches, and only one more than 30 inches, and the days with more than 0.01 inch of rain number 57. About 50 percent of the rain falls during the period January to May.

The number of days with cloudless skies is probably in excess of 150. Generally on the flatter lands at low altitudes the sunshine is strong and little interrupted by clouds, but in the deep, narrow gorges it barely squeezes in. Some stretches of canyon floor receive direct sunshine for less than an hour a day. At higher altitudes where the rainfall is greatest and also least variable, cloud-covered skies are more frequent. Cumulus clouds may envelop the Markagunt Plateau while clear skies lie above the Virgin River Valley. At times raindrops start from the clouds and seem to stop in midair as if unwilling to enter the hot canyons. In Piute terms, the rain reaches downward and sends messages to the earth but is too weary to complete its journey.

For a region whose maximum precipitation is insufficient for agriculture without irrigation and for the continuous growth of "free range" forage plants, the widely varied and unpredictable annual rainfall has much meaning. The great variations from year to year make farming somewhat speculative and limit the utilization of the abundant unoccupied land. Of greater significance is the amount received in corresponding seasons and months from year to year. With respect to seasonal variation, the only constant feature is the relatively dry season that includes April, May, and June—a period characteristic of the entire plateau province. In order of decreasing wetness the seasons rank as winter, spring, summer, fall at Alton and Kanab; as winter, spring, fall, summer at Springdale; and winter, summer, fall, spring at St. George. (See fig. 17.) With respect to monthly precipitation no two stations show even approximately the same records. and at each station the

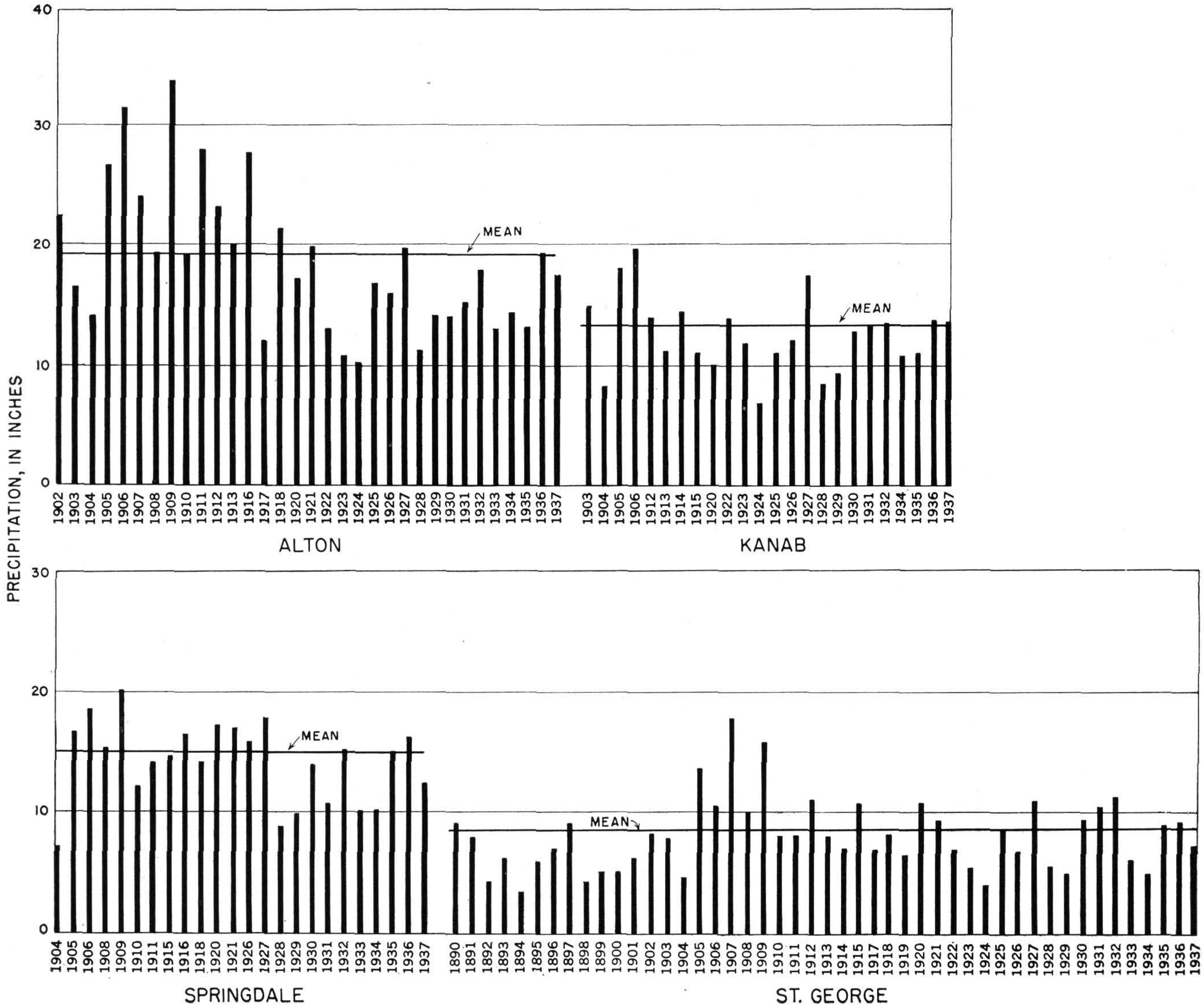

FIGURE 16.—Diagram showing total and mean annual precipitation at stations in southwestern Utah.

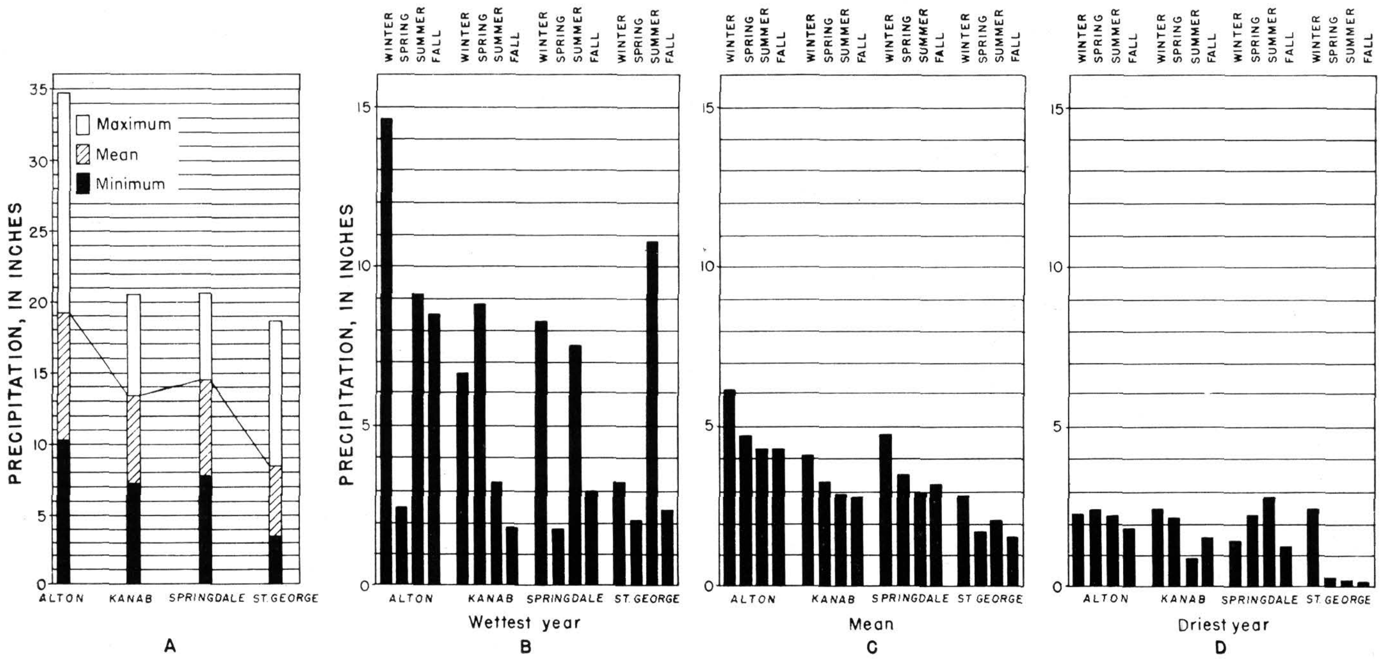

FIGURE 17.—Diagram showing the seasonal distribution of rainfall at stations in southwestern Utah.

range is wide. Thus at Alton for March, the wettest month, the precipitation, the heaviest recorded in southern Utah, has ranged from 0.18 to 12.02 inches; for June, the driest month, from a trace to 2.93 inches. At Springdale, the station within Zion National Park, the recorded ranges by months for different years are January, 0.00 to 4.88; February, 0.00 to 5.02; March, 0.05 to 4.26; April, 0.19 to 5.42; May, 0.00 to 2.13; June, 0.00 (for 12 of 31 years) to 1.02; July, 0.06 to 3.59; August, trace to 4.27; September, 0.20 to 4.32; October, 0.00 to 5.30; November, 0.00 to 3.22; December, 0.00 to 4.67. For October and May at this station the rainfall of the driest year much exceeded that of the wettest year, and similar contrasts appear in the records at other stations.

At all stations in southwestern Utah June is the driest month and February or March the wettest. The other months fit into no orderly scheme. In contrast with dry June, July and August are wet months—in some years wetter than February and March at all stations. October and November, otherwise much alike in rainfall, usually show sharp and wide contrasts from year to year. Thus in successive years at Alton the range has been 0.00 to 3.73 and 0.19 to 7.78 for October; 0.00 to 3.25 and a trace to 5.88 for November. At Springdale, Kanab, and St. George similar variations are recorded. For Utah as a whole the driest month of record was November 1904, when 55 of 66 stations recorded no precipitation and 8 others only a trace. The wettest month known in the State was October 1912, when 3.17 inches fell—2.13 inches above normal.

The season of least rainfall, April through June, is unfortunately the growing season for most crops, and therefore the distribution of rain in southwestern Utah is unfavorable for agriculture and for the reproduction of many grasses. For 25 years at St. George, 27 at Springdale, 7 at Kanab, and 4 at Alton the combined yearly precipitation for April, May, and June was less than 1 inch. Moreover, the plants may obtain but a portion of this meager supply, for during the clear, dry, hot days early in summer evaporation takes a large toll—not only from the water that falls as rain but also from the water already in the ground. The average net loss by evaporation is estimated as 10 inches. Generally the ground moisture supplied by the rains and melting snows early in spring is sufficient to allow seeds to germinate and send their shoots above ground but is insufficient to bring a crop to maturity. The rainfall of July therefore becomes the critical climatic factor in agriculture. At St. George the July average is 1.04 inches; at Springdale 1.17, at Kanab 1.35, and at Alton 1.77. With deficient spring rains and great fluctuations in July rains, agriculture without irrigation is profitable only in a few favored places and in exceptionally good years. Many "dry farms" have been abandoned.

Much of the irregularity in rainfall is due to its very local distribution. Some monthly rainfalls are the records of single showers, and the larger monthly means may comprise but a few heavy downpours. Thus on August 5, 1929, Zion Canyon recorded one-tenth of its annual rainfall in 20 minutes. The usual showers, particularly those of summer at lower altitudes, are short-lived, far apart, and cover no large areas. These infrequent showers are torrential and seem to flood the surface with water. Sheets of water cover the flat land, pour over the canyon rims, and convert dry washes into turbulent, muddy streams. Scores of waterfalls start suddenly, only to disappear within an hour. At no time is Zion Canyon more beautiful than after a thunderstorm.

Often during field work we experienced showers that were not recorded at any meteorologic station, and on these occasions we found that only a short trip from rain-soaked ground was necessary to reach land that had been dry for weeks. Hail accompanies many showers on the highlands and even in the canyons, and during these storms and for some time afterward, the air is uncomfortably chilly. Lightning also accompanies most summer showers, interrupting electric transmission, and taking a toll of trees, livestock, and people. In Piute folk tales the spirit of the ice is passing, and to herald his coming "the rocks are ringing in the mountains."

The meteorologic stations in the Zion Park region show no consistent wet and dry cycles. The records of precipitation are unsuited for general climatic studies. They are brief and fragmentary and lack other features needed for the recognition of climatic cycles. Their lack of accord with the long records at Fort Defiance, in the Navajo country, Los Angeles, and Salt Lake City remains to be explained

At Alton 1905 to 1913 were generally wet years; 1928 to 1935, dry years. The wettest year at St. George (1907) was the fourth wettest at Alton and the third wettest at Cedar City.

TEMPERATURE

As shown by a comparison of the available records, the mean annual temperature in southwestern Utah varies in general with the altitude, and in amount of heat experienced the months present a fairly regular order. The mean annual temperature ranges from 44.1° at Alton, the station highest in altitude, to 59.8° at Springdale. At all stations the warmest months rank July (warmest), August, June, September; the coldest months January (coldest), December, February except at St. George, where December is colder than January. With some shifting of position from year to year the other months take rank as November (coldest), March, April, October, May, except that at Alton and Kanab March is cooler than November. The figures for mean annual temperature, for range in monthly means, and for the position of the month in the heat scale are not unlike those prevailing in temperate latitudes elsewhere. However, because of different topographic setting and the erratic distribution of hailstorms, clouds, and winds the daily records on which the monthly means are based vary widely each year and year by year. Differences of as much as 30° are recorded for corresponding days in successive years. In fact, the difference in mean temperature for the spring and fall months is sufficient to give each year a different season to which agricultural practice must be adjusted.

At Alton, the coldest station, the thermometer rarely records as much as 90° and the highest recorded in 33 years was 94°. At the other stations in the Zion Park region temperatures exceeding 100° are normal for May, June, July, and August; at Springdale and St. George for September also. Temperatures below zero have been recorded at all stations; at Alton and Kanab they may occur at any time during November to February, at Springdale during December to February. St. George, however, has experienced subzero weather only once in 51 years. Except in the low valleys west of the Hurricane Cliffs the soil in southwestern Utah is frozen in winter to depths of 1 to 3 feet and the streams are coated with ice, in places thick enough to support teams and wagons.

By far the coldest period of record in southwestern Utah was January 1937, during which the departure from the normal monthly temperature was –14.8° at Alton, –14.1° at Kanab, –13.8° at Springdale, and –16.1° at St. George. For the week January 21 to 27 St. George, which rarely feels temperatures below freezing, presented the amazing record of –1° to –11°. Grapes, figs, and pomegranates were destroyed, and such native plants as creosote bush (*Covillea*) and mesquite (*Prosopis*) were badly damaged. Utah climate is so irregular that in spite of the highly abnormal January the departures from the normal mean annual temperatures for 1937 were only –0.2° at St. George and –0.6° at Alton. At Springdale the year was 1.6° warmer than usual and at Kanab 2.9° warmer.

The annual ranges of temperature, though great, are those characteristic of the plateau province. The maximum annual range recorded for Alton is 114°, for Kanab, 120°, for St. George, 117°, for Springdale, 121°.

The daily range of temperature varies widely in time and place. Ranges of 40° to 50° have been recorded for all months at all stations, and those exceeding 50° are not uncommon at Kanab and St. George. On the floors of some deep canyons the daytime summer heat continues unchanged into the night, but generally during June, July, and August the sunset marks the division between excessive heat and moderate heat. During the summer the climate in the larger valleys and along the base of the Vermilion Cliffs is uncomfortable and in the lowlands west of the Hurricane Cliffs almost intolerable. On the high terraces warm days of summer are followed by cool nights. At times during the field work when any clothing seemed unnecessary at midday, the nights called for heavy blankets. Even in July at altitudes above 6,000 feet ice has been known to form. Alton, which during the winter experiences zero weather nearly every day and heavy snows that cause the residents to "hole up," has an ideal summer climate. Springdale, Rockville, Orderville, Glendale, Kanab, Moccasin, and Cane Beds are at their best in the spring and fall; St. George is a delightful place in winter.

The time of killing frosts that determine the length of the growing season varies directly though not consistently with the altitude. A compilation of instrumental records supplemented by State reports and diaries indicates that in southwestern Utah at altitudes above 7,000 feet the time between the last killing frost of spring and the first killing frost of fall is too short for crops and that in the areas where farming is practiced the growing season in the lower valleys is 150 to 200 days; in the higher valleys, 80 to 100 days. The normal growing season for Kanab is 141 days; for St. George, 188 days, for Springdale, 198 days; for Alton, 97 days. These approximate figures are subject to drastic changes in abnormal years. As corn requires, on the average, 90 to 150 days to reach maturity, and fruit an even longer period, it is obvious that crops suitable for the Zion Park region must be selected with discrimination, and that crop failures are to be expected. (See p. 43.)

WIND

Dunes and rippled flats of eolian origin widely spread over the Zion Park region bear witness to the occurrence of winds that are highly variable in direction, strength, and persistence. In a few places the rocks are being polished and etched by wind-blown sand, and on tributaries of Kanab Creek large dunes long established are still in process of formation. The prevailing direction of wind is southwest at St. George, west at Alton (1905–21), and south-southwest at Springdale and Kanab (1922–35). Before reaching the Zion Park region the far-traveled air currents have passed over the wooded Beaver Dam Mountains, Pine Valley Mountains, and Markagunt Plateau, and their direction and force thereby have been modified.

Generally in southwestern Utah the effectiveness of the prevailing wind is much modified or entirely overcome by the topography. Winds blow in and out of canyons, up canyons, down canyons, and around buttes and mesas as compact masses of moving air or as a group of air streams roughly parallel but with different speeds. They start, stop, pick up and deposit sands at relatively short intervals and change their direction so often that the dunes seem capriciously distributed along canyon walls and floors and about headlands and towering rock buttresses and frequently change form and position. At the junction of canyons small ridges of sand are alternately moved and replaced. In some canyons sand streaming over the rim reaches the stream below, thus forming a route for pack trains to places otherwise inaccessible.

Mountain and valley breezes caused by uneven radiation are climatic features of the Zion Park region. During summer nights cool air flows over the rims and along the floors of the deep canyons that head in the Markagunt Plateau, and during the day it flows back upward. The upcanyon drift is usually feeble, but during seasons of clear skies and high temperature the downcanyon drift may be strong and persistent, a welcome relief from the heat that in July and August seems to pile into the deep bare-rock gorges. The prevalence of the night breeze is a guide in the selection of camps and of permanent dwellings.

SOIL

In the Zion Park region the soil is very unevenly distributed and varies widely in quantity, quality, and depth. Disintegrated rock is abundant, but decomposed rock mixed with humus and perpetually moistened with water is scarce. Many mesa tops and the larger terraces are sparsely coated with residual soil, but even in these situations thick soil underlain by subsoil and grading downward to bedrock—the products of weathering in place—is almost absent, and most of the soil that remains in rock crevices and about seeps and small springs—patches a few square yards in area—is unsuitably placed for cultivation. Over many square miles of plateaus, cliffs, and valley slopes the rock is bare. In general the conditions for the formation and retention of residual soil are unfavorable; the sparse vegetation, the absence of sod, the low water table, and the torrential showers and rapid runoff favor its removal about as fast as it is formed.

Except in small areas here and there the soil has been brought to its present position by streams and winds or has been torn from cliff faces as talus and landslides. The most valuable transported soils lie in narrow bands along streamways. In Johnson, Kanab, and Virgin River Valleys and along their tributaries such soil, derived from many sources, has accumulated in quantities sufficient for agriculture and, where water is available for irrigation, has proved to be productive. Also on lower Kolob Terrace and on slopes about the base of the Vermilion Cliffs the soil is suitable for dry farming, principally for cereal crops. On the otherwise bare tops of some mesas, on the broad Wygaret Terrace and about the Block Mesas the soil is mainly wind-blown sand, which fills depressions and lodges at the base of stunted vegetation. In a few places shifting dunes constitute the only soil. The boulder-strewn talus is too steeply inclined and contains too little fine material to be of value in agriculture. Likewise the landslides are coarse and become usable soil only at their lower margins and about small lakes embedded in their rough surfaces.

In amount of mineral plant food available for incorporation in soil the rock formations show a considerable range. The limestone, sandstone, and calcareous shale of the Wasatch formation contain the necessary ingredients, but unfortunately they lie at altitudes where the climate is too cold for crops. Likewise the limestone and calcareous shale of the Carmel formation, the miscellaneous assemblage of rocks in the Kaiparowits and parts of other Cretaceous formations, and some beds in the Chinle and Kayenta formations contain mineral food in fair abundance. The basaltic lavas furnish soil of good quality. On the other hand, the Navajo formation, much of the Straight Cliffs and Wahweap formations, and the thick beds in the upper part of the Chinle formation are prevailingly quartzose and thus supply little plant food. Soil from most of the beds in the Moenkopi formation, from the "variegated beds" in the Chinle formation, and from the shales of the Tropic and Entrada formations is so heavily charged with gypsum as to be almost useless for agriculture. For the region as a whole mineral plant food is adequate and the acidity problem is not serious, but the soil is deficient in nitrogen, organic matter, and water. The scarcity of humus and water rather than the absence of suitable minerals makes most soils of southern Utah infertile. Climate and topography are much more effective controls than rock composition.

In favorable places on flat highlands, at canyon heads, and in valley bottoms compact groves of deciduous aspen, oaks, boxelder, and cottonwood provide leaf mold, which remains in place and thus facilitates the downward percolation of water, but in most of the Zion Park region the evergreens, annual shrubs, and weeds are scattered over steep slopes of coarse debris or bare rock. The small amount of litter resulting from their decay is removed by torrential showers. To a considerable degree the texture and composition of the soil have determined the type of vegetation. Thus, along streamways sagebrush on deep soil at the edge of the flood plain is replaced by junipers and mountain-mahogany on adjoining slopes of rock and gravel and by greasewood and shadscale in fine-textured alkaline bottom lands. In forests of juniper and piñon, where other conditions are favorable, thin porous soil permits a luxuriant growth of sage.

VEGETATION

In the Zion Park region the physical geographic features are unfavorable for luxuriant plant growth, especially at the lower altitudes. Temperature changes are large and often sudden; precipitation is small and erratically distributed in time and place; most of the soil is siliceous; and the intricately dissected topography prevents wide spreading from favorable centers of growth. On scores of canyon walls the only noticeable plants are trees or shrubs growing in cracks, too few to be helpful in climbing, and from the canyon rim to the edge of a neighboring canyon the rock surface may be bare. Even on the great stretch of flatlands extending southward from the Vermilion Cliffs, on the dissected highland between the Vermilion Cliffs and the Parunuweap, and on Wygaret and Moccasin Terraces the area of bare rock or of drifting sand is about as large as the area occupied by plants. For some miles along the Hurricane, the Vermilion and the White Cliffs, and the Parunuweap, Zion, La Verkin, and Kanab Canyons vegetation is nearly absent.

In consequence of the unfavorable environment for continuous and homogeneous plant cover, the flora is remarkable in variety and distribution. The number of species is probably as much as three times that in areas of equal size in Ohio, Illinois, or Iowa. Over most of Kane County and southward to the Grand Canyon, the grass grows in bunches, the shrubs in clumps, and the trees in scattered groves. The bare soil between the smaller plants may extend a few feet or tens of feet; between trees, a mile or more. Except in cultivated areas and on the Kolob Terrace and the Markagunt Plateau, continuous patches of green are a small part of the landscape. Over areas of many square miles grass, weeds, and low shrubs seem lost in the general surface of brightly colored rock and sand, and in distant view the only conspicuous object may be a lone piñon pine. Grass stems are too scattered to be cut as wild hay, and in many places the grass has been completely replaced by introduced weeds; the only continuous turf lies closely about springs. In protected recesses on cliff and canyon walls seepage makes possible the growth of species that seem out of place in the regional flora; their habitat is a "boreal oasis" that perhaps dates from the time when the climate of southern Utah was colder.

The wide range in altitude and topographic environment is reflected in the wide range of floral types, from subtropical to subalpine, from pronounced lowland desert forms to forest trees and water-loving plants characteristic of ridges and meadows in the Uinta Mountains and the central Rocky Mountains.

Southwestern Utah is the meeting ground for plants from the Rocky Mountains, the Sierra Nevada, the intermountain basins, Arizona, and the Mexican plateaus. Along the Virgin River from St. George to the rim of the Markagunt Plateau the succession in life zones is from Lower Sonoran to Canadian. The line of demarcation between the southern and northern elements lies near the Hurricane Cliffs, the northern limit of the creosotebush (*Covillea*) and a region where figs, almonds, pomegranates, and cotton are successfully grown. In this region the dovetailing of the northern and southern floras is facilitated by the general north-south trend of plateaus and canyons.

As shown in a preliminary survey by Tidestrom,[55] the plants listed for Utah and Nevada (2,990 species) include 1,142 northern species (those ranging southward from British Columbia and Alberta), 667 Mexican plants, 353 Colorado plants, 333 California plants, and 497 Great Basin elements. He remarks that "if the Great Basin elements are added to the Mexican plants there is an almost exact balance of northern and southern elements in this flora."

In general, the zonal arrangement of vegetation in the Zion Park region is that outlined for other parts of the Plateau province and, as elsewhere, the number of zones and subzones that seem worthy of recognition varies with the purpose in view.

If the standard botanical terminology were adopted, most plants in the Zion Park region would find appropriate positions in the Lower Sonoran, Upper Sonoran, Transition, Canadian, and Hudsonian zones. If treated as dominant features of a regional landscape they might be assigned to four general groups: (1) desert shrub, widely spaced units of such arid-land plants as cactus, yucca, mesquite, creosotebush, and blackbrush; (2) pygmy forest, individuals and clumps of juniper, piñon, and sage; (3) coniferous forest of spruce and fir that include groves of aspen; and (4) valley deciduous forest, narrow bands of cottonwood, willow, ash, and boxelder. The desert-shrub, pygmy-forest, and coniferous-forest groups lie in broad, indefinitely bounded belts that roughly correspond to altitude. The valley deciduous forests stand along stream courses at different altitudes but grow best along perennial streams at relatively low altitudes. In broad views of areas below 3,000 feet, creosotebush and blackbrush are the most conspicuous; at altitudes above 7,000 feet yellow pine, scrub oak, and aspen stand out; on intermediate slopes juniper and sagebrush seem to be everywhere; and in valleys cottonwoods attract chief attention.

In the classification of Weaver and Clements[56] the

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[55] Tidestrom, Ivar, Flora of Utah and Nevada: U. S. Nat. Herbarium, Contr. vol. 25, 1923.

[56] Weaver, J. E., and Clements, F. E., Plant ecology, 1929. Woodbury, A. M., Biotic relationship of Zion Canyon, Utah, with special reference to succession: Ecol. Soc., America Ecol. Mon., vol. 3, p. 171, 1933.

plants belong to the Petrar-Montana, deciduous chaparral, pygmy forest, and desert shrub formations. To this series Woodbury has added the Virgin River formation.

As a guide in establishing a grazing policy on the public lands of Utah Plateau, the Forest Service outlined eight general plant formations as follows:

1. Southern desert shrub; creosotebush formation. Altitude 2,000–3,500 feet (Lower Sonoran). 2. Northern desert shrub; sagebrush formation. Altitude 4,000–5,000 feet (Upper Sonoran). 3. Salt desert shrub; greasewood formation (Lower Sonoran and Upper Sonoran). 4. Pygmy forest; piñon-juniper belt. Altitude 4,000–7,000 feet (Upper Sonoran). 5. Yellow pine; scrub-oak formation. Altitude 6,000–8,000 feet (Transition Zone). 6. Aspen formation. Altitude 7,000–8,000 feet (Canadian Zone). 7. Spruce-fir formation. Altitude 7,500–11,000 feet (Canadian and Hudsonian Zones). 8. Alpine grasslands (Arctic Zone).

Another classification used by Utah foresters recognizes the following six "vegetation types" on the plateaus and adjoining lowlands of southern Utah above about 4,000 feet:

1. Spruce-balsam type. Limited to the high rugged mountainous areas between altitudes of 7,500 and 11,500 feet, where both the soil and the air contain a large amount of moisture. The predominant tree is Engelmann spruce, with which grow balsam and some Douglas fir.

2. Yellow-pine type. Characteristic of all high plateaus, between altitudes of 6,700 and 9,000 feet. It grows best on deep soils of sandstone origin; on clay soils it produces open stands and parks.

3. Piñon and juniper type. Altitude 5,000–8,000 feet. Consists chiefly of piñon and Utah juniper, with yellow pine, mountain-mahogany, oak, and serviceberry, growing on benches and plateaus.

4. Brushland type. Grows regardless of altitude, soil, or exposure, except under fairly dense stands of trees. Oak and serviceberry are dominant, though manzanita, snowberry, buckbrush, and sage are present. This type covers about half of the area classed as forest.

5. Sagebrush type. At altitudes below 9,000 feet sagebrush is commonly associated with the species that constitute the brushland type. Over areas of considerable size it is the dominant shrub.

6. Mountain-meadow type. Altitude 7,600–11,000 feet. Found mainly in the form of open grassy parks, consisting of blue, grammagrass, and pinegrass, bluestem, white clover, sedge, wire grass, and many species of weeds. This type covers less than 1 percent of the highland areas.

As shown elsewhere,[57] this scheme takes into account two features of distribution not generally noted in the plateau country—the types overlap as much as 2,000 feet in altitude, and brushland is a characteristic part of all zones, constituting fully half of the vegetation in the national forests.

In the Zion Park region and generally throughout southern Utah topography, with its attendant influence on rainfall, temperature, evaporation, insolation, and wind, is a major control in the distribution and character of plant life. The remarkably complex vertical and horizontal arrangement of canyons, stream flats, slopes, cliffs, mesa tops, plateau tops, areas of rich soil, and bare rock naturally provides local environments with little regard to contour lines. In consequence, the vegetation comprises a series of diverse communities or biotic groups rather than zones or ecologic provinces, and because of the local dominance of special conditions many units are small and their borders sharply drawn. Especially in the narrow, deep, meandering canyons, where temperature, humidity, evaporation, and the amount and intensity of sunshine vary widely within short distances along the floor and up the walls, the standardized zonal arrangement has little meaning. As Woodbury[58] has pointed out, "plants ordinarily associated with three life zones—Lower Sonoran, Upper Sonoran, and Transition—are often telescoped or 'scrambled' together."

On the floor and lower walls of Zion Canyon rabbitbrush, cottonwood, boxelder, willow, grape, sage, oak, juniper, yellow pine, and fir seem to find congenial environments, and the creosotebush grows within a few miles. At the mouth of Refrigerator Canyon the thick leaved yucca (*Yucca baccata*) and the white fir (*Abies concolor*) grow side by side. About the seeps on canyon walls travertine accumulations provide favorable conditions for "hanging gardens"—beautiful groups of moss, ferns, and such seed-bearing plants as orchids, false Solomonseal, and columbine. (See fig. 18.)

The Virgin River, Kanab and Short Creeks, and many smaller streams and branches are almost devoid of plant life. Because of frequent scouring by floods of muddy water, even algae and diatoms have difficulty in maintaining themselves. Back from the streams the flood plains and alluvial terraces support an attractive and varied flora. The little ponds and swamps contain cattails and tules (*Scirpus*), and at their edges grow sedge, crowfoot, water cress and rushes (*Juncus*). The higher plants bordering the stream plain constitute a deciduous forest of broad-leaved trees. On the present flood plain of the Virgin and along the short tributaries where ground water is near the surface the groves consist of cottonwood, boxelder, desert ash, red birch (*Betula fontinalis*), and several species of willow. In places the Arizona grape nearly covers the tree branches. On the higher alluvial terraces and at the base of talus slopes the forest comprises maple, single-leaved ash, locust, Gambel oak, and such smaller forms as huckleberry and lemonade sumac (*Rhus trilobata*). The cottonwood is the monarch of the valley flora. It grows persistently in the lowest canyons and in dry washes above 6,000 feet, and its seedlings cover sand bars

[57] Gregory, H. E., The San Juan country, Utah: U. S. Geol Survey Prof. Paper 188, pp. 22–23, 1938.

[58] Woodbury, A. M., Biotic relationship of Zion Canyon, Utah; Ecol. Soc. America, Ecol. Mon., vol. 3, p. 169, 1933.

exposed during periods of temporary low water. Single trees attain ages exceeding 200 years and may be 6 feet in diameter and 70 feet high. In many places the cottonwood has no companions and provides the only shade for man and beast and the only available timber for cabins. In the life of the western pioneers it stands for the elm, the oak, and the maple of New England.

FIGURE 18.—Hanging gardens, Narrows of Virgin River. Dense masses of water-loving plants grow on travertine at seeps in Navajo sandstone. Photograph by National Park Service.

Woodbury[59] has called attention to the interesting cyclical progression in the growth and flowering of the plants of southwestern Utah. To avoid the prohibitive heat and dryness of summer a large group of annuals complete their life cycle before June. Another group of annuals begin their life cycle with the moist period of late spring and complete it in the fall. Some biennials likewise have a two-season cycle; they survive the winter and June drought and bloom in the following fall. But such perennials as *Pentstemon* (several species), *Allium, Fritillaria, Calochortus, Abronia, Astragalus,* and *Sphaeralcea* grow, bloom, and produce seed before the summer drought. In Zion National Park late summer and fall is the season of floral grandeur. There is an amazing display of geranium, monkeyflower, lobelia, coleus, goldenrod, aster, sage, groundsel (*Senecio*), and wild gourd.

[59] Woodbury, A. M., op. cit., pp. 224–229.

Few plants are in bloom during the early summer, when the day temperature may reach 100, even at altitudes as high as 6,000 feet. Their place is taken by such night-blooming species as spiderwort, four-o'clock, sacred datura, and several species of evening-primrose.

Among trees of commercial value the yellow pine stands first. From it comes nearly all the lumber milled in southern Utah and northern Arizona. It amply supplies all local needs for bridge girders, planking, and the frame and walls of houses and is exported for heavy beams, railroad ties, and mine props. Cottonwood hewn to the desired form is still used for foundation sills, bridges, and poles for corrals; in pioneer days it provided shingles. Aspen is used for fence rails and seems likely to become a source for paper pulp. Juniper makes enduring fence posts and, though coal is abundant, is widely used for fuel. Distance from market rather than quality and abundance of softwood timber prevents the development of a profitable lumbering industry.

The hardwood trees—oak, ash, maple, and boxelder—are too small for structural timbers. In pioneer days they were used in making ax handles, wagons, agricultural implements, household utensils, and furniture, and because of the scarcity of trees of suitable size and grain, cutting was strictly regulated.

Since the days of the earliest settlers the Mormons have given devoted attention to the introduction of shade trees, fruit trees, and ornamental shrubs and vines, wherever water for irrigation was available. Along ditches, country roads, and village streets are rows of Lombardy poplars—the distinctive mark of a Utah village—and here and there are plantations of mulberry, silver maple, and ailanthus. Areas originally bare of plants associated with the home life of more-favored regions have been converted into beautiful groves, orchards, and gardens.

Some 20 native plants were used by the Piutes as medicine. Their origin and potency form the theme of interesting legends and religious ceremonies, and special knowledge of their curative properties insured high rank to the healer (Mo-sost-qui-aut). Exchanging medicine was a friendship rite of deep meaning.

Probably the most highly prized medicinal plant was the sacred datura (*Datura meteloides*), which could "make one sleep and see ghosts." Its root, which yields the powerful narcotic hyoscin, was used to relieve pain and as an antiseptic. The leaves and stems of *Ephedra nevadensis,* steeped in hot water, made a favorite tonic and cure for intestinal disorders. Under the name "Brigham tea" it replaced coffee and other tabued drinks among the Mormons. The puccoon

(*Lithospermum linearifolium*), prepared in ceremonial fashion, was prescribed for sore throat, also for boils and tumors of all sorts. The ground root of the sunflower and the smoke of the wild tobacco (*Nicotiana attenuata*) was a cure for snake bite.

Discussion of the botany of the Zion Park region forms part of the comprehensive work of Tidestrom,[60] and extensive collections have been made by the Forest Service, by the National Park Service, and by Marcus E. Jones of Pomona College. Check lists prepared by A. M. Woodbury (1929), K. E. Weight (1937), and others are incorporated in a publication by Presnall.[61]

ANIMALS

As elsewhere in the Colorado Plateau province, the Zion Park region provides acceptable habitats for a great variety of animal forms. The fauna is therefore rich in species, especially terrestrial forms, and naturally has attracted the attention of students of Utah zoology.[62]

Published lists give the estimated number of species in Kane and Washington Counties as 1,390—265 vertebrates and 1,125 invertebrates. They comprise 75 mammals, 150 birds, 15 lizards, 10 snakes, 7 amphibians, 8 fishes, 20 snails, 100 arachnids, 5 crustaceans, and 1,000 insects.

Like the plants, the animals include those characteristic of two or more life zones; the region is a mixing ground for southern and northern species. Such southern elements as the Gila monster (*Heloderma*), chuckwalla, California king snake (*Lampropeltis*), road runner (*Geococcyx*), and Abert's towhee (*Pipilo*) have made their way northeastward along the Virgin River instead of directly north across the Grand Canyon, which acts as a barrier to some species.[63] Most of the northern elements have come from the Great Basin and over the High Plateaus by way of north-south valleys. Such endemic species as the snail *Petrophysa zionis*[64] are either isolated remnants of a widespread race or forms locally developed in response to changed environment. In adjusting themselves to their new environment both the northern and the southern immigrants had wide choice. Erosion forms, temperature, moisture, kinds of soil, and plant cover are exceptionally variable and thus provide innumerable specialized habitats, and most of these distinctive habitats seem to support distinctive animal communities or are used for special purposes. The fauna is rich in birds, squirrels, chipmunks, porcupines, insects, and, in the warmer places, lizards and snakes.

The mule deer range throughout the highlands during the summer but descend to the foothills and canyons for winter. They have been able to maintain themselves in the face of severe competition with domestic livestock. In the protected areas of Zion Park and the Dixie National Forest they have multiplied rapidly and are wandering into surrounding areas, where many are killed each year by hunters.

Grizzly bears, which formerly ranged through the timbered highlands, are now probably extinct. A few black and brown bears survive in the more inaccessible parts. Like the bears, the cougars (mountain lions), which feed upon deer, sheep, cattle, and horses, have been subject to incessant warfare from the stockmen. Systematic round-ups in 1914, 1926, and 1931 reduced their numbers drastically, and each year skilled hunters with trained dogs take further toll. At present the most harmful predatory animal is the coyote, complete extermination of which seems impossible.

Trappers of the period 1835–50 found beavers (now extinct in southwestern Utah) along most of the streams in the High Plateaus. Wheeler (1872) reports that "beavers * * * still hold possession of the part of the stream in the vicinity of the valley (Strawberry Creek), their dams recurring at short intervals." To the Piutes the headwater region of tributaries to the Sevier, the Kanab, and the Paria was "Pa-unco-a-gunt, the place of beavers."

The herds of elk that long frequented Paria Valley (Piute: Pah Reah, "elk water") and the few animals that roamed along the Arizona border in 1850 were soon exterminated by the pioneer settlers. In 1925 a small herd was reintroduced on the Kolob Terrace. Antelopes, the chief large game of the Piutes and probably of the Pueblos before them, were an important item of food for the Mormon colonists. Of the "great herds" seen by members of the Powell and Wheeler Surveys on Wonsits (Piute name for antelope) Plains, none remain. Mountain sheep, fairly common as late as 1880, are now represented by about 25, protected in Zion Park. That buffaloes grazed in the Zion Park region before their introduction to House Rock Valley (1895) is suggested by a picto-

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[60] Tidestrom, Ivar, Flora of Utah and Nevada: Contr. U. S. Nat. Herbarium, vol. 25, 1923.

[61] Presnall, C. C., Plants of Zion National Park: Zion-Bryce Mus. Bull. 1, pp. 1–69, 1937.

[62] Barnes, C. T., The mammals of Utah: Utah Univ. Bull., vol. 12, no. 15, 1927. Chamberlin, R. V., and Woodbury, A. M., Notes on the spiders of Washington County, Utah: Biol. Soc. Washington Proc., vol. 42, pp. 131–142, 1929. Chamberlin, R. V., and Jones, D. T., The Mollusca of Utah: Utah Univ. Bull. 19, pp. 1–203, 1929. Presnall, C. C., The birds of Zion National Park: Utah Acad. Sci. Proc., vol. 12, pp. 196–210, 1935. Tanner, V. M., Notes on birds collected in the Virgin River Valley of Utah: Condor, vol. 29, pp. 196–200, 1937; The *Coleoptera* of Zion National Park, Utah: Entomol. Soc. America Annals, vol. 21, pp. 269–281, 1928. Silver, A. L., Notes on mammals of southern Utah: Am. Naturalist, vol. 14, pp. 673–674, 1880. Woodbury, A. M., The reptiles of Zion National Park, Utah: Copeia, vol. 166, pp. 14–21, 1928; The snails of Zion National Park, Utah: Nautilus, vol. 48, pp. 54–61, 1929; The reptiles of Utah: Utah Univ. Bull., vol. 21, pp. 1–129, 1931; Biotic relationships of Zion Canyon, Utah, with special reference to succession: Ecology, vol. 3, pp. 147–245, 1933. Zion-Bryce Nature Notes, mimeographed pamphlets.

[63] Goldman, E. A., The Colorado River as a barrier in mammalian distribution: Jour. Mammalogy, vol. 18, pp. 427–435, 1937.

[64] Pilsbry, H. A., A fresh-water snail, *Physa zionis*, living under unusual conditions: Acad. Nat. Sci. Philadelphia Proc., vol. 77, pp. 325–334, 1925.

graph in Johnson Canyon and by fragments of buffalo hide and bones in Pueblo ruins.

INHABITANTS

PREHISTORIC RACES

Though it seems probable that the "Gypsum Cave people," who lived near Las Vegas, Nev., 12,000 to 15,000 years ago, occupied sites farther north and east, the oldest definable culture in the Zion Park region is that of the Basket Makers, who as early as 2,000 B. C. were growing maize, beans, and squash (?), hunting rodents, making attractive baskets, weaving cloth, shaping implements of wood, horn, bone, and stone, and molding a little crude pottery. Near the beginning of the Christian era the Pueblo tribes, immigrants from Mexico and Central America, established residences in southern Utah.

Exploration of the prehistoric ruins in the Zion Park region by members of the Wheeler and Powell Surveys, by Palmer,[65] Judd,[66] and Nusbaum,[67] and by me has shown that the Basket Makers and Pueblos successively or contemporaneously occupied hundreds of sites, mesa tops, open valleys, canyon floors, rivers, and recesses in cliffs. Along the western base of the Markagunt Plateau and in lower Virgin Valley many mounds mark the sites of adobe-walled "pit houses." At Pipe Spring, Moccasin Springs, Short Creek, and generally at sources of permanent water on the Uinkaret and Kanab Plateaus walls of ancient stone structures remain. Cists and storehouses occupy niches in the walls of Zion Canyon, and ruined villages border the stream in Parunuweap Canyon. (See figs. 19, 20, 21.) In Kanab Canyon south of the White Cliffs and in branches of Johnson Canyon many recesses in the walls was once occupied. Kanab itself is built over the site of an ancient agricultural settlement. Cave Lakes Canyon and Cottonwood Canyon seem to have been especially adapted for use by a primitive agricultural people. (See fig. 22.) Here the Basket Makers and early Pueblos had abundant water and considerable arable soil, were near the grazing ground for deer and antelope, and were provided with ready-made house sites. Well-built houses and stratified refuse heaps in some 20 caves explored indicate long undisturbed occupancy.

During their seven or eight centuries on the Colorado Plateaus the peace-loving Pueblos seem to have occupied most of the lands suitable for primitive farming and to have attained a commensurate population. North of the Colorado River their settlements were small and widely scattered and may have been pioneer outposts, some of them occupied for short periods only. The houses and artifacts are inferior to those left by the aborigines of the San Juan country and still more inferior to the architectural masterpieces in the Navajo country.

About 800 A.D. the northward expansion of the Pueblos was checked, and within a short time the race had disappeared from Utah. South and east of the Colorado some tribes continued their existence and even went further along the road to cultural excellence. The best-designed and best-built houses and much of the finest pottery date from about 1050 A.D., the Golden Age of Pueblo civilization. The living remnants of this once great people are at Moenkopi, the Hopi villages, Zuñi, Acoma, and scattered settlements along the Rio Grande.

PIUTES

The Indians now living in the Zion Park region are the Piutes (Pah Utah, "water Utahs"), a Shoshonean tribe represented by weak clans in Nevada, California, southeastern Utah, and southwestern Colorado. Their nearest relatives are the nomadic Utes, who, however, have treated them as "poor relations," inferior in social and economic status. In general their homeland lies between that of the Utes of central Utah and the Navajos south of the Colorado. The Piutes came from the north, but the date of their southward migration and whether it was voluntary or forced are not known. It seems likely, however, that they came in contact with the Pueblos, learned irrigation farming from them, and later drove them out. In their seminomadic life they established homes along streams, where corn, melons, and squashes could be grown by primitive irrigation, and temporary camps about springs and water holes in regions where game and seeds could be obtained. Their family and tribal groups were too small and too widely scattered for any defensive or offensive action against the powerful, war-loving Utes and Navajos. Their safety lay more in their isolation and their knowledge of hiding places. Without horses and livestock, their only possessions of value to their neighbors were their children, who were captured in raids or obtained by forced barter with the Navajos and the Mexicans. Under these conditions it is not surprising that the white explorers found them "shy," "suspicious," "timid," "cowardly," or "mild," "inoffensive," and "friendly."

The Piutes of southern Utah recall with pride the time when their tribe combined with the Utes was dominant over large parts of Nevada, Utah, Colorado, Idaho, and California, but the total population of the 40 or more living and extinct clans in Utah and adjoining parts of Nevada and Arizona has probably not exceeded 10,000 at any time since the days of

[65] Palmer, Edward, Plants used by the Indians of the United States: Am. Naturalist, vol. 12, pp. 593–606, 646–655, 1878; Cave dwellings in Utah: Peabody Mus. Archeology and Ethnology, 11th Ann. Rept., pp. 269–272, Cambridge, 1878. See also notes by Palmer and others in U. S. Dept. Agr. Ann. Rept., 1870.

[66] Judd, N. M., Archeological observations north of the Rio Colorado: Bur. Am. Ethnology Bull. 82, 1926.

[67] Nusbaum, T. L., A Basket Maker cave in Kane County, Utah: Mus. Am. Indians, Mon. 29, 1922.

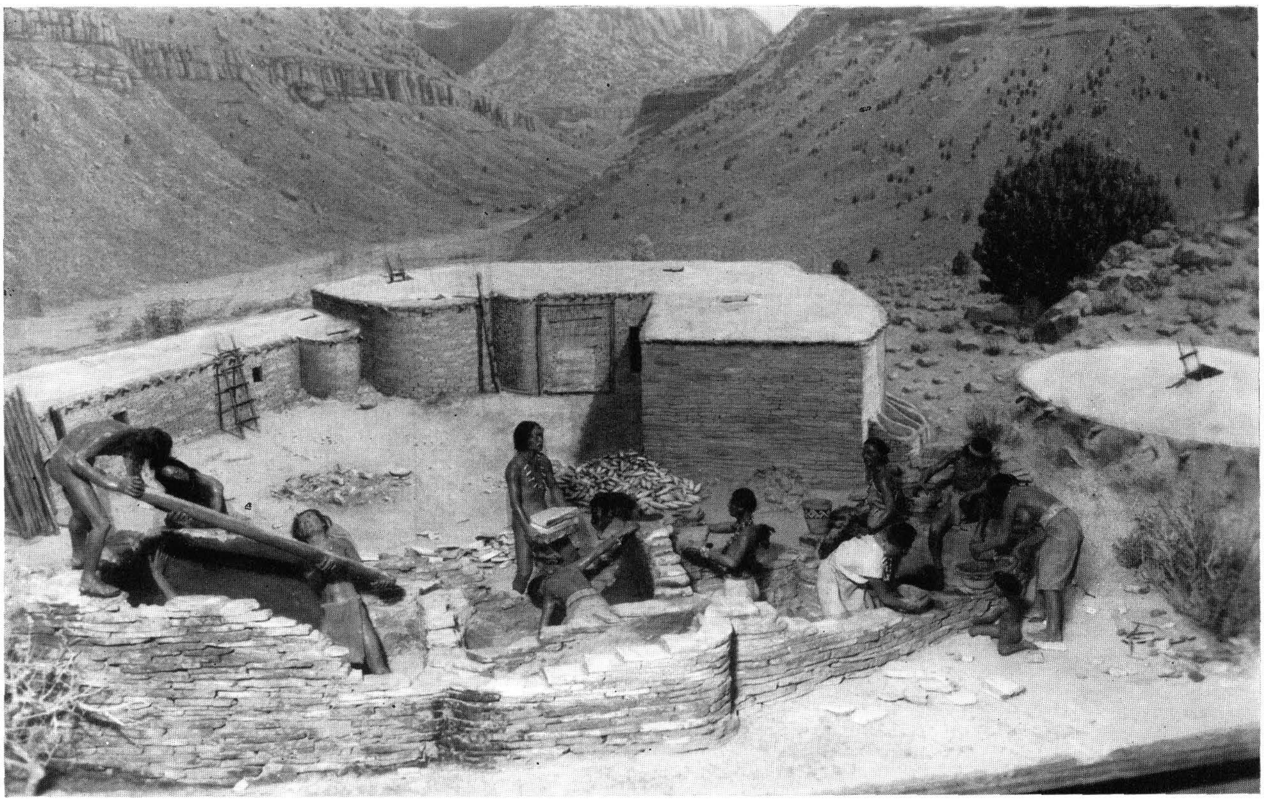

FIGURE 19.—Restoration of a pueblo community house in Parunuweap Canyon, based on a study of ruins by Benjamin Wetherill, National Park Service.

Gregory, H.E 1275

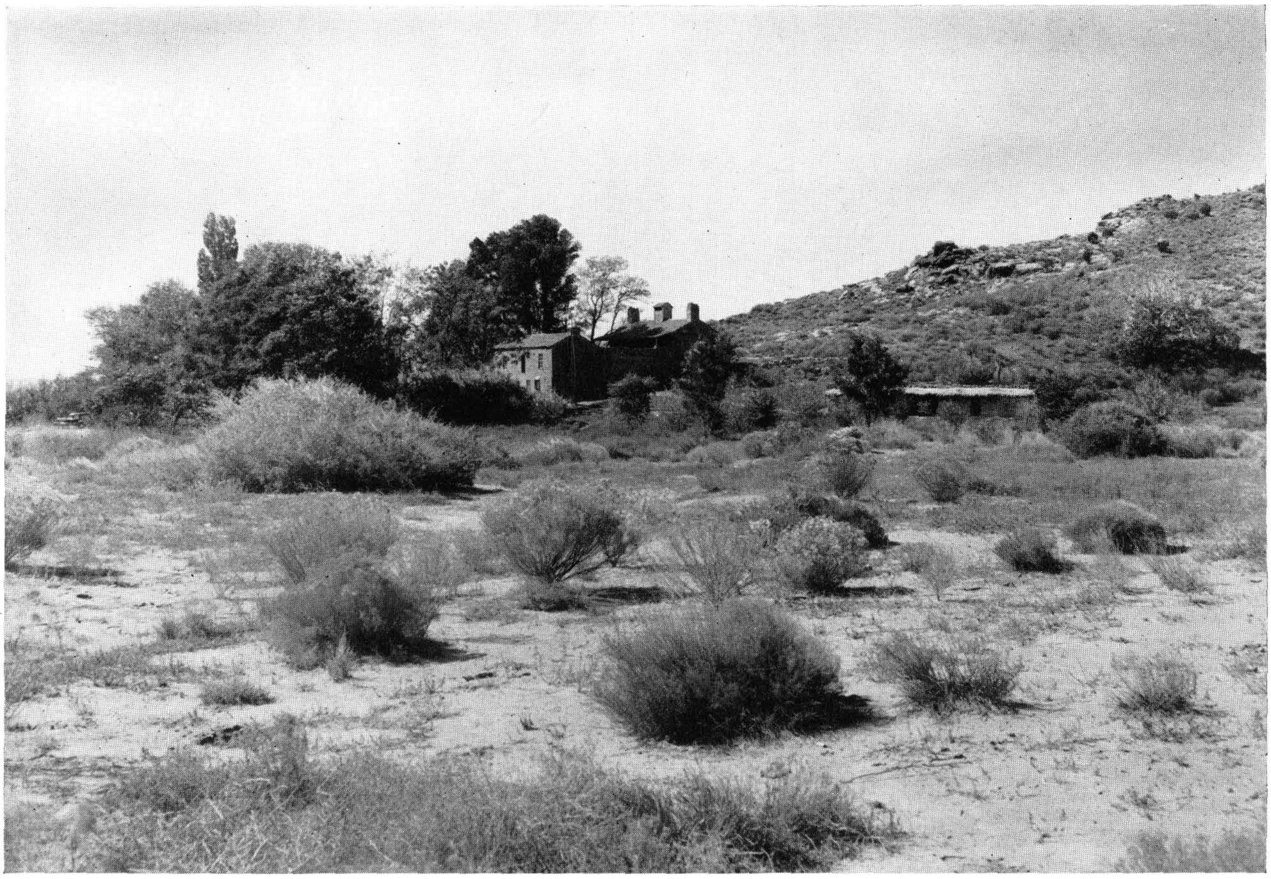

FIGURE 20.—"Winsor Castle" fort built in 1870, now headquarters of Pipe Spring National Monument. Spring on Sevier fault, which crosses flat ground in front of buildings.

H.E. Gregory 949

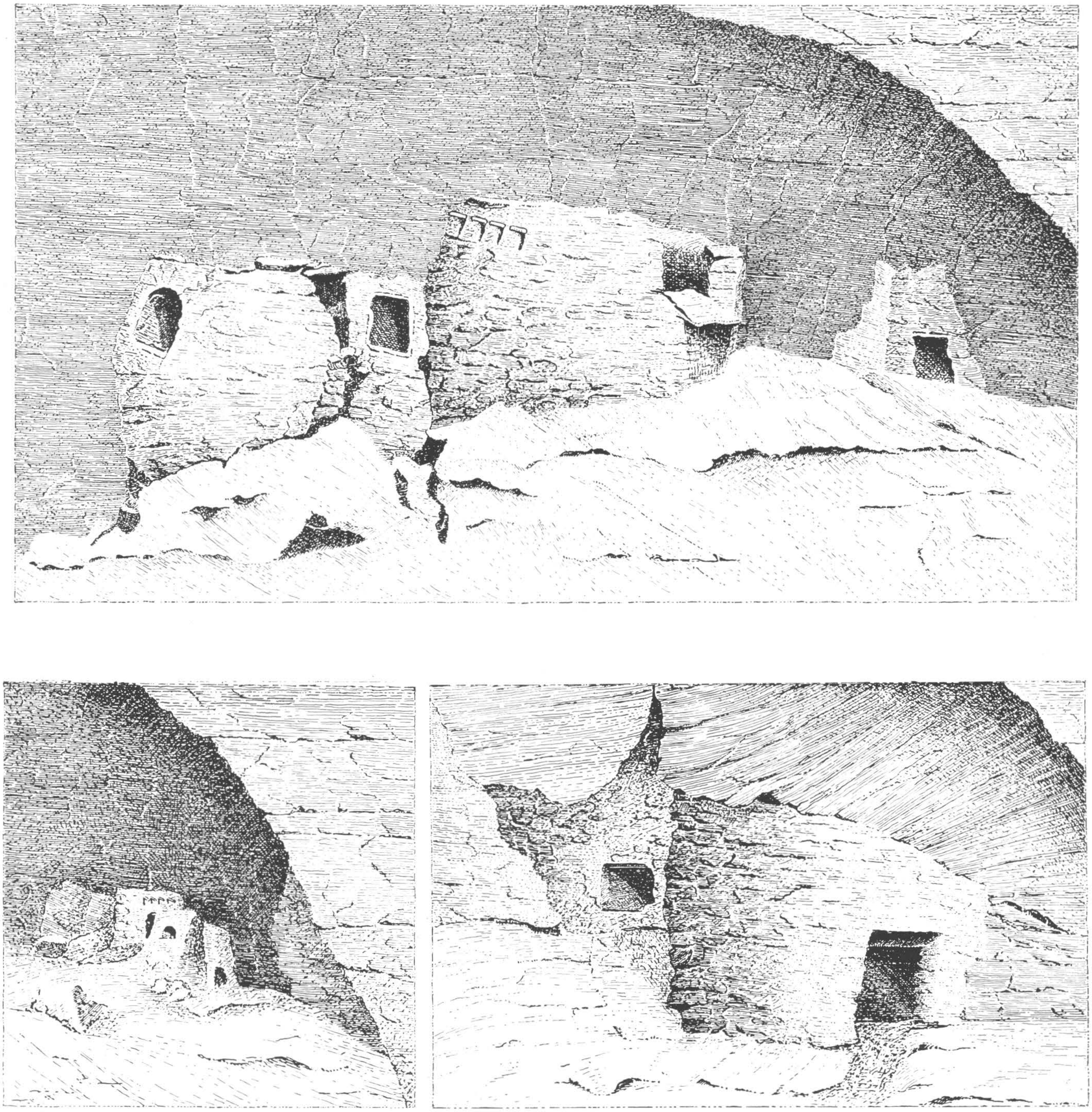

FIGURE 21.—Ruins of Pueblo houses in "caves" on wall of Parunuweap Canyon. Sketches by Elinor Stromberg.

Coronado, and those in the Virgin River Valley and on the Kanab and Uinkaret Plateaus in Utah and Arizona not more than 3,000. In 1854 the early missionaries to southwestern Utah found 250 Piutes "farming in a rude manner along the Santa Clara" and estimated the number of Indians within reach of the mission and under the noted chief Tutsegavit, as 800.[68] Snow[69] writes:

> The number of Indians who rendezvous on the Rio Virgin near this place [St. George] and higher up the stream is about 300 men, 150 women, and 300 to 400 children, nearly all of whom stay in the region all the year. These are all Pah Utes, more commonly called Pi-edes among us, and are split up into 8 or 10 bands.
>
> Besides these the She-bits, who live south and southeast from here in the Territory of Arizona, and the Ma-ah-pats, who live southwest, on the Muddy and near the mouth of the Rio Virgin, are in the habit of frequenting this section of country and often call on me for presents.

Wheeler (1872) estimated the Piute population of southern Utah and northern Arizona as 523, con-

[68] Bleak, J. G., Annals of southern Utah missions (manuscript, under dates July 7 and December 1854).

[69] Letter from Erastus Snow to Col. J. E. Fourtellotte, Superintendent Indian Affairs, July 14, 1870.

stituting 8 tribes, of which the Shivwits, the largest, numbered 284. The present population, about 80 Kaibabs and 96 Shivwits, are cared for by the Office of Indian Affairs on small reservations near Moccasin and Santa Clara. From this remnant of a vanishing race little can be learned. They well remember their misfortunes, but to most of them history and tradition seem matters of little consequence.

Knowledge of Piute culture comes from brief accounts of missionaries, trappers, traders, and scientific explorers and from miscellaneous reports by the early settlers preserved in diaries and records of the Mormon Church. In recent years the trustworthy fragments of Piute history, especially those relating to tribal organization and language, have been pieced together by Palmer.[70] A highly technical treatise on linguistics based on interviews with Toney Tillahashe, a Carlisle student, has been published by Sapir.[71]

The Kaibab clan of Piutes, the only Indians in the Zion Park region, now number about 80. They originally lived in House Rock Valley, Kanab Valley, and favored places along the base of the Kaibab Plateau and used the top of the plateau as a hunting ground. Except for occasional raids of the Navajos from the country south of the Colorado River they lived the peaceful, unambitious life characteristic of their tribe. When white men came these Piutes drifted toward the settlements at Johnson, Kanab, and Pipe Spring and made their home at Pa-it-spick-ine ("bubbling springs"), the present Moccasin Springs (Sand Springs). At first they were driven out but later were allowed to use water for the irrigation of a small tract. Their children were sent to school at Panguitch. In 1907 a reservation (12 by 18 miles) was set aside for their use as homes, garden plots, and cattle range.

Though the aboriginal Piutes lived close to nature, they developed adjustments to climate, to food supply, and to their fellow-men that made life tolerable and even pleasant. They could not, however, readjust themselves to the culture, mode of life, code of ethics, and the order of government of the white intruder. The winter settlements of the Indians, their summer camping grounds, and their favorite places for collecting seeds, roots, and nuts are abandoned, and their cultivated plots have passed to other hands; the little agriculture and stock raising they now carry on is planned and directed by white men.

WHITE MEN

POPULATION

The distribution and growth of the population of the Zion Park region are shown in the accompanying table, in which, except as otherwise noted, the figures are those given by the Bureau of the Census. Washington County, which includes not only the villages of Virgin, Grafton, Rockville, and Springdale, east of the Hurricane Cliffs, but also St. George (population 2,434), Hurricane (population 1,197), and 13 other settlements of considerable size, has shown a substantial growth in population. The 691 colonists listed in 1860 had become 3,064 in 1870 and thereafter slowly enlarged their number to 4,612 in 1900, then rapidly to about 9,000 in 1937. Only for the decade 1880–90, after the abandonment of the mining activities at Leeds, is a decrease recorded. For Kane County the fluctuation in population is noteworthy. The number of inhabitants in 1930 (2,235) is but 742 greater than in 1870, and about 300 less than in 1880; in 1910 it was less than in the preceding two decades.

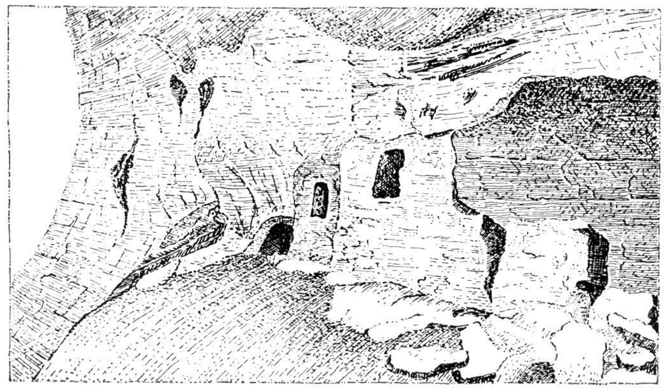

FIGURE 22.—Cliff houses in Cottonwood Canyon in a recess at base of Navajo sandstone. Sketch by Elinor Stromberg.

The distribution of population has likewise shown interesting changes. During the past half century, especially since 1900, the strictly rural districts and the more remote settlements have lost population. Many farms and ranches have been abandoned, and the occupants of small villages have moved into nearby larger villages or into more populous centers elsewhere in Utah. As self-contained economic units, many settlements were more prosperous and efficient in 1880 than at any subsequent time. Since 1900 Toquerville, Virgin, Grafton, Johnson, and Glendale have decreased in size and importance, while Springdale has tripled its population, and Hurricane has developed from a ranch to a village of more than 1,000 inhabitants. In 1880, when Kane County had its greatest population, Kanab contained about 17 percent of the total; in 1900, 30 percent; and in 1930, more than 50 percent.

The population of Kane County, 2,235 (0.5 to the square mile); of Washington County, 7,420 (3 to the square mile); and of Arizona north of the Grand Canyon, 540 (?) (about 0.001 to the square mile), seems small for an agricultural and grazing region settled 60 years ago by an unusually industrious people, little interested in luxurious living, but it

[70] Palmer, W. R., Utah Indians, past and present: Utah Hist. Quart., vol. 1, pp. 35–52, 1928.

[71] Sapir, Edward, Southern Paiute, a Shoshonean language: Am. Acad. Arts Sci. Proc., vol. 65, pp. 1–730, 1930.

adequately represents the "carrying capacity" of southwestern Utah. As the resources of the region are barely able to support the present population, the rate of increase is slowing down. For Kane County the percentage of increase for the decade 1910–20 was 24.3 percent; for 1920–30, 8.8 percent. For Washington County the corresponding figures are 32 percent and 9.7 percent.

From 1851 to 1880, by which time Kane and Washington Counties had received about 77 percent of their present population, immigration was the dominant factor. Since that time emigration has more than offset immigration; the population has been maintained by natural increase—excess of births over deaths—which for southern Utah is about twice that for the United States as a whole. Most of the families are large, and in consequence the percentage in all age groups below 25 years is abnormal.

Like that of other parts of rural Utah, the population of the Zion Park region is strongly marked by race purity and physical vigor. It is almost wholly Nordic—descendants of immigrants from Great Britain, Ireland, Scandinavia, Germany, and Switzerland. To a remarkable extent the present inhabitants are the descendants of the pioneer settlers, and the families of each village are related through marriage. As given in the census for 1930, the population of Kane County (2,235) comprised 2,187 "native-born whites," 44 "foreign-born whites"—all but 2 from northern Europe—and 4 "others." The population of Washington County (7,420) included 82 "others." In fact the entire population of Utah in 1930 (507,847) included only 8,681 "nonwhites."

In the Zion Park region the population is almost wholly restricted to villages surrounded by large areas without settlements. Continuously occupied homesteads along country roads and isolated ranches, characteristic of most agricultural and pastoral regions, are exceedingly rare. Except in the closely spaced tiny settlements of Short Creek and Cane Beds only five families reside along the road from Hurricane to Fredonia (58 miles). One family maintains a permanent home on the Springdale-Mount Carmel road (26 miles), and two families in Kanab Valley between Kanab and Alton (about 35 miles). The farmer lives on a town lot, which constitutes his garden and orchard, and goes back and forth to his dry land or irrigated tract at various distances and directions from home. During planting and harvesting seasons he may camp some days at his fields.

Population of Zion Park region, 1860–1937

Settlement	1860	1870	1880	1890	1900	1910	1920	1930	1937
Virgin (1858)	79	[1,2] 336	254	213	269	136	212	202	170
Mountain Dell (1859)	[2] 33	30	12	6	----	----	----	----	----
Duncans Retreat (1861)	[1,2] 50	47	13?	[2] 6	----	----	----	----	----
Grafton (1859)	----	[1,2] 168	71	104	98	106	46	23	19
Rockville (1861)	[1] 70	[1,2] 95	232	194	214	189	208	361	330
Shunesburg (1861)	----	[1,2] 45	36?	[2] 51	8?	----	----	----	----
Northrup (1861)	----	[1,2] 17	14	8	12?	[2] 4	----	----	----
Springdale (1862)	----	[1] 54	50	73	144	186	204	351	456
Little Zion (1861)	----	6?	[2] 14	20?	16?	----	----	----	----
Mount Carmel (1864)	----	200? (1871)	137	122	137	131	143	133	175
Orderville (1875)	----	----	514	[2] 429	418	380	378	439	494
Glendale (1864)	38 (1865)	----	338	[2] 264	319	244	250	239	270
Graham: Ranch P.O. (1865)	([3])	([3])	30?	30?	----	----	----	----	25?
Kanab (1864; 1867)	----	[2,4] 73	394	[2] 572	710	733	1,102	1,195	1,215
Upper Kanab (1872), Alton (1908)	----	----	106	[2] 110	[2] 91	98	169	193	224
Short Creek (1862)	----	----	----	----	----	----	36	[7] 61	180?
Cane Beds (1868)	----	----	----	----	----	5	42	40?	36
Moccasin (1865)	----	([5])	([5])	([5])	([5])	----	----	----	77
Fredonia (1868)	----	----	----	[6] 96	[2] 178	175	210	254	210
Johnson (1871)	----	----	87	[2] 104	[2] 62	66	12	5	----

[1] Church census, July 1864.
[2] Records of the Church of Jesus Christ of Latter Day Saints.
[3] Reported as 14 in 1865 and 34 in 1872; since 1900, farm population classed as part of Alton.
[4] Reported as 299 in 1872.
[5] Reported as "10 families," 1870–90; "3 families," 1890–1910.
[6] Church census records 216 in 1895.
[7] In 1931–35 population increased by 110 families (114 persons) members of a Mormon sect who practiced polygamy.

The stockmen likewise live in the villages, but during the summer many of them establish wagon camps or occupy cabins on the Kolob Terrace and Skutumpah Terrace, on Block Mesas, Big Plains, and at other "herd grounds," where their flocks may receive closer attention. Essentially life in Kane County and eastern Washington County is that on oases where large expanses of partly utilized land contribute to the support of small, rather compact settlements. This grouping of the population, in part the necessary result of geographic factors and in part deliberately planned, brings to these rural communities certain social, educational, and economic advantages otherwise possible only in urban centers.

INDUSTRIES

AGRICULTURE AND HORTICULTURE

The history of agriculture in the Zion Park region begins with cultivation by Basket Makers of corn and beans as foods supplementary to grass seeds, piñon nuts, and the edible parts of such plants as the agave and cactus. The early Pueblo clans added squash to the list of food plants and also introduced cotton. Corncobs form part of the debris at nearly all ruins examined, and in places whole ears of corn have been preserved. From a cliff ruin southwest of St. George a loaf of "fossil bread" made from flour of mesquite beans was taken by Nelson Empey about 1928. Among the artifacts in Johnson Canyon are wooden "shovels" suitable for planting, cutting weeds, or digging ditches. On coming to Utah the Piutes adopted the Puebloan type of agriculture, but with less skill and smaller acreage. They cultivated many irrigated plots of 2 to 5 acres along the Virgin River, North, Kanab, Johnson, and Cottonwood Creeks, in Long Valley, at Short Creek, Moccasin, and elsewhere about springs and on the floors of canyons. These ancient farms close to streams and springs are the sites of the present agricultural fields, but white men have been able to enlarge them by bringing water to adjoining bench lands and to increase their yields by more extensive and more skillful use of water and by better tillage.

In the Zion Park region, modern farming began at Virgin in 1859 with the construction of an irrigation ditch to water a few acres of bottom land on which general farm crops were raised. Later immigrants to the Virgin Valley came with the intention of raising cotton on a commercial scale in the hope that the income from its export would sustain a considerable population. They soon learned that cotton growing yielded no adequate returns, even at Civil War prices, that they must raise their own cereals, fruit, and garden crops, and that the only marketable export was livestock, pastured on the surrounding highlands. The experience of the farming communities in Parunuweap, Kanab, and Johnson Valleys was in accord with that gained in the Virgin Valley. The raising of food crops became a secondary industry, and much of the land suitable for wheat, corn, and potatoes was utilized for forage crops, supplementing the range. In Utah as a whole the acreage given to hay crops is three times that of wheat and seventy times that of corn. Alfalfa occupies 82 percent of the cropped lands.

In the Colorado Plateau province the area of land available for irrigation farming is remarkably small. For Utah the State Board of Agriculture lists 3.5 percent of cultivated land, and estimates that "only 5 percent of the area will ever yield to cultivation, either by irrigation or dry farming." The remaining 95 percent is excluded by aridity or broken topography. In Washington County 2.5 percent of the area is under cultivation; in Kane County 0.25 percent.

Of the 2,698,000 acres of land in Kane County only 5,000 acres is irrigated. For Washington County the corresponding figures are 1,578,000 and 28,000. In the Zion Park region irrigated lands comprise only the narrow strips of alluvial soils in the larger valleys and a few isolated spots on benchlands and low mesas. The estimated area under ditch in 1937 was 6,470 acres; in Upper Virgin Valley, 600; Long Valley, 1,800; lower Kanab Valley, 2,000; Upper Kanab (Alton) region, including Sink Valley, 1,200; Johnson Valley, 670; Moccasin and Short Creek, 200. These irrigated areas are substantially those cultivated 50 years ago, when water during the growing season was brought to all lands within practicable reach. Increase would involve the construction of dams to impound summer flood waters and winter flows, at costs disproportionate to the value of the lands.

To maintain this small but essential area in cultivation is an endless, wearisome task. In most years the streams are at low-water stage from mid-June to mid-September, and as this is the critical period of growth for field crops, agriculture is limited to areas that can be irrigated in midsummer. But the work of the irrigation farmer is seriously hampered by summer floods, which come frequently and with little warning. The steep gradients that make practicable the diversion of water to benchlands in short distances also convert the swollen streams into torrents. Earth dams and inexpensive rock dams are ineffective, and the cost of large concrete structures is prohibitive. In practice after each flood a new intake dam of earth, sand bags, and brush is built, and the ditches are cleaned of flood-borne silts. In most settlements the irrigation system is community property, and led by the indispensable "water master" the able-bodied men respond to the call to "get the water in the ditch." When floods scour the stream bed below the intake, new ditches must be dug or the fields abandoned.

Dry farming on benches, mesa lands, and alluvial fans outside the narrow valleys is a profitable industry in favorable years. On Big Plains and the adjoining Little Plains and Rattlesnake Flats, where about 5,000 acres is considered suitable for wheat, 400 to 600 acres is planted each year. In 1914 a town site was laid out in this area and supplied with water from a 4-mile pipe line heading in Little Creek Spring. On Smith Mesa about 1,700 acres is listed as "nonirrigated crop land." At Short Creek, Cane Beds, and Antelope Springs and in upper Johnson Valley, most of the small acreage is in dry farms, and on the eastern Kolob and the western Skutumpah Terraces about half the scattered farms are watered only by rains and melting snows. In the vicinity of Kanab, Fredonia, and Alton several thousand acres of dry land has been intermittently cultivated.

In Kane County, as recorded for 1932,[72] dry-farming land comprised 4,000 acres and nonirrigated forage-crop land 4,000 acres; in Washington County the corresponding figures were 3,000 and 11,000 acres. The present acreage of dry farms is estimated as one-third of that cultivated from time to time during the past 30 years.

In general, dry farming has proved to be speculative. During years when the rainfall is sufficient 8 to 25 bushels of wheat to the acre is harvested, but inadequate rainfall during any month of the growing season is disastrous.

Generally throughout the Zion Park region wheat, corn, oats, and alfalfa yield satisfactory returns, and garden crops and some fruits do well. At the lower altitudes along the Virgin River, apples, peaches, apricots and even such semitropical fruits as figs, pomegranates, and almonds reach maturity. Hurricane and La Verkin are commercial fruit centers. About Alton, rye and barley are successfully grown, and potatoes, lettuce, cabbage, and cauliflower attain record yields. In 1919 a farm in Sink Valley produced 825 bushels of potatoes an acre.

STOCK RAISING

Like other parts of rural Utah, the Zion Park region is essentially a grazing district; the villages serve primarily as homes and supply points for stockmen. The chief business of farms and ranches is to supply winter feed for cattle, horses, sheep, and goats; of the national forests, to provide forage during a restricted summer season. In fact, nearly all the lands of Utah and the adjoining parts of Arizona and Nevada are used for grazing stock. Utah ranks second nationally as a producer of mutton and wool, and the sale of livestock, livestock products, and feed for livestock constitutes about 60 percent of the gross farm income.

Of 2,698,000 acres in Kane County, 2,685,000 acres, including national forests, is grazing land. In Washington County 1,435,000 acres of a total 1,578,000 acres is available for grazing; and of about 12,000,000 acres in the Arizona strip, only a few small farms and the Grand Canyon National Park are excluded. In addition to these vast range lands, about two-thirds of the farm lands and fenced pastures of Utah and northern Arizona are given to forage crops, of which alfalfa forms 82 percent.

Incomplete census returns for the last 50 years show wide fluctuations in the number and value of livestock pastured in the Zion Park region. In Kane and Washington Counties there was a rapid increase in both sheep and cattle from 1880 to a maximum in 1900–1905. In the Arizona strip the maximum was reached a few years later, followed by a rapid decline. A second large increase in cattle was again shown for several years after the World War. The maximum production of sheep is recorded for the years 1901–3 and 1909–10; of Angora goats for 1920. For Kane County the livestock credited to farms and ranches during the years 1900–35 is shown in the following table:

	1900	1910	1920	1925	1930	1935
Cattle	7, 697	13, 157	14, 300	6, 451	10, 102	7, 725
Sheep	59, 199	106, 534	98, 350	46, 880	55, 321	80, 346
Goats	6	10, 087	17, 498	9, 700	13, 667	15, 000

As grazing has always been the primary industry of the lands north of the Grand Canyon, its story is replete with interest. The evidence is conclusive that during the period 1850–80 grass and other succulent herbage were abundant on the High Plateaus and along their southern rims, and that ample forage, conveniently placed springs, small streams and water holes, and a climate that permitted a long grazing season combined to make of the Zion Park region one of the best areas of free range in America.

In their pioneer travels (1852) John D. Lee and his companions found the Markagunt Plateau, Long Valley, Block Mesas, and the base of the Vermilion Cliffs "delightful places" of water and grass. In 1863 Levi Savage reported "grass knee deep" in Kanab Valley. In 1864 the floor of Zion Canyon was a rich meadowland with many beavers. In 1869 Edwin G. Woolley said of Pipe Spring, "This is the best stock range in the South. The country west from here thirty miles or more is a sea of grass; and running northeast from this point some 30 miles is the same." In 1872 Thompson found grass thick in the Paria

[72] Deeds, J. F., and Falck, Depue, Land-classification report for Utah: U. S. Geol. Survey, 1932. (Mimeographed.)

Valley and all about the Kaibab Plateau, Pipe Spring, Johnson, Skutumpah, and Glendale; and Powell camped in "beautiful meadows" at Upper Kanab.

In the days of the early pioneers the grass was so plentiful that milch cows and even small herds of beef cattle were pastured near the settlements and returned to corrals at night. As the number of cattle increased and the local forage became less abundant, herd grounds were selected on nearby highlands in summer and in the valleys and plains in winter, and the same ground might be occupied each year. With additional increase in cattle and the introduction of sheep, which further depleted the home ranges, distant new ranges were found, but not before the older ranges had been seriously damaged, especially in the vicinity of water holes.

Dutton[73] saw the beginning of the devastation that changed the lands of "good grass and herbage" into lands nearly barren of palatable forage:

> Pipe Spring is situated at the foot of the southernmost promontory of the Vermilion Cliffs and is famous throughout southern Utah as a watering place. * * * Ten years ago the desert spaces outspreading to the southward were covered with abundant grasses, affording rich pasturage to horses and cattle. Today hardly a blade of grass is to be found within ten miles of the spring, unless upon the crags and mesas of the Vermilion Cliffs behind it.

By 1880 the larger well-grassed areas of range land had been fully stocked, and within a few years less desirable lands were brought into use. At the same time zones devoid of palatable vegetation about settlements, springs, water pockets, and streams were increasing in size and number. Under these conditions the drought of 1896–1900 was a major range catastrophe. As the forage on used lands became less abundant and water supplies failed, space for cattle and sheep necessarily was sought by building trails to grass otherwise inaccessible, and the dwindling water supplies were augmented by making reservoirs and developing seeps not previously used. Competition for forage and water was keen, and despite the most strenuous efforts nearly half the stock died from thirst or starvation.

With the return of more normal years stock raising expanded to its maximum (1900–1914) but under changed conditions. Individual owners of many small herds were replaced by incorporated companies with capital sufficient to restock the ranges and to develop adequate water supplies. But the new prosperity was short-lived. Sheep in large numbers were introduced, and these animals, moving with the season from place to place as forage and water were most suitable, made systematic range management impracticable. In particular, the spring range soon became deficient and the competition between owners of large and small herds of cattle and between cattlemen and sheepmen again became bitter. Relief came with the establishing of national forests (1903) providing excellent summer range for a restricted number of cattle and sheep, but the increased pasturage in forests was in large part offset by the introduction of Angora goats and their rapid increase. Furthermore, the forests afforded no relief from overgrazing during spring and fall. Outside the forests in favorable years stock fares reasonably well. They graze on the highlands in summer, on the foothills in spring and fall, and on the lower desert areas in winter. But in years of heavy snowfall, and in such dry years as 1919, 1924, 1928, and 1933, conditions are desperate. Because of their restricted movement many cattle die during winters when forage is buried in snow, and during the spring of dry seasons the sheep find little or no palatable feed. At the present time 5 to 10 percent of the stock in Kane County is fed on pasturage 4 to 6 months a year. Improved conditions are anticipated from the recent establishment of Federal grazing districts, designed to restrict grazing lands to their carrying capacity and to permit recuperation.

Though the forage on unappropriated public lands is now deficient, it is still much in demand, as the cost of feeding an animal on harvested crops is four to eight times that on the open range. Fortunately the native forage is nutritious. In this semiarid region the grasses are but slightly decomposed by rain and snow. The scattered bunches stand throughout the winter and "cure" on the ground. It is interesting to note that, because of heavy grazing, sagebrush has greatly increased in some areas since human occupation. On foothills, benches, and plateau tops it has to a large extent replaced the grasses that during the period of pioneer settlement (1850–80) made southern Utah an excellent grazing district.

MINING

Except for the Silver Reef district, at Leeds, which during its brief, spectacular life produced ore to a value of about $9,000,000, mining has played little part in the development of southwestern Utah. In Washington County the cost of treatment and marketing made the considerable deposits of copper at Tutsagubut unprofitable, the gold and arsenic "mines" at Goldstrike in the Bull Valley region have yielded little of value, and prospecting for a second "Silver Reef" in the sandstones of the Virgin River Valley has been futile. In Iron County, likewise, the gold and silver "mines" at State Line and Gold Hill and about the northwest base of the Pine Valley Mountains hold no commercial interest.

At present the mineral resources exploited in southwestern Utah are iron, coal, and oil. The Iron

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[73] Dutton, C. E., Tertiary history of the Grand Canyon district: U. S. Geol. Survey Mon. 2, pp. 78–79, 1882.

Springs district, which produces most of the iron mined in the United States west of the Rocky Mountains, ships annually some 300,000 tons of ore to Provo for smelting. Smaller deposits similar to those at Iron Springs have been prospected in the Bull Valley region but have not become productive. "Coal land" with a workable body of coal estimated as 2,600,000,000 tons forms a belt along the front of the Markagunt and Paunsaugunt Plateaus and eastward nearly to Glen Canyon. Oil in small amounts is obtained from a few wells in the Virgin oil field on North Creek. More than 100 other wells in this field, also wells near Grafton and Antelope Springs and east of Harrisburg, Washington, and St. George, have not been commercially productive. (See p. 190.)

OTHER INDUSTRIES

Sawmills on the Markagunt Plateau, on eastern Kolob Terrace, in the Parunuweap Valley, and at Alton are operated intermittently, and the coal mines in Meadow Brook Valley, at Mount Carmel, and at Glendale provide seasonal work for a few men. Since 1930, when access to the scenic areas of southern Utah was made practicable for automobiles, the income from tourists has been added to that from crops and livestock. In payments for labor and supplies the National Park Service, Bureau of Public Roads, and other Federal and State bureaus have contributed much to the new prosperity that has come to the Zion Park region, especially to Springdale, Orderville, and Kanab.

SEDIMENTARY ROCKS

GENERAL STRATIGRAPHIC RELATIONS

The consolidated sedimentary rocks in the Zion Park region are grouped in the Permian, Triassic, Jurassic, Cretaceous, and Tertiary systems; the unconsolidated deposits in the Quaternary (Pleistocene and Recent series). They include marine, brackish-water, and fresh-water deposits. (See pl. 2.)

By far the most abundant rock is sandstone. Massive sandstone forms most of the wide rock platforms and innumerable steps and shelves on slopes. Except in the Shinarump and Dakota (?) formations the sandstone is prevailingly fine or medium grained. Most of the beds roughly classed as "shales" are in reality thin beds of very fine grained sandstone; true clay shale is rare. Likewise much of the "limestone" might as appropriately be classed as "calcareous sandstone." Gypsum is a conspicuous part of the Entrada and the Curtis formations.

To a remarkable degree the major stratigraphic units in this region are also topographic units. (See pl. 4; figs. 7, 23, 24, 25, 36.)

Powell's classification of the great pile of sediments that rise above the Grand Canyon platform as Chocolate Cliffs, Vermilion Cliffs, White Cliffs, Gray Cliffs, and Pink Cliffs is a record not only of color bands and escarpments but also, roughly, of the age and origin of some 10,000 feet of Mesozoic and Eocene strata. Dutton long ago pointed out that the larger groups of sandstones in Utah are distinctive in color and architectural forms and that in distant views and near views their gross composition and structure are unmistakable. He also stressed the continuity of beds without significant change in character—"homogeneity in horizontal range, with great heterogeneity in vertical range."[74] More recent field studies corroborate the view that, at least superficially and en masse, "the beds are remarkable for their homogeneity and constancy over vast areas" but also show wide variations in extent, distribution, and stratigraphic position.

Some of the formations in the Zion Park region retain their individuality wherever exposed in southern Utah, northern Arizona, western New Mexico, southwestern Colorado, and southeastern Nevada; in fact, some of them are approximately coextensive with the Colorado Plateau province. Others increase and decrease in thickness, lose or add definable members, and undergo marked changes in composition and texture. Thus the Navajo sandstone, which has been traced almost continuously across Utah and into Nevada and Arizona, shows everywhere closely similar lithologic character and topographic form, but its companions, the Wingate and Kayenta formations, in the Glen Canyon group, disappear in the Virgin River Valley; the Dakota (?), elsewhere a prominent cliff maker, is represented in the Parunuweap Valley by a thin black band of poorly consolidated pebbles; the Moenkopi in Timpoweap Canyon and in Little Creek and Short Creek Valleys includes beds of fossiliferous limestone, and the Chinle, in the Vermilion Cliffs, great thicknesses of sandstone not found at their type localities; the Morrison, prominent in southeastern Utah, is absent from the Zion Park region; the inconspicuous sandy Carmel of the San Juan country becomes a thick sequence of limestone on the Kolob Terrace; and the Eocene gray sandstone of western New Mexico is replaced in southwestern Utah by the pink limestone of the High Plateaus.

The unconformities that separate the groups of strata assigned to different ages present some unusual features. Some of them that are believed to mark a considerable lapse of time appear merely as division planes between beds representing two types of sedimentation. Others are surfaces of feeble erosion, and the most reliable proofs of unconformity—discordance in dip, profound erosion, and abrupt change in fauna—can not be generally applied. Over

[74] Dutton, C. E., Tertiary history of the grand Canyon district: U. S. Geol. Survey Mon. 2, p. 7, 1882.

FIGURE 23.—General view northward from Dutton Pass across Virgin River (middle distance) to "Towers and Temples of the Virgin" terminating in West Temple (top center). Eagle Crags overlooking Parunuweap Canyon (extreme right), Smithsonian Butte (extreme left), Zion Canyon lies at right and beyond West Temple. Sketch by W. H. Holmes, 1872, reproduced from Dutton.

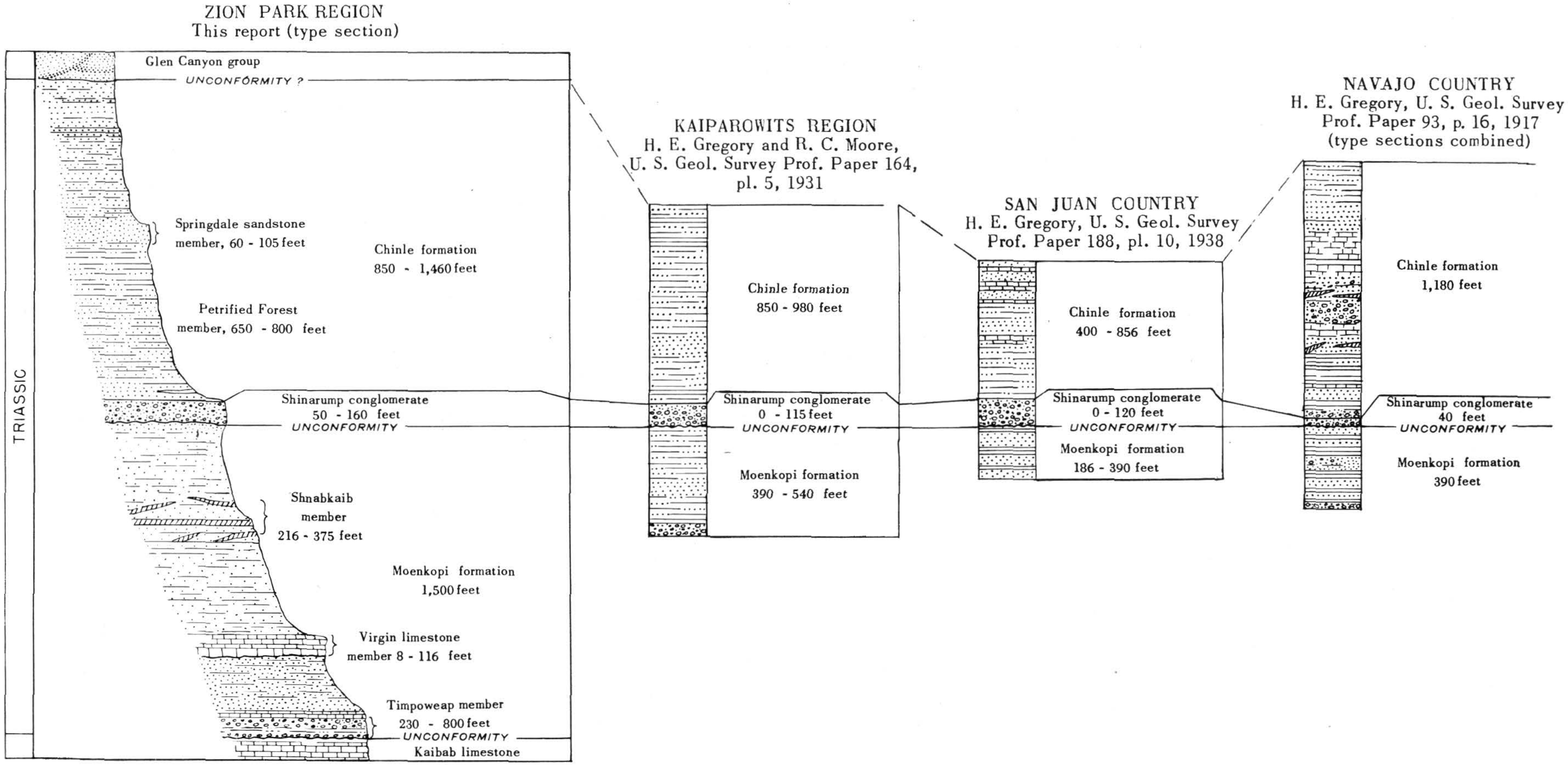


FIGURE 24.—Sections of Triassic rocks in Zion Park and adjoining regions.

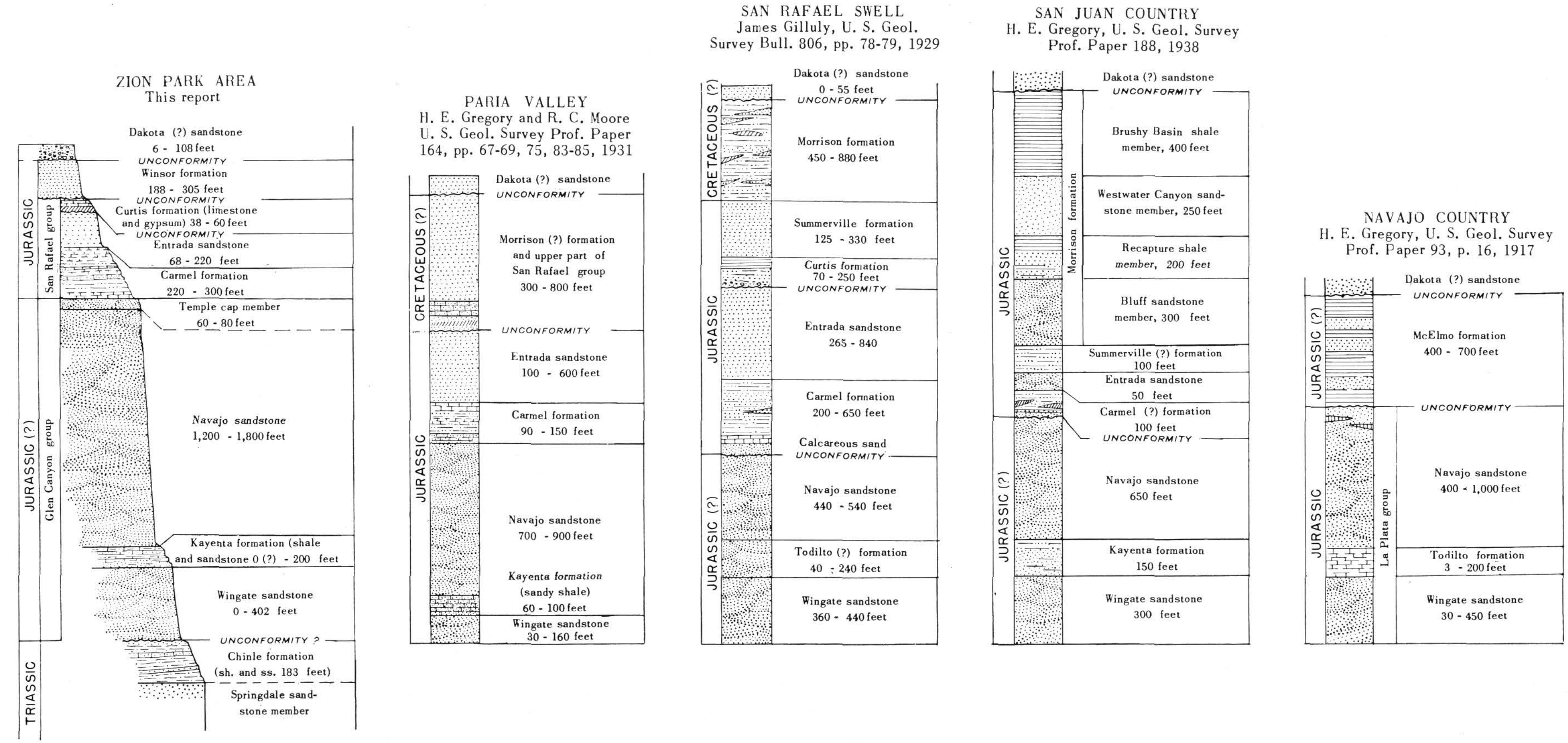


FIGURE 25.—Sections of Jurassic rocks in Zion Park and adjoining regions.

wide areas the beds below and those above planes of unconformity have the same attitude; hollows of erosion in the underlying beds are local and generally shallow; and in few places do the beds immediately above and below contain diagnostic fossils. The evidence is further confused by the presence of many local unconformities. Strongly contrasted types of unconformity appear as the division planes between the Wasatch (Eocene) and the Kaiparowits (Cretaceous), between the Carmel (Jurassic) and the Navajo (Jurassic?), and between the Moenkopi (Triassic) and the Kaibab (Permian). The beds of the Kaiparowits formation were channeled, beveled, and in some places entirely removed before the deposition of the Wasatch. On the other hand, the fossiliferous beds of the marine Carmel lie nearly flat upon the desert-made Navajo sandstone; and the faunally distinct Moenkopi and Kaibab meet in a series of beds unformable among themselves but not terminated above or below by unconformities of wide extent.

Gilbert[75] and Dutton[76] thought that the Mesozoic formations of the plateau country were prevailing marine and that the few unconformities noted were normal features of oceanic and near-shore deposition.

In contrast with these views it now appears that most of the sedimentary rocks in the Zion Park region are terrestrial—eolian, fluviatile, and lacustrine—and that their interpretation relates not so much to their origin as to their structure. The evidence seems conclusive that nearly all the beds were deposited on surfaces of very slight relief and remained vertically parallel and substantially horizontal during intermittently progressive sinking and elevation for some 200,000,000 years. On such surfaces great erosion incident to mountainous landscapes was impossible, and the time intervals between the periods of deposition of successive beds, though great, might be represented by inconspicuous unconformities.

In the correlation of the formations of the Zion Park region with those in other parts of the plateau province the marine beds may be treated with reasonable confidence, though regionally they present considerable differences in lithic features and arrangement of bedding. The ages of the Kaibab (Permian), the Moenkopi (Lower Triassic), the Carmel and Curtis (Jurassic), the Tropic and Straight Cliffs (Cretaceous) have been determined by marine invertebrates. The age of the Shinarump and Chinle (Upper Triassic), and Kaiparowits (Cretaceous), and the Wasatch (Eocene) has been acceptably established by nonmarine fossils. For the other formations the evidence from fossil plants, dinosaur bones and tracks, and long-lived species of land shells is too meager to establish more than broad time zones, and the lithologic features of several of the formations are closely similar. Fortunately the terrestrial beds are so widely exposed that it has been found practicable to trace with few intervals the Moenkopi, Shinarump, Chinle, Wingate, Kayenta, and Navajo from their type localities on the Navajo Reservation to the Virgin River Valley and the Dakota (?) and Kaiparowits from the rim of Glen Canyon to the Hurricane Cliffs. Even with these observations, supplemented by scores of measured sections, some of the correlations rest largely on impressions gained during many years of field work in Utah and adjoining States and, though not subject to detailed proof, are believed to be substantially correct.

Three correlation papers[77] on the Mesozoic, particularly the Jurassic, include material pertinent to the Zion Park region. Though generalized and necessarily in large part theoretical, they take into account much of the evidence derived from field studies as known at the time of their publication. The paper by Baker and others has been found particularly helpful, inasmuch as it is based on recent mapping in eastern Utah, where several formations are equivalent to those in southwestern Utah.

The stratigraphic features of the formations represented in the Zion Park region are summarized in the table (pp. 51–52). (See also columnar sections on plate 5.)

PERMIAN FORMATIONS

KAIBAB LIMESTONE

LITHOLOGIC FEATURES

Sedimentary rocks of known Permian age in the Zion Park region constitute the Kaibab limestone (†Aubrey limestone).[78] A yellow and white bedded sandstone 10 to 70 feet thick exposed at Rock Canyon and elsewhere along the base of Hurricane Cliffs may represent the Coconino but more likely is basal Kaibab, thus duplicating features in sections measured in the Kanab and Paria Valleys, the Muddy Mountains, and the Waterpocket Fold. The Kaibab is exposed along the front and in places the crest and the immediate back slopes of the Hurricane Cliffs and in canyons tributary to the Virgin River and Ash Creek. In positions favorable for study it appears in the walls of Rock Canyon of Short Creek, Gould Canyon of Little Creek, and Timpoweap Canyon of the Virgin River. (See figs. 26, 27.) South and southeast

[75] Gilbert, G. K., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 187, 1875.

[76] Dutton, C. E., U. S. Geol. Survey 6th Ann. Rept., p. 185, 1885.

[77] Lee, W. T., Early Mesozoic physiography of the southern Rocky Mountains: Smithsonian Inst. Misc. Coll., vol. 69, no. 4, 1918. Crickmay, C. H., Jurassic history of North America—its bearing on the development of continental structure: Am. Philos. Soc. Proc., vol. 70, no. 1, 1931. Baker, A. A., Dane, C. H., and Reeside, J. B. Jr., Correlation of the Jurassic formations of parts of Utah, Arizona, New Mexico, and Colorado: U. S. Geol. Survey Prof. Paper 183, 1936.

[78] A dagger (†) preceding a geologic name indicates that the name has been abandoned or rejected for use in classification in publications of the Geological Survey.

of these exposures it constitutes the prevailing surface rock on both sides of the Colorado River in its course through Marble and Grand Canyons. In a sense the Kaibab of the Uinkaret, Kanab, and Kaibab plateaus is the broad platform on which rests the buttresses, towers, and terraces of Mesozoic rocks developed along the rim of the High Plateaus of Utah.

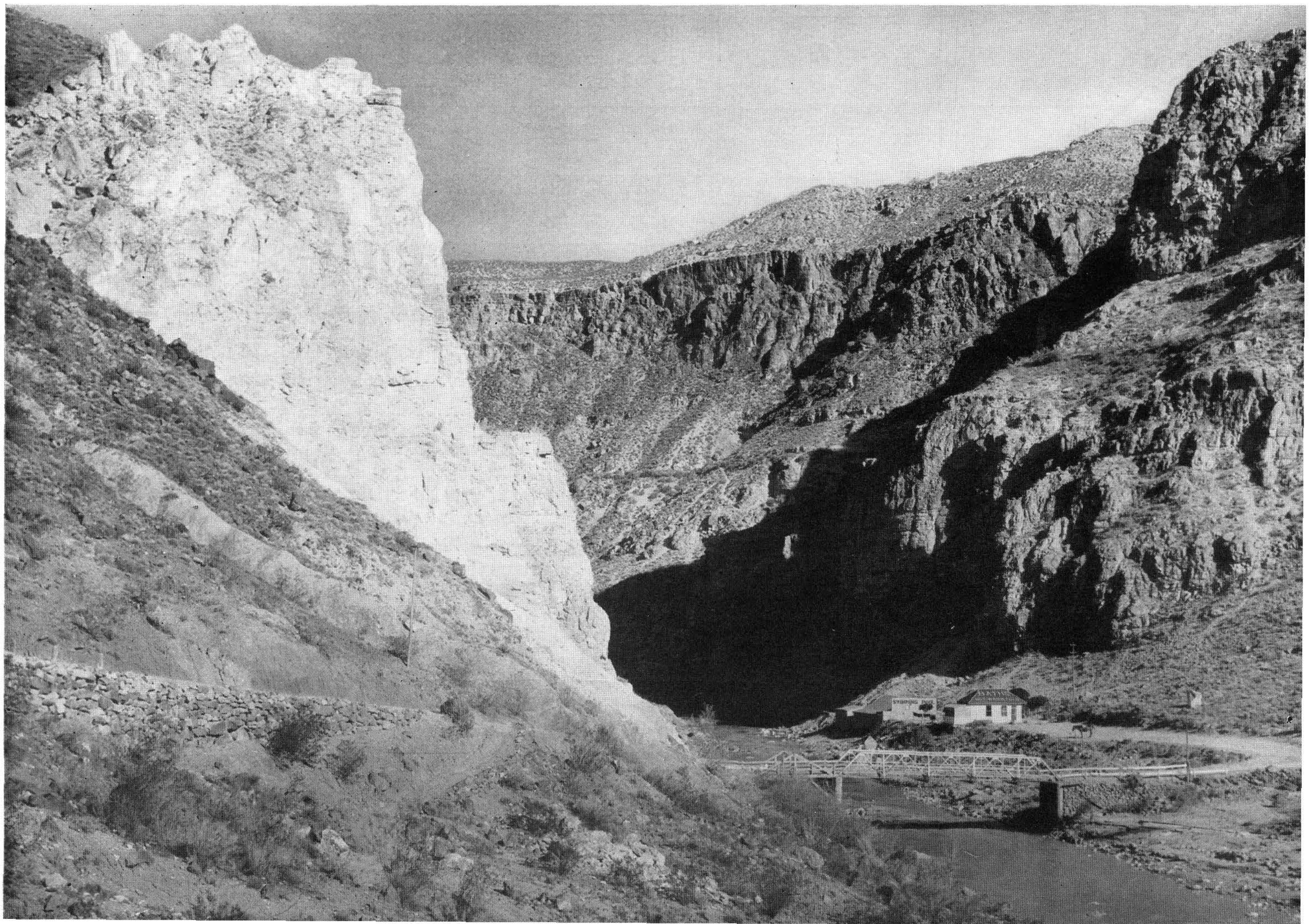
Because of its wide exposure, its role as a maker of cliffs, and its prominence in the Colorado canyons, the Kaibab has received attention in all surveys of the plateau province. It has been mapped in Arizona, Utah, and Nevada by Newberry, by the Wheeler and Powell surveys, and by many geologists of the United States Geological Survey. Standard sections have

Generalized section of the rock formations in the Zion Park region, Utah

System	Series	Group and formation	Character	Thickness (feet)
Tertiary.	Eocene.	Wasatch formation.	Limestone and calcareous sandstone, pink, white, and varicolored; soft; conglomeratic at the base; fresh-water deposit; forms cliffs bordering the High Plateaus.	200+
		–Unconformity		
Cretaceous.	Upper Cretaceous.	Kaiparowits formation.	Bluish-drab, fine- to moderately coarse grained arkosic sandstone and sandy shale, with a weak calcareous cement; forms slopes and badlands; plants, vertebrates, and fresh- and brackish-water shells.	600–750
		–Unconformity		
		Wahweap and Straight Cliffs sandstones.	Buff, gray, and yellow massive sanstone in thick and thin, hard and soft, irregular beds; subordinate calcareous, carbonaceous, and argillaceous shale; marine and brackish-water fossils; forms a series of escarpments.	600–1, 200
		–Unconformity		
		Tropic formation.	Drab, sandy, argillaceous, calcareous; many beds of sandstone, more abundant in lower part; beds of coal; marine, brackish-water, and fresh-water fossils; forms broken slopes and badlands.	400–1, 250
		Dakota(?) sandstone.	Yellow to nearly white sandstone; conglomeratic in part; irregularly bedded; contains thin beds of coal and large silicified trees in places.	6–100
		–Unconformity		
Jurassic.	Upper Jurassic.	Winsor formation.	White and red-banded, fine-grained, even-bedded sandstone.	180–300
		–Unconformity		
		San Rafael group: Curtis formation.	Gray roughly bedded limestone and thick gypsum; marine fossils.	40–50
		San Rafael group: –Unconformity		
		San Rafael group: Entrada sandstone.	Light-red, white-banded, fine, even-grained thin-bedded gypsiferous sandstone; very friable.	70–220
		San Rafael group: Carmel formation.	Bluish-gray limestone in resistant massive beds and soft shaly beds; a little argillaceous and gypsiferous shale; marine fossils; forms low cliffs and a bench on top of the Navajo sandstone.	200–300
		–Unconformity		
Jurassic(?).		Glen Canyon group: Navajo sandstone.	Light creamy-yellow, white, pinkish, and buff, highly cross-bedded sandstone; weathers in high cliffs and innumerable cones, towers, and domes; forms caves, alcoves, and natural bridges; at the top a separate unit (Temple cap member).	1, 200–2, 200
		Glen Canyon group: –Local unconformity–		
		Glen Canyon group: Kayenta formation.	Maroon coarse-grained cross-bedded sandstone, conglomerate, blue-gray hard, dense limestone; and maroon and brown shale; all in thin irregular beds.	60–180
		Wingate sandstone.	White to reddish-brown massive sandstone; prominently jointed; crops out commonly in a single vertical cliff; strongly cross-bedded.	0–400

Generalized section of the rock formations in the Zion Park region, Utah—Continued

System	Series	Group and formation	Character	Thickness (feet)
		–Unconformity (?)		
Triassic.	Upper Triassic.	Chinle formation.	Red, brown, and buff sandstones and subordinate limestone conglomerate, particularly abundant near the top; near the middle a topographically prominent sandstone ledge (Springdale sandstone member); in lower half brightly variegated shales, sandstone, and conglomerate that weather as badlands and contain fossil wood and fish (Petrified Forest member); a series of slopes and cliffs.	950–1, 250
		Shinarump conglomerate.	Light-gray to yellow, coarse-grained to conglomeratic sandstone, very irregularly bedded; contains silicified wood; forms prominent bench.	70–130
		–Unconformity		
	Lower Triassic.	Moenkopi formation.	Brown, red, and yellowish platy, thin-bedded gypsiferous and calcareous sandstone; soft pink and white strongly gypsiferous band (Shnabkaib member) in upper half; fossiliferous marine limestone (Virgin limestone member) in the middle; and limestone and conglomerate (Timpoweap member) at the base.	1, 500–1, 760
		–Unconformity		
Permian.		Kaibab limestone.	White to yellowish massive, more or less dolomitic limestone, in part cherty; fossiliferous; locally gypsiferous.	580+



been measured and described by Noble[78a] for the Grand Canyon and the northern Kaibab Plateau, by Reeside and Bassler[79] for the Virgin River Valley, and by Longwell[80] for the Grand Wash Cliffs.

Studies of the Kaibab at scores of localities reveal the formation as a composite of limestone, sandstone, shale, gypsum, travertine, breccia, and conglomerate, which in composition and stratigraphic sequence varies much from place to place. It includes both marine and terrestrial sediments. The limestone beds range in thickness from a few inches to as much as 20 feet. Those from 3 to 6 feet thick are most common and retain their individuality for considerable distances along the strike. Nearly all of them are arenaceous and might equally well be classed as calcareous sandstones in which silica constitutes 30 to 45 percent. They reveal much replacement, and the upper beds in particular are dolomitized. But beds with as much as 70 percent of combined dolomite and calcite are rare, and few of them have value in making cement. The sandstones are likewise impure. In places thin layers or thick lenticular masses of dominantly quartz sand alternate with calcareous materials, but generally the grains of silica and calcite are mingled, and all sandstones analyzed have lime, magnesian, or gypsum cement. In addition to sand grains, silica is present as chert nodules, pancakes, linings of cavities, and as geodes that in places constitute nearly half the bulk of the rock. This chert, yellow, gray, and brown in color, massive or laminated, some of it fossiliferous, is a distinctive feature of the Kaibab. Gypsum, white, pink, or gray, appears in many measured sections as thin and thick beds, short lenses and nodules, as cement for calcitic and siliceous grains, and as linings of fissures and interbed spaces. Iron oxides in granular aggregates and concretions are sporadically distributed.

As compared with outcrops farther south and east, the Kaibab of the Zion Park region is less arenaceous but much more calcareous and gypsiferous. On the rim of the Grand Canyon at Bass Trail 562 feet of Kaibab includes 136 feet of bedded sandstone and 134 feet of shaly sandstone and limestone in alternating beds. At the north end of the Kaibab Plateau about half of the formation is sandstone, and east of Glen Canyon its probable equivalent, the Cedar Mesa sandstone member of the Cutler formation, is nearly all sandstone.[81] In the Virgin River Valley true quartz sandstone is absent from measured sections, and some of the limestones are nearly pure. East of the Kaibab Plateau gypsum has not been recorded as beds and is exceedingly rare as cement. In the Kanab Valley, Ariz., it appears as thick beds and thin beds, and in southwestern Utah bedded gypsum, gypsiferous shales, and limestone constitute 15 to 30 percent of some Kaibab sections measured.

FIGURE 27.—Kaibab limestone, at the "shute," inner gorge of Timpoweap Canyon.

STRATIGRAPHIC SUBDIVISIONS

The evidence presented by Newberry[82] and by Gilbert[83] that the Kaibab comprises various units, perhaps of different age, has been greatly strengthened

[78a] Noble, L. F., The Shinumo quadrangle, Grand Canyon district, Ariz.: U. S. Geol. Survey Bull. 549, 1914; A section of the Paleozoic formations of the Grand Canyon at the Bass trail: U. S. Geol. Survey Prof. Paper 131, pp. 23–73, 1922; A section of the Kaibab limestone in Kaibab Gulch, Utah: U. S. Geol. Survey Prof. Paper 150, pp. 40–60, 1928.

[79] Reeside, J. B., Jr., and Bassler, Harvey, Stratigraphic sections in southwestern Utah and northwestern Arizona: U. S. Geol. Survey Prof. Paper 129, pp. 51–77, 1922.

[80] Longwell, C. R., Geology of the Muddy Mountains, with a section through the Virgin Range to the Grand Wash Cliffs, Ariz.-Nev.: Am. Jour. Sci., 5th ser, vol. 1, pp. 46–47, 1921.

[81] Gregory, H. E., The San Juan country: U. S. Geol. Survey Prof. Paper 188, pp. 43–45, 1938.

[82] Newberry, J. S., in Ives, J. C., Report on the Colorado River of the West, pt. 3, pp. 59–60, 62–63, 1861.

[83] Gilbert, G. K., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, pp. 161, 177, 1875.

EXPLANATION OF FIGURE 26

Kaibab limestone at La Verkin Hot Spring, mouth of Timpoweap Canyon. Moenkopi strata, top of canyon wall and slopes above (upper right); lava, upper left; Hurricane fault near base of photograph. Photograph by George Grant, National Park Service, No. 2161.

by later investigation. Noble[84] subdivided the formation into six lithologic units at Fossil Mountain on the Coconino Plateau, five in Kaibab Gulch, and three in Jump Up Canyon, a tributary to Kanab Creek. Longwell[85] recognized four subdivisions in the Muddy Mountains. For the Virgin River Valley Reeside and Bassler[86] outlined five subdivisions: (1) At top, thin-bedded limestone, sandstone, shale, and gypsum (Harrisburg gypsiferous member); (2) massive cherty limestone; (3) siliceous limestone with subordinate beds of sandstone; (4) massive cherty limestone; (5) calcareous sandstone, shale, and gypsum with subordinate limestone. As generalized units these five subdivisions may be traced for some distance eastward. But published and manuscript sections, 483 to 1,059 feet in thickness, show wide variation in their composition, bedding, continuity, and relative positions. In particular, the topmost subdivision, the "Super Aubrey beds" of Huntington and Goldthwait,[87] the "Harrisburg gypsiferous member" of Reeside and Bassler, is difficult to correlate. In some sections the salient features of the Harrisburg are recognizable in a different combination of beds, but in many sections the content and arrangement of upper 100 feet of Kaibab strata are quite unlike those in the typical Harrisburg. At its type locality, Harrisburg Dome, where the member is about 280 feet thick, it constitutes a conspicuous broken slope of thin-bedded light-colored gypsiferous limestone and shale between massive gray or tan cherty limestone below and red shales (Moenkopi) above, and generally west of the Hurricane Cliffs gypsum is a prominent constituent. Traced eastward up the canyons that emerge from the Hurricane Cliffs, the Harrisburg member loses its individuality. In distances of 1 to 3 miles its stratigraphic position is occupied by arenaceous and calcareous shales and chert-speckled impure limestones—part Permian and part Triassic—which lie above the topmost fossiliferous Permian beds, or by a coarse breccia, which is underlain by evenly bedded limestones and overlain by irregularly bedded limestones and calcareous sandstones; the lowermost gypsiferous rocks are some distance above, in beds that contain Triassic fossils. As treated by Reeside and Bassler (1922) this breccia is the bottom of a series of beds collectively defined as the Rock Canyon Conglomerate member, and classed by them as basal Moenkopi (Triassic). A reconsideration of the field evidence that includes observations by Reeside[88] in cooperation with C. E. Dobbin shows that the Rock Canyon conglomerate at its type locality is substantially equivalent to the Harrisburg gypsiferous member of the Kaibab. As a stratigraphic term "Rock Canyon conglomeratic member" is therefore abandoned. In this paper it is proposed to treat the discontinuous irregularly bedded sandstone shales, conglomerates and limestones that immediately overlie known Permian beds as the basal unit of the Moenkopi. For this member the term Timpoweap seems appropriate. (See p. 60.) To the Piutes Timpoweap is the narrow gray rock canyon of the Pa-roos (Virgin River) between Pe-keep-wan-ar (La Verkin Hot Springs) and Par-oos Uave (middle Virgin Valley).

In his recent study of the ecologic conditions of Permian time, McKee[89] describes a "western," a "transition," and an "eastern" phase of Kaibab sedimentation, stresses the interbedding of marine and terrestrial deposits, and divides the "Kaibab limestone" into two formations, Toroweap and Kaibab, separated by a regional unconformity. He writes:

> The Kaibab limestone of Darton, the writer believes, actually represents not one but two distinct formations. The basis for separation is found, first, in the presence of a widespread unconformity involving local warping and general erosion; secondly, in the distinctive faunas in the limestone phases of each; and lastly, in an abrupt change in lithology.

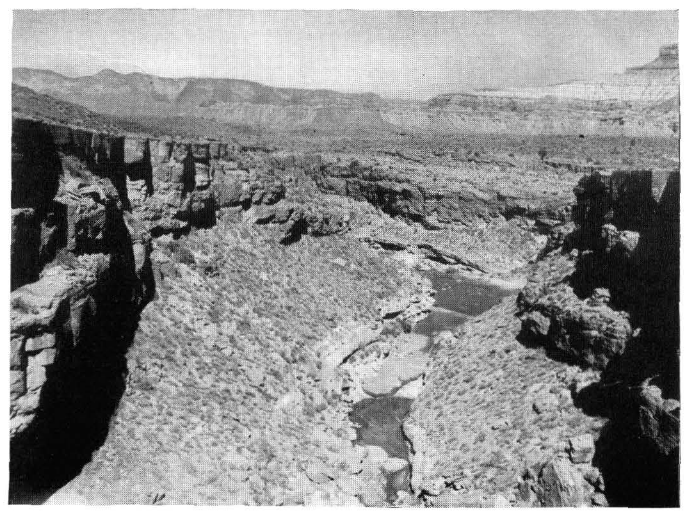


FIGURE 28.—Kaibab limestone (stream bed) and calcareous sandstone (stream and lower part of slope); Moenkopi, upper part of slope and cliffs. In *Alkali Wash. Permian-Triassic contact undetermined.*

Representative sections of the Kaibab are shown on page 112. (See also figs. 26, 27, 28.)

Fossils from the Kaibab of the Zion Park region, collected by Reeside, Bassler, and Gregory, and iden-

[84] Noble, L. F., The Shinumo quadrangle, Grand Canyon district, Ariz.: U. S. Geol. Survey Bull. 549, p. 70, 1914; A section of the Kaibab limestone in Kaibab Gulch, Utah: U. S. Geol. Survey Prof. Paper 150, pp. 40–60, 1928.

[85] Longwell, C. R., Geology of the Muddy Mountains: Am. Jour. Sci., 5th ser., vol. 1, p. 48, 1925.

[86] Reeside, J. B., Jr., and Bassler, Harvey, Stratigraphic sections in southwestern Utah and northwestern Arizona: U. S. Geol. Survey Prof. Paper 129, p. 58, 1922.

[87] Huntington, Ellsworth, and Goldthwait, J. W., The Hurricane fault in the Toquerville district, Utah. Harvard Coll. Mus. Comp. Zoology Bull., vol. 42, p. 203, 1904.

[88] Reeside, J. B., Jr., personal communication, Feb. 28, 1938.

[89] McKee, E. D., The environment and history of the Toroweap and Kaibab formations of northern Arizona and southern Utah: Carnegie Inst. Washington Pub. 492, 1938.

tified by Girty are included in the following list. Some of the species are included also in lists previously presented.[90]

Acanthopecten coloradoensis.
Acanthopecten? sp.
Aviculopecten, 3 sp.
Aviculopecten? sp.
Batostomella n. sp.
Batostomella n. sp.
Bellerophon majusculus.
Bucanopsis aff. *B. bella.*
Campophyllum? n. sp.
Chonetes hillanus.
Chonetes quadratus.
Composita mexicana?
Composita n. sp.
Composita subtilita.
Composita sp.
Derbya aff. *D. nasuta.*
Derbya? sp.
Dielasma sp.
Echinocrinus sp.
Euomphalus sp.
Euphemus sp.
Favosites? n. sp.
Fenestella sp.
Goniospira sp.
Hemitrypa sp.
Leda obesa.
Lioclema sp.
Lithostrotion? n. sp.
Lophophyllum? sp.
Marginifera? aff. *M. splendens.*
Marginifera splendens?
Metacoceras sp.
Myalina aff. *M. deltoidea.*
Myalina sp.
Naticopsis? sp.
Nautilus sp.
Nucula levatiformis.
Orthoceras sp.
Orthotetes sp.
Phyllopora? sp.
Plagioglypta canna.
Platyceras sp.
Pleurophorus mexicanus.
Pleurotomaria sp.
Polypora sp.
Productus indet.
Productus ivesi.
Productus ivesi var.
Productus occidentalis.
Productus popei.
Productus sp.
Productus subhorridus?
Productus (*Waagenoconcha*) *montpelierensis.*
Pseudomonotis? sp.
Pteria (*Bakewellia?*) sp.
Pugnax osagensis var.
Pustula aff. *P. irginae.*
Pustula subhorrida.
Pustula subhorrida var.
Rhombopora sp.
Schizodus wheeleri.
Septopora n. sp.
Spiriferina sp.
Spirorbis sp.
Sponge, undetermined.
Squamularia aff. *S. perplexa.*
Squamularia guadalupensis.
Tabulipora sp.

[90] Walcott, C. D., The Permian and other Paleozoic groups of Kanab Valley, Ariz.: Am. Jour. Sci. 3d ser., vol. 20, pp. 221–225, 1880. Shimer, H. W., Permo-Triassic of northwestern Arizona: Geol. Soc. America Bull., vol. 30, pp. 471–494, 1919.

KAIBAB-MOENKOPI EROSION INTERVAL

An unconformity of considerable proportions between Permian and Triassic beds in the Colorado Plateau province, first recorded by Howell[91] at Hurricane Cliffs, was noted by Gilbert[92] at Marble Canyon, by Dutton[93] on the Uinkaret Plateau, by Ward[94] in the Little Colorado Valley, by Cross[95] on the Grand (upper Colorado) River, by Robinson[96] on the Coconino Plateau, and by Gregory[97] on the Navajo Reservation. The regional extent and stratigraphic significance of the unconformity seem to have been first recognized by Dake.[98]

For nearly 40 years after the observations of Walcott in the Kanab Valley (1880), the unconformity supposed to mark the end of the Permian was placed by paleontologists at the base of the Shinarump conglomerate, hundreds of feet above the "Upper Aubrey" (Kaibab limestone), in the belief that the "lower Shinarump shales" (substantially the Moenkopi formation) were Permian or Permo-Carboniferous, and unconformities also were indicated at the base of the "Shinarump shales" and at other horizons within formations once classed as Permian or doubtful Permian.

Field work during the past 2 decades has increased the number of places where an interval of erosion at the end of Permian time is apparent and also has shown the invalidity of many previous interpretations. Thus the unconformity near Toquerville illustrated by Howell[99] is now known as a feature of faulting, the unconformities described by the Wheeler and Powell surveys are within Triassic formations, and some of those recorded by Gregory and others

[91] Howell, E. E., Report on the geology of portions of Utah, Nevada, Arizona, and New Mexico: U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 285, 1875.

[92] Gilbert, G. K., Report on the geology of the Henry Mountains, p. 8, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1877.

[93] Dutton, G. E., Geology of the High Plateaus of Utah, pp. 146–147, U. S. Geog. and Geol. Surveys Rocky Mtn. Region, 1880; Tertiary history of the Grand Canyon district: U. S. Geol. Survey Mon. 2, pp. 44–45, 1886.

[94] Ward, L. F., Status of the Mesozoic floras of the United States: U. S. Geol. Survey Mon. 48, p. 19, 1905.

[95] Cross, Whitman, Stratigraphic results of a reconnaissance in western Colorado and eastern Utah: Jour. Geology, vol. 15, pp. 634–635, 1907.

[96] Robinson, H. H., The San Franciscan volcanic field, Ariz.: U. S. Geol. Survey Prof. Paper 76, p. 24, 1913.

[97] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, p. 24, 1917.

[98] Dake, C. L., The pre-Moenkopi (pre-Permian?) of the Colorado Plateau: Jour. Geology, vol. 28, pp. 61–74, 1920.

[99] Howell, E. E., op. cit., p. 285, 1875.

are below the top of the Permian. These more recent studies have demonstrated that the Permian in the San Juan Valley includes formations not represented west of Glen Canyon, that the Permian of central Utah is unlike that of the Kaibab and Coconino Plateaus; that for the plateau province as a whole the Permian-Triassic boundary lies between beds different in composition, structure, and origin, and that the features of the unconformable contact vary widely. In few places does the generally uneven plane that separates the characteristic shales of the Lower Triassic from the equally characteristic gray-blue cherty massive limestone of the upper Permian Kaibab mark the actual systemic boundary, but wherever exposed the beds now classed as Moenkopi appear to rest on a surface of erosion. In the Little Colorado Valley the contact of Kaibab and Moenkopi shows little channeling and slight if any discordance in dip; the basal conglomerate is thin and in places absent. In the Kaiparowits region, where there is no significant discordance in bedding and little conglomerate, pre-Moenkopi erosion has removed in places 40 to 100 feet of Permian (?) beds. Generally east of Glen Canyon the surface of the beds underlying the Moenkopi is channeled and pitted, broad depressions are filled with conglomerate, and much of the pre-Moenkopi has been removed by erosion. Near Moab all the Permian beds have been removed, and the Moenkopi rests on the Hermosa (Pennsylvanian). In southeastern Nevada the Kaibab is dissected by valleys 50 to 100 feet deep and partly filled with conglomerate; at the Spring Valley [Charleston] Mountains, as at Moab, the entire Kaibab was removed before Moenkopi sedimentation began.

Fortunately, comparative studies, chiefly by Girty and Shimer,[100] of fossils classed as Permo-Carboniferous (?), Permian (?), or Triassic (?) in Arizona, Utah, and Idaho have made much clearer the relations of the Triassic and Permian and have brought the paleontologic evidence into harmony with that shown by other features of sedimentation. With reasonable assurance the "Upper Aubrey limestones" of the Powell and Wheeler Surveys has been assigned to the Permian (Kaibab limestone) and the overlying beds to the Triassic (Moenkopi formation); and an interval of erosion between them has been shown to be represented over an uninterrupted expanse of as much as 60,000 square miles. Even if diagnostic lithologic and structural features were lacking a considerable interruption in sedimentation at the Kaibab-Moenkopi contact must needs be postulated on faunal evidence—in the Kaibab of southwestern Utah the latest Permian beds are not represented nor in the Moenkopi, the earliest Triassic. This interval is of particular interest because it records a change in climate, in the relation of sea to land, and in the environment of plants and animals. In the geologic time scale it is the division zone between the Paleozoic and the Mesozoic, between the Permian and the Triassic as represented in the intermountain region.

In the Zion Park region a time break between the Moenkopi and Kaibab is easily demonstrated, but the exact position of the unconformable contact is not everywhere determinable. In places along the face of the Hurricane Cliffs the division plane between the two formations is marked only by indefinitely bounded lenses of conglomerate or by slight differences in texture and bedding.

In Timpoweap, Gould, and some other canyons that extend back from the Hurricane Cliffs an interval of 100 to 200 feet between known Moenkopi and Kaibab deposits includes two, in places three, beds of conglomerate, short or more than 100 feet long. At the mouth of Alkali Wash the richly fossiliferous, cherty Kaibab is overlain in turn by about 40 feet of brown sandy gypsiferous, iron-stained limestone containing Permian fossils, by conglomerate, and by dense limestone containing Triassic fossils along the strike. (See fig. 28.) In Rock Canyon, a thick conglomerate, which may be Kaibab, grades into Triassic fossiliferous limestone—the "Meekoceras zone," 16 feet above. Because of the many unconformities near the top of the Kaibab and the bottom of the Moenkopi, the discontinuity and varied composition of beds that might serve as guides and the sporadic distribution of fossils, it was found impossible to place the regional Kaibab-Moenkopi contact with assurance. As tentatively mapped, the contact doubtless lies in different places above, below, or at the actual plane of separation. For the region as a whole the limestones and sandstones of pre-Moenkopi age seem not to have been beveled by the waves of a progressing sea. The Kaibab strata are substantially parallel with the marine Moenkopi strata a short distance above, and though the top of the Kaibab shows small-scale "hill and valley" topography, and many pebbles in the conglomerate came from distant sources, there is no deep weathering or other evidence to show that the normal erosion represented by the unconformities was of long duration. The general absence east of the Hurricane Cliffs of the gypsiferous beds (Harrisburg gypsiferous member), which are so prominent at the top of the Kaibab in the lower Virgin Valley, seems more likely the result of nondeposition than of erosion.

TRIASSIC FORMATIONS

GENERAL FEATURES AND RELATIONS

About the base of the High Plateaus the Triassic formations are displayed in two lines of cliffs, each

[100] Shimer, H. W., The Permo-Triassic of northwestern Arizona: Geol. Soc. America Bull., vol. 30, pp. 492–497, 1919. Shimer cites the published and unpublished observations of Girty, Schuchert, and others.

clearly outlined by color, by manner of erosion, and by topographic form. From the Kolob Terrace southward the lower line of cliffs—a magnificent escarpment of color-belted thin-bedded gypsiferous shales, sandstones, and limestone—borders the Gooseberry, Little Creek, and Lost Spring Mountains and extends eastward past Pipe Spring and Fredonia to the Paria River, a distance of about 100 miles. The base of the escarpment is limestone, its top a conglomeratic sandstone. Above this lower escarpment and set some miles back of it is a second line of cliffs that extends from Smithsonian Butte past Short Creek, Cane Beds, Moccasin Springs, Kanab, and Johnson. In the Virgin Valley these two brightly colored and intricately carved escarpments are particularly bold and picturesque. Below Rockville they are sharply separated by a band of resistant gray rock, a 100-foot wall set into the face of slopes some 3,000 feet high. As the beds in these two escarpments—dominantly thin-bedded variegated sandstone—are strikingly unlike the buff limestones (Kaibab) below and the massive red sandstones above (Wingate and Navajo), the geologists of the Wheeler and Powell Surveys treated them as a group, the "Shinarump group," and for convenience of description spoke of the beds in the lower escarpment as the "Chocolate Cliffs sandstones" and those in the upper escarpment as the "Vermillion Cliffs sandstones." The gray ledge (Shinarump conglomerate) midway up in the series was found to be a useful plane of separation. As the only fossils then know from the "Shinarump" were plants and reptile fragments determined by Newberry and Cope as Triassic, the entire Shinarump group was assigned to that period. In Gilbert's opinion[1] these beds were laid down in an "inland sea entirely separate from the ocean." While the Powell Survey was in progress Walcott[2] found fossils in limestone near the base of the "lower Shinarump," which he identified as Permian. This discovery led naturally to a reclassification, in which the Shinarump conglomerates in the midst of the "Shinarump group" became the division zone between Permian and Triassic sediments.

The conclusions of Walcott regarding the Permian age of the "lower Shinarump" remained unchallenged for some 30 years and determined the stratigraphic chronology in papers on the plateau country by Darton, Dutton (Grand Canyon), Gregory (Navajo country), Noble, Robinson, Walcott, and others. Later studies of the "Permian" and "Triassic" of Arizona and Utah have led to the recognition of definable subdivisions and a reconsideration of the fossils that serve as evidence of age. In 1917 beds equivalent to those in the "Shinarump group" of Dutton, Gilbert, and Powell were re-classified by Gregory[3] as the Chinle formation ("Upper Shinarump" in part) and Shinarump conglomerate, both Triassic, and the Moenkopi formation ("Lower Shinarump"), of doubtful Permian age. Still later studies have established the age of the Moenkopi as Triassic and that of the underlying limestones as Permian. (See p. 62.)

The Upper Triassic age of the Shinarump conglomerate and of the lower two-thirds of the Chinle seems also established, but there is some reason to doubt that the top of the Triassic is the top of the Chinle.

As treated in the present paper the Triassic of the Zion Park region embraces three formations—the Moenkopi of Lower Triassic age and the Shinarump and Chinle of Upper Triassic age. In the Moenkopi six stratigraphic subdivisions are recognized, of which at least two consist of marine sediments; the other four, possibly only three, show features characteristic of terrestrial sediments. The Chinle includes four subdivisions, none of them of marine origin. As shown in figure 24, the thickness of the formations and the thickness, composition, and arrangement of their component subdivisions differ materially from place to place. The middle and upper red sandstones of the Moenkopi, the distinctively variegated shales (Petrified Forest member) of the Chinle, and the unconformity at the base of the Shinarump are remarkably continuous and uniform throughout the plateau province; but other features are locally dominant, inconspicuous, or absent. In the Moenkopi, gypsum, though everywhere present, is prominent only west of the Paria River, and marine limestones have not been recorded in southern Utah east of the Kanab Valley. In the Chinle the limestone beds, numerous enough to characterize a subdivision in northeastern Arizona and abundant in southwestern Colorado (Dolores formation of Cross), are represented in Zion Park by very thin beds and plasters, and in southeastern Nevada no limestone is listed in sections published by Longwell.[4] On the other hand, sandstones everywhere present in the upper part of the Chinle increase greatly in amount from east to west. In fact, the wide range in thickness of the entire Chinle formation, roughly 400 to 2,000 feet, is in large part due to the unequal amounts of the sandstone. (See fig. 24.)

MOENKOPI FORMATION

EXTENT AND CHARACTERISTIC FEATURES

In the Zion Park region the Moenkopi formation attains its most complete development and is brought into topographic prominence by its position between formations that are much more resistant to erosion.

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1 Gilbert, G. K., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 187, 1875.

2 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.

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

4 Longwell, C. R., Geology of the Muddy Mountains, Nev.: U. S. Geol. Survey Bull. 798, pp. 57-62, 1928.

Where it rises abruptly from the broad platform of Kaibab limestone and is capped by the Shinarump conglomerate it forms cliffs, mesas, and flat-topped towers marked by bands of attractive color. Where the protecting cap of conglomerate is absent the shales of the Moenkopi are intricately dissected into a maze of tiny canyons, ridges, benches, and tables, which gradually merge downward with gullied slopes. Generally the slopes are broken by a prominent cliff of relatively resistant limestone, on top of which the softer beds have been stripped far back, forming a terrace in places as much as half a mile wide. In nearby and distant views the stratification seems remarkably even. The strong bands of chocolate brown, red, and white that mark groups of unlike strata wind in and out along the headlands and reentrants and across the badland stretches with surprising uniformity and occupy the same relative positions. On both sides of the Virgin River from the Hurricane Cliffs to Rockville the Moenkopi is beautifully exposed. (See figs. 29, 30.) Along the 14-mile highway the eroded edges of successively higher-lying beds are displayed as bright bands concealed here and there by patches of black lava. In this brilliant landscape the color bands outline clearly the minor erosion forms characteristic of the Moenkopi—flights of tiny steps in thin sandstone, slopes and mounds in soft gypsiferous shales, and low cliffs in the hardest beds—features prominent in themselves but inconspicuous in this region of enormous steep-walled mesas. South of the Virgin Valley the Moenkopi extends as the boundary wall of Gooseberry, Little Creek, and Lost Spring Mountains with no diminution of its magnificent coloring and sculpture. East of Pipe Spring, erosion by tributaries of the Kanab has dissected the Moenkopi into low mesas and steep-walled ridges which increase in height and angularity as their master cliffs are approached. These outliers are generally capped by limestone, but along the Moccasin-Fredonia highway eastward to Johnson Creek such remarkable structures as the Steamboat (fig. 31), Round Tower, and Cowboy Butte are protected from erosion by a cover of Shinarump conglomerate.

As shown in the measured sections (p. 112), the beds of the Moenkopi are predominantly sandstone, most of them thin enough to be classed as shales. They consist chiefly of well-worn quartz grains, rare feldspar, largely decomposed, and rarer biotite and include lenses of conglomerate made of limestone and mudstone pebbles 0.15+ centimeter in diameter embedded in a matrix of sand and recrystallized calcite. Gypsum is common in beds and lenses as originally

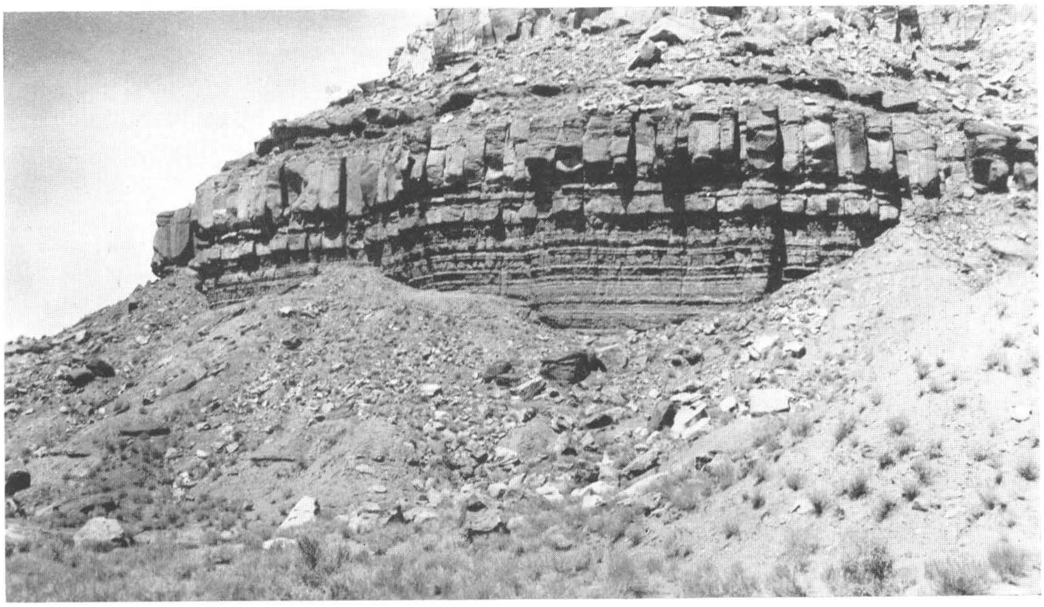


FIGURE 30.—Sandstone at top of Moenkopi in contact with Shinarump at Rockville.

laid down (Shnabkaib member), as secondary deposits in cracks and parting planes, and as cement. Limestone in sheets, lenses, and beds 1 to 3 feet thick, much of it arenaceous or earthy, some of it conglomeratic, constitutes perhaps one-tenth of the formation. It assumes prominence only at the base (Timpoweap member) and at a horizon some 500 feet above, where it is exposed as cliffs with characteristic talus (Virgin limestone member). True argillaceous shale and siliceous conglomerate are rare.

From east to west or perhaps from southeast to northwest the Moenkopi of the plateau country increases in thickness, in distinctness of its subdivisions, and in range of color. In southeastern Utah, at Comb Wash and in White, Copper, and Nokai Canyons, measured sections 190 to 360 feet in thickness include no marine limestone and no definitely bedded gypsum. Likewise in the vicinity of Lees Ferry sections 390 to 420 feet thick consist essentially of chocolate-brown or dark-red shaly sandstone. Near Paria the formation, 480 to 550 feet thick, includes a series of very thin strongly gypsiferous shales and a few thin beds of fossiliferous limestone. In the Kanab Valley, where more than 700 feet of Moenkopi is exposed in five subdivisions, both limestone and gypsum are prominent. In the Zion Park region no recorded sections measure less than 1,600 feet and six clearly defined subdivisions are present.

The many published and unpublished sections of the Moenkopi in Arizona, Utah, and Nevada show clearly enough an irregularly progressive westward thickening and a gradual change from terrestrial to intermittently marine conditions of sedimentation. Observations in a score of places make it seem probable that the range in thickness at places as much as 300 miles apart is the result of unequal deposition, but locally and regionally the post-Moenkopi erosion

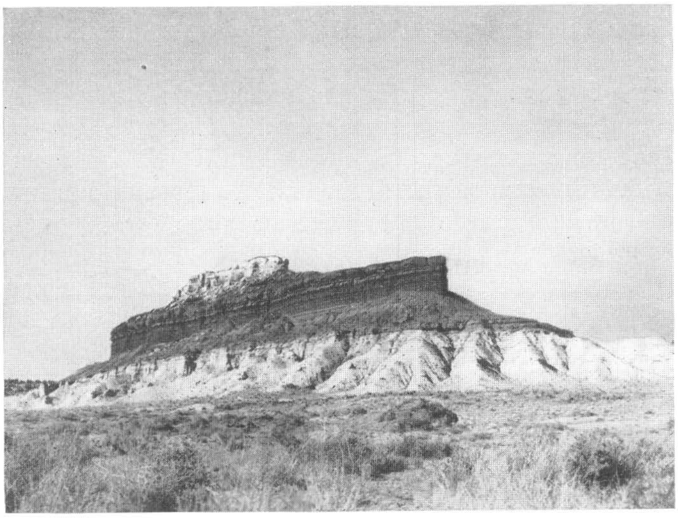


FIGURE 31.—The Steamboat, on highway between Fredonia and Pipe Spring, an outlier of the Shinarump Cliffs. Upper part of Moenkopi formation capped by Shinarump conglomerate. Photograph by J. C. Anderson.

interval and erosional unconformities within the Moenkopi must represent strata of considerable thickness. (See p. 63.) The Moenkopi-Shinarump unconformity that divides Lower Triassic and Upper Triassic beds and the erosional break in deposition between the terrestrial middle red beds and the marine Virgin limestone are features of considerable significance. Within the Moenkopi numerous vertical as well as lateral unconformities show that erosion

EXPLANATION OF FIGURE 29

Moenkopi formation near Virgin; Shinarump conglomerate on top of cliff and on caps of adjoining mesas. *lr*, Lower redbeds, foreground; *vl*, Virgin limestone member, an outlier of the Shinarump Cliffs; *mr*, middle redbeds; *sh*, Shnabkaib member; *ur*, upper redbeds; *s*, Shinarump conglomerate (Timpoweap member of Moenkopi not exposed). Photograph, National Park Service.

alternated with deposition through most of Lower Triassic time.

Fossils from the Virgin limestone and Timpoweap members of the Moenkopi establish Lower Triassic as the age for the lowest one-third and probably for the entire formation, but certain beds heretofore classed as basal Moenkopi contain fossils of Permian age. (See pp. 55 to 56.)

SUBDIVISIONS

In a section measured at Jacobs Pool, Gilbert[5] recognized three subdivisions of the beds now classed as Moenkopi: "chocolate arenaceous shale, 50 feet; white soft shale, 100 feet; chocolate soft shale, 300 feet [at the base]." For the Kanab Valley Walcott[6] outlined two groups: "Upper Permian," with four subdivisions, unconformably above "Lower Permian" with two subdivisions. (See p. 62.) Huntington and Goldthwait[7] divided the strata exposed in La Verkin Canyon above the "Carboniferous Aubrey limestone" into five stratigraphic units, constituting the "upper Verkin" and lower Verkin groups, assigned to the Permian. In a later paper[8] these authors substituted the term "Moencopie" for "Verkin." The subdivisions outlined by Huntington and Goldthwait were recognized by Reeside and Bassler,[9] who defined them in somewhat different terms and facilitated descriptions by giving two of the divisions the standing of members within the Moenkopi: division B, Shnabkaib shale member[10]; and division D, Virgin limestone member. To a basal unit which varies widely in composition from place to place and is not everywhere present they gave the name Rock Canyon conglomeratic member. (See p. 54.)

As generalized lithic and color units, six groups or subdivisions of Moenkopi strata may be traced throughout the Zion Park region and beyond its borders. In all sections measured west of the Kaibab Plateau the formation includes a basal series of gray, red and yellow shales and arenaceous, somewhat brecciated gray limestone, in places fossiliferous and oil-bearing; a compact group of gray-white gypsiferous shales; a distinctive tan-gray limestone; and three series of red gypsiferous sandstones. In composition these units are not exclusive; all of them include sandstone, shale, limestone, and gypsum, and in all of them the amount and arrangement of the material vary widely.

As treated in the present paper the outstanding features of the subdivisions are as follows. The measurements represent 8 sections, including those recorded on pp. 112–123.

General section of Moenkopi formation

	Feet
Shinarump conglomerate (Upper Triassic).	
Unconformity.	
Moenkopi formation (Lower Triassic):	
1. Upper red member. Dominantly thin, fine grained, ripple-marked, evenly stratified, shalelike sandstones and mudstones, deep red and yellow brown. Uppermost sandstones thicker, coarser, some darker in color, some cross-bedded. Gypsum abundant. Few lenses of gray shale pellets and fossiliferous oolitic limestone. Carbonaceous in places. Many lateral unconformities. Steep slopes	404–564
2. Shnabkaib member. Cream-white, pink, and green-white gypsum in regular beds ⅛ to 3 inches thick and deep-red soft arenaceous, gypsiferous mud shales. Few thin layers and oolitic aggregates of marine fossiliferous limestone. Conspicuous ragged slope	216–376
3. Middle red member. Sandstone, red, ripple-marked, sun-baked, generally fine grained, thin and regularly bedded, siliceous, calcareous and gypsiferous. Sporadic lenses of fossiliferous nodular limestone. Steep slope of short steps	436–520
4. Virgin limestone member. Marine limestone in beds 1 to 15 feet thick that change along the strike from even-bedded dark-blue massive rock to earthy, in places porous, irregular slabs. Between and below limestones red, brown, and blue-gray shales and thin calcareous sandstones 3 to 20 feet thick. Prominent cliff	8–116
Unconformity: eroded surface; discordant beds.	
5. Lower red member. Largely shalelike sandstones, dark red, brown; shows ripple marks, sun cracks, and worm trails; gypsum in layers, streaks, veinlets, and cement more common as continuous white bands near top. Many lateral and vertical unconformities. Steep slope of many steps	220–310
Gradational contact between marine and terrestrial sediments; horizon of alkali seeps.	
6. Timpoweap member. Yellow, red, and gray gypsiferous sandy shales; lenticular brown sandstones, mostly in hard, thin sheets; sandy limestones, massive and shaly, some minutely brecciated with angular black cherts. Most beds fossiliferous and oil-bearing. Weathers as a flight of firm steps	80–230
Unconformity: eroded surface, in places coated with conglomerate.	
Kaibab limestone, fossiliferous and cherty.	

[5] Gilbert, G. K., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 160, 1875.

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

[7] Huntington, Ellsworth, and Goldthwait, J. W., The Hurricane fault in southwestern Utah: Jour. Geology, vol. 11, pp. 46–63, 1903.

[8] Huntington, Ellsworth, and Goldthwait, J. W., The Hurricane fault in the Toquerville district, Utah: Harvard Coll. Mus. Comp. Zoology, Bull., vol. 42, p. 203, 1904.

[9] Reeside, J. B., Jr., and Bassler, Harvey, Stratigraphic sections in southwestern Utah and northeastern Arizona: U. S. Geol. Survey Prof. Paper 169–D, p. 58, 1922.

[10] As the name of the prominent color-banded butte 2 miles southeast of the village of Washington, "Shnabkaib" appears to be a misspelling of the Piute Shinob (Great Spirit), Kaib (mountain), which might be translated as "Mountain of the Lord." William R. Palmer, the acknowledged authority on Piute place names, writes (January 24, 1938): "I went to the mountain several years ago with a group of Indians. Their belief is that many Indians went there at the time of the great waters, and they were saved from perishing of starvation by the god Shinob changing them into big black ants. Then as the waters receded God marked that mountain by putting bands of color around it."

Viewed as a whole from a distance, the upper five subdivisions appear as two very steep slopes of red, evenly bedded shales separated by the gray cliffs of the Virgin limestone member and marked by one broad band and several narrow bands of white. (See fig. 29.) The lowest subdivision, more resistant to erosion, appears as a platform that slopes gradually into the Permian strata beneath. When studied in detail the upper, middle, and lower red numbers are found to have much in common—all are gypsiferous, have the same general composition, vary little in size of grain, and derive their color chiefly from ferruginous clay. In these three groups the dominantly fluvial beds, marked by rapid lateral change in thickness and position, sun-baked surfaces, sun cracks, and tracks of animals, have not yet been segregated from the few thin lenses and aggregates of marine limestone, nor the brackish-water gypsum from that laid down in a sea. The evidence shows that most of the red beds were deposited by ephemeral streams of low gradient and poorly marked channels and were frequently exposed to the sun. A semiarid climate with seasonal changes, dry to humid conditions, is shown by the occurrence of crystals of halite, angular pebbles of selenite, rusted bits of iron, rotted feldspars, limestones weathered in place, and lenses that in texture and structure resemble lacustrine clays, sand dunes, and gravel bars. In the Shnabkaib member many gypsum beds are even and regular for as much as a mile and immediately overlie or underlie equally regular, uniform, extremely fine-grained calcareous mud, thus indicating rather extensive quiet lagoons or detached ponds. Likewise some beds in the intervening shales consist of gypsum-cemented silt in paper-thin layers deposited without interruption. Other beds are irregularly lenticular, show some sorting of materials, and are marked by incipient cross channels to which the gypsum has been adjusted. Most of the rare short lenses of limestone are at the top or the bottom of these red arenaceous shales. Beds 60 feet and 160 feet above the base of the member contain poorly preserved marine pelecypods and gastropods. In the Virgin member the limestone range in composition from solid masses of nearly pure calcite or dolomite to friable, earthy arenaceous materials and in style of bedding from relatively thick, uniform deposits to hard, thin uneven layers. Though the member as a whole is a conspicuous part of all Moenkopi sections in the Zion Park region, most of its limestone beds retain their thickness, composition, and texture for only short distances. Its shale layers also vary widely in thickness—from less than a foot to more than 25 feet—in composition from dominantly calcareous to dominantly arenaceous or gypsiferous, and in color from yellow to red gray and blue green. The marine fossils, chiefly pelecypods, come from both limestones and shales. The Timpoweap member seems to have been deposited without time breaks. Except in the basal conglomerate no interbed unconformities were noted, the strata, though differing in extent and thickness, being regularly bedded; all are limestones and calcareous sandstones and contain the same fossils. The petroleum in southwestern Utah seems restricted to the Timpoweap.

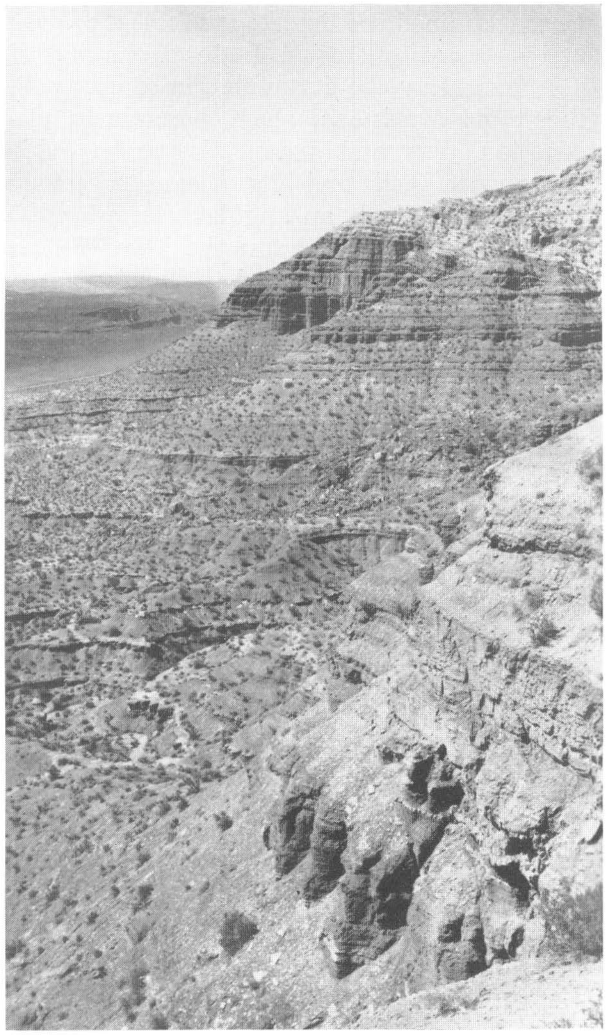


FIGURE 32.—The upper redbeds in the Moenkopi formation at Isom Wash. Photograph by J. C. Anderson.

The boundaries between the members are in some places clear-cut, in others difficult to recognize. The transition from the characteristic gray limestone of the Timpoweap member to the equally characteristic red sandstones of the lower red member is made through a deposit of yellow ferruginous, gypsiferous, and calcareous sand that along the strike thickens and thins irregularly. The transition from the Virgin limestone to the upper red member is even more definitely gradational.

The Shnabkaib member likewise seems to grade into the progressively less gypsiferous strata of the middle and upper red members. (See fig. 32.) The only conspicuous lapse in sedimentation was that preceding the deposition of the Virgin limestones.

Along the Virgin River and about Gooseberry and Little Creek Mountains the relief in the ridge and valley topography developed on gypsiferous red shales is as much as 10 feet in areas of less than an acre. At Lost Spring Mountain it exceeds 15 feet and in the Kanab Valley the redbeds are beveled progressively southward and westward, decreasing their thickness about 100 feet in a distance of 3 miles. At all places examined the limestone fits neatly into the hollows produced by erosion. In detail the unconformity is marked by the accumulation of clay pellets, fragments of sandstone, short irregularly placed lenses of tan, gray, and blue-mottled shale, and here and there worn shells and bits of carbonaceous materials. In Isom Wash an angular discordance has been produced by slumping in the lower beds and incipient talus on the sides of the ancient stream channels. In some places shallow weathering has changed the color of the top beds from red to ocher yellow.

The evidence so far gathered indicates that during Lower Triassic time the Zion Canyon region was a lowland without deep canyons or high hills and was alternately below and above sea. The periods of emergence were perhaps longer than those of submergence but not long enough to develop well-articulated drainage or to produce deep soil in an arid climate. The uniform fineness of grain and rarity of rock-making minerals except quartz and mica indicate long travel of the sandstone grains, perhaps even from Colorado, toward a western sea.

It seems reasonable to picture a region bordered inland by low plains that extended seaward as stream flats and deltas, including lagoons and shallow-water inlets, and a strand line frequently shifting in response to changes in water level. Beginning with limestone deposits in shallow marine water, the sediments show intermittently progressive retreat of the sea until, near the end of Moenkopi time, terrestrial conditions prevailed and continued throughout the Triassic. Of the probably sparse vegetation only unidentified fragments have been found, and of land animals only tracks of reptiles.

AGE

Below the Shinarump conglomerate "near Toquerville" Howell[11] found in the Triassic "a few fragments of lamellibranch shells * * * too indefinite for determination." In Kanab Valley about 3 miles below Fredonia, Ariz., Gilbert[12] obtained "*Pleurophorus*, *Schizodus*, and *Bakewellia*, a group of shells suggesting the Permo-Carboniferous of the Mississippi Valley and indicating that the great lithological change at this horizon [shaly brown sandstone to thin yellow-gray limestone] marks the absolute close of the Carboniferous age." Walcott,[13] directed by Gilbert to the Kanab outcrops, studied in detail the fossiliferous limestones and related beds. The interval between the Shinarump conglomerate, "which is considered the base of the lowest Mesozoic group," and the Upper Aubrey "massive cherty limestone" (Kaibab) he divided into upper Permian, 701 feet, and lower Permian, 145 feet.

From beds now known as equivalent to the Virgin limestone member Walcott collected 23 genera of fossils represented by 34 species and remarked: "The Permian character of the fauna clearly establishes the Permian as a distinct group in the Colorado Valley." On a traverse (1906) from Lees Ferry to the Toroweap Valley and Hurricane, Shimer[14] obtained fossils from the Moenkopi and noted that the fossiliferous limestone beds increase in number and thickness westward. He calls attention to the apparent mingling of Permian and Triassic forms in the Moenkopi fauna but concludes that "in the absence of the most typical Permian genera, in the characteristic Triassic reduction of brachiopods and increase of pelecypods, and in the presence of typical Triassic forms, a Triassic age for the Moenkopi seems indicated." This conclusion had been tentatively reached by Girty[15] in 1910 and was more definitely stated in 1917: "There no longer seems substantial reason to doubt that Walcott's Permian is the Lower Triassic (*Meekoceras* zone) of Idaho and the 'Permo-Carboniferous of Utah' [Wasatch Mountains; 40th Parallel Survey]."

As the "Permo-Carboniferous" of the Wasatch had been proved by Girty[16] to be equivalent to "Lower Triassic" of Idaho, the Lower Triassic age of the Moenkopi of southern Utah thus seemed established. Fossils collected by Reeside and Bassler in 1919 from the base of the Moenkopi (the Rock Canyon conglomeratic member) and from beds 530 feet above (Virgin limestone member) added further support to this correlation. After a study of these fossils and a restudy of Walcott's collections and other pertinent material, Girty[17] concluded:

There is almost a complete faunal change from the Kaibab to the Moenkopi. Both faunas are fairly extensive, but I know

[11] Howell, E. E., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 285, 1875.

[12] Gilbert, G. K., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, pp. 161, 17, 1875.

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

[14] Shimer, H. W., Permo-Triassic of northwestern Arizona: Geol. Soc. America Bull., vol. 30, pp. 471–498, 1919.

[15] Girty, G. H., The fauna of the phosphate beds of the Park City formation in Idaho, Wyoming and Utah: U. S. Geol. Survey Bull. 436, p. 316, 1910; letter quoted in Gregory, H. E., The Navajo country: U. S. Geol. Survey Prof. Paper 93, p. 31, 1917.

[16] Girty, G. H., in Butler, B. S., and others, The ore deposits of Utah: U. S. Geol. Survey Prof. Paper 111, pp. 642–643, 1920.

[17] Girty, G. H., in Reeside, J. B., Jr., and Bassler, Harvey, Stratigraphic sections in southwestern Utah and northwestern Arizona: U. S. Geol. Survey Prof. Paper 129, p. 68, 1922.

of no species that they contain in common. * * * In brief, I think that we have here an almost complete example of a boundary between two geologic systems, the formations being separated by a profound erosional unconformity and by an almost complete change of fauna, the upper formation containing many diagnostic fossils of the later system and the lower formation containing many diagnostic fossils of the earlier system.

The revised determination of the age of the Moenkopi fossils has brought the laboratory evidence in accord with the field observations, which strongly suggest that the sediments above the Kaibab-Moenkopi unconformity were deposited at a time and under conditions unlike those which characterize the sediments below the unconformity.

The fossils from the Timpoweap, the Virgin, and the Shnabkaib members of Moenkopi of the Zion Park region, listed below, are those collected by Reeside, Bassler, and Gregory, and described by Girty.

Ammonite?
Ammonite (external mold).
Aviculipecten? n. sp.
Aviculipecten? sp.
Aviculipecten, 4 sp.
Bakewellia n. sp.
Bakewellia n. sp. (small form).
Bakewellia sp. (small form).
Bakewellia? sp.
Bulimorpha n. sp.
Discina sp.
Entolium? sp.
Goniatite or ammonite undetermined.
Indeterminate pelecypods.
Inoceramus? sp.
Isocrinus sp.
Leda? sp.
Lingula sp.
Macrocheilina? sp.
"*Meekoceras*" *micromphalus* Smith (deter. by Reeside).
Meekoceras aff. *M. mushbachanum*.
Monotis? sp.
Myalina n. sp.
Myalina platynotus.
Myalina sp.
Myalina sp. (small form).
Myophoria sp.
Myophoria? sp.
Natica lelia.
Natica? sp.
Naticopsis n. sp.
Naticopsis sp.
Numerous undetermined gastropods.
Ostracoda.
Pelecypoda undet.
Pinna? sp.
Pleurophorus? (*Modiola?*) n. sp.
Pleurophorus n. sp.
Pleurophorus sp.
Pleurophorus? sp.
Pleurotomaria, 2 sp.
Pseudomelania n. sp.
Pseudomelania?, several n. sp.
Pseudomelania? sp.
Pseudomonotis n. sp.
Pseudomonotis sp.
Pseudomonotis? sp.
Pugnax n. sp.
Pugnoides triassicus.
Pugnoides triassicus var.
Spirorbis sp.
Sponge spicules.
Terebratula? n. sp.
Terebratula sp.
Terebratula thayensiana?
Trigonodus nevadensis.
Trigonodus nevadensis?
Trigonodus? sp.
Turritella, several n. sp.
Wasatchites cf. *W. seeleyi* Mathews (deter. by Reeside).

MOENKOPI-SHINARUMP CONTACT

The interval of erosion between the Moenkopi and the Shinarump conglomerate, described in reports on the Navajo country, the Kaiparowits region, the San Juan country, the San Rafael Swell, the Muddy Mountains, and other parts of the plateau province, is also a feature of Triassic sections about the base of the High Plateaus. At all outcrops observed these formations are separated by an erosional unconformity.

In the Virgin River Valley the dark-red, imbricated, shaly sandstone typical of the topmost Moenkopi is overlain by paper-thin, fine-grained, flaky red layers of ripple-marked shale and green-white lenses and pellets of consolidated sand, immediately on which lies petrified driftwood embedded in quartzite gravel. At the headwaters of Little Creek some 60 feet of Moenkopi strata have been removed for distances of a quarter to half a mile and the space occupied by consolidated gravel, sand, and silt on the bed of a broad valley. Likewise in cliffs east of Antelope Springs the top layers of the Moenkopi were beveled before the Shinarump was deposited. In Cottonwood Canyon west of Fredonia, a 4-foot bed of Moenkopi has been sharply cut out for a distance of 30 feet. Northeast of Fredonia a gravel bar at the top of the Moenkopi may be traced for nearly half a mile; at many places channels as much as 5 feet deep and 100 yards wide are filled with grits and sand drawn out as interbraided ropes that are believed to represent ephemeral flood-water drainage channels on a surface of moderate relief. Two miles west of the village of Paria the white Shinarump rests in a channel some 30 feet deep and 400 feet wide cut into the red Moenkopi, and pre-Shinarump erosion of comparable dimensions has been recorded at Kaibab Gulch and in the Little Colorado Valley (fig. 33).

The significance of this unconformity is minimized by Darton,[18] who found "no evidence of any notable unconformity or time break" between the Moenkopi and the Shinarump.

Though in places the unconformity might be interpreted as representing an interval when the Moenkopi

[18] Darton, N. H., A resume of Arizona geology: Arizona Univ. Bull. 119, p. 119, 1925.

beds were being deposited in shallow water and now and then exposed at the surface, its substantial continuity over an area of some 80,000 square miles and the evidence of stream erosion for long periods of time are believed to demonstrate a feature of major importance in the history of the Triassic.

SHINARUMP CONGLOMERATE

GENERAL CHARACTER

The geologists of the early western surveys speak often of the peculiar composition and the remarkable continuity of the bed of rock that Powell named the Shinarump (Shin-ar′-ump) conglomerate—the middle member of a "Shinarump group." They also recognized the erosional unconformity at the base. Howell[19] seems first to have recognized in the Virgin River Valley this

> * * * very singular formation. Having a maximum thickness at St. George of 100 feet, it seldom exceeds 40 or 50 to the east. Occasionally it is little more than a coarse sandstone and sometimes thins out to 8 or 10 feet, but never have I passed that horizon without seeing it. One of its constant features, almost as constant as its existence, is the great amount of silicified wood which it contains.

A formation so peculiar and at the same time so persistent could scarcely escape attention, even in the most cursory geologic traverse. It is a gray band in the midst of red rocks, a capping for cliffs and mesas, and the obvious source of exotic pebbles and petrified wood strewn thickly along trails between the Virgin and Paria Rivers and southward into Arizona. The formation was familiar to the Piutes and Navajos as a place in which were buried the weapons (petrified trees) of Shunav (the wolf god) and to the Mormon pioneers as the "tree rocks" and "gravel beds."

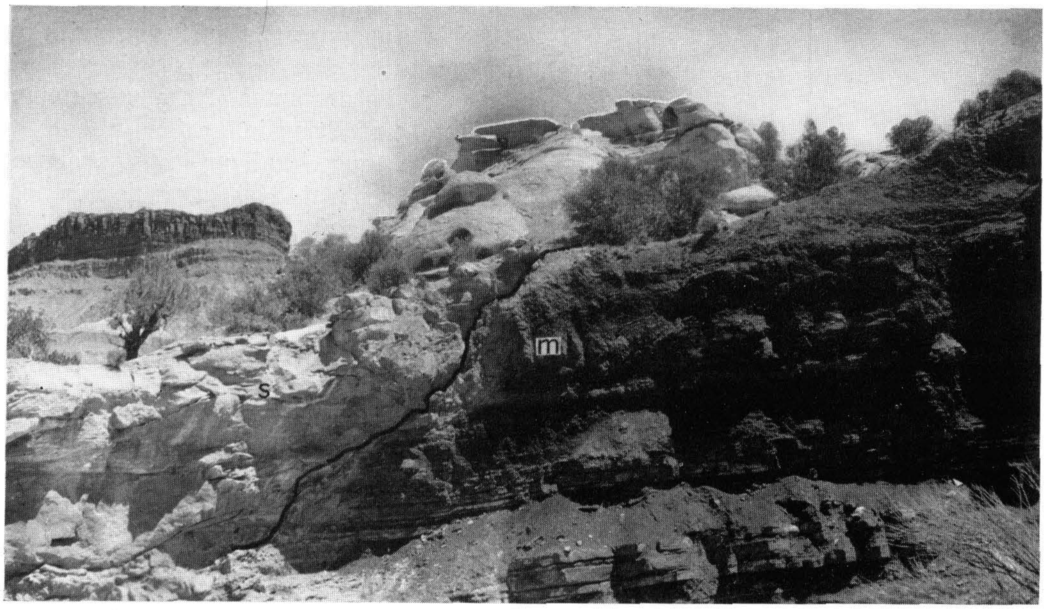


FIGURE 33.—Unconformable contact of Moenkopi (lower right) and Shinarump (lower left) on Kanab-Paria highway.

In the Zion Park region the Shinarump is well displayed. The formation together with its upper and lower contacts may be traced for as much as 80 miles along cliff faces, in and out of canyons, and across broken plateaus. In the Virgin River Valley it comes to the surface at the mouth of the Parunuweap River and continues westward as the cap of a score of prominent mesas, buttes, and ridges on both sides of the main stream and its tributaries. For many square miles it is the surface rock of Gooseberry, Little Creek, and Lost Spring Mountains and elongated mesas south of Short Creek. Beginning anew at the Sevier fault, it forms the crest and stripped-back slope of a cuesta that extends eastward from Moccasin to the Kaibab Plateau. At all outcrops studied it displays the major features that characterize the Shinarump elsewhere—great and abrupt variations in texture and bedding, innumerable vertical and lateral unconformities, and a seemingly haphazard distribution of component materials. Everywhere the formation consists chiefly of white, gray, and brown conglomerate and coarse sandstone; thin, short lenses of fine-grained brown and red sandstone and mudstone; varicolored arenaceous shale; and fossil wood. The dominant pebbles are quartzose, most of them well rounded and set in a matrix of quartz sand. They include clouded and translucent white, yellow, and gray quartz, part of it crystalline; red, brown, yellow, and green-white jasper; red, gray, brown, and white quartzite, some of it banded and re-cemented after rock crushing; black chert; mud lumps; and rare slate, schist, blue-gray limestone, magnetite, pyroxene, and garnet. Locally cavities in the fossil wood

[19] Howell, E. E., U. S. Geog. and Geol. Survey W. 100th Mer. Rept., vol. 3, pp. 283–285, 1875.

contain carnotite or other uranium minerals, and some of the spaces between the pebbles are filled with iron and manganese oxides, vanadium minerals, and copper sulphides in quantities sufficient to lure inexperienced prospectors. Only about 10 percent of the pebbles exceed 1 inch in long diameter, and some 50 percent have the size of peas. The fossil wood consists of silicified broken logs, fragments of bark, and impressions of twigs, and some of it is carbonized. The dominant cement is silica, but part of it is lime and part iron, which gives a yellow tone on weathering. The conglomerate grades upward into coarse white crossbedded strongly arkosic sandstone, fairly even grained except for a few strings of pebbles and scattered flat fragments. The bedding is everywhere lenticular.

In the Zion Park region the thickness of the Shinarump measured sections ranges from 75 to 200+ feet. Reported greater thicknesses are believed to include beds here classed as Chinle.

ORIGIN AND AGE

Howell[20] classed the Shinarump as a marine deposit. Gilbert[21] likewise writes "The chocolate shales and shaly sands [Moenkopi] were unevenly worn, and the first deposit that the returning sea spread over them was a conglomerate, * * * logs and leaves drifted from the shore." Dutton[22] thought the conditions of deposition "similar in some respects to those attending the formation of coal." Huntington and Goldthwait[23] concluded that "in part at least" the Shinarump is "probably nonmarine," though in their opinion both the Chinle above and the Moenkopi below are marine. More recent studies of the Shinarump conglomerate in its wide extension in Arizona, Utah, and Nevada present satisfactory evidence for terrestrial deposition.

The structure and texture of the beds are those characteristic of modern stream work in arid regions where the fluctuation in volume, and consequently in power, of rivers ranges from extreme to insignificant. Of the hundreds of outcrops examined none shows evidence of marine shore lines or of offshore deposits, usual features of marine transgression, and the only "marine fossils" reported have been reidentified by Reeside[24] as probably nonmarine. But though the evidence for terrestrial deposition seems adequate, the implications are not easy to understand. Generally land-laid gravel is associated with rugged topography or with tectonic movements that provide suitable catchment areas, and also generally the pebbles and cobbles may be traced to their source at the head or along the course of individual streamways. Such conditions exerted little control in Shinarump deposition. Extensive field work shows that the gravel lies on a surface of low relief unaffected by noticeable faults, folds, or regional upwarps and that it is not restricted to long trains but spreads as an almost continuous sheet nearly 100,000 square miles in area. Such remarkable persistence, so seemingly out of accord with lithologic character, seems not to have been duplicated in ancient or recent deposits. The nearest approaches are the sloping plains east of the Rocky Mountains and the southern Andes and the coalescing fans of the Great Basin, in all of which, however, the pebbles have obvious sources and lines of travel. The manner of distribution suggests a surface covered with an enormous net of interlacing streams in poorly defined channels, each strand capable of changing its position and habit periodically, perhaps even seasonally.

Possibly the Shinarump might be thought of as materials of huge fans about the rim of an interior basin graded laterally to form a slightly dissected plain and crossed and recrossed by streams that somehow were able to transport pebbles 3 inches in diameter for a distance of 300 miles on slopes as small as 2 feet to a mile. For such a hypothetical basin or regional slope neither the top nor the bottom has been located. Outcrops at the areal edges of the Shinarump closely resemble those within the periphery. In fact the range of difference may be as great at places 10 miles apart as at those 200 miles apart. Everywhere features of stream deposition are conspicuous, and everywhere the pebbles show the rounding incident to long travel. The differences lie chiefly in thickness of the deposit, the proportionate amounts of conglomerate and sandstone, and the size and number of pebbles of various composition.

However, two kinds of evidence—size of pebbles and the distribution of limestone fragments—indicate that part at least of the Shinarump sediments found their source in the highlands of southwestern Arizona. From its southernmost exposures northward across Arizona and into Utah the size of pebbles generally decreases, though not progressively; some of the largest pebbles, perhaps one in a cubic rod, appear at the northernmost outcrops, and sandstone without pebbles constitutes nearly all the formation at some intermediate places. Along the Mogollon rim pebbles in the Shinarump 6 inches in diameter are common. At Lees Ferry, 150 miles north, few pebbles exceed 2 inches in diameter, and along Virgin River about 1 in 100 exceeds 1 inch. Still farther north, in the Escalante and Fremont Valleys, the formation consists mainly of sandstone. Furthermore about the

[20] Howell, E. E., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, pp. 283–285, 1875.

[21] Gilbert, G. K., The geology of the Henry Mountains, 2d ed., p. 8, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1880.

[22] Dutton, C. E., Report on geology of the High Plateaus of Utah, p. 147, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1880.

[23] Huntington, Ellsworth, and Goldthwait, J. W., The Hurricane fault in the Toquerville district of Utah: Harvard Coll. Mus. Comp. Zoology Bull. vol. 42, pp. 210–213, 1904.

[24] Reeside, J. B., Jr., Two new unionid pelecypods from the Upper Triassic: Washington Acad. Sci. Jour., vol. 17, pp. 476–478, 1927.

southern edge of the formation the pebbles of limestone, igneous rock, quartz, and schist are most numerous and least worn. Thus Robinson[25] writes:

> In Sycamore Canyon, at the southern edge of the plateau, many pebbles are distinctly subangular and are composed of gneiss, jasper, and other metamorphic rocks as well as basic igneous rocks of granite texture. Fairly rounded cobbles of sandstone and chert up to 8 inches in diameter are less abundant.

A possible southeastern source for some of the material is suggested by the coarseness of the deposit at Fort Defiance, where 10 percent of the constituent pebbles have diameters of more than 3 inches, some 5 to 7 inches, and 50 percent more than 1 inch; likewise a possible western source is indicated by the coarse deposits near Kanarraville.

Some of the pebbles in the Shinarump came from the Moenkopi and the Kaibab as is shown by their composition and fossils—*Aviculopecten, Productus,* crinoids, *Fusulina*—but fully 80 percent of the pebbles exceeding a quarter of an inch in diameter came from beds not represented in Paleozoic rocks of the plateau province. They closely resemble rocks in the talus slopes of the Bradshaw Mountains, Ariz., and the Uncompahgre Range in Colorado, and at the bottom of the Grand Canyon.

No truly diagnostic fossils were found in the Shinarump of the Zion Park region, but the fossil wood, chiefly *Araucarioxylon arizonicum,* has a Triassic aspect. The age of the formation is determined chiefly by its stratigraphic position. It lies above the Lower Triassic Moenkopi and continues upward without a break into the Upper Triassic Chinle. In this sense the Shinarump is a "basal conglomerate."

CHINLE FORMATION

EXTENT AND GENERAL FEATURES

In the Zion Park region the Chinle formation is remarkably well displayed. Immediately along the Virgin River highway from the mouth of the Parunuweap northward into Zion Canyon the entire formation is in plain sight as a broken slope that leads upward toward the base of the towering cliffs of Navajo sandstone. From Springdale westward the Chinle rises above the platform developed on Shinarump conglomerate and is conspicuously exposed in the walls of Coalpits Wash, North Creek Canyon, and La Verkin Canyon. Large parts of the Vermilion Cliffs between Smithsonian Butte and the Paria River consist of Chinle strata, but unlike the continuous cliffs along the Virgin and its tributaries, the less resistant lower part of the Chinle at Big Plains, Cane Beds, Pipe Spring, Moccasin, and Kanab has been broken down into knobby plains, and the upper part stands as cliffs. About half of the Chinle is exposed in Sand, Cotton, wood, Kanab (Fig. 34), and Johnson Canyons. The formation is easily distinguished even in distant views. It is sharply limited below by a dull-gray cliff, above by towering red cliffs, and midway up it is crossed by a third strong cliff (Springdale sandstone member), which divides the profile into a lower slope of moderate gradient and an upper slope too steep to be scaled without assistance. Near the base of the formation the cliffs are replaced by brightly colored mounds of fluffy marllike material (the Petrified Forest member), quite unlike any other rocks in southern Utah.

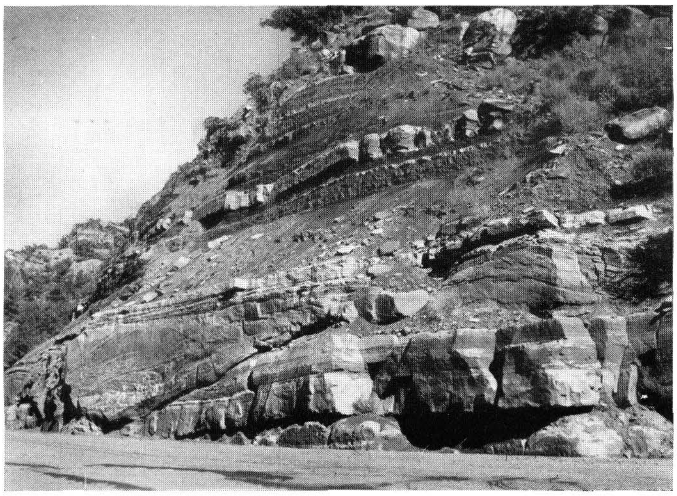


FIGURE 34.—Chinle formation, limestone, sandstone, and fossiliferous shale beds above Springdale sandstone member, Kanab Canyon. Locally faulted.

Viewed as a whole the Chinle formation is a huge pile of consolidated coarse and fine sands, silts, muds, gypsum, bentonite, and calcareous oozes and is remarkable for its vividness and variety of color, for its unusual kinds of rocks, and for the abruptness of its changes in color, composition, texture, and bedding. Though the beds that compose the formation constitute an unmistakable stratigraphic unit, they show wide variation in order of deposition, composition, texture, color, and structure. The colors of individual beds change along the strike, and the relative amount and position of the sandstones, shales, and limestones differ in each measured section. Some beds, particularly those in the upper third of the formation, may be traced for a mile, but most of them lose their individuality within much shorter distances. Many of the sandstone, shale, limestone, and conglomerate beds are little more than thin, narrow lenses that appear and disappear within a few feet. Lateral unconformities, the sidewise abutting of thin sandstone against coarse sandstone or of shale against conglomerate, and many vertical unconformities show that interruptions in deposition were common. In some places the hiatuses are marked by accumulations of such extraneous materials as mud balls, shale slabs, pseudomorphs of halite, and small quartz and chert pebbles; in other places by sun-cracked surfaces of

[25] Robinson, H. H., The San Francisco volcanic field, Arizona: U. S. Geol. Survey Prof. Paper 76, p. 30, 1913.

fine sandstone or shale overlain by poorly sorted coarser material. In particular the unconformity at the base of the Springdale member, recorded in all sections, may have a regional significance not now understood. In nine measured sections in the Zion Park region the thickness of the Chinle formation ranges from 950 to 1,380 feet—measurements greater than those recorded in the Navajo country and the Kaiparowits region, to the east, but less than those reported from Nevada.

SUBDIVISIONS

As exposed in the Zion Park region the Chinle comprises the following four subdivisions, characterized by diverse lithic features and topographic form:

1. Upper sandstones. Sandstones, red, white streaked, fine to medium grained, in beds 1 to 16 feet thick; stratified with sandy shale in groups 1 to 12 inches thick; include lenses of limestone and of conglomerate made of pebbles of sandstone, shale, and limestone. Vertical ledges and steep slopes. 540 to 800 feet.
2. Springdale sandstone member. Sandstone, light red, medium to coarse grained, in lenses 3 to 30 feet thick, combined to form a single ledge 80 to 150 feet thick; small amounts of mud shale and limestone conglomerate. Name derived from the village of Springdale, where the unit forms a prominent cliff. 60 to 105 feet.
3. Petrified Forest member. Upper half irregularly bedded thin sandstones and shales in tones of yellow, red, white, purple, and gray; some limestone and mudstone; weathers as steps on steep slopes. Lower half brilliantly variegated friable shales and "marls." Gypsum and petrified wood common; weathers as mounds and buttes with typical badland expression. For this unit, a conspicuous band on the Chinle cliffs containing abundant fossil wood and closely resembling the dominant rock in the Petrified Forest of Arizona, the name Petrified Forest member is here introduced. 650 to 800 feet.
4. Lower sandstones. Sandstone and subordinate sandy shales; irregular beds 1 to 4 feet thick; buff, brown, and purple; resistant beds, cemented with gypsum, iron, and lime; include petrified wood and saurian bones; weather as broken steps. 10 to 80 feet.

The upper sandstones, generally red, banded with white, are fairly uniform in color and bedding. They are ledge makers in which the sandstones are more massive and thicker near the top and much of the shale is hard enough to form steep slopes. The longer, finer-grained, brick-colored beds are divided into thin, regular layers one sixty-fourth to half an inch thick, ripple-marked, faintly cross-bedded and made up of barely megascopic subrounded grains of iron-coated quartz (70$\pm$ percent), feldspar, calcite, garnet, pyroxene, tourmaline, and ferruginous clay. Some of the sandstone is gnarly and cross-bedded, and the surfaces of some limestone beds are made rough by fossil aggragates resembling algae. Distinctive features are lenticular conglomerates of shale, limestone, sandstone, and ironstone pebbles and slabs a quarter to three-quarters of an inch in diameter. The cement is lime and iron. All but the white beds effervesce freely with acid. Where these upper beds underlie the Wingate sandstone their top is readily established. Where the Wingate is absent the Chinle continues upward into the Kayenta with little change except in thickness of bedding. The base of the unit is generally a surface of erosion, probably of no great stratigraphic significance, but in places the lowermost beds are groups of lenticular limestones, sandstones, and fossiliferous shales. (See fig. 34.)

The Springdale sandstone member, in local parlance the "big ledge," is expressed in the topography as a cliff and platform fully as prominent as the Shinarump and Virgin limestone (Moenkopi) cliffs in the same Triassic sections. (See fig. 36.) In distant views it appears as a single massive red, in some lights mauve or purple, bed, which retains its form and thickness as far as the eye can reach. Near views show it to be a series of laminated, in places ripple-marked and cross-bedded ledges and lenses, most of them less than 300 feet long and 30 feet thick. (See fig. 34.) Between the larger sandstone masses are beds of red and green shale, also lenticular, and within them are pockets of mud lumps, which on weathering produce a porous or pitted surface. Even fresh quarried rock shows voids and cavities filled with soft mud, and the strength of the member as a whole seems due as much to its porosity as to the firmness of its cement. As the comparative sections show, the Springdale sandstone member is best developed in southwestern Utah. (See fig. 24.) Eastward along the Vermilion Cliffs it becomes progressively thinner, and beyond the Paria River no equivalent beds appear in measured sections. The unconformity at the base of the Springdale member is marked in most places by angular gravel, sunbaked surfaces and cracks, and balls and slabs of bluegreen shale. In the Vermilion Cliffs near Kanab it is a surface of erosion above and below which the bedding is discordant.

The Petrified Forest member, which begins abruptly at the base of the Springdale sandstone member, consists of two parts. The upper part is a series of sandstones, conglomerates, shale, gypsum, and limestone very irregular in bedding, texture, and composition. (See figs. 37, 38.) The colors, chiefly shades of red, gray, yellow, and lavender, come and go along the strike and across the beds in a seemingly capricious manner. The lower part of the Petrified Forest member is even more irregularly bedded and more highly colored. It is a marvelous assemblage of shales, soft sandstones, weathered volcanic ashes, and many kinds of calcareous rocks colored with bands, streaks, and irregular blotches of yellow, lavender, purple, pink, lilac, ash gray, and various shades of red, blue, and brown. These are the most richly colored beds in Utah. Generally along the Vermilion Cliffs the materials of the Petrified Forest member, which resist neither rainwash nor streams, are spread out as a

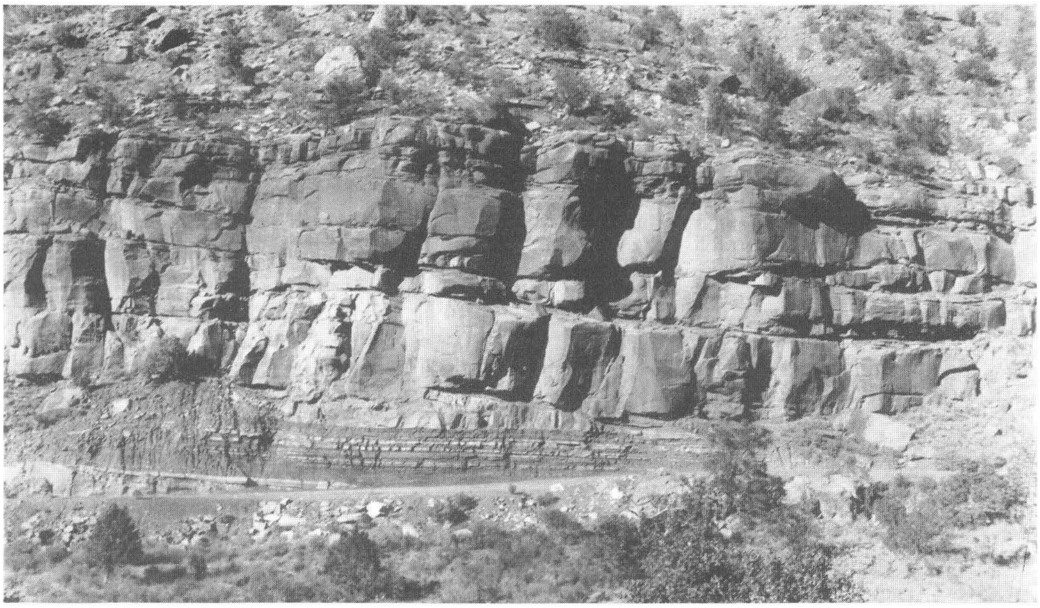
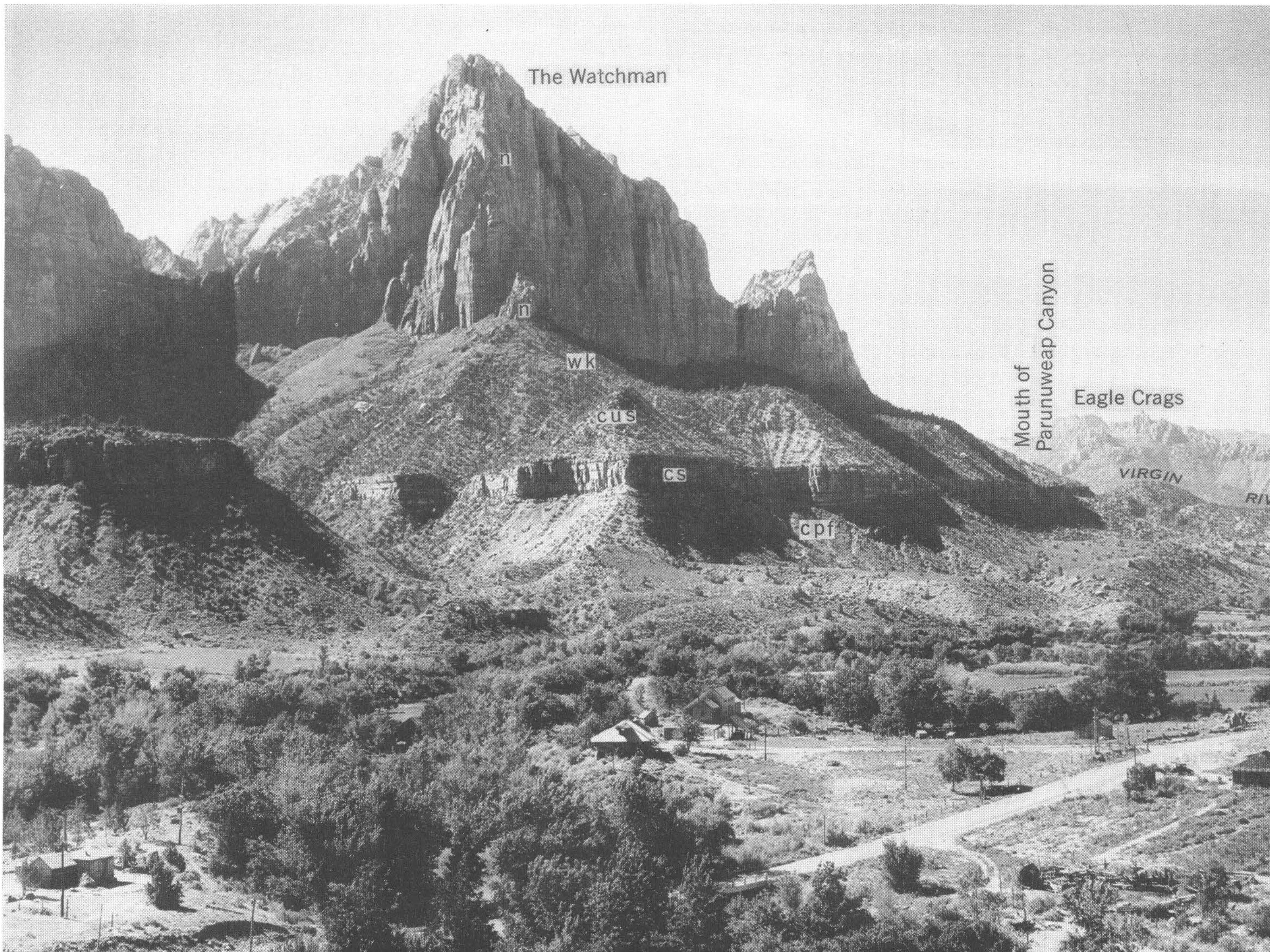


FIGURE 35.—Springdale sandstone member of Chinle formation, Pine Creek. Shales at base contain fossil fish.

hummocky, intricately desiccated plain also in the Virgin, Parunuweap, and La Verkin Valleys, where they are protected from erosion by the Springdale sandstone member, they constitute an outstanding scenic feature, even in a region where most rocks are colored and eroded into picturesque forms. The continuous exposure of these fantastic beds and the strongly colored Moenkopi below them in the region between Holbrook and Cameron led Ives and Newberry (1851) to map the Little Colorado Valley as the "Painted Desert."

The lower sandstones of the Chinle seem out of



place in a Triassic section. They lack both the thick-bedded red sandstones and the variegated "marls" and in the topography are expressed as poorly defined flat ridges and low mesas. Though these bottom beds rest comformably on the wavy surface of the Shinarump, they are quite unlike that formation in composition and structure. They include some very resistant dense rocks not cut by seams or joints and only on weathering reveal their structure as cross-bedded sandstone interleaved with brittle, hard calcareous shale in which are embedded here and there pellets of clay shale. A bed of fine-grained purple sandstone, locally known as the "blue ledge," 12 to 16 feet thick, is exceptionally tightly bound together by gypsum mingled with nearly pure calcite. Microscopic examination of this rock shows not only quartz in angular to subrounded grains but feldspar, muscovite, biotite, garnet, a green micaceous mineral, bits of carbonaceous material, and some angular isolated clay pellets so indurated as to retain their form on the weathered surfaces. Petrified wood, abundant above and below, is sparsely represented.

LITHOLOGIC FEATURES

Much of the material that makes up the Chinle closely resembles that in red beds of the Kaibab (Permian), Moenkopi (Triassic), and Kayenta (Jurassic?) formations, but the limestones, silt beds, and fossil wood are diagnostic. The limestone, commonly conglomeratic, the "saurian conglomerate" of Cross,[26] is part of all Chinle sections, but in the Zion Park region it constitutes a smaller proportion of the entire series than in regions farther east and rarely is compact and resistant enough to determine the topography. The limestone conglomerate appears as thin greenish-gray in part cross-bedded, and consists of round gray limestone pebbles somewhat resembling pisolite, though rarely with concretionary structure. It grades upward and downward into calcareous sandstones. Parts of many beds are extremely nodular, and the pebbles are mixed with sand, the "mortar beds" in local parlance. In the Springdale sandstone member limestone conglomerate constitutes about 1 percent of the rock, and of this part limestone fragments and pellets make about 10 percent.

The shales of the Petrified Forest member, roughly classed as "marls," according to the usage of Marcou, Newberry, Ward, and Walcott, are stream-laid and lacustrine silts, in some places regular in bedding and uniform in composition, elsewhere mingled with limestone and conglomerate, calcareous sandstone, and loose clay pellets, grains of quartz, mica, garnet, gold, silver, and other minerals of metamorphic and igneous rocks. Aside from bedding, much of the material is structureless and has the appearance of tallow that under pressure has become minutely fragmented along slickensided planes. Some of the marl resembles bentonite; it swells in water to nearly twice its bulk

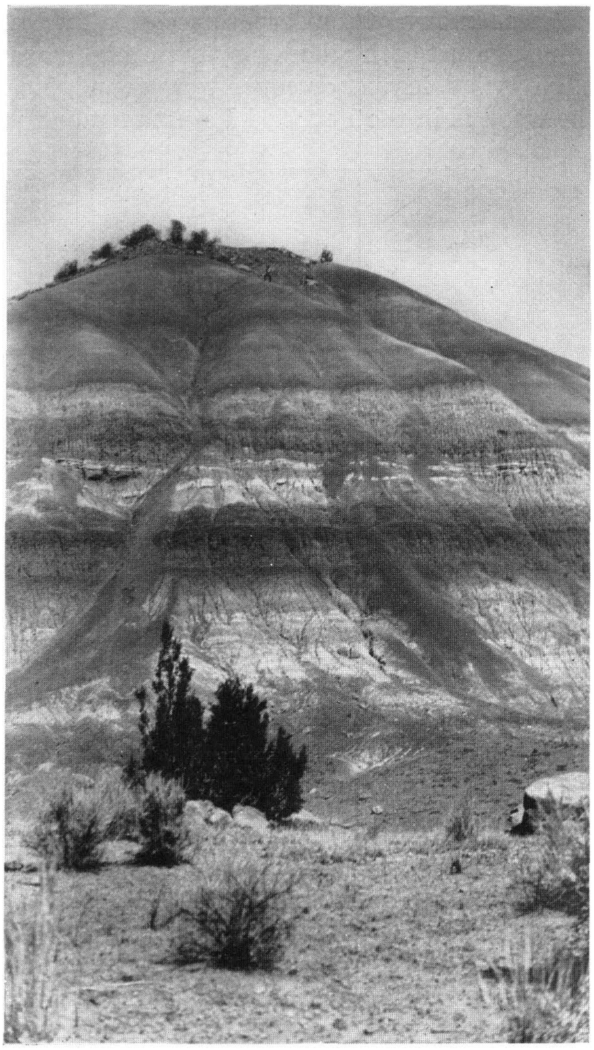


FIGURE 37.—Petrified Forest member of Chinle in Sand Canyon; typical of variegated "marls."

and on drying leaves a residue that passes through filter paper and under the microscope appears colloidal. Chemical tests indicate that a considerable portion of the flocculent colloidal substance is probably silicic acid. Allen[27] has shown that the dominant mineral in the Chinle marls of the Painted Desert region is montmorillonite, much of it derived from volcanic ash without entire loss of structure, and that some of the clay balls are bentonite that includes prisms of apatite. Of eight specimens from the Zion Park region

[26] Cross, Whitman, U. S. Geol. Survey Geol. Atlas, Rico and Engineer Mountain Folios (Nos. 130, 171), 1905, 1910.

[27] Allen, J. T., Triassic bentonite of the Painted Desert: Am. Jour. Sci., 5th ser., vol. 19, pp. 283–288, 1930.

EXPLANATION OF FIGURE 36

East side of the valley of Virgin River near Springdale, displaying members of Chinle formation (Triassic) and the Glen Canyon group (Jurassic?). *cpf*, Petrified Forest member; *cs*, Springdale sandstone member; *cus*, upper sandstones; *wk*, Wingate sandstone and Kayenta formation covered by talus; *n*, Navajo sandstone. Shinarump conglomerate beneath landslide (right center). Photographs by National Park Service.

two tested in the Geological Survey laboratory include angular grains of quartz, feldspar, mica, apatite, and garnet embedded in clay in a manner that suggests decomposed volcanic ash.

The fossil wood of the Chinle is distributed as widely scattered small chunks, as single logs, and as large accumulations of trunks, branches, and roots, all so far as known of coniferous species, all worn by grinding against each other or by buffeting in gravel beds. No twigs, leaves, or cones were found. Nearly all the wood is in the Petrified Forest member, particularly in the coarse sand layers and not generally associated with fossil bones. Most of the fossil wood is composed wholly of silica in the form of clear quartz, jasper, and chalcedony; some consists partly of copper or of iron; and some is merely lignite or charcoal. At the famous Silver Reef mines, near Leeds, Utah, the wood is impregnated with silver (cerargyrite, horn silver) and various copper and iron minerals. It is unlikely that any of the wood represented by fossils in the Zion Park region grew in the place where it is now found. It is believed to have been driftwood carried by streams and buried in mud and silt. Stumps in place like those at Cameron and Adamana were not seen.

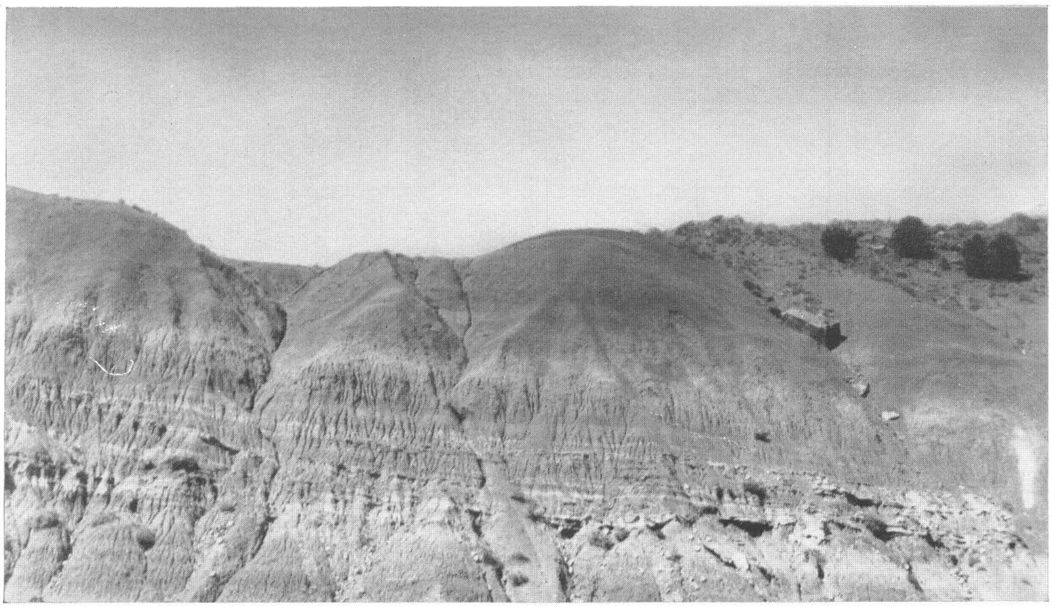


FIGURE 38.—Petrified Forest member of Chinle at Springdale, showing calcareous lenses.

ORIGIN, CORRELATION, AND AGE

Of the geography of Chinle time a few major features are known. That the landscape was without steep slopes that would induce vigorous erosion is shown by the shallowness and breadth of stream channels, the generally fine sands, and the evidence that bodies of standing water were common. The streams, however, though not powerful enough to cut deeply or to carry at one time great quantities of material, were strong enough and persistent enough to transport and grind up plant and animal remains left on the surface. Fallen trees were stranded on sand bars, heaped into log jams, or broken into short sections after their branches and twigs had been worn or rotted off. Most of the chunks of fossil wood are well worn, and the fossil bones are little more than elongated pebbles, some of them partly decomposed before burial. During the first half of Chinle time bodies of fresh water, perhaps square miles in area, were deep enough and persistent enough to permit the deposition of from 1 to 10 feet of lacustrine muds. These water bodies may have been lakes, detached lagoons, or sheets of water cut off by bars and filled at times of seasonal high waters.[28] Camp remarks that the Chinle phytosaurs "occupied the same kind of habitats in the Triassic world as the Crocodilia do in the present."

In the upper part of the Chinle, lacustrine deposits are rare and consist commonly of sheets of siliceous (algal?) limestone less than an inch thick. It thus appears that the generally or at least seasonally humid climate of early Chinle time became more arid toward the end of the epoch and progressively led to arid conditions in Wingate (Jurassic?) time. It seems also probable that the Chinle sediments, especially the youngest ones, originated in regions of humid climate and were transported to semidesert plains too rapidly to effect complete sorting.

The ultimate source of the sediment that made up the Chinle is not fully known. Little if any came directly from the underlying Mesozoic beds. The Shinarump contributed no material, and because this formation is coextensive with the Chinle it has protected the underlying Lower Triassic from the attack of Upper Triassic streams. Present evidence seems to

[28] Camp, C. L., A study of the phytosaurs: California Univ. Mem., vol. 10, pp. 1–174, ix, 1930.

show that the Moenkopi, Shinarump, and Chinle sediments in southern Utah came from a common distant source, and that during Triassic time a large part of the plateau province was rimmed about, completely or partly, by highlands. A source in the highlands of central and southwestern Arizona is indicated by coarser sandstone, more conglomerate, many more fragments of fossiliferous limestone, and much more bentonite near the southern edge of the Chinle deposits in the Puerco Valley. A possible eastern source in the early Paleozoic and pre-Cambrian rocks of Colorado is indicated by the relatively greater coarseness and amount of sandstone and relatively lesser amount of marls in the Chinle east of Glen Canyon. The floor of the hypothetical basin and the slope of its piedmont plains must have been nearly flat to permit the deposition of several hundred feet of clay silt and generally fine sandstones.

The Chinle formation in the Zion Park region is the equivalent of the "upper Shinarump" "clays" and shales and the lower part of the Vermilion Cliffs "group" as these terms are used by Powell, Gilbert, and Dutton. It also is clearly the equivalent of the formation at its type locality on the Navajo Reservation. With few interruptions it may be traced down Pueblo Colorado Wash, the Puerco and Little Colorado Rivers, along Echo Cliffs and Paria Plateau to the old town of Paria, thence westward to the Virgin River Valley. Along this course, also northward to Fremont Valley and westward into Nevada, it retains its chief characters—fossil wood, peculiar limestone conglomerates, and variegated shales that weather after the manner of marls. At most outcrops subdivisions that record regional changes in type of deposition are easily recognized, though in keeping with the other highly variable features of the formation the subdivisions are not everywhere alike in thickness or composition. Thus in the Zion Park region the lower sandstones closely resemble division D of the type section,[29] the upper sandstones division A, and the lower half of the Petrified Forest member division C. The upper part of the Petrified Forest member, extended to include the Springdale sandstone member, constitutes a much modified form of division B of the type section. The prominent Springdale member, if present east of the Paria River, is an inconspicuous unit or series of sandstone in the midst of shales and limestones.

The geologists of the Wheeler and Powell Surveys, also Huntington and Goldthwait, treated the Chinle of southern Utah as marine deposits of early Triassic time. Branson[30] regards the Chinle strata as part marine and part subaerial, "probably topset beds of a great delta." On the contrary, widely extended field studies seem to demonstrate satisfactorily that the entire formation is terrestrial in origin and Upper Triassic in age. The mode of bedding, composition, and structure reveal the presence of strong streams, of streams able to carry only the finest material, and of shallow bodies of standing water. Such features as sun cracks, ripple marks, tracks of land animals, fresh-water fishes, coprolites, and playalike areas of gypsiferous and calcareous muds indicate frequent and localized exposure to air. Some of the fossil bones were decomposed when buried, and the fish beds seem to represent accumulations in dried-up lakes.

That the Chinle is of Triassic age is now unquestioned, but some difference of opinion exists regarding its position within the system. Von Huene[31] has suggested that the lower part of the formation is Middle Triassic and the upper part Upper Triassic. Branson and Mehl[32] treat the whole formation as Middle Triassic; most other geologists as Upper Triassic.

The evidence for the Upper Triassic age of the Chinle as summarized elsewhere[33] has been strengthened by recent studies. It consists chiefly of saurian fossils determined by Lucas,[34] Case,[35] Camp,[36] and others; of plants identified by Knowlton,[37] Jeffrey,[38] and Dougherty;[39] and of mollusks studied by Henderson.[40]

A list of identified Upper Triassic fossils from the Chinle and Shinarump of the Petrified Forest National Monument, by M. V. Walker, park naturalist, includes 3 species of trees, 7 (doubtfully 8) saurians, and several unios. Material not specifically identified includes plants, trackways, worm trails, and wood borers.

In the Zion Park region the animal and plant remains in the Chinle have so far received no special study; though abundant, most of them are too fragmentary for specific identification. Saurian bones and teeth are fairly common in the calcareous and sili-

[29] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, pp. 42–43, 1917.

[30] Branson, E. G., Triassic-Jurassic "red beds" of the Rocky Mountain region: Jour. Geology vol. 35, p. 627, 1927.

[31] Von Huene, F. R., Notes on the age of the continental Triassic beds of North America: U. S. Nat. Mus. Proc., vol. 69, pp. 1–5, 1926.

[32] Branson, E. B., and Mehl, M. G., Triassic amphibians from the Rocky Mountain region: Missouri Univ. Studies, vol. 4, No. 2, p. 18, 1929.

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

[34] Lucas, F. A., Vertebrates from the Triassic of Arizona: Science, new ser., vol. 14, p. 376, 1901; A new batrachian and a new reptile from the Triassic of Arizona: U. S. Nat. Mus. Proc., vol. 27, pp. 193–195, 1904.

[35] Case, C. E., Indications of a cotylosaur and a new form of fish from the Triassic of Texas, with remarks on the Shinarump conglomerate: Michigan Univ. Mus. Paleontology, Contr., vol. 3, no. 1, pp. 8–12, 1928.

[36] Camp, L. C., A study of the phytosaurs: California Univ. Mem., vol. 10, 1930.

[37] Knowlton, F. H., New species of fossil wood (*Araucarioxylon arizonicum*) from Arizona and New Mexico: U. S. Nat. Mus. Proc., vol. 11, pp. 1–4, 1888.

[38] Jeffrey, E. C., A new araucarian genus from the Triassic: Boston Soc. Nat. History Proc., vol. 34, pp. 325–332, 1910.

[39] Dougherty, L. H., *Schilderia adamanica*: a new fossil wood from the petrified forests of Arizona: Bot. Gazette, vol. 96, pp. 363–366, 1934.

[40] Henderson, Junius, Some new Mesozoic Mollusca from the Rocky Mountain region and Arizona: Jour. Paleontology, vol. 5, pp. 259–263, 1934.

ceous conglomerates, and tracks in long series are exposed in Trail Canyon and Hog Canyon. Mollusks, including *Unio cristonensis,* have been found at several places, cycads, ferns, and neocalamites have been collected, and fossil wood determined as *Araucarioxylon* and *Woodworthia* has been found common. Scales, fragmentary skulls, and ribs of ganoid and other (?) fish, plentiful in Chinle strata near the mouth of Pine Creek, in the cliffs at Kanab, and in Sand and Johnson Canyons, seem to represent species not restricted to the Upper Triassic. Of the fishes from Kanab collected by C. D. Walcott in 1879, Eastman[41] says, "The general aspect of the *Lepidotus*-like forms is suggestive of Jurassic rather than of Triassic relations." In a later publication he identified one of the species as *Lepidotus walcotti,* "closely related to *L. gallineki, Upper Triassic.*" Fossil fish from the same beds at Kanab were identified by Lull[42] as *Pholidophorus* sp. (Lower and Middle Triassic) and *Seminotus* sp. (Triassic." Large collections of fish remains from the Petrified Forest member in Pine Creek Canyon were reported by Kilmore[43] as ganoids too fragmentary for specific identification. Of the dinosaur trackways Gilmore writes:

> The tracings of fossil tracks found near Kanab, Utah, are those of typical Triassic carnivorous dinosaurs. The larger ones pertain to the genus *Eubrontes* sp., the smaller ones to *Grallator* sp. The latter, if the presence of a four digit (the hallux) could be detected, might equally well be referred to the genus *Anchisauripes.*

CONTACT OF CHINLE AND OVERLYING FORMATIONS

In the plateau country an interruption in deposition between the Chinle and the overlying Wingate sandstone was noted by Gilbert[44] at the Henry Mountains, by Dutton[45] "in the vicinity of the Hurricane fault," by Gregory[45a] in northwestern Arizona, by Emery[46] in the Green River Desert, by Gilluly and Reeside[47] at the San Rafael Swell, and by Gregory and Moore[48] in Paria and Escalante Valleys. The evidence of this unconformity, even where best expressed, consists chiefly of deep sun cracks and fragments of Chinle embedded in the Wingate. Though generally in distant views the boundary between the dark-red thin-bedded, regularly bedded Chinle and the light-colored massive Wingate is conspicuous, traverses of miles along outcrops reveal few places where the topmost Chinle strata have been much eroded or are discordant with the Wingate above, and in some measured sections 30 to 60 feet of sandsone has been recorded as "undifferentiated Chinle and Wingate." In the Zion Park region the observed contacts show exposure to the sun and some conglomeratic lenses but no well-defined erosion features. They mark a somewhat lessening of regularity in upward sequence, an abrupt change in texture and color, and the replacement of stream-laid sediments by sediments deposited largely by wind. However, this evidence of unconformity seems insufficient to demonstrate a time break of major importance. As well expressed by Baker,[49] "The wind-blown sand [of the Wingate] accumulating upon the fluviatile Chinle sediments would naturally preserve minor local irregularities, even though deposition were continuous in most of the region."

Because of this poorly marked Chinle-Wingate contact the top of the Chinle cannot everywhere be drawn with assurance, even where the Wingate is present, and in areas where the Wingate is absent and the Chinle is in contact with the Kayenta or the Navajo, and the lower part of the Navajo is bedded, further difficulties in mapping appear. Thus in the Virgin Valley below Rockville and along the Vermilion Cliffs west of Sand Canyon the lower 300 to 500 feet of the Navajo, otherwise characteristic, is displayed as white and red beds 10 to 50 feet thick, which except in color and texture differ little from the thick beds of sandstone at the top of the Chinle, and owing to the thinning and final disappearance of intervening beds the two formations meet along a zone occupied by miscellaneous beds. (See pl. 39.) This arrangement is shown on a cliff a mile northwest of Pipe Spring, where the following section was measured:

Section 1 mile northwest of Pipe Spring

Navajo sandstone.

Sandstone, alternating light red and white, in beds 6 to 42 feet thick; in part cross-bedded, in part thinly laminated; fine, even grains; lime and iron cement; the lowermost 300 feet of an otherwise nonlaminated mass, 800 + feet thick; lies unevenly on No. 6.

5–6. Sandstone, red and purple; a series of irregularly placed, overlapping, and intertonguing lenses; highly calcareous; quartz grains (90 percent) 0.01 to 0.3 millimeters in diameter, the smaller ones sharply angular; feldspar (6 percent), mica flakes, well-rounded tourmaline, magnetite, and zircon; cement lime and ferruginous clay; within 100 feet along the strike thickness 1 to 6 feet.

Unconformity; surface of erosion; in places weathered to red clay.

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41 Eastman, C. R., State Geologist of New Jersey, Ann. Rept. for 1904, p. 66, 1905.

42 Lull, R. S., quoted in Gregory, H. E., and Moore, R. C., The Kaiparowits region: U. S. Geol. Survey Prof. Paper 164, p. 58, 1931.

43 Gilmore, C. W., personal communication, Feb. 18, 1938.

44 Gilbert, G. K., The geology of the Henry Mountains, p. 9, U. S. Geol. and Geog. Survey Rocky Mtn. Region, 1877.

45 Dutton, C. E., Report on the geology of the High Plateaus of Utah, p. 148, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1880.

45a Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, pp. 48, 191, 1916.

46 Emery, W. B., The Green River Desert section: Am. Jour. Sci., 4th ser., vol. 46, p. 563, 1918.

47 Gilluly, James, and Reeside, J. B., Jr., Sedimentary rocks of the San Rafael Swell and some adjacent regions in Utah: U. S. Geol., Survey Prof. Paper 150, p. 68, 1928.

48 Gregory, H. E., and Moore, R. W., The Kaiparowits region: U. S. Geol. Survey Prof. Paper 164, p. 58, 1931.

49 Baker, A. A., Geology and oil possibilities of the Moab district, Grand and San Juan Counties, Utah: U. S. Geol. Survey Bull. 841, p. 41, 1933.

1–4. Sandstone, dark red, streaked and dotted with white; lenses irregularly bordered by argillaceous and calcareous iron-stained shale; coarse angular and rounded grains of quartz and ferromagnesian minerals; individuals and chains of clay pellets; a ledge 25 to 35 feet thick, face marked by pits, knobs, and benches.

Chinle sandstone, red, in beds 1 to 8 feet thick.

In a branch of Pipe Wash beds corresponding to Nos. 1 to 4 of this section are truncated and here and there coated with gravel and sand concretions, and near the mouth of the Parunuweap an unconformity in this position is marked by green shales, mud lumps, and fragments of sandstone. At several places between Moccasin and Short Creek seeps issue from the base of rocks corresponding to Nos. 5–6.

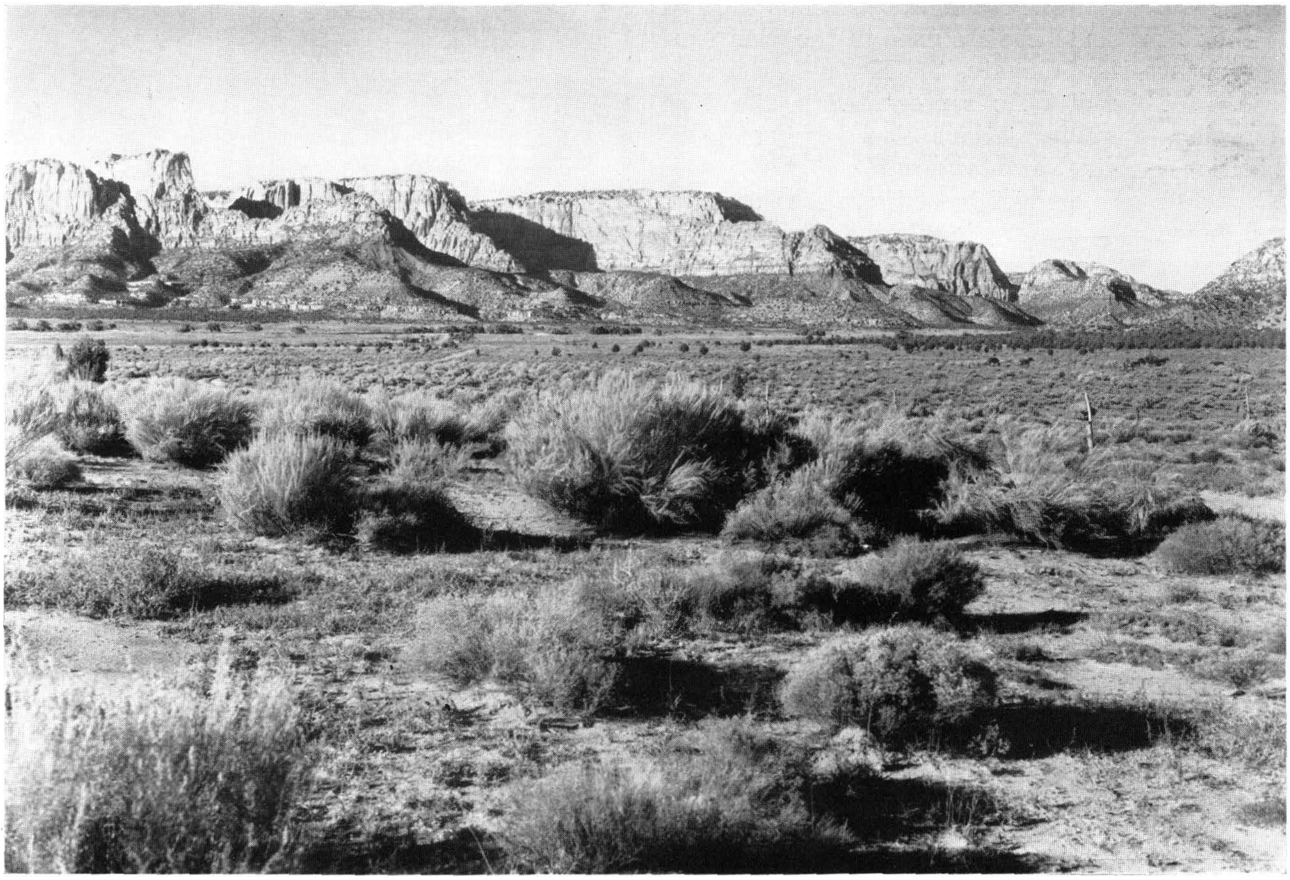


FIGURE 39.—Chinle lower slopes overlain by strata of Glen Canyon group in which distinctive Kayenta and Wingate are not recognizable. Vermilion Cliffs near village of Short Creek, north edge of Uinkaret Plateau in foreground. H. E. Gregory 945

JURASSIC FORMATIONS

The Jurassic of the Zion Park region includes most of the formations assigned to that system elsewhere in the plateau province. Its two great component groups, the Glen Canyon and San Rafael, present everywhere the same general features, but because of their strongly contrasted composition, color, mode of deposition, and topographic expression they are readily distinguished. Also, as broadly defined units in the Mesozoic sequence they are clearly unlike the Triassic Chinle below and the Cretaceous Dakota (?) above. A third Jurassic division—the Morrison formation, conspicuous in eastern Utah—is not clearly represented west of the Paria River and, if present, has lost its most characteristic features. The regional relations of the formations classed as Jurassic are shown in figure 9.

GLEN CANYON GROUP

In his analysis of the Jurassic of the Navajo country, Gregory described two massive cliff-making sandstones, separated by a series of thin sandstones and shales, that lie between the Chinle and †"McElmo" formations.[50] for the lowermost bed he adopted the term Wingate sandstone, the Wingate sandstone of Dutton; for the uppermost bed, which completely surrounds Navajo Mountain, Navajo; and for the intermediate bed Todilto, from Todilto Park, New Mex. For convenience in mapping and in stratigraphic description, he treated these three formations as comprising a "La Plata group," which he considered to be substantially the equivalent of the La Plata sandstones in southwestern Colorado as described by Cross.[51] When more extended studies cast doubt on

[50] A dagger (†) preceding a geologic name indicates that the name has been abandoned or rejected for use in classification in publications of the Geological Survey.

[51] Cross, Whitman, U. S. Geol. Survey Geol. Atlas, Engineer Mountain folio (no. 171), 1910.

this correlation, possible confusion was avoided by substituting the name "Glen Canyon group" for "La Plata group." The new term seemed appropriate, inasmuch as rocks of this group form both walls of Glen Canyon and extend far up tributary canyons into the San Juan country, the Henry Mountains, the Waterpocket Fold, and as far as the base of the High Plateaus. Also doubt regarding the correlation of the "Todilto formation" has led to the replacement of that name by "Kayenta formation."

In accordance with the practice in previous publications, the formations here assigned to the Glen Canyon group are the Wingate, the Kayenta, and the Navajo. (See fig. 40.) As represented in the Zion Park region, these formations closely resemble in composition, bedding, and texture those at the type localities, and the agents of deposition were the same. They differ much, however, in relative thickness and in their strength as guides to erosion. Westward from Colorado and New Mexico the Navajo becomes increasingly prominent, changing from a single massive bed less than 200 feet thick to huge ledges more than 2,000 feet thick; the Kayenta, typically developed in northeastern Arizona and represented at most Jurassic outcrops across southern Utah, disappears before reaching the Hurricane cliffs; and the Wingate, a prominent cliff maker east of the Paria River, ends as a recognized unit in the walls of Zion Canyon. The upper limit of the Glen Canyon is definitely placed at the unconformable contact of the marine Carmel formation and the terrestrial Navajo sandstone. The lower limit is difficult to place, particularly where the contact with the thick-bedded upper Chinle sandstones seems gradational. (See p. 72.)

The geologists of the Wheeler and Powell Surveys treated the "White Cliff sandstone" (upper Navajo) and the "Vermilion Cliffs series" (lower Navajo, Kayenta, and Chinle) as marine. Likewise Branson[51a] states that "the La Plata, Navajo, and Wingate have none of the qualities of subaerial deposits," and that "*no apprehensible amount of the red beds was eolian in origin*"; and he quotes Twenhofel as saying that "such an origin is clearly impossible." However, the evidence presented by Gregory,[52] by Reeside,[53] and by other students of Mesozoic stratigraphy seems to demonstrate terrestrial deposition in which wind played a prominent part. In the light of present knowledge, it seems appropriate to say that no part of the Glen Canyon group is marine and that eolian sandstones constitute the bulk. The earliest deposits (Wingate) are predominantly eolian, though in many places fluvial beds of Chinle type appear at their bases and also at higher horizons. In Kayenta time streams became the dominant agent of deposition; then, in some places abruptly, in others gradually, they lost their power and gave way to wind, the agent chiefly concerned in the deposition of the Navajo.

The Glen Canyon group comprises a series of water-laid and wind-laid beds of much the same texture and mineral composition, in places distinct, elsewhere mingled. In the plateau province

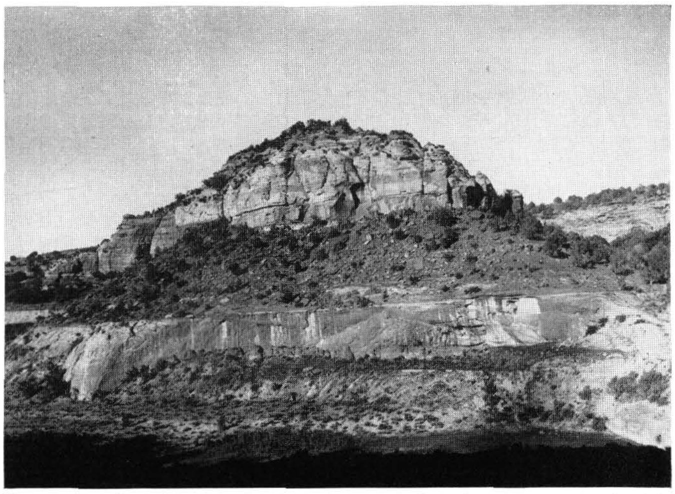


FIGURE 40.—Glen Canyon group in Kanab Canyon: Wingate, Kayenta (middle slope), and basal Navajo. Photograph by J. C. Anderson.

as a whole the physical characteristics of the Wingate closely resemble those of the Navajo. Topographically both formations form cliffs; both are elaborately cross-bedded and marked by vertical jointing, more commonly in the Wingate; and on weathering both develop attractive alcoves and recesses. In some outcrops the lower and upper boundaries of the Navajo are clean-cut, but in many places beds of Navajo type are incorporated in the underlying Kayenta, and generally west of the Paria River the great massive core bed is capped by variegated shales which in turn are overlain by a second massive bed of Navajo type (Temple cap member) immediately in contact with the Carmel. The massive cross-bedded Wingate likewise in some places terminates abruptly downward and upward, but in many more places its contact with the Chinle and with the Kayenta is reached by passing through thin beds of Wingate character; and sporadically within the massive bed are long lenses of shalelike sandstone. Such stratigraphic features seem not out of place in a series of strata that include both fluvial and eolian deposits.

A surprising feature of the Glen Canyon group is the lack of regional unconformities that represent pauses in deposition and coincident widespread erosion. Deposition of the Wingate, the Kayenta, and Navajo seems to have been almost continuous. A change in type of deposit seems not to have been accompanied by large-scale breaks in continuity of de-

[51a] Branson, E. B., Triassic-Jurassic "red beds" of the Rocky Mountain region: Jour. Geology, vol. 35, pp. 620–630, 1927.

[52] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, pp. 58–59, 1917.

[53] Reeside, J. B., Triassic-Jurassic "Red Beds" of the Rocky Mountain region, a discussion: Jour. Geology, vol. 36, pp. 47–63, 1929.

position nor by tectonic movements of importance. This absence of demonstrated crustal movements, other than regionally uniform lowering or raising of the land within an area of some 80,000 square miles for a period long enough for the accumulation of 2,000 to 3,000 feet of fine-grained sandstone, is so out of accord with the sedimentary history as known elsewhere that search for features indicative of local uplift and erosion was made along miles of cliffs and canyon walls; but no such evidence was found and none has been reported by others. These observations are even more difficult to explain in view of the fact that no marked discordance in dip characterizes the contact of Navajo and Carmel nor that of the Wingate and Chinle. The general stability seems thus to have lasted not only through Lower and Middle Jurassic time but also through Upper Jurassic and Upper Triassic time—perhaps as much as 55,000,000 years. The impression is strong that detailed structural mapping will show that the discordance between the Jurassic formations is greater than now appears. Though no local regional slopes are necessary for eolian deposition, such stream-laid beds as the Kayenta, some of them coarse, suggest a topography with at least moderate relief. Furthermore, a sloping surface must have been provided for the encroaching Carmel seas.

Deposition during all of Glen Canyon time seems to have taken place in a huge interior basin bounded on the east, south, and west by granitic and metamorphic highlands and characterized by nearly flat and fairly even slopes on the floor and sides. The evidence indicates that an arid or semiarid climate with cyclical fluctuations prevailed until in Upper Jurassic time the sea coming from the north introduced marine sediments (Carmel). The extent of the basin of deposition and doubtless also its depth and continuity were not always the same, and there is evidence to suggest that at times the regional basin included local basins. Thus the Wingate is thickest and most purely eolian in a belt that extends northwestward from Wingate, N. Mex., to the Fremont River, Utah. The thickest Kayenta lies west of this belt, and the Navajo reaches its greatest development in southwestern Utah. In places marginal phases marked by interleaving of eolian and fluviatile deposits mark the borders of successive basins.

The recognition of wind as an agent of deposition for the thick widespread sands of the Navajo and Wingate naturally came slowly. In contrast to Dutton Davis and Gregory thought them to represent terrestrial sediments but could find no satisfactory explanation for the marvelous cross-bedding in the cliffs at the Paria Plateau, in the Kanab Valley, and along the Virgin River. In the words of Davis,[54] "Wind action in an ancient desert seems more competent than any other agent to produce the observed structures, but we could not discover any critical and decisive proof of this suggestion." Huntington and Goldthwait[55] likewise doubted the marine origin of some of the Jurassic beds. They write:

> It seems to be a fair question whether the cross-bedded strata of the Colob and Kanab [formations] may not be continental deposits laid down by wind. * * * The Colob [upper, white part of the Navajo] suggests a piedmont deposit formed during a time when the climate had become so dry that a great desert drifted its sands in huge dunes over an area as large as the State of Indiana.

Study of the Mesozoic formations in northeastern Arizona[56] gave an opportunity to test the hypothesis of the eolian origin for the Navajo and similar beds and led to the conclusion that "the structure and composition of the rock suggests aridity and the uninterrupted control of the winds—there is little doubt that desert conditions prevailed." Evidences of wind work as listed were the style of bedding; the sorting, form, and size of grains; the relations of eolian to lacustrine beds; and other features, like those of modern dunes and wind-laid coatings of flat lands but unlike those characteristic of large-scale fluvial or marine deposits.

More recent studies by many geologists in the field and in the laboratory make it seem clear that the distinctive structural and petrographic features of the Wingate and Navajo are those characteristic of wind-laid sediments. If the outcrops were small no question need arise. Doubt comes with the recognition that these beds are thicker, more extensive, and much more uniform than other known eolian deposits and with the difficulty in visualizing a climate and a topography that would make such accumulations possible. Generally modern dune sands rest on eroded surfaces of much relief, but the Navajo and Wingate are but slightly discordant with their underlying formations. Furthermore, the agent and the process concerned in the repeated truncation of sets of curved and straight laminae are not clearly recognizable. That streams took part in the deposition of the Wingate and Navajo is obvious, but except in the Temple cap member of the Navajo stream-laid sediments constitute a very small part of the formations. Broad stream valleys, floored with sand and gravel, then overlain with dunes, thus becoming part of the general mass, have not been found in any of the many canyons that cut the formations from top to bottom. It seems likely that in a prevailingly arid climate the sediments of ephemeral streams soon dried and were built by the wind into local dunes or carried far away.

[54] Davis, W. M., An excursion to the plateau province of Utah and Arizona: Harvard Coll. Mus. Comp. Zoology Bull., vol. 42, p. 9, 1903.

[55] Huntington, Ellsworth, and Goldthwait, J. W., The Hurricane fault in the Toquerville district, Utah: Harvard Coll. Mus. Comp. Zoology Bull., vol. 42, pp. 214, 216, 1904.

[56] Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, p. 59, 1917.

The age of the Glen Canyon group has not been satisfactorily determined. In his analysis of the reports of the Powell Survey Gregory[57] assigned the White Cliffs sandstone (upper Navajo of present usage) to the Jurassic and assigned also to that age the "Todilto" (Kayenta) and Wingate, theretofore considered Triassic. The bottom of the Jurassic was placed at the zone of unconformity between the Wingate and Chinle as expressed in east-central Utah, northeastern Arizona, and northwestern New Mexico. These conclusions were based on stratigraphic studies supplemented by the identification of dinosaur remains from the Kayenta as "not older than the latest Triassic." Also, the formations comprising the Glen Canyon group were described as Jurassic by members of the Geological Survey and others in papers published prior to about 1925, but since that time the continued absence of conclusive proof of Jurassic age has led to the general use of the noncommittal term "Jurassic (?)." The paleontologic evidence of age is inconclusive; the fossils are few and not diagnostic, and their interpreation shows considerable discordance. Of recent studies Camp[58] writes: "The only fossils reported from the Wingate are dinosaur tracks which have not been identified. Consequently the age of the formation remains somewhat doubtful, with the strong probability that it is Jurassic." Regarding *Segisaurus halli* recently discovered in the Navajo, Camp[59] says, "Despite its primitive character it could be placed in either the Triassic or the Jurassic," and adds the remark, "Owing to the lack of information regarding the distribution and occurrence of small dinosaurs it has usually been inadvisable to employ these forms in age determinations." Brady[60] writes that in northern Arizona the evidence "strongly suggests that the whole series of Red Beds [Glen Canyon group and Chinle] * * * should be considered Upper Triassic or still more probably * * * as representing in part or whole the Triassic-Jurassic interval."

However, Brady quotes R. S. Lull as saying regarding fossils from the Navajo: "*Ammosaurus* is at the very summit of the Triassic, and I imagine that its Jurassic successor would not have varied greatly in the parts your specimen shows." He also quotes from a letter by C. L. Camp: "The upland Mesozoic faunas are very little known * * * It seems, therefore, that the use of these fossils in correlation would be extremely limited." Further doubt regarding the age of the Glen Canyon group has resulted from the discovery by Brown,[61] in beds described as "part of the Chinle," of *Protosuchus*, a form related to other primitive crocodiles in the Lower Jurassic of Europe and South Africa. At present the Glen Canyon group is classed as Jurassic (?), chiefly because it lies between the Upper Triassic Chinle formation and the Upper Jurassic Carmel and includes no widespread unconformity that might represent long intervals of erosion. It seems probable that eventually the Navajo will be definitely assigned to the Middle Jurassic and that the Kayenta and Wingate will find their places among Lower Jurassic formations. However, both lithologic features and areal distribution suggest that the conditions of deposition in Triassic time continued into the Jurassic and that the limits of the two systems can be established only by detailed paleontologic studies. The difficulties in determining the age of the Glen Canyon group lie not only in the absence of diagnostic fossils but also in the inconclusiveness of lithologic studies, which so far have thrown little new light on the source of materials or the date of their deposition.

Thus it appears that after 50 years of intermittent study the history of the "red beds" of the plateau remains a tantalizing problem. Much has been learned, but much more remains to be known. The present-day field worker can but share the feeling of Dutton:[62]

> To the student whose mind is engaged chiefly with problems of stratigraphy the Jura-Trias system of the plateaus * * * is a most alluring field of study. True, it yields more questions than answers, but the questions are full of suggestion, opening many avenues of thought which he is fain to follow.

WINGATE SANDSTONE

DISTRIBUTION AND GENERAL FEATURES

In the generalized descriptions and sections of the Triassic and Jurassic of the plateau country previously published by Gilbert[63] and Howell[64]—the first on record—no beds are recognizable as Wingate.

Dutton[65] surmised that a "group or subgroup of sandstone 450 feet thick, which I have named provisionally in my field notes the Wingate sandstone," extended from the Zuñi Plateau, New Mex., across Arizona and was "the equivalent of the 'Vermilion Cliffs series' in southern Utah, * * * where its aspect is somewhat different." Along the base of the

[57] Gregory, H. E., op. cit., pp. 51, 56.

[58] Camp, C. L., A study of the phytosaurs with description of new material from western North America: California Univ. Dept. Geol. Sci. Mem., vol. 10, pp. 4–5, 1930.

[59] Camp, C. L., A new type of small bipedal dinosaur from the Navajo sandstone of Arizona: California Univ. Dept. Geol. Sci. Bull., vol. 24, No. 2, p. 52, 1936.

[60] Brady, L. F., Preliminary notes on the occurrence of a primitive theropod in the Navajo: Am. Jour. Sci., 5th ser., vol. 30, pp. 214, 215, 1935.

[61] Brown, Barnum, An ancestal crocodile: Am. Mus. Novitates, No. 638, June 20, 1933.

[62] Dutton, C. E., Tertiary history of the Grand Canyon district: U. S. Geol. Survey Mon. 2, p. 34, 1882.

[63] Gilbert, G. K., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 160, 1875.

[64] Howell, E. E., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 272, 1875.

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

High Plateaus Dutton[66] mapped the upper Chinle, the Wingate where present, the Kayenta, and the lower, red part of the Navajo as "the Vermilion Cliff series," undifferentiated Triassic, and contrasted it with the Jurassic "White Cliffs" sandstones (upper Navajo). In the Zion Park region the strata now classed as Wingate were first segregated by Walcott,[67] who measured in the Kanab Valley 310 feet of "massive gray sandstone, cross-bedded" (Wingate), overlain by 120 feet of "evenly-bedded red sandstones" (Kayenta) and underlain by beds characteristic of the Chinle. Gregory and Noble[68] mapped the white "massive cross-bedded sandstones" at the junction of Three Lakes and Kanab Creek Canyons as the equivalent of the Wingate in Arizona. Gregory and Moore[69] tentatively assigned to the Wingate distinctive beds in Paria, Johnson, and Kanab Canyons. More recent studies show that these beds extend to the Virgin River Valley in relations that justify correlation with the Wingate east of Glen Canyon.

Generally across southern Utah the Wingate is strongly expressed in the topography as a massive cross-bedded stratum that in texture, structure, and even in color is readily distinguished from the formations immediately above and below. (See pl. 39.) Generally also it is a maker of cliffs that are exceeded in boldness only by those carved from the Navajo sandstone. As recorded in measured sections, it is thickest along a broad zone extending northwestward through Mesa Ventana, Ariz. (375 feet), and the mouth of the San Juan River (300 feet) to Capitol Reef (420 feet), beyond which it is concealed by younger beds in Thousand Lake and Fish Lake plateaus; but even within this zone the range in thickness is considerable. South and west of the Waterpocket Fold the Wingate is concealed for about 60 miles. Where it reappears in the Paria Valley its characteristic massive part is less than 50 feet thick. West of the Paria it measures 80+ feet in Deer Springs Canyon, 200+ feet in Johnson Canyon and with irregularly decreasing thickness extends to the Virgin River.

In the Zion Park region the Wingate sandstone is best exposed in the walls of Johnson, Hog, Kanab, Cottonwood, and Sand Canyons and in mesas and towers along the southern edge of Wygaret Terrace. In all these places it is a conspicuous part of the Mesozoic sections—a band of massive cross-bedded sandstone, gray, red, or tan in general color, which in canyon walls and on the mesa faces lies between bedded red sandstones (Chinle and Kayenta). (See fig. 40.) In Johnson Canyon the Wingate, 200 to 310 feet thick, forms a red wall along the highway for about a mile. (See fig. 41.) At its base a zone of conglomerate material—clay balls and slabs of shaly sandstone associated with sun-cracked slabs—provides an exit for several strong springs. In Kanab Canyon and the tributary Trail, Three Lakes, Cave Lakes, Bunting, and Tenney Canyons the massive part of the Wingate is 150 to 265 feet thick, generally white, streaked with red and buff. (See fig. 42.) Its cross-bedding is an amazing display of curved and straight laminae, many of them folded and crumpled. In the branches of Cottonwood Canyon and sand canyon the friable, strongly cross-bedded Wingate, white at the top, red lower down, is characteristic in texture and position. Southwestward it thins and becomes less distinctive and is absent from the Vermilion Cliffs. Also northwestward from Sand Canyon the formation for some 20 miles is buried beneath younger sediments of Moccasin Terrace, and where it reappears in Parunuweap Canyon it lacks some of its usual features. Here it is a dark-red massive sandstone about 60 feet thick, composed of incompletely sorted, fine, even quartz grains, with a little tourmaline and garnet, and marked by closely spaced cross-bedding laminae, inconspicuous except on weathered surfaces; at its base an unconformable leached zone includes paper-thin green shales, mud lumps, and gravel. From the narrows of the Parunuweap the Wingate thins irregularly and disappears as a recognizable unit in the walls of Zion Canyon. Along this 30-mile stretch the formation thins and thickens and changes from a single massive bed to a series of lenticular beds in short distances along the strike, and in places it is interleaved with laminated sandstone and shale. Were it not that tracing shows it as a unit specifically like the typical Wingate and generally unlike the beds below and above, it might

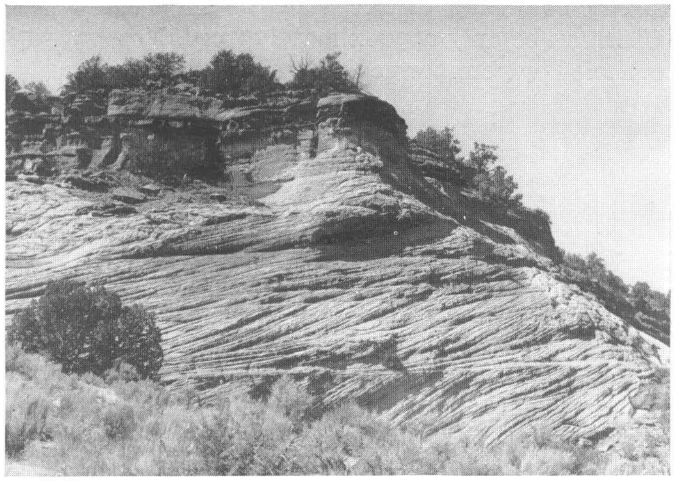


FIGURE 41.—Wingate and Kayenta showing unconformable relations, Johnson Canyon. H. E. Gregory 931

[66] Dutton, C. E., Tertiary history of the Grand Canyon district: U. S. Geol. Survey Mon. 2, pp. 40–41, pl. 4, 1882.

[67] Walcott, C. D., quoted by Cross, Whitman, and Howe, Ernest, Geol. Soc. America Bull., vol. 16, p. 485, 1905.

[68] Gregory, H. E., and Noble, L. F., Notes on a geological traverse from Mohave, Calif., to the mouth of the San Juan River, Utah: Am. Jour. Sci., 5th ser., vol. 5, p. 236, 1923.

[69] Gregory, H. E., and Moore, R. C., The Kaiparowits region: U. S. Geol. Survey Prof. Paper 164, pp. 164–169, 1931.

reasonably be classed as an exceptional feature of the Kayenta or even of the Chinle. But though the Wingate at its westermost outcrops is inconspicuous among the beds that form the great red cliffs, measured sections reveal its characteristic composition, texture, and relative resistance to erosion. On the geologic map the Wingate and the Kayenta are in places combined to form one color unit.

The boundary of the Wingate in southwestern Utah can be only approximately fixed. Northward it is buried by younger sedimentary rocks, westward in upper Zion Canyon it is covered by the Kayenta, and about the base of Eagle Crags and across the Virgin River at Kinesava Mountain it is indistinguishable. Southward from Sand Canyon and the Parunuweap the formation could have extended only short distances; it is an indistinct bed at Moccasin Springs, and no definable outcrops appear in Potter, Parashant, Rosecrans, and Short Creek Canyons or westward along the Vermilion Cliffs. East of Kanab the Wingate that now caps the Vermilion Cliffs doubtless extended southward to an undefined limit. In the Paria Valley below the mouth of Road Canyon and southward along the Echo Cliffs the formation is not clearly represented. It thus appears that, as in areas of modern dunes, the border of the Wingate eolian sands is irregularly sinuous on a large scale.

In contrast with the interpretation here outlined Baker[70] states that the Wingate "probably did not extend beyond the middle of Arizona and Utah" and that "it cannot be recognized at Lees Ferry or westward in southern Utah."

The materials that compose the Wingate, the style of bedding, the shape and arrangement of grains, the pockets of conglomerate, and sheets of fresh-water limestone are accepted as evidence of deposition on land at a time when the climate was generally arid. Much of the sand was transported by wind, some of it by ephemeral streams. In these respects the Wingate closely resembles the Navajo. (See p. 81.)

The source of the Wingate sands is not known. Doubtless a little material was contributed by the underlying Chinle, but most of it must have come from distant areas where igneous and metamorphic rocks were exposed to erosion.

H. E. Gregory '53

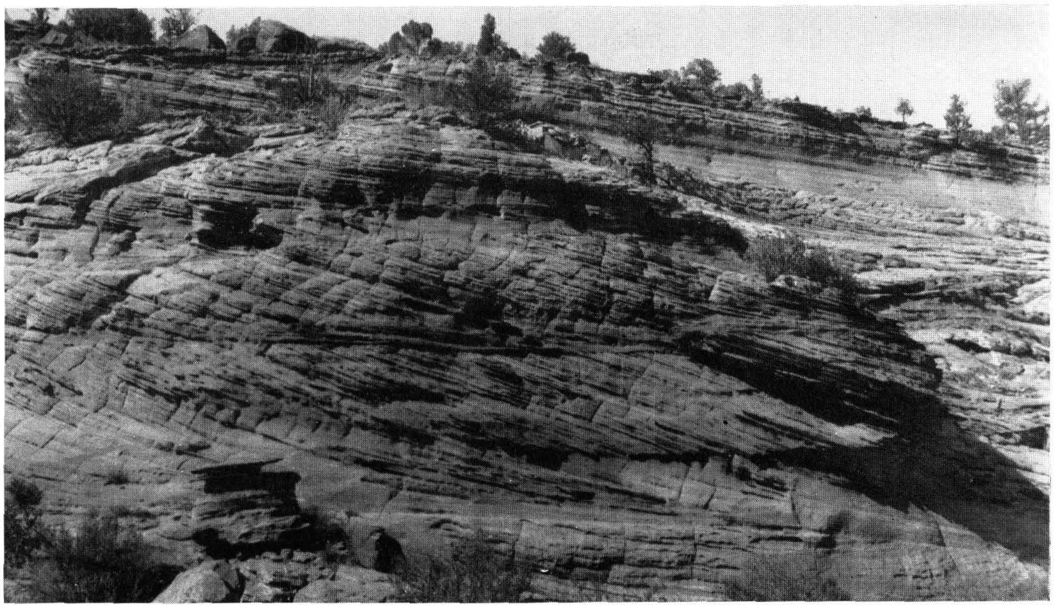


FIGURE 42.—Wingate sandstone, middle Kanab Canyon.

TEXTURE AND COMPOSITION

In essentials the descriptions of the Wingate sandstone, as exposed at its type locality and elsewhere east of the Paria River, hold good for the Zion Park region. Its outstanding lithic feature is a very massive, fine- to medium-grained, strongly cross-bedded sandstone, part of it in places divided into beds. In addition to the massive bed the formation here and there includes patches of sandy shale, limestone, and conglomerate, and at the base 5 to 15 feet of earthy nodular sandstone mottled red, white, and purple. The shales are highly calcareous, lenticular, and otherwise irregularly stratified and include some coarse-grained beds. The limestones, usually less than 2 feet thick, are in places nearly pure, firm, hard, compact, obscurely laminated, and marked on their upper surfaces with sun cracks; in other places they are merely plasters of highly calcareous materials irregularly disposed among lenses of coarse and fine standstone. The conglomerates consist chiefly of rounded and angular fragments of limestone, sandstone, and shale but include clay pellets, iron and lime concretions, chert, and elongated twisted aggregates perhaps formed by algae. They are much like beds in the upper part of the Chinle and doubtless have the

[70] Baker, A. A., and others, Correlation of the Jurassic formations of parts of Utah, Arizona, New Mexico, and Colorado: U. S. Geol. Survey Prof. Paper 183, pp. 4, 12, 1936.

same general history. As these subordinate beds are relatively more resistant than the major bed, they stand on cliff faces as steps and assist in forming the little pinnacles and hoodoos that characterize some Wingate outcrops. The cement is so weak that where not protected by Kayenta or Navajo beds, the rock crumbles readily under foot, and much of the fresh rock in road cuts may be crushed in the hands. Showers and even strong winds remove the material with seeming ease. Joint cracks and tiny faults are common, and many of them are lined by material more resistant than the body of the rock. On weathered surfaces these fractures are indicated by projecting ridges in places closely enough spaced to form "stone lace."

Two classes of grain are revealed by the microscope. Those in the body of the rock average about 0.12 millimeter in diameter and include many smaller ones, which on weathering form "blow dust." Many grains tightly plastered on foliation surfaces measure 0.30 to 0.70 millimeter in diameter, and mingled with them are sparse flat and angular pieces of shale and limestone that are considerably larger. C. S. Ross reports the Wingate in Parunuweap Canyon as a very fine-grained quartz sandstone with only a trace of feldspar and having subrounded grains, size variation 0.1 to 0.5 millimeter. Of the heavy minerals only tourmaline was noted. The Wingate "contains lenses (sheets 1 grain thick) in which there is a concentration of quartz grains about twice the size of those in the main mass of the rock. These are well rounded, somewhat frosted, and very well sorted. With these are other grains of the same size, apparently well-rounded fragments of quartzite." As much as 98 percent of the massive Wingate consists of round or egg-shaped grains of clean-washed translucent quartz. The rarer material includes tourmaline, garnet, feldspar, and hard little angular chunks of limestone and clay. Magnetite is present in two thin sections, and biotite in one. Many of the grains are frosted, some of them delicately etched as if by wind. The cement is mainly calcite mingled with iron in various stages of oxidation, and to it is chiefly due the color of the rock. The relative deficiency of red iron oxide permits the quartz and calcite to give generally white color to exposures in Kanab and Sand Canyons and, owing largely to the kind of iron cement, many otherwise white or gray outcrops show irregular areas of dark red, light red, tan, yellow, and greenish white. In some sections of canyon walls the Wingate is persistently red; in others it is merely coated red by drippings from the overlying Kayenta. "Desert varnish" is uncommon. West of Kanab Canyon outcrops of orange-yellow rock suggest the Orange Cliffs along the Green River. In a few places the lower part of the formation is marked by horizontal white bands not related to bedding.

As generally elsewhere, the Wingate of the Zion Park region is cross-bedded on both a large and a small scale. (See figs. 41, 42, 45.) Sets of parallel laminae in various positions are truncated along horizontal and oblique planes. In the more massive portions many laminae are curved and in places twisted and bent downward into saucer-shaped depressions. In Cave Lakes Canyon beds originally laid down as conformable laminae were disturbed before they became consolidated, and consequent slumping and sliding has produced areas within which the material seems to have been kneaded. Faulting of the unconsolidated sediments has added other irregularities. (See figs. 43, 44.) It is interesting and may be significant that a comparison of scores of photographs shows the most complex and distorted bedding near the regional edges of the Wingate sandstone—at Dutton Plateau, New Mex., west-central Colorado, and southwestern Utah.

KAYENTA FORMATION

DISTRIBUTION AND GENERAL FEATURES

Throughout the plateau province where the entire Glen Canyon group is present the Navajo and Wingate are separated by a series of dark-red lenticularly bedded sandstones. For this stratigraphic unit Gregory introduced the term "Todilto formation," and as "Todilto" or "Todilto"? the formation has been recognized at many localities in Arizona, Utah, and Nevada. In the belief that the Todilto at its type locality (Todilto Park, New Mex.) is younger than the Glen Canyon group, perhaps equivalent to Morrison, Baker[71] substituted the term "Kayenta formation," which has since been generally adopted. As the field relations are clear and the terms "Todilto," "Todilto?," and "Kayenta" have been applied to substantially the same sections, no problem in correlation is involved. In the Zion Park region the Kayenta is exposed in canyons that pass through the Vermilion Cliffs and forms part of the platform in front of the White Cliffs. It is nearly coextensive with the Wingate but not with the Navajo. West of the Wingate outcrops it retains its characteristic features for only a few miles, and where like the Wingate it disappears, its position is generally held by a few feet of miscellaneous jumbled material, but in places the bedded sandstone of the Chinle formation is in contact with the Navajo. It thus appears that along its regional borders the Kayenta was not laid down under uniform conditions; that within Kayenta time strong streams, weak streams, and wind combined in forming the deposits.

The thickness of the Kayenta in the Zion Park region is 75 to 110 feet in Johnson Canyon, 118 to

[71] Baker, A. A., Geology of the Monument Valley—Navajo Mountain region, San Juan County, Utah: U. S. Geol. Survey Bull. 865, pp. 50–52, 1936.

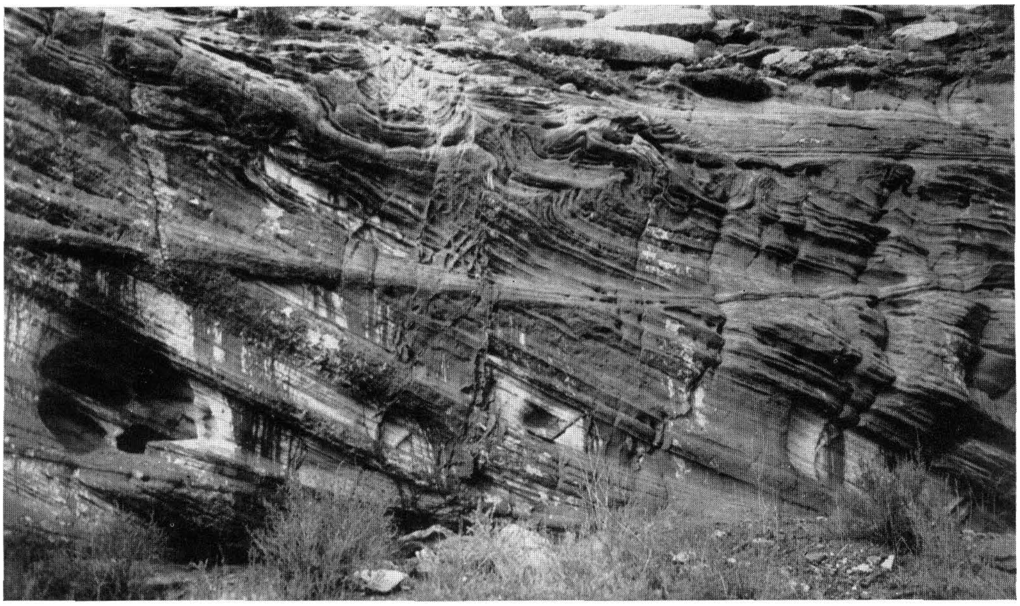


FIGURE 43.—Wingate sandstone in Cave Lakes Canyon, showing structure caused by slumping and incipient faulting before Kayenta sandstones (at right top) were deposited. H. E. Gregory 762

200 feet in Kanab Canyon, 130 to 165 feet in Sand Canyon, and 0 to 180 feet within Zion Park. East of Paria the range is 25 to 310 feet, including large differences within a few square miles. Some of this wide

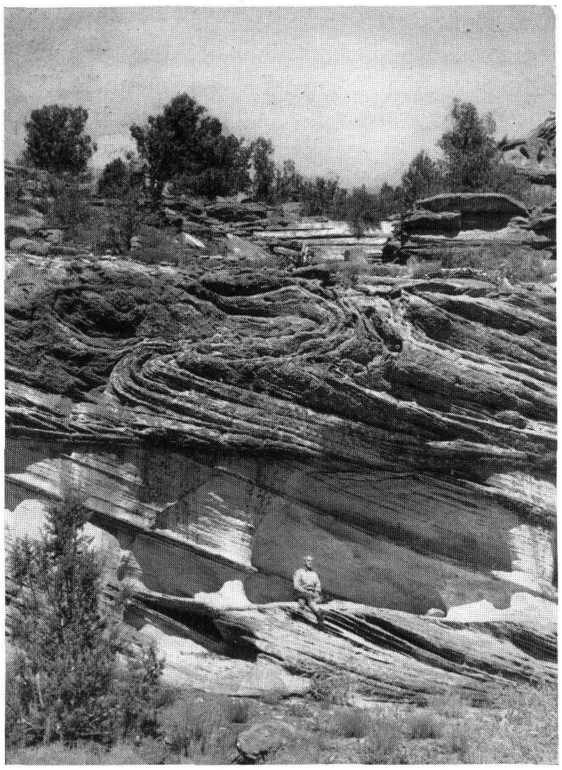


FIGURE 44.—Detailed structures in Wingate sandstone. Cave Lakes Canyon. H. E. Gregory 900

range in measured thickness is due to post-Kayenta erosion, evident in a few places, and perhaps more to the lack of unanimity in selecting the poorly marked contacts with other formations, but most of it is believed to record original deposition and to be consistent with its mode of origin.

As a regional topographic feature the Kayenta is a slope between cliffs. Unlike most other rocks whose cement is chiefly lime, it does not disintegrate readily. On weathering, its tough lower beds, particularly the limestones, remain in places as a narrow platform—a roadway along the top of the Wingate. There is abundant evidence to show that the Kayenta was laid down on a land surface by streams vigorous enough to carry fragments of considerable size, regular enough to produce sorting, and free to shift channels laterally. Also that shallow depressions in the surface held lakes and ponds suitable for the chemical and organic deposition of limestone and concretionary conglomerate. The source of the stream-borne material can only be conjectured. Some of it is reworked Wingate, but most of it probably came from the unknown highlands which supplied all the Triassic and the Lower Jurassic sediments. The few fossils from the formation are insufficient to establish a specific age. The very rare dinosaur tracks and bones and the worn wood fragments have "Jurassic affinities"; the Unios are wide-ranging species.

BEDDING, TEXTURE, AND COMPOSITION

As the detailed sections show, the Kayenta formation consists of sandstone with subordinate limestone and conglomerate. Some sandstone layers are as much as 10 feet thick, but thinner beds are more common, and in places shalelike beds identical in composition and texture with the thicker beds constitute large parts of the outcrops. Some coarse-grained, stubby lenses are completely embedded in fine material, as if a groove had been prepared for their occupancy. Cross bedding is fairly common, most of it expressed as laminae that traverse the rock obliquely. Many local unconformities marked by erosion, sun-baked surfaces, or sharp change in texture separate the beds both vertically and laterally. Like other sediments deposited by ephemeral streams, the Kayenta strata vary considerably in arrangement, composition, and color.

The bulk of the Kayenta is medium-grained, but coarse-grained beds or parts of beds are little less common, and fine-grained mudstones and silts are features of many sections. Except for the coarsest materials the sorting of grains is fairly complete—about that of the sands in nearby stream beds. Quartz in rounded grains is the predominant mineral. With it are a little mica segregated in tiny patches and rare clay lumps that may represent feldspar. One thin section shows a fragment of staurolite. The cement is chiefly calcite mingled with iron in films wrapped tightly about the grains. It is sufficiently abundant and resistant to make the rock essentially impervious; water percolating downward through the overlying porous Navajo emerges as springs at the top of the Kayenta. Limestone beds form part of most Kayenta exposures and though irregularly placed and of no great extent are prominent because of their color and their resistance to erosion. Where most fully developed they are hard, dense, cherty blue-gray, or white layers, 6 inches to 2 feet thick. But most of the purer beds tail out into calcareous sandstones, and some are chiefly lime aggregates in a groundmass of quartz sand. Where its bottom is suitably disposed for observation the limestone is seen to occupy shallow depressions, and at one place in Hog Canyon thinly laminated lacustrine silt separates it from the Wingate. The conglomerates, like the limestones, are sporadically distributed. Most of them are lenses less than 1 foot thick and 100 feet long, composed of angular or worn chunks of shale, sandstone, and limestone and mud balls and concretions about an inch in diameter surrounded by sand cemented with lime. The prevailing color of the Kayenta is maroon, thus contrasting with the underlying grayish white of the Wingate and the overlying light red or tan of the Navajo. In places individual beds or groups of beds are lavender, buff, yellow, greenish gray, or mottled. Locally white bands are conspicuous, but as many of them are discordant with the bedding, they seem not to be features of original deposition.

NAVAJO SANDSTONE

DISTRIBUTION AND GENERAL FEATURES

The Navajo sandstone is the most prominent formation in southern Utah. In the San Juan country it forms both flanks of the upwarps trenched by the San Juan River and the rough floor of Red Rock Plateau. It rims Glen Canyon throughout its 160-mile course, surrounds the Henry Mountains, forms the floor of Escalante Valley, and continuing westward across Paria, Kaibab, Johnson, Kanab, Virgin, and La Verkin Canyons gives form and color to the outstanding topographic features. Few viewpoints may be chosen that do not include the Navajo, and airplane photographs give the impression that in a wide strip across Utah the Navajo is bedrock.

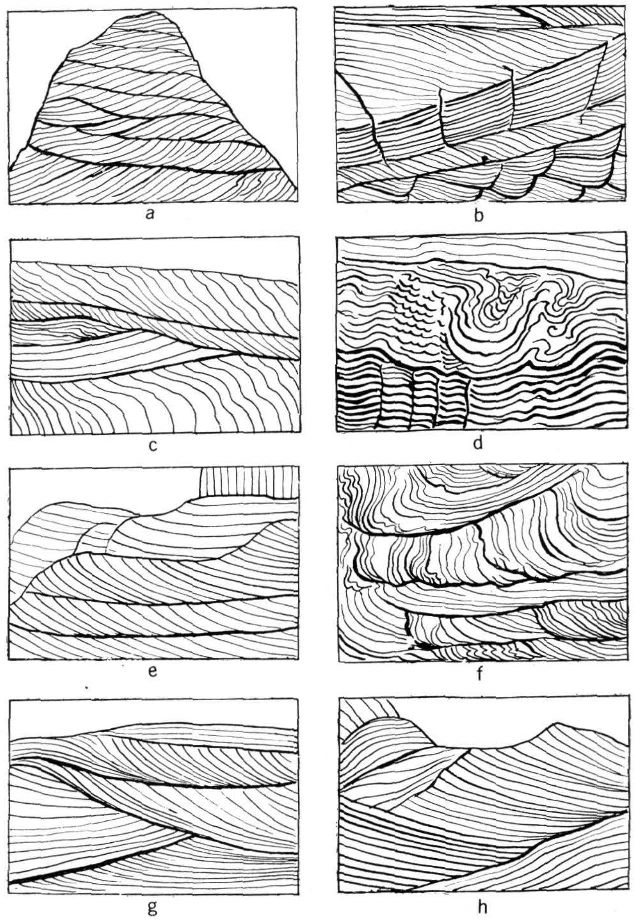


FIGURE 45.—Types of cross bedding. *a–e*, In Navajo sandstone; *f–h*, In Wingate sandstone.

In the Zion Park region the Navajo sandstone forms the floor of Wygaret and Moccasin Terraces, the pinnacled tops of the outlying Eagle Crags and Smithsonian Butte, the southern edge of Kolob Terrace (fig. 5), and the magnificent walls of Parunuweap, Zion, and La Verkin Canyons. Within the Zion National Park it constitutes the massive block from which have been carved the canyon walls, the buttresses, towers, spires, and "mountains," and such enormous erosion features as West Temple, the Watchman, and the Great White Throne. (See figs. 36, 46.) The White Cliffs ending at Heaton Point and the equally white Block Mesas on Moccasin Terrace are the upper white part of the Navajo, which farther south has been stripped away to form a platform on red lower Navajo beds. At Checkerboard Mesa and elsewhere along the highways east of Pine Creek Tunnel the peculiar bedding of the Navajo attains

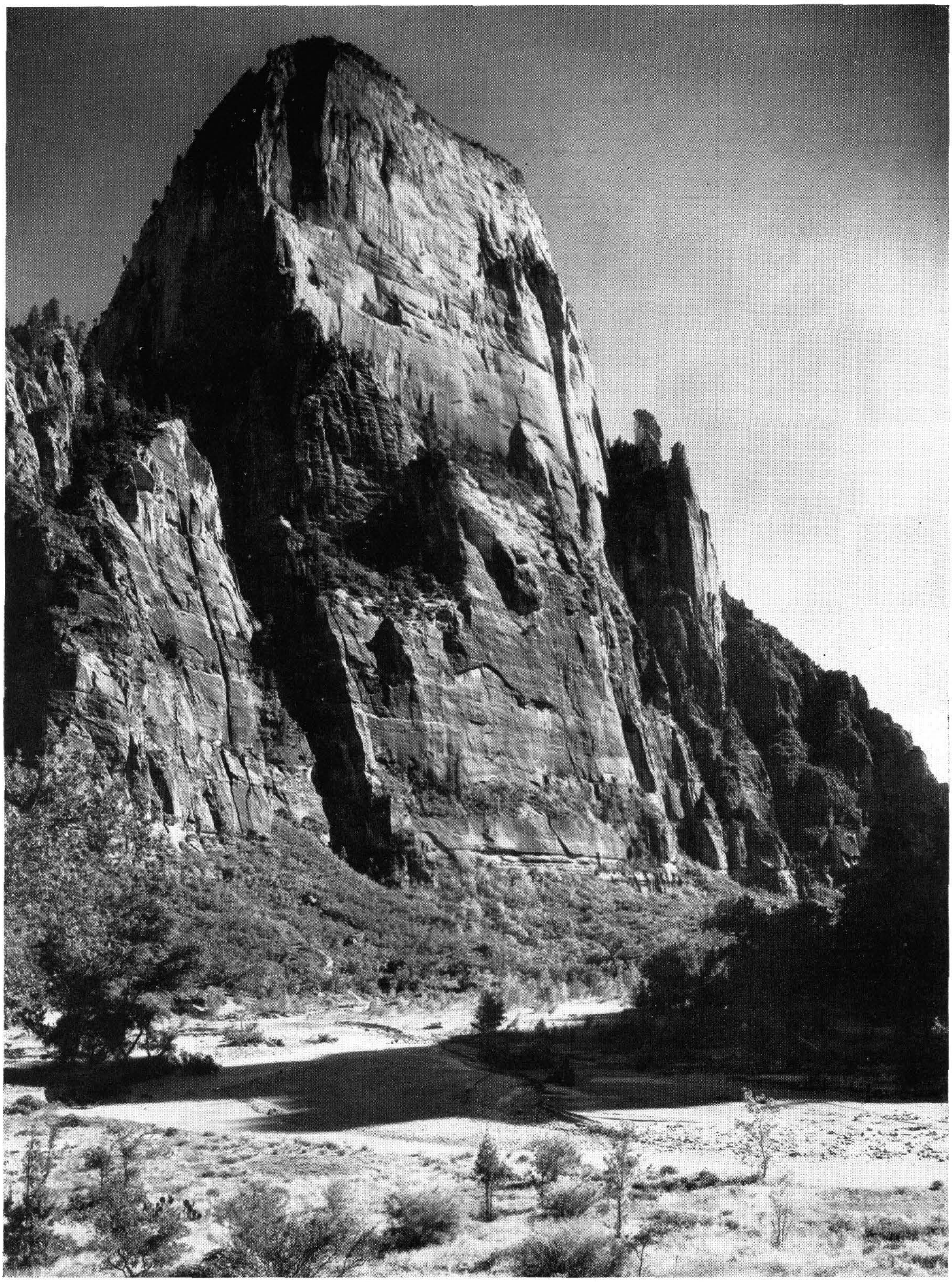


FIGURE 46.—The White Throne, monolith of Navajo sandstone; upper half, white. Height above Virgin River at base, 2,394 feet. Photograph by National Park Service No. Z2.

unparalleled perfection of detail and attractiveness of design and color. (See figs. 45, 47, 48.)

Everywhere throughout its broad expanse the Navajo is a major topographic control. To it are chiefly due the long lines of towering cliffs and the deep, narrow canyons that characterize the rim of the High Plateaus. Unlike the Kaibab and Shinarump formations below and the Carmel, Straight Cliffs and the Wasatch above, which on erosion form nearly horizontal platforms and mesa tops, the Navajo yields eroded surfaces that are very uneven. In the absence of resistant covering beds the rock breaks down into mounds and conical towers and is so friable that its products of disintegration are carried away by showers. Large areas are bare and devoid of vegetation. Southern Kolob, Mocassin and Wygaret Terraces, and the platform bordering the Parunuweap form a bewildering maze of flat mounds, steep mounds, short rounded ridges, "mosques," "nipples," and "haystocks," and at the inner edge of the terraces detached from the nearby cliffs stand such conspicuous round-topped erosion remnants as Bridge Mountain, the Guardian Angels, and Tabernacle Dome. (See fig. 49.) Rising above the hummocky surface are low slim towers, "demoiselles," protected from erosion by a cap of limestone or ferruginous sandstone. (See fig. 47.) Here and there erosion has developed water pockets—deep, narrow circular pits which even during dry seasons may retain sufficient water for stock. Crossing a Navajo surface involves climbing hills, smooth or ribbed by cross-bedding structure, and crossing saucer-shaped depressions and sharply cut gulches so closely and intricately spaced that hours may be needed for a journey of a mile.

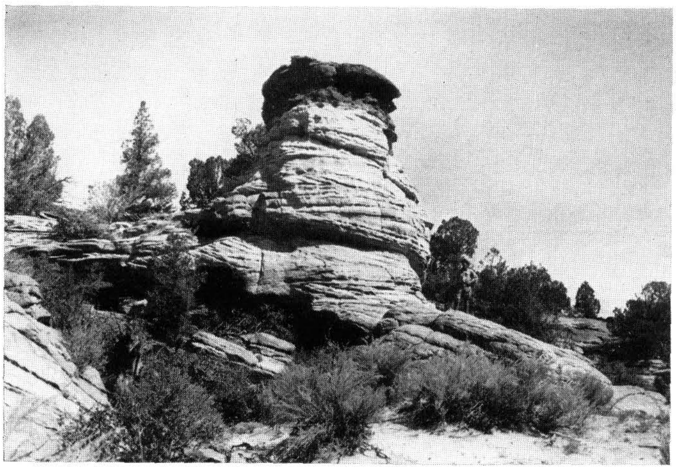


FIGURE 47.—Butte of Navajo sandstone capped by ironstone. On Cane Beds-Pine Springs trail.

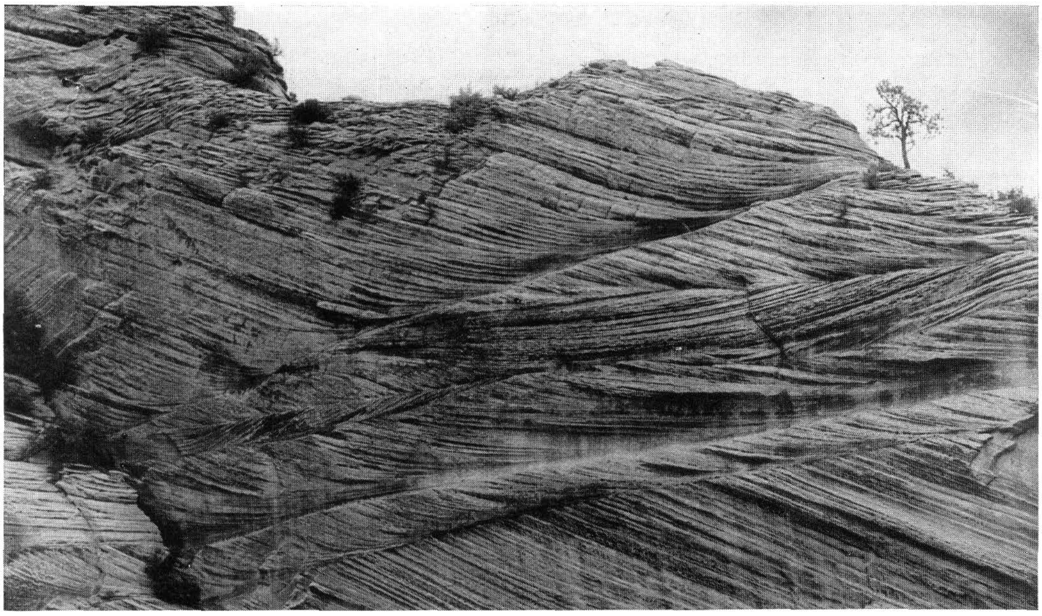
The Navajo is traversed by innumerable vertical and oblique joints, which extend part way or wholly through the formation. (See figs. 8. 9, 49.) As the material that fills them is commonly more resistant than the rock, the joint cracks stand as tiny walls, crisscrossing the formation in a capricious manner, and outlining on the surface checkerboard squares. Guided by the joint cracks and by the entangled bedding, weathering has covered the surface with elaborate and picturesque carving.

Unlike the Wingate, which shows considerable local range, the Navajo with few notable variations increases in thickness from east to west. Beginning with a thickness of some 200 feet at the Colorado line, sections record 880 feet at the mouth of San Juan Canyon; 1,000–1,400 feet at Waterpocket Fold and the Paria River, and more than 1,800 feet in the Zion Park region. Its maximum measured thickness of 2,280 feet at the Temple of Sinawava is greater than that of the whole Glen Canyon group elsewhere.

Though correlation of the Navajo by fossils is vague, the texture of the rock, its composition, its position in the stratigraphic column, and the fact that its closely spaced outcrops permit almost continuous tracing leave no doubt that the beds mapped as Navajo in Arizona, Utah, and Nevada are substantially of the same age. Outside of the plateau country the Nugget sandstone of Wyoming is probably its equivalent.

STRATIGRAPHIC AND PETROGRAPHIC FEATURES

Essentially the Navajo is a huge mass of remarkably homogeneous fine-grained friable quartz sandstone held together by calcareous cement. Everywhere most of it, and in places all of it, appears as a single massive, elaborately cross-bedded stratum that includes irregularly disposed lenses of limestone, limestone conglomerate, sandy shale, and ferruginous sandstone. Generally in the Zion Park region and particularly where the Wingate and Kayenta are absent, its basal portion, 50 to 300 feet thick, consists of somewhat regularly bedded strata, much like the sandstone beds of the topmost Chinle. (See figs. 50, 51.) The top beds also are distinctive. They consist of variegated sandy shale capped by massive sandstone—the two divisions of the Temple cap member. Of the subordinate strata in the formation, the limestones examined are brittle, dense, siliceous, suncracked layers less than a foot thick and of no great extent, which along the strike are abruptly replaced by coarse sandstone or more commonly tail out into a conglomerate of broken or concretionary limestone, fragmentary shale, mudstone, and wormlike aggregates, perhaps representing algae. Some of the limestone is mottled with black and gray specks of carbonaceous material. Generally the purer limestones rest in shallow depressions floored with shale and tightly cemented coarse sandstone, sufficiently impervious to have served as a water table, thus permitting the local rainfall and runoff to form lakelets in which calcareous material might be deposited directly or with the aid of organisms. It seems significant that west of the Paria River the limestones are less abundant, more thinly laminated, and more restricted to the lower half of the formation than in eastern Utah. It would seem that in late Navajo time the region where deposition was most abundant was the region of greatest aridity and that most fully in control of the winds. Also interpreted as lacustrine deposits are thinly and regularly laminated beds, only slightly more calcareous than the bulk of the rock, that form groups 2 to 6 feet thick and, like the limestones, thin and become coarser at their margins and seem to occupy shallow depressions.



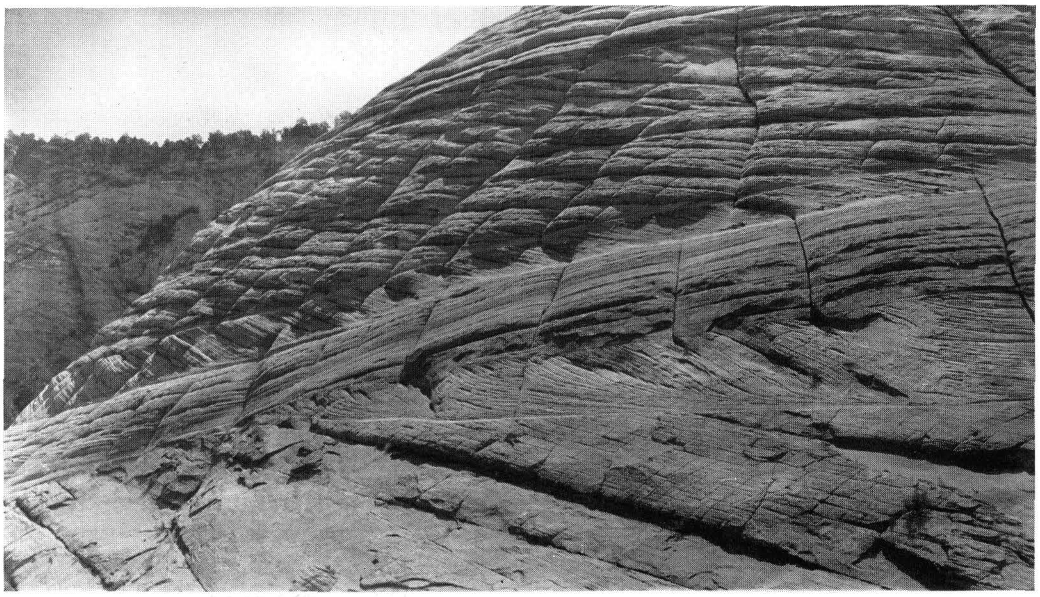
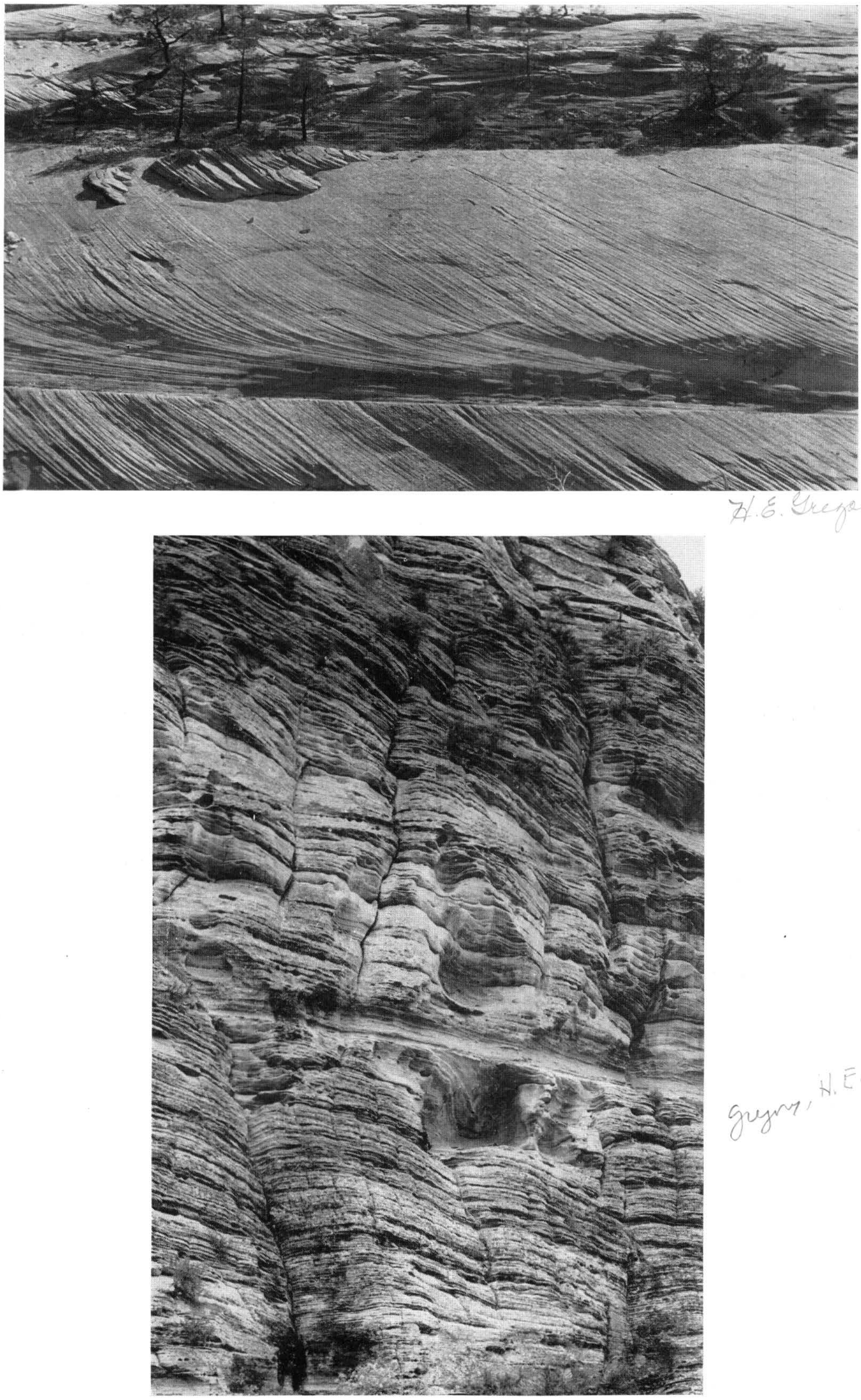


FIGURE 48.—*A*, *B*, Navajo sandstone exposed along Zion-Mount Carmel highway, showing styles of bedding. (See fig. 45.)

Here and there embedded in the sand matrix of the Navajo outcrops are irregular lumps of maroon shale, which in places combine to form lenses of thin-bedded shale mingled with concretionary material. Though generally thin and less than 50 feet long, these deposits are prominent because of their color and their ease of disintegration. Even in fresh road cuts drippings from these red beds stain the surrounding rock.

The outstanding feature of the Navajo is the bedding. Unlike most sedimentary rocks, which over wide areas consist of horizontal layers superposed in orderly fashion, this sandstone is built of laminae disposed in all sorts of positions. Some laminae appear as groups of parallel straight lines, vertical, horizontal, or oblique, and are sharply truncated along inclined or horizontal planes. Others are curved, sweep through long arcs, and gradually decrease in curvature until they become tangent to those beneath. Series of parallel curves overlap or merge with series of different radii. Some are grouped as wedges like those in the Coconino sandstone of the Grand Canyon. In places the laminae are wrinkled and squeezed into loops. Many sets of laminae retain their individuality for a few hundred feet, though commonly they extend tens of feet; some are measured in inches and are recognizable only on weathered surfaces. These straight lines, curved lines, and truncate planes that characterize the Navajo cross bedding vary so widely in dimension, position, and arrangement that adequate detailed description seems impracticable. Even attempts to outline types of cross bedding have proved unsatisfactory. Fortunately, photographs record the features with fidelity and make leisurely study possible. (See figs. 45, 48.)



H.E. Gregory 681

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FIGURE 48.—*C, D,* Navajo sandstone exposed along Zion-Mount Carmel highway, showing styles of bedding. (See fig. 45.)

Ripple marks are uncommon. Those noted are short series with a trough depth of half an inch to 2 inches and show the eolian type of sorting. Longwell[72] reports that in the Navajo of the Muddy Mountains "many of the fine-grained sandstone layers are ripple-

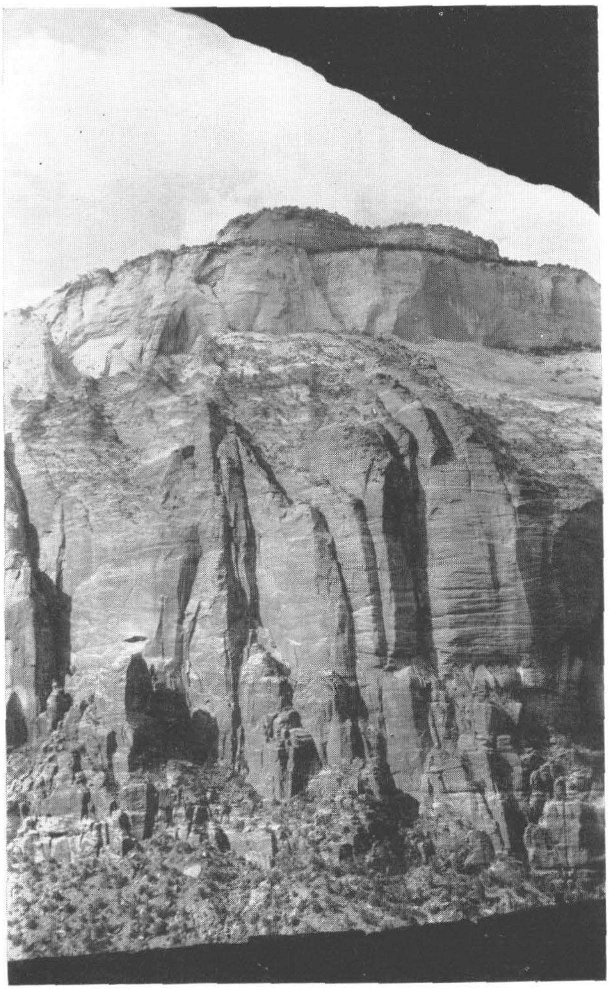

FIGURE 49.—Navajo sandstone, south wall of East Temple, Zion National Park. Shows typical jointing, local faulting, and style of erosion. Temple cap member at top. Vertical distance in view, 2,100 feet.

marked." The scarcity of ripple-marked beds in the Zion Park region in the Navajo seems indicative of the strength and shifting of winds. Dune ripples are ephemeral features; they are soon removed by successive winds and may be destroyed by heavy showers. In modern dunes ripple-marked surfaces are not common.

A score of mechanical analyses and many thin sections reveal the Navajo as essentially an aggregate of quartz grains weakly cemented by calcite and brown or red iron oxide. Fully 98 percent of the entire formation consists of grains of translucent quartz that under the microscope glisten like fish roe. Rounded, spherical, discoid, or lentiform grains make up 40 to 70 percent of tested samples, 5 to 10 percent of them perfectly round. The remainder show small angularity of outline. In addition to the quartz the Navajo contains some feldspar, staurolite, tourmaline, very rare biotite, zircon, magnetite, and garnet —all suggesting metamorphic source rocks—and fragments of limestone and of hard clay like those on the broken surface of playas. The material is fairly well sorted into grains of two general sizes. In the bulk of the rock, excluding the mustard-seed bits of dust, the grains range in diameter from 0.01 to 0.25 millimeter and average about 0.15 millimeter. Scattered or grouped on steep bedding planes are the partly rounded ferromagnesian minerals and bits of sedimentary rock that range in size from 0.50 to 0.1 millimeter and include here and there fragments as large as peas and thin, narrow sheets as much as half an inch long. Many of the grains are frosted, and some of the larger ones are wind etched. Krynine[73] notes that in a specimen from Co-op Creek "there are no pitted and frosted grains smaller than 0.14 millimeters in diameter."

Scattered throughout the Navajo are lenticular brown-black amorphous or roughly foliated masses of iron that seem to be stratigraphically and areally grouped. The rock also contains round-ended lenses of green, red-blotched, solidly cemented ferruginous sandstone that appear on cliff faces like inclusions and, on weathering, remain on the talus as resistant blocks. Of a specimen of this material from Parunuweap Canyon, Ross[74] writes:

> This rock is composed essentially of quartz with lesser amounts of feldspar iron oxides and a green micaceous mineral. Though related in chemical composition to glauconite the green mineral is rather clearly not marine glauconite. The brown spots are due to the local oxidation of the iron. The differing color appears to be due to differences in the degree of oxidation of the iron.

In the "green Navajo" along the Mount Carmel highway Professor Bronson Stringham recognized "a chlorite of the chamasite variety—brunsvigite". He remarks, "brunsvigite may be hydrothermal but is usually sedimentary. The green streak in the Navajo is horizontal and cuts across the bedding suggesting deposition by grand waters."

The cement of the Navajo sandstone, chiefly lime and iron oxides, includes minor dolomite and silica. The lime, in spaces between the quartz grains, is a universal constituent, all specimens tested effervesce with acid; the iron, wrapped tightly about the quartz grains, mingled with the claylike material or segregated, is most abundant in the darkest-red, finest-grained beds; silica, sparingly distributed in the rock as a whole, is the binder in the rare lenses of quartzite. The iron is the coloring matter in the rock. Hematite chiefly produces the red colors, limonite the yellow, and ferruginous clay the brown and the green. Analytical tests yield almost no manganese and no

[72] Longwell, C. R., Geology of the Muddy Mountains, Nev.: U. S. Geol. Survey Bull. 798, p. 65, 1928.

[73] Krynine, P. D., personal communication.

[74] Ross, C. S., personal communication.

combination of other minerals capable of producing the pigment. The various shades of red seem roughly the measure of the amount of iron rather than of its stage of oxidation. Some of the dark-red shaly layers include as much as 5 percent of iron but in the whitest rock iron in any form is rare. Because of its weak cement the rock is remarkably friable, particularly the parts deficient in iron. Big slabs on falling to the talus may crumble into dust, and seemingly solid boulders may crush under foot and disintegrate in place. Projecting ledges are precarious footholds. Specimens for laboratory study may be trimmed by hand and may disintegrate in transit. In quarrying the material, blasting with powder was ineffective. Tests show that the Navajo strata in the Pine Creek tunnel have a pore space of 12 percent, and high porosity of the rock is further shown by the ease with which percolating water passes through it; the base of the Navajo is a spring zone. Largely due to the kind and amount of cement, the color of the Navajo is far from uniform. Generally in eastern Utah and northeastern Arizona the color of the Navajo is some shade of red, though large exposures are prevailingly brown, tan, buff, cream, gray, or white. In the White Cliffs, Elkheart Cliffs, Block Mesas, and the cliffs and towers of Zion Park the upper part of the formation is dominantly white and the lower part red. This contrast in color, accompanied in places by a somewhat different topography, led Dutton and Powell to treat the white beds as different in age from the red beds below and led Huntington and Goldthwait to define two formations—"Colob, hard white cross-bedded sandstone"—and "Kanab—hard red sandstone, often cross-bedded." However, the boundary between these great expanses of red and white has no definite position; within short distances it rises or sinks as much as 100 feet or is lost in the mergence of colors. On the lower Kolob the red Navajo beds continue upward as white beds, but a few miles to the west, in La Verkin Canyon, the formation is red from bottom to top. The white rock of Bridge Mountain and the Watchman, a thousand feet thick, takes on red tones eastward in Parunuweap Canyon. Local changes in color are even more conspicuous. Most of the cliff and flat-land outcrops display sheets, patches, and circular dots of one color above, below, or side by side with those of another color; and at their frayed contacts the colors merge, interleave, or end abruptly. In places fingers of bright-red rock, singly or in groups, extend far into white rock; and fractures are the division planes between contrasted colors. Some red or white areas appear like hills flanked and covered by rock of other colors.

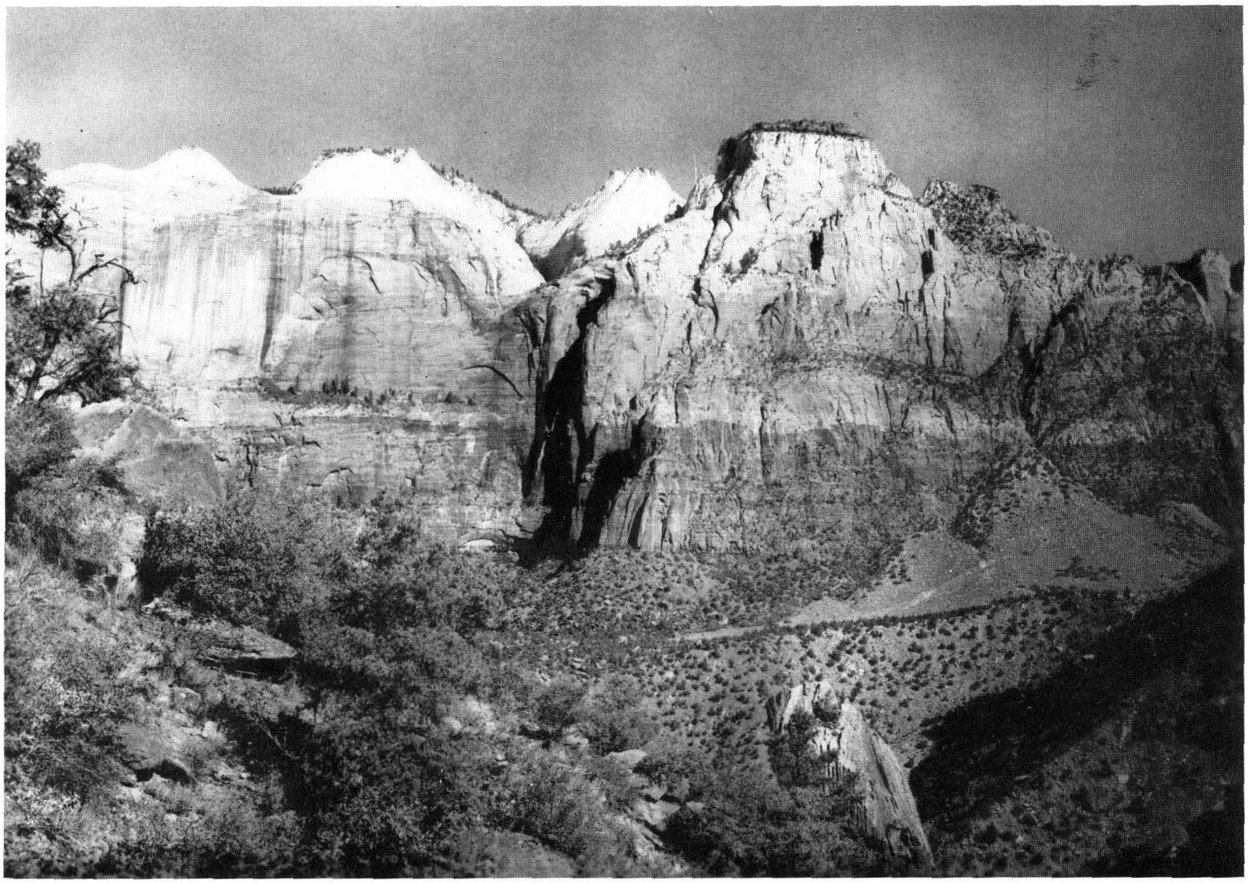

FIGURE 50.—Navajo sandstone that forms the Sentinel in Zion National Park. Upper part white, massive, cross-bedded, capped by limestone of Carmel formation; lower part, made dark red by abundant iron cement, consists chiefly of bedded sandstone. Talus cone and landslide debris (middle and lower left).

Regional surveys and detailed observations show that the color of the Navajo has no stratigraphic significance, or at least none that has been demonstrated. Though in many places the planes that separate colors are horizontal, they rarely conform to the bedding; they cut indiscriminately across beds inclined in various directions; and the texture and composition of the beds below are identical with those above. In places broad bands of white or of red seem to be painted on the cliffs regardless of the composition and texture of the surface. The chief value of the color is the evidence it affords of the conditions of sedimentation, of postdepositional processes, and of physiographic history.

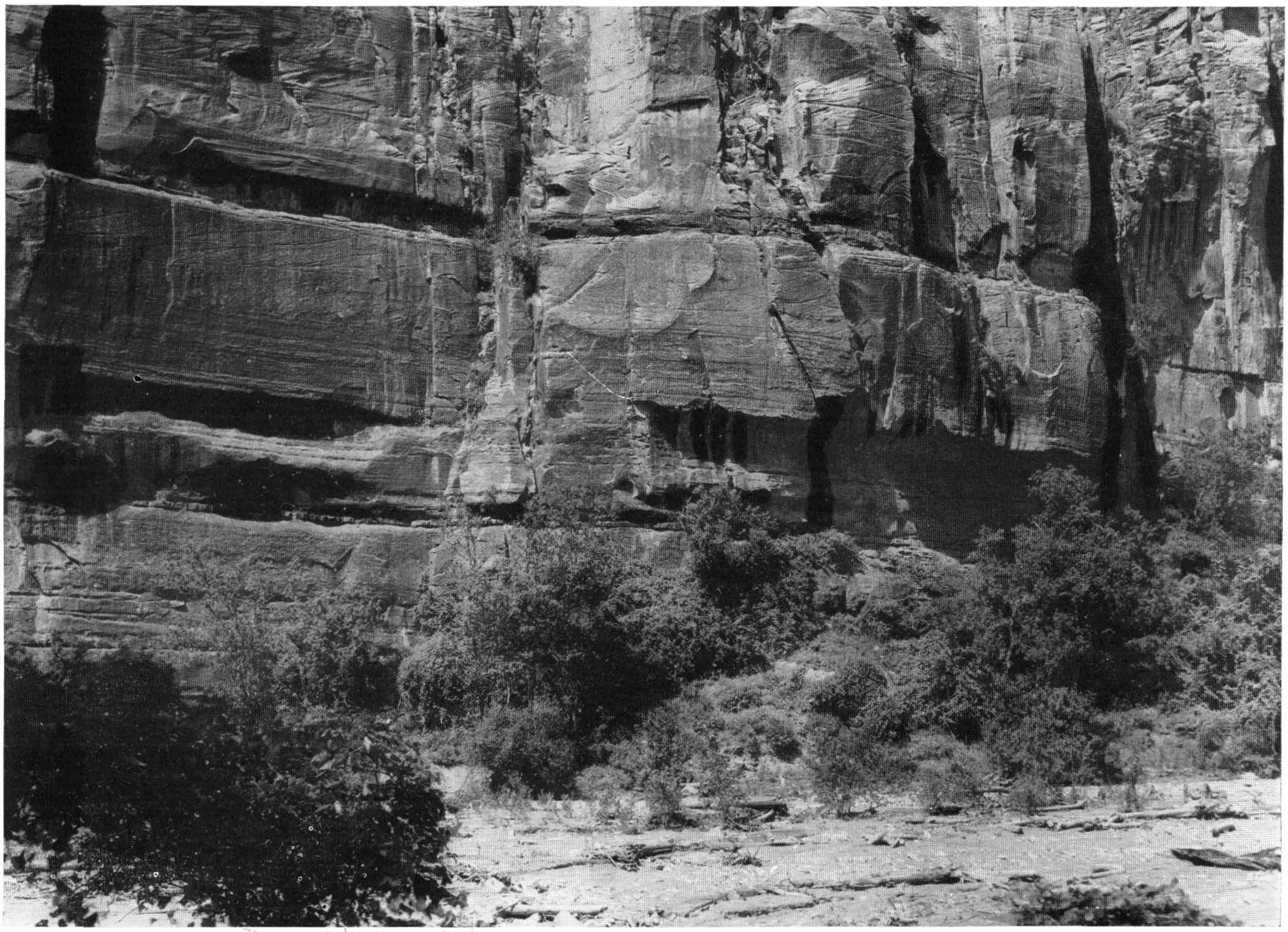

FIGURE 51.—Navajo sandstone base of wall in Virgin Narrows. Unusually even cross-bedded strata separated by shaly sandstone. Water seeps from joints and along beds. Photograph by National Park Service, No. Z238.

The source of the iron, its mode of transport, and the conditions under which it became incorporated in the sandstones have been but partly determined. The original crystalline source rocks could have contained few iron-colored minerals. That they contained much ferruginous material is shown by the large amount of ferric oxides in their disintegration products. As Dorsey[75] remarks,

[75] Dorsey, George, The origin of the color of red beds: Jour. Geology, vol. 34, pp. 135, 143, 1926.

> The agencies, which form ferric oxides are the normal everyday processes of erosion * * * The color is not due merely to the presence of ferric oxide as opposed to ferrous oxide * * * the red color is caused by ferric oxide which has had time to dehydrate and turn to the red hydrate (turgite) and the red anhydrate (hematite).

Dorsey further points out that a warm, moist climate is most favorable for rapid and large-scale oxidation and an arid climate for the preservation of oxidized products.

The conditions would seem satisfied by the assumption that the ultimate source rocks were reconstructed as sedimentary deposits in which red color was developed and that these beds served in turn as the source of the material in the Navajo. But no such beds have been found, and the unconformities within the Mesozoic sequence indicate no intervals of erosion that might represent them. In any event the films of iron about the grains could scarcely have withstood the buffeting and grinding recorded in the rounded grains of not only quartz but of such hard minerals as staurolite and tourmaline. It may be, therefore, that the Navajo sands are the products of primary disintegration and weathering, that their places of origin and deposition were far apart, and that their texture and color afford a measure of the rate and manner of transport. On these assumptions ferric iron was a considerable constituent of the rock at the time of its deposition, and the sands were given their red and yellow tones by the distribution of the original red hematite and turgite and their dehydrated products. It is possible that in the absence of iron or its presence in unsuitable form some of the present white rock may never have been colored, but most of it is believed to be the result of leaching of the iron and the consequent removal of the coloring matter. It is significant that much of the rock that is white on weathered surfaces is red in deep road cuts and tunnels, that the white rock everywhere is much more porous than the red, and that about many springs and seeps the regional red rock is white.

TEMPLE CAP MEMBER

Generally in the plateau province the Navajo is essentially a single thick, massive cross-bedded stratum immediately overlain by marine shale and limestone or by thin, irregularly bedded stream-laid sandstones. In the Zion Park region the formation comprises not only this great bed but also at its top a series of shaly sandstones and a second massive sandstone of Navajo type in contact with the Carmel. As displayed in the Elkheart Cliffs and in the walls of canyons tributary to the Virgin River, these beds combined constitute a stratigraphic unit readily distinguished from units above and below and also a topographic unit of prominence. For this unit, which forms an entablature for East Temple, West Temple, and similar lofty structures, the name "Temple cap member of the Navajo formation" is here introduced. (See figs. 49, 52.)

The upper part of the Temple cap member is a cliff-forming sandstone, generally massive and strongly cross-bedded but in places obscurely or definitely separated into layers 5 to 20 feet thick, most of them cross-bedded. Like the massive part of the Navajo, the rock consists chiefly of uniformly rounded, clean quartz grains weakly cemented by lime and iron. Also like the main bed, the general color of the member is light red, tan, or white, but, particularly at its base and top, it includes much yellow displayed in bands and irregular areas; and much of its weathered product is yellow sand. The lower part of the member is a miscellaneous assemblage of irregularly bedded shaly calcareous sandstones, siliceous limestones, and limestone conglomerates colored red, gray, or brown, which on weathering form a steep red slope between two prominent white ledges and provide coloring matter for staining the cliffs below. The color bands on the Streaked Wall and the "blood" on the Altar of Sacrifice are drippings from the Temple cap member. The entire member is not everywhere present. In places the Carmel formation lies directly on the central massive Navajo bed or is separated from it by thin patches of red sandy shale; in other places only the lower shale portion of the Temple cap member is present; and in still other places the two sandstones are in contact or are separated only by a topographic groove developed by ground-water seepage. Along the Zion-Carmel highway the upper part, 70 to 180 feet thick, is an intricately cross-bedded mass divisible into thick beds, the lower part, 6 to 30 feet thick, a series of lenticular sandstones. East of Kanab Canyon the upper division becomes thinner, less massive, and more varied in composition and the lower part becomes thicker and more calcareous. From the Hurricane Cliffs westward into Santa Clara Valley the entire member is represented by yellow-gray sandy shale.

The series of fluvial and eolian beds, that lies unconformably below fossiliferous marine limestone, and here treated as the Temple cap member of the Navajo sandstone, is assigned by Baker[76] and his associates to the Carmel formation. "At Mount Carmel the Carmel formation * * * contains a variable basal member, 150 to 200 feet thick, of red shale and yellow sandstone."

SAN RAFAEL GROUP

HISTORICAL SKETCH

The series of beds here classed as the San Rafael group were first recognized by the geologists of the Wheeler and Powell Surveys.[77, 78, 79]

Dutton[80] summarized the results of his work and that of Powell, Gilbert, Howell, and Walcott as follows:

> The Jurassic * * * consists of a series of bright-red fossiliferous shales resting upon a very massive bed of white sandstone nearly a thousand feet thick. The shales, which are from 300 to 500 feet in thickness, consist of beds which vary much in quality, some being calcareous, some gypsiferous, and others thinly bedded sandstones. Their interest is chiefly paleontological, since the calcareous layers abound in typical Jurassic fossils, which fix their horizons with certainty.

These pioneer geologists correlated "marine jurassic," the beds between the White Cliff sandstone and the Cretaceous, with the Flaming Gorge group of Powell.

After the reconnaissance surveys of the decade 1870–80 the outstanding features of the Juraissic of southwestern Utah were recorded by several geol-

[76] Baker, A. A., and others, Correlation of the Jurassic formations of parts of Utah, Arizona, New Mexico, and Colorado: U. S. Geol. Survey Prof. Paper 183, p. 22, 1936.

[77] Gilbert, G. K., U. S. Geog. and Geol. Surveys W. 100th Mer. Rept., vol. 3, p. 174, 1875.

[78] Howell, E. E., U. S. Geog. Surveys W. 100th Mer. Rept., vol. 3, pp. 271, 281, 1876.

[79] Walcott, C D., quoted by Cross, Whitman, and Howe, Ernest, Geol. Soc. America Bull., vol. 16, p. 484, 1905.

[80] Dutton, C. E., Tertiary history of the Grand Canyon district: U. S. Geol. Survey Mon. 2, pp. 34–35, 1882.

ogists, largely incidentally to economic investigations.[81, 82, 83]

Along the Utah-Colorado and Arizona-New Mexico boundary lines, where the Mesozoic of the Colorado Plateaus was first studied in detail, the arrangement of the Upper Jurassic beds little resembles that in southwestern Utah. The color, style of bedding, and topographic expression are different, and such unmistakable horizon makers as fossiliferous limestones and persistent thick bands of gypsum are lacking. Under these circumstances correlation of formations east of Glen Canyon with the "marine Jurassic" and related beds of the distant High Plateaus seemed highly speculative—more so even than correlation with established formations in eastern Colorado. Cross,[84] therefore, introduced the term "McElmo formation" for the beds between the "La Plata" (White Cliffs; Navajo in part) and the Dakota (?). "They correspond closely to the Morrison and Como beds and the Flaming Gorge group of Powell."

With various modifications the terminology of Cross was adopted by Coffin,[85] Dake,[86] Emery,[87] Gregory,[88] Lee,[89] Longwell,[90] Lupton,[91] Moore,[92] Prommel,[93] and others, with the recognition that well-defined lithic units justified such descriptive terms as "upper McElmo," "lower McElmo," "Salt Wash member," "undifferentiated La Plata and McElmo," "gypsiferous shales and sandstones," and "varicolored shales and sandstones."

In the progress of studies west of Glen Canyon it became evident that beds in the position of the †McElmo included not only series like those in the typical

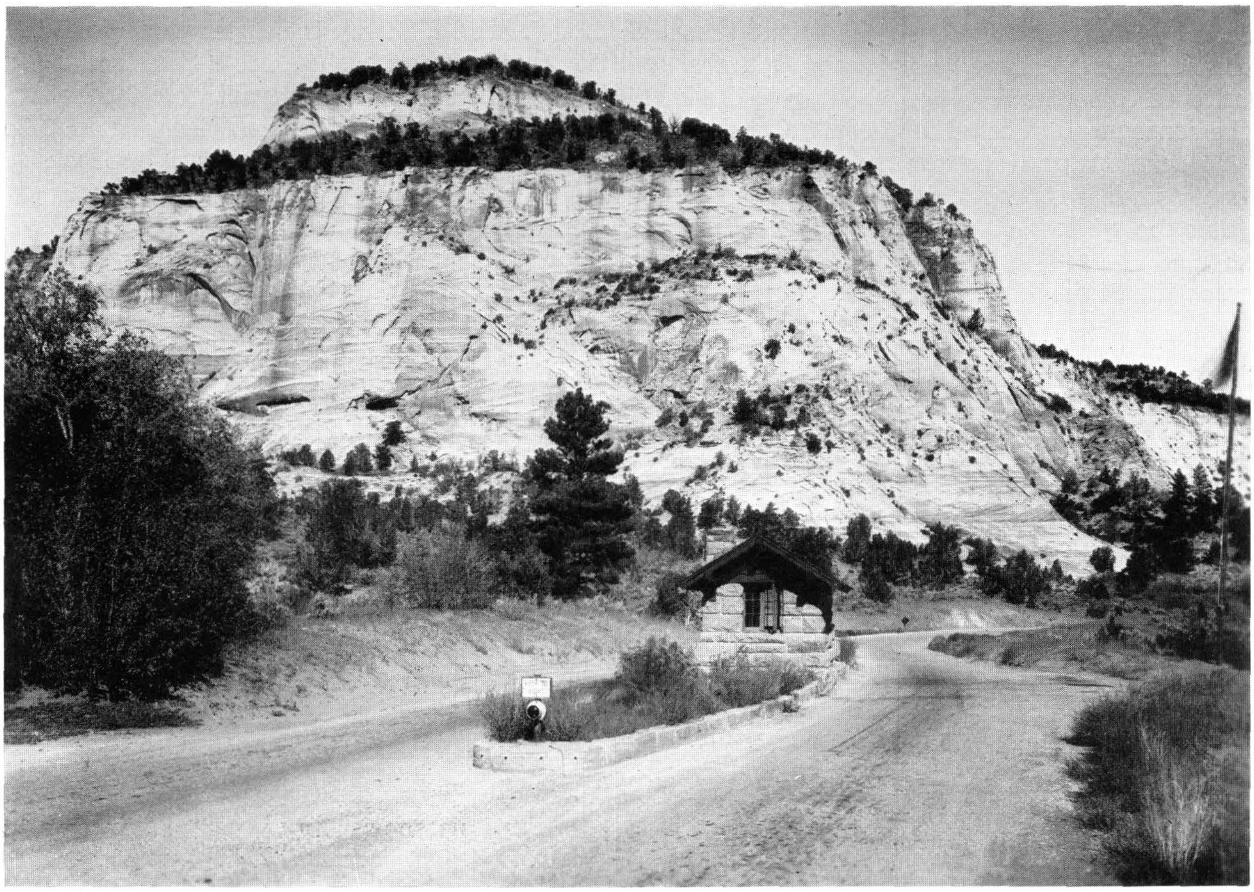

FIGURE 52.—Navajo sandstone, upper part, at east entrance to Zion National Park. Lower cliff is upper part of main bed of massive cross-bedded sandstone; upper cliff is massive sandstone of Temple cap member extending downward into shale (tree-covered slope) and upward to limestone of Carmel formation. Photograph by J. C. Anderson.

81 Stanton, T. W., (Report on a Cretaceous section measured in 1892), personal communication, 1918.

82 Lee, W. T., The Iron County coal field, Utah; U. S. Geol. Survey Bull. 316, p. 362, 1907.

83 Richardson, G. B., The Harmony, Colob, and Kanab coal fields, southern Utah: U. S. Geol. Survey Bull. 341, pp. 381–382, 1909.

84 Cross, Whitman, Red beds of southwestern Colorado and their correlation: Geol. Soc. America Bull., vol. 16, p. 496, 1905.

85 Coffin, R. C., Radium, uranium, and vanadium deposits of southwestern Colorado: Colorado Geol. Survey Bull. 16, pp. 77–97, 1921.

86 Dake, C. L., Horizon of the marine Jurassic of Utah: Jour. Geology, vol. 27, pp. 634–646, 1919.

87 Emery, W. B., The Green River Desert section, Utah: Am. Jour. Sci., 4th ser., vol. 46, pp. 551, 577, 1918.

88 Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, pp. 59–60, 1917.

89 Lee, W. T., Early Mesozoic physiography of the southern Rocky Mountain: Smithsonian Misc. Coll., vol. 69, No. 4, pp. 13, 39–40, 1918.

90 Longwell, C. R., Miser, H. D., Moore, R. C., Bryan, Kirk, and Paige, Sidney, Rock formations in the Colorado Plateau of southeastern Utah and northern Arizona: U. S. Geol. Survey Prof. Paper 132, pp. 1–23, 1923.

91 Lupton, C. T., Oil and gas near Green River, Grand County, Utah: U. S. Geol. Survey Bull. 628, pp. 23–28, 1916.

92 Moore, R. C., Stratigraphy of a part of southern Utah: Am. Assoc. Petroleum Geologists Bull., vol. 6, No. 3, pp. 199, 227, 1922.

93 Prommel, H. W. C., Geology and structure of portions of Grand and San Juan Counties, Utah: Am. Assoc. Petroleum Geologists Bull., vol. 7, No. 4, pp. 384–399, 1923.

†McElmo but also well-defined series unlike those farther east and fortunately containing fossils at two horizons. It was thus possible to segregate the Morrison, to establish the base of the "marine Jurassic," and to outline units sufficiently distinct and extensive to be classed as formations. To ascertain the distribution and content of the "Marine Jurassic" of southern Utah the sequence of strata above the Navajo was traced[94] from Pine Valley Mountain eastward across the Virgin, Kanab, and Paria Valleys to Meskin Bar, in Glen Canyon.

In the canyon of the Parunuweap near Mount Carmel, Utah, a proposed type section * * * shows fossiliferous limestones and calcareous shales occupying the lower part of an assemblage of beds which include gypsum, sandstone, consolidated variegated muds, and lenses of conglomerate.

These observations, supplemented by other studies, were used in classifying the lower 269+ feet of a measured section as the Carmel formation.[95] Fossils near the base, in middle zones, and at the top of the formation demonstrated its age as Upper Jurassic (Sundance). It was recognized that subdivisions of the Jurassic younger than the Carmel and older than the Morrison attain their most complete development in widely separated places and are not coexsive but are all well exposed in the San Rafael Swell. Therefore by agreement among field workers the terms "Entrada," "Curtis," and "Summerville" formations were introduced[96]—named from places in the San Rafael Swell—and these formations together with the Carmel were recognized as members of a San Rafael group, everywhere readily distinguished from the underlying Glen Canyon group and in most places from the uppermost Jurassic—the Morrison formation. As originally defined for the Zion Park region the Carmel formation comprised 20 units—at the base, conglomeratic limestone and calcareous sandstone unconformably overlying the Navajo; in the middle, gypsum and gypsiferous sandstone; at the top, lenticular fossiliferous limestone. The remaining Jurassic beds were classed as doubtful Summerville and Morrison. With increasing knowledge of the strata between the Navajo and the Dakota(?), gained by reexamination of outcrops as far west as the Santa Clara Valley and eastward across Skutumpah Terrace to the Paria, Escalante and Fremont Valleys, it became probable that the Morrison and Summerville formations are not represented in the Zion Park region; that the limestone at the top of the original Carmel section is somewhat younger than that near the base; and that the contact between the lower limestones and the friable variegated sandstone above—the horizon of an abrupt, strongly marked change in sedimentation—might appropriately be considered the boundary of two formations. Accordingly the Carmel was redefined to include only the lower limestones and associated calcareous shales. In the absence of satisfactory evidence for correlation with established formations elsewhere the beds above the Carmel were described as "undifferentiated Jurassic(?)" with the suggestion that they may "represent the rest of the San Rafael group and the overlying Morrison formation."[97] Doubts regarding the correlation of the post-Carmel Jurassic remain. Because of long stretches of covered rock continuous tracing is impossible, and in mass expression and in details of bedding and texture the formations between the Dakota (?) and the Carmel in the Zion Park region bear little resemblance to those in the Navajo and San Juan regions. However, some of the inconsistencies disappear with the recognition that east of Glen Canyon all of the San Rafael group is terrestrial in origin and that west of a shore line extending southward from the Henry Mountains its component formations become increasingly marine. Thus west of Paria Canyon the Entrada changes along the strike from a massive cross-bedded stratum to a series of thin, even-bedded gypsiferous variegated sandstones, and beds above the Entrada include here and there short thin lenses of fossiliferous limestone, probably of Curtis age. Furthermore a wide-ranging reexamination of the type sections of the Jurassic shows that certain diagnostic features of the post-Carmel Jurassic in the Kanab, Parunuweap, and Virgin Valleys are recognizable in the Entrada and Curtis formations in Paria Valley, Escalante Valley, Circle Cliffs, Capitol Reef, and San Rafael Swell; and that beds corresponding to the Summerville and the Morrison are not clearly represented west of Paria Valley. Their place is occupied by the Winsor formation age. (See p. 96.) Therefore, despite a general unlikeness sufficient perhaps to justify the introduction of local formation names or even a new group name, it has been deemed wise to retain the term "San Rafael group" and tentatively to consider the Jurassic gypsiferous sands, the thick gypsum beds, and the sporadic limestones of southwestern Utah as much modified equivalents of formations in east-central Utah, described in the literature cited. Pending the results of studies in progress, the San Rafael group as exposed in the Zion Park region is subdivided into three formations—the Carmel, Entrada, and Curtis. (See figs. 25, 53.) As thus restricted the group is 521 to 823 feet thick. In east-central Utah some sections are twice as thick.

94 Gregory, H. E., and Noble, L. F., Notes on a geological traverse from Mohave, Calif., to the mouth of San Juan River, Utah: Am. Jour. Sci., 5th ser. vol. 5, pp. 229–238, 1923.

95 Gregory, H. E., and Moore, R. C., The Kaiparowits region: U. S. Geol. Survey Prof. Paper 164, pp. 73–74, 1931.

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

97 Gregory, H. E., The Colorado Plateau region: 16th Internat. Geol. Cong. Guidebook 18, pp. 15–16, 1933.

CARMEL FORMATION

DISTRIBUTION AND GENERAL RELATIONS

The series of beds next above the Navajo sandstone, the Carmel formation, is present in all complete Mesozoic sections across southern Utah, but within this belt its composition, texture, and topographic expression are far from uniform. In the San Juan country the formation, 0 to 107 feet thick in measured sections, consists of "red and white, earthy, lumpy, unevenly bedded sandstones and mud shales," and generally east of Glen Canyon its exposures are designated "Carmel" chiefly because of their position in the stratigraphic column.

At Rock Creek, on the southwest base of the Kaiparowits Plateau, the Carmel begins to assume the features characteristic of its type locality, Mount Carmel, Utah—thin regular beds of marine limestone and shale. Traced westward for 120 miles along almost continuous outcrops the formation increases in thickness and includes an increasing amount of limestone. At Meskin Bar, where the formation is 55 feet thick, greenish-white and red ripple-marked soft calcareous shale exceeds in amount the interleaved sectile hard limestones. On branches of the Paria River measured sections 89 to 110 feet thick include 4 to 6 definite beds of impure unfossiliferous (?) limestone. In Kanab and Parunuweap Canyons, at the Block Mesas, and on the Kolob Terrace true limestone constitutes 40 to 60 percent of sections 150 to 240 feet thick, and nearly all the shales are highly calcareous, many of them fossiliferous. In the Santa Clara Valley, the westernmost outcrop examined, fossiliferous limestone constitutes about 95 percent of a section 325 feet thick.

In the Zion Park region the Carmel formation is widely exposed and readily accessible to study. Because it is a series of resistant beds in the midst of friable beds it assumes a prominence in the topography not otherwise possible. (See figs. 54, 89.) From Johnson Canyon westward it is the cap rock of the White Cliffs, in many places left bare by the removal of the overlying friable Entrada. On the Kolob Terrace it is the surface into which have been cut the profound canyons of the Virgin River. Such outliers of the stripped platforms as the Temples of Zion National Park and the magnificent Block Mesas on the Moccasin Terrace owe their preservation to their Carmel caps. In Kanab Canyon and in many canyons tributary to Johnson Creek, the Parunuweap, and the Virgin the Carmel forms picturesque waterfalls and, within the zone of its outcrops, the vertical walls of scores of shallow canyons.

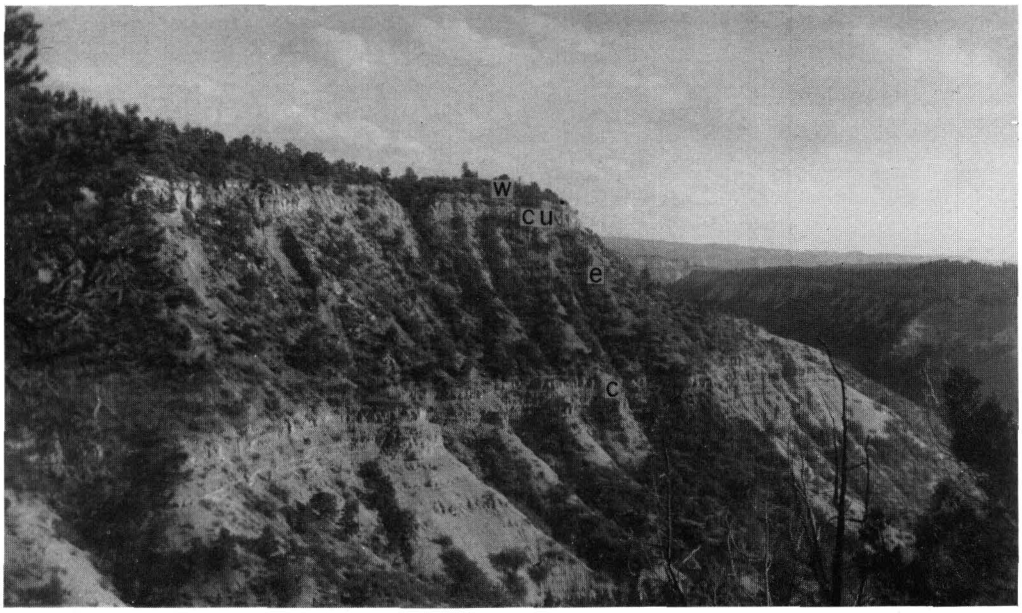

FIGURE 53.—San Rafael group and Winsor formation, east wall of Meadow Creek Canyon. *c*, Carmel; *e*, Entrada; *cu*, Curtis; *w*, Winsor. Navajo in bed of canyon.

The stratigraphic limits of the Carmel formation are well marked. At the top of the formation, where compact resistant limestone underlies friable gypsiferous sands, the contact in most places is sharp; the sands lie directly on the limestone and fill the little hollows in its surface. In attitude the topmost Carmel beds and the bottom Entrada beds are generally accordant. The contact of the Carmel with the underlying Navajo, in contrast with its upper limit, is a conspicuous unconformity. The complex cross-bedding structures in the Navajo are beveled and directly on this truncated surface rest horizontal beds of the Carmel. Immediately at the contact the surface is generally strewn with green, white, and red quartz grains mingled with clay chips and pellets and bits of nodular conglomerate, calcareous red shale, and sandstone, too siliceous to form a weathered zone. In places all the disintegrated material has been swept off, and variegated shale or brittle limestone has taken its place. The material from the Carmel-Navajo contact in Kanab Canyon is thus described by C. S. Ross: "The pinkish-gray sandstone-like specimen is essentially a limestone containing quartz, quartzite and a few feldspar grains; the pink shaly specimen is a kaolinitic shale; the gray specimen is made up of clay material in which are embedded large rounded quartz grains." Some of this material is obviously reworked Navajo. It is difficult to imagine a more abrupt and fundamental change in sedimentation: desert dunes covered by ocean silts.

However, the lapse of time represented by the Carmel-Navajo interval probably was not great. As the surface of the Navajo lacks the ruggedness produced by vigorous erosion, it seems likely that it lay near sea level. Under such circumstances the waves and currents of the encroaching Carmel sea could easily level off the low mounds and ridges of unconsolidated Navajo sands.

The ripple marks, current marks, worn shells, and worm (?) trails, the intermingling of sand with lime silt, and the scattered lenses of conglomerate and gypsiferous materials indicate the shallowness of the sea water in which the Carmel was deposited. The age of the sediments is shown by fossils collected at many places during the course of field work. According to Reeside they fix the age of the Carmel as "early Upper Jurassic (Callovian)." They are listed below.

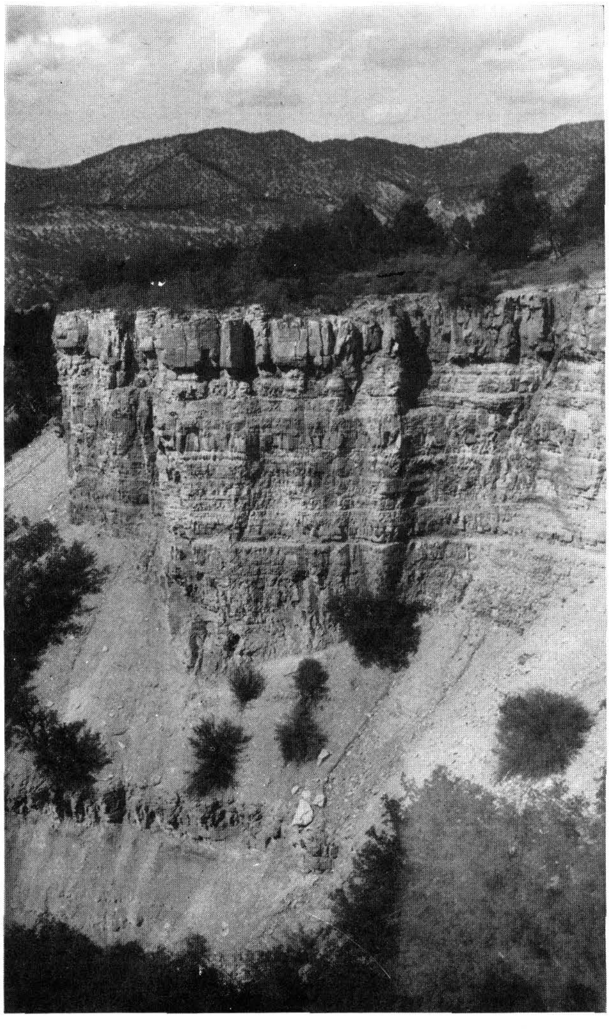

FIGURE 54.—Carmel formation (center) and higher Jurassic and Cretaceous beds (background) separated by Sevier fault. Flume Canyon. (See also fig. 89.)

H.E. Gregory 867

Fossils from the Carmel formation

Astarte packardi White.
Astarte meeki Stanton.
Ammonite fragment?
Camptonectes platessiformis White.
Camptonectes stygius White?
Camptonectes sp.
Cardinia? n. sp.
Dosinia jurassica Whitfield.
Dosinia sp.
Dosinia? n. sp.
Eumicrotis curta.
Gastropods, small, indeterminate.
Gervillia sp.
Lima occidentalis Hall and Whitfield.
Lima, n. sp.
Modiola pertenuis Meek and Hayden.
Modiola subimbricata Meek.
Modiola sp. indet.
Natica n. sp.
Nerinea n. sp.
Neritina n. sp.
Ostrea engelmanii Meek.
Ostrea strigilecula White.
Ostrea sp.
Pentacrinus asteriscus Meek and Hayden.
Rhynchonella sp. indet.
Tancredia? n. sp.
Trails, undet.
Trigonia americana (Meek).
Trigonia quadrangularis Hall and Whitfield.
Trigonia n. sp.
Volsella pertenuis (Meek and Hayden).
Volsella subimbricata (Meek).
Volsella sp.

The fossiliferous zones are generally in the upper third of the formation and are not continuous for long distances. Within a few hundred feet along the strike they merge with barren zones, and vertically they grade into calcareous shale or hard, brittle limestone devoid of organisms. To an interesting extent the various species are segregated. Of the most abundant forms, *Camptonectes* thickly packed together constitutes in places fully 90 percent of the fossils; in other places *Trigonia* or *Astarte* are dominant. At Mount Carmel Junction a rock section 20 feet thick is composed almost entirely of *Pentacrinus*. It would seem that throughout Carmel time differences in depth and in quality of water provided local habitats.

The present or former extent of the Carmel outside of southwestern Utah is not known. Equivalent beds seem to be absent in southeastern Nevada and in north-central and western Arizona but are reported in the Wasatch Mountains, and Carmel fossils are characteristic of the Twin Creek limestone of southwestern Wyoming.

STRATIGRAPHIC AND LITHOLOGIC FEATURES

As a stratigraphic unit the Carmel formation of southwestern Utah is essentially a group of limestone beds that contain marine fossils of Upper Jurassic age. Subordinate beds include highly calcareous shale, rare argillaceous shale, and a very rare conglomerate. In most places the arenaceous beds are grouped in the middle of the formation, and their less resistance to erosion is expressed in the topography as a slope between two cliffs (see figs. 54, 55, 89), locally spoken of as the upper and lower "limerocks."

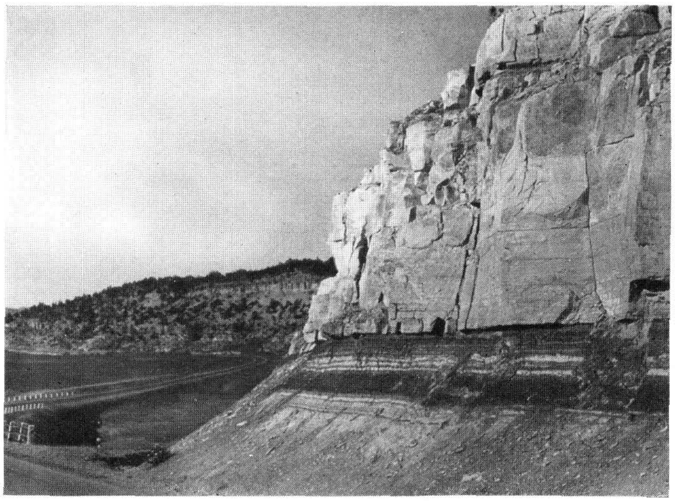

FIGURE 55.—Carmel formation, basal limestone underlain by shales that are in contact with Navajo sandstone. Mount Carmel Junction. Photograph by J. C. Anderson.

The thicker limestone beds are dense, hard, and compact and consist of calcite and minor crystalline dolomite. The thinner beds, likewise almost pure calcite, are particularly hard and so brittle as to break into sharp-edged chips under the hammer. Some of them glisten like porcelain. Because of this resistance to weathering the fragments of limestone remain long on the talus slopes and are conspicuous parts of stream gravel as much as 20 miles from their source. Because of their uniformity, moderate thickness, and conveniently spaced joints, the limestones are inexpensively quarried for building material. Some of them are suitable for the manufacture of plaster and cement, an industry of pioneer days. The calcareous shales, perhaps better called arenaceous limestones, contain 5 to 50 percent of throughly rounded quartz grains mingled with calcite crystals. Most of them are lenticular and many of them are ripple-marked. The argillaceous shales where present, in places as much as 15 feet thick, occur at the base of the formation near its contact with the Navajo sandstone. They consist of soft red, purple, white, and green layers, which include quartz and calcite grains in addition to the consolidated mud. (See fig. 55.) A lens in these shales is described by C. S. Ross as "siliceous oolite, made up of large oolitic grains that are almost wholly chertlike quartz. With these are smaller grains that are partly silicified calcite." The arrangement of the beds and the composition and texture of the Carmel are shown in the representative sections. (See pp. 112–133.) Of other measured sections one near Harris Springs, Block Mesas, 155 feet thick, consists mainly of paper-thin hard, pure limestone that weathers as a flight of minature steps. In this series are included beds of yellow sandy limestone 4 to 8 inches thick and lenses of broken shells piled together like coquina. At the "box" in Johnson Canyon, where the Carmel is 176 feet thick, shaly beds are more abundant than true limestones, and fossils are extremely rare. In the Zion Park region as a whole the average thickness of Carmel sections is about 200 feet, and the greatest measured thickness 296 feet.

ENTRADA SANDSTONE

Because of its topographic and textural prominence among beds formerly classed as "McElmo" the Entrada is a well-known member of the Mesozoic sequence. It has been described many times. Generally east of the Paria River its diagnostic feature is a massive cross-bedded sandstone, 100 to 500 feet thick, that rivals the Navajo in topographic outline, color, and decorative carving. In places it so closely resembles the Navajo in mass, texture, and composition, also in the kind and arrangement of its subordinate beds, as to have been mistaken for that formation by some writers unfamiliar with its regional relations.

The type section of the Entrada, measured at Entrada Point, on the San Rafael Swell, consists chiefly of thick-bedded red sandstones, among them several massive cross-bedded sandstones 13 to 30 feet thick. No gypsum beds are included, and the cement is reported as lime. West of the Paria, along the base of the Paunsaugunt Plateau, the usual massive buff or red sandstone cemented with calcite and iron is progressively replaced by a series of friable, evenly bedded variegated sands thoroughly impregnated with gypsum. The excellent exposures in the Kanab, Parunuweap, and Virgin Valleys and westward across Kolob Terrace are superficially quite unlike those in the Navajo, San Juan, and Kaiparowits regions.

In the Zion Park region the strata assigned to the Entrada are chiefly even-bedded friable sandstones. (See figs. 56, 57.) Associated with them are lenticular beds of gypsiferous shales, rare calcareous shales, and conglomerates. The sandstone beds are 6 inches to 4 feet thick and alternately light red and white—the red bands more numerous near the top. Over wide areas they are uniform in composition and texture except that some of the thicker white strata are

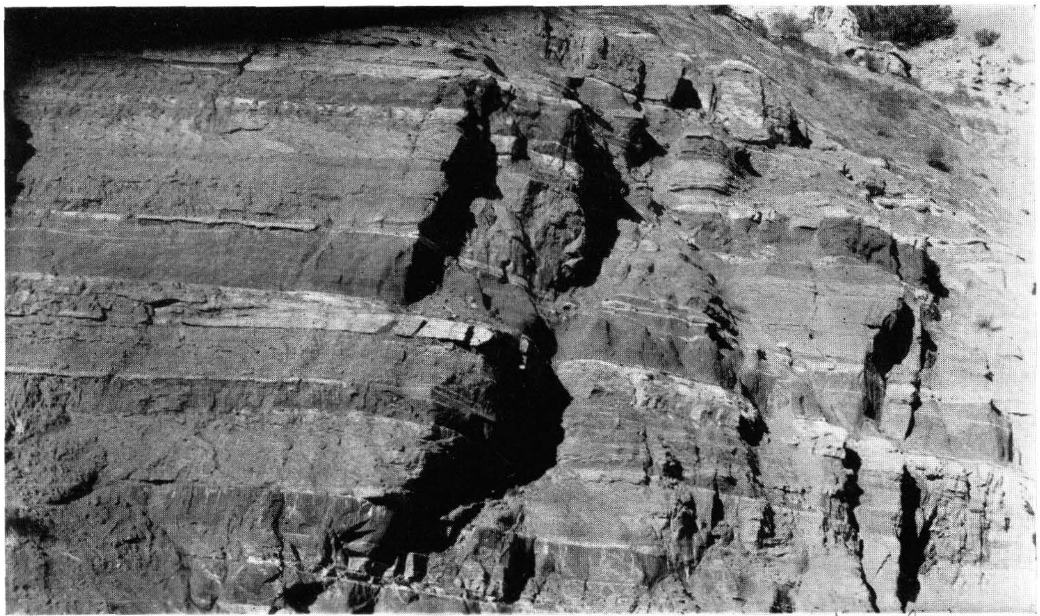

FIGURE 56.—Entrada sandstone in road cut west of Mount Carmel. H. E. Gregory 823

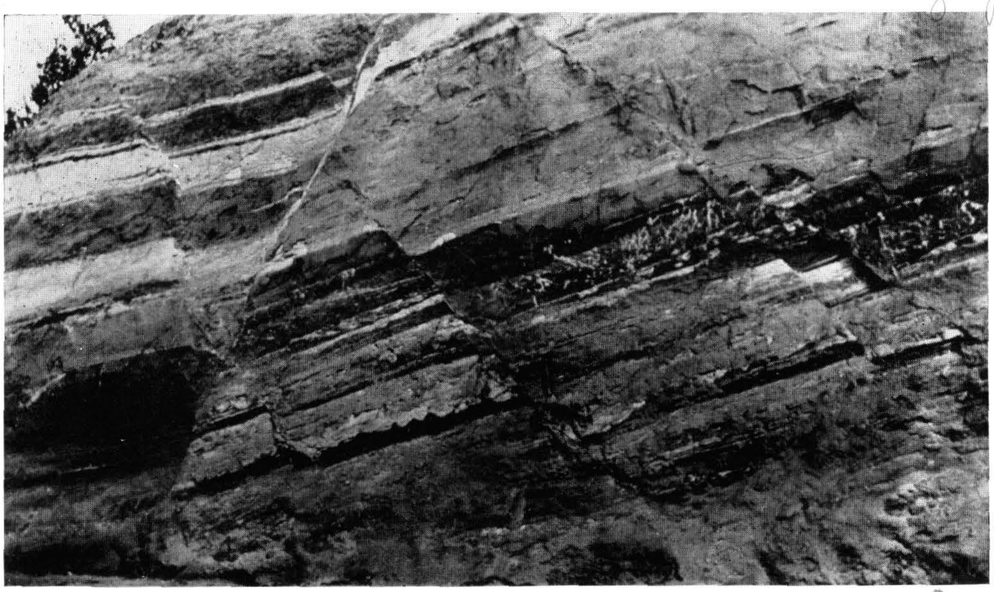

FIGURE 57.—Faults in Entrada sandstone near Zion Park Junction. Length of exposure, ±12 feet. Gregory, H. E. 1282

obliquely cross-bedded. The microscope reveals about 15 percent of spherical and 80 percent of subangular, glistening quartz grains 0.12 to 0.20 millimeter in diameter and some conspicuous, well-rounded, frosted grains that reach a maximum size of 1 millimeter. All thin sections examined show a little biotite, feldspar, and chert. The material would not be out of place in the Navajo sandstone. The cementing material is almost entirely gypsum; the iron and calcite shown on slides amount to less than 1 percent. In addition to filling spaces between quartz grains, gypsum constitutes here and there more than half of some lenticular shale beds and in places the entire bed. Secondary amorphous or crystalline gypsum is common on bedding planes, joint cracks, and cavities developed by ground water, and shining fragments of selenite are strewn over the talus. The conglomeratic material, small in amount, is chiefly an assemblage of unsorted, weakly cemented white quartz grains, red and green pellets of clay, and bits of rusty shale.

Because of its weak cement the Entrada decomposes on exposure so quickly that even in fresh road cuts the surface evidence of its bedding may be obliterated within a few years or even a few months. Surfaces covered with Entrada material, such as parts of the Skutumpah and Kolob Terraces, and the valley of Muddy Creek, have been dissected into mounds and ovate ridges flanked by heaps of sand, which during heavy showers clog the drainage channels with red and white mud. The most resistant parts are the gypsum beds that stand out as miniature cliffs and benches.

The lower boundary of the Entrada, the contact of red-banded friable gypsiferous sandstone and solid gray fossiliferous limestone (Carmel), is in most places not difficult to draw. Likewise the upper limit of the formation is fairly well marked. Generally the uppermost Entrada is a heterogeneous gravelly layer, in places tightly cemented with iron and lime, forming a brown sandstone that includes aggregates of variegated clay. This material or, in its absence, bedded red sandstone presents an irregularly wavy surface upon which is laid a thick layer of nearly pure gypsum. Locally at least the contact is a surface of erosion. In measured sections the thickness of the Entrada in the Zion Park region is 160 to 240 feet; at its type locality it is 312 to 844 feet.

CURTIS FORMATION

The beds of the Curtis formation comprise two subdivisions, a basal gypsum bed and a fossiliferous limestone conglomerate, which together measure 40 to 60 feet in thickness. The gypsum in many places is a massive bed 15 to 30 feet thick, which, because of its color and position, is a prominent topographic feature. (See fig. 58.) Combined with the thin sandstones and conglomerate that are plastered on its upper surface it forms a cap for mesas and cuestas and, where decomposed in badland topography, appears as a broad white band extending across gullies, flats, and inclined surfaces. For long distances west of the Paria River it is the top bed in a line of cliffs, rimming many canyons tributary to the Johnson, Parunuweap, and Virgin Rivers. In its thickest beds the gypsum is massive, much of it anhydrite, and includes waxlike areas that resemble gristle in bacon. In places, particularly at its base, it is definitely bedded; white amorphous gypsum is interlaminated with paper-thin crumpled green, highly gypsiferous shale. In other places the single gypsum bed is replaced by two or more beds separated by banded sands.

The conglomerate above the gypsum bed is a coarse gray aggregate of quartz, quartzite, and fragmentary calcareous shale cemented chiefly by lime. Though distributed as patches rather than continuous sheets, its exposures are not widely separated, and the spaces between them are occupied by irregularly bedded calcareous sandstones in composition much like the coarser rock. On the back slope of a cuesta adjoining Muddy Creek the conglomerate includes 14 feet of this sandy fossiliferous limestone interbedded with light-red sandstones. At Meadow Creek the corresponding zone comprises four beds 1 to 5 inches thick of stratified limestone, mingled with nodules, pellets, concretions, and fragmentary fossils. Here the limestone is in contact with the thick gypsum bed or separated from it by 3 to 12 feet of gray calcareous shale irregularly bedded with red sands. From these conglomerate beds came the only identified post-Carmel Jurassic fossils so far reported in southwestern Utah, and these from only two outcrops. It seems possible, however, that systematic search would show the fossiliferous limestone to be more widespread.

The fossils include rather poorly preserved *Ostrea* sp., *Dosinia jurassica* (Whitfield) ?, *Neritina* sp., Ostracoda *Trigonia* sp., and *Pentacrinus* sp.—a fauna appropriately classed as "indeterminate." From presumably equivalent beds in the San Rafael Swell, Reeside identified five species of fossils "that belong to the fairly well-known fauna of the upper part of the Sundance formation," and larger collections of this age have been obtained from beds in the Uinta Mountains and Colorado. From a study of the available material Reeside[98] concludes that "the fossils in the Curtis place it below the middle of the Upper Jurassic (mainly Argonian)."

The recorded distribution of fossiliferous limestone at the Curtis horizon seems to indicate that the shore line of the Curtis sea was broadly flexed; that in addition to the bays that extended from Wyoming into central Colorado and east-central Utah, a third narrow bay with waters suitable for the growth of marine organisms reached southward into Parunuweap Valley.

WINSOR FORMATION

Unconformably in contact beneath the Dakota (?) a series of bright-colored sandstones is part of measured sections in the upper Virgin Valley, Orderville Gulch, Meadow Creek, Muddy Creek, Flume Canyon, and eastward along the base of the Gray Cliffs to the Paria Valley at Cannonville. In the topography they are very conspicuous as a zone of white rocks banded with red that form steep cliffs beneath the protecting cap of Dakota (?) sandstone. (See figs. 59, 60, 61.) Because they are the most brightly colored beds in the 3,000-foot interval between the White Cliffs and the Pink Cliffs they are features of scenic interest, and where exposed along the highway at Meadow Creek they attract much attention.

The formation consists of sandstone and very subordinate conglomerate. The bulk of it is an unbroken series of horizontal white or yellow-white beds, remarkable for regularity of stratification and consistency of texture and composition. Few beds are more than 2 feet thick—most of them are measured in inches—and except in the uppermost 50 feet of the formation the continuity of the beds is noticeably broken by the inclusion of lenses of extraneous material. The grains are fine like those in the siliceous silts of the Carmel and the Chinle and as shown by the microscope are prevailingly angular or subangu-

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[98] Baker, A. A., Reeside, J. B., Jr., and Dane, C. H., Correlation of the Jurassic formations of parts of Utah, Arizona, New Mexico, and Colorado: U. S. Geol. Survey Prof. Paper 183, pp. 8, 58, 1936.

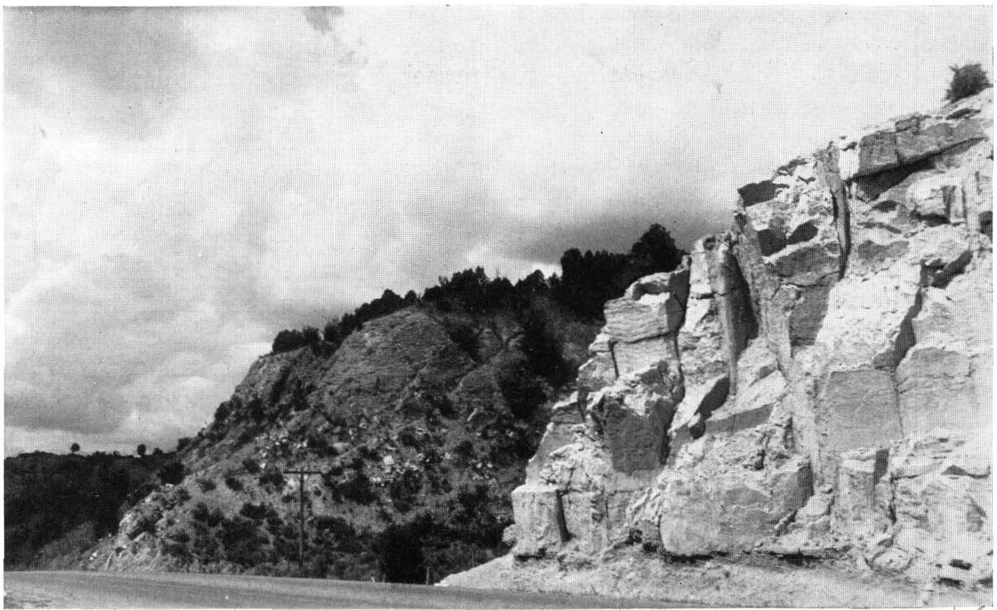

FIGURE 58.—Gypsum bed ± 30 feet thick in Curtis formation on highway 1 south of Mount Carmel. H. E. Gregory 825

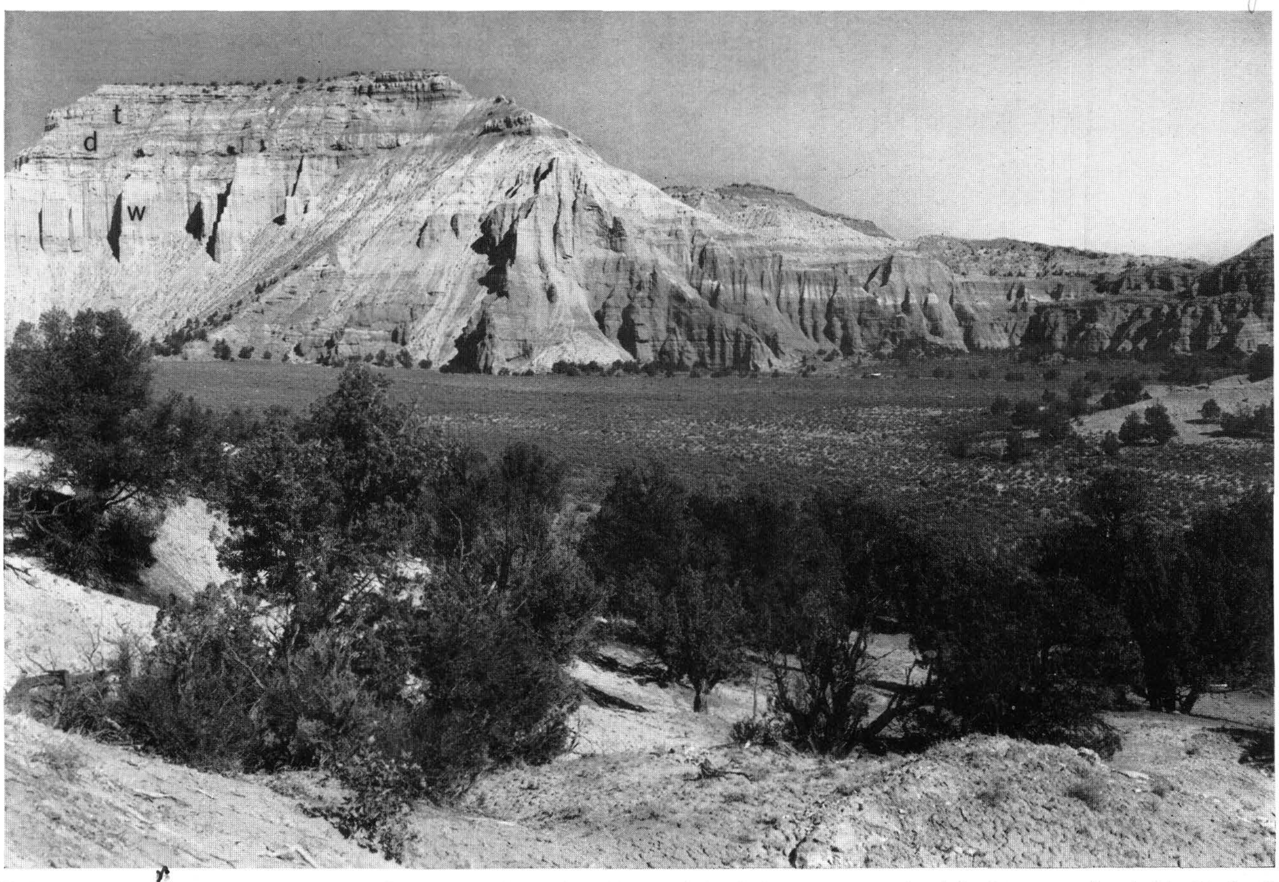

FIGURE 59.—Winsor formation (*w*) overlain by Dakota(?) sandstone (*d*) and Tropic shales (*t*). Sandstone, white, banded red (upper part), red with white bands below. Yellow Creek, Paria Valley. H. E. Gregory 963

lar. An analysis by Horace Winchell of a specimen considered representative shows 6.2 percent of grains more than 1 millimeter in diameter, 68.5 percent less than 0.25 millimeter, and 10 percent less than 0.16 millimeter. The light constituents (about 95 percent of the rock) are dominantly quartz and clay minerals and some calcite or dolomite; the heavy constituents include biotite ("moderate amount"), zircon ("not rare"), magnetite ("large amount"), and apatite? ("rare"). "No feldspar was identified in any of the size fractions, but that mineral may have been passed over inadvertently."

Except for a larger amount of iron in the red bands the white and red are alike in texture and composition. Here and there along the strike and in vertical sequence the regular layers of fine translucent quartz grains are replaced by patches of conglomerate half an inch to 3 inches thick and 1 to 4 feet long, which, because of their relative resistant to weathering, project as narrow steps helpful in climbing. Generally in these lenticular masses the sharply angular pebbles of concretionary limestone and of rhyolite and other acidic igneous rocks are not in contact; they are embedded as individuals in a muddy mass of extremely fine red sand. Fully 60 percent of the pebbles and concretionary aggregates are less than half an inch in diameter; the largest noted is 1 inch thick and 2½ inches long. Near the top of all measured sections the conglomeratic lenses increase in number and are associated with short lenticular beds of coarse sand-

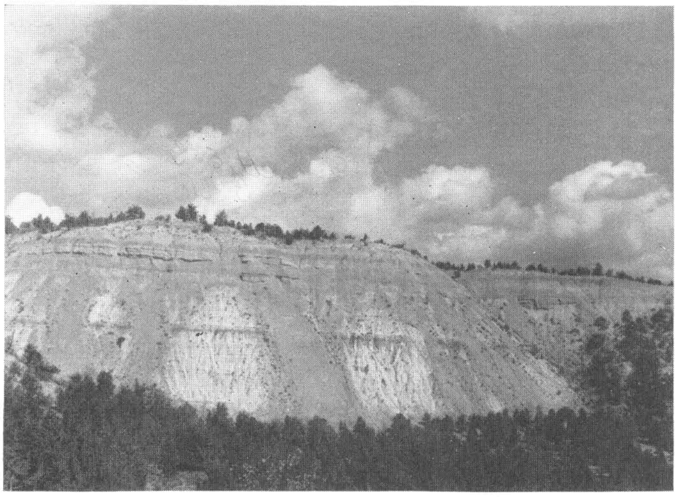

FIGURE 60.—Winsor formation, Winsor Cove, type section, 3 miles southwest of Mount Carmel. White banded with red, overlain by Dakota(?) sandstone (not visible), upper right. H. E. Gregory 875

stone and rare greenish-white shale. Locally, otherwise friable sandstone is compacted into balls of sand tightly cemented by lime. In Flume Canyon and Orderville Gulch the lowermost 10 to 20 feet is nodular, stringy, and irregularly conglomeratic and differs little from some parts of the Curtis formation below except in containing larger amounts of iron and no gypsum.

The angularity of the grains suggests a source not greatly distant; the mineral content suggests an arkose in which the feldspars have been reduced to clay; and the regularity of bedding suggests marine deposition, but in the light of present knowledge questions as to the position and character of the terrane from which the sediments came, and the mode of transportation, find no satisfactory answer.

Chiefly because of their position in the stratigraphic column these beds at widely separated localities have been tentatively correlated with the Morrison, the Summerville, the Curtis, and the Entrada. But tracing of continuous or closely spaced outcrops for some 50 miles, the comparison of many sections, and petrographic analyses reveal a group of beds of persistent distinctive features that lies unconformably below the Dakota(?) and above the Curtis as represented in the Zion Park region and, where the presence of the Curtis is doubtful, above the Entrada. These studies show the absence of any of the widely varied subdivisions of the Morrison in the Escalante, Hall Creek, Fremont, Green River, and San Juan Valleys and of features characteristic of the Summerville in Fremont and San Rafael Valleys. They also show that west of the Paria River this formation is readily distinguished from the Curtis formation, on which it lies, and also from beds assigned to the Entrada. It therefore seems appropriate to treat these beds as a heretofore unrecognized Winsor formation. The name is derived from Winsor, the original settlement at Mount Carmel. In the absence of fossils, which were diligently sought, the age of the Winsor formation is uncertain. Provisionally it is classed as Jurassic. The thickness of the formation in the Zion Park region is about 180 to 300 feet; in the Paria Valley, 450 to 800 feet.

CRETACEOUS FORMATIONS

DISTRIBUTION AND REGIONAL RELATIONS

In the Zion Park region the Cretaceous is exposed as a belt 7 to 18 miles wide that extends from the Hurricane Cliffs eastward across the headwater tributaries of the Virgin and Kanab Rivers and on beyond the limit of the area shown on the accompanying map. Because of erosion both the southern and northern boundaries are highly sinuous. The southern boundary is recessed where it crosses canyons and projects on mesas and plains. At Coal Hill it extends as a finger pointing southward. In consequence of faulting the boundary is offset some 8 miles along the Parunuweap between Mount Carmel and Glendale, but thence resumes its easterly trend across the Skutumpah Terrace. Its northern boundary lies along the base of the Pink Cliffs, which it follows up canyons and around headlands of the Markagunt Plateau. The area of the Cretaceous in the Zion Park region is approximately 180 square miles. The thickness of measured sections is 1,888 to 3,222 (?) feet.

Differences in hardness of the rocks that make up the Cretaceous are strongly expressed in the topography. The sandstones form narrow platforms bounded by vertical cliffs, and the shaly beds form slopes that incline at various angles. Traverses along Orderville Gulch and Meadow Creek involve ascending scores of ledges 6 to 40 feet high, the thickness of individual beds. Along Muddy Creek 33 sandstone cliffs mark steps in the broken slope that leads upward to the Pink Cliffs. The highest cliffs are those at the heads of the deep, narrow canyons, which extend like slits into the face of the Markagunt Plateau, in areas where vigorous erosion has not yet extended to intercanyon spaces. Characteristically the topography is expressed in ridges, rounded mesas, and steep slopes extending to low cliffs. Where they pass through massive sandstones the streams flow in canyons; in shaly sandstones they flow between walls that are terraced and flaring; in argillaceous and carbonaceous shale they are bordered by gentle slopes that rise little above the stream beds. Particularly in the soft shales near the base of the Cretaceous the lands along streams are flat enough and broad enough for cultivation. The "cove" west of Orderville, the "meadows" on Meadow Creek, ranch sites on Muddy, Lydia, Grass, and Dairy creeks, and the wide valley of the Kanab at Alton are floored with shales of the Tropic formation. This succession of narrows and wides in valleys within the Cretaceous area is well shown in the upper Parunuweap Valley (Long Valley) where the highway crosses in turn the Tropic shale, the Straight Cliffs sandstone, the Wahweap sandstone, and the Kaiparowits formation.

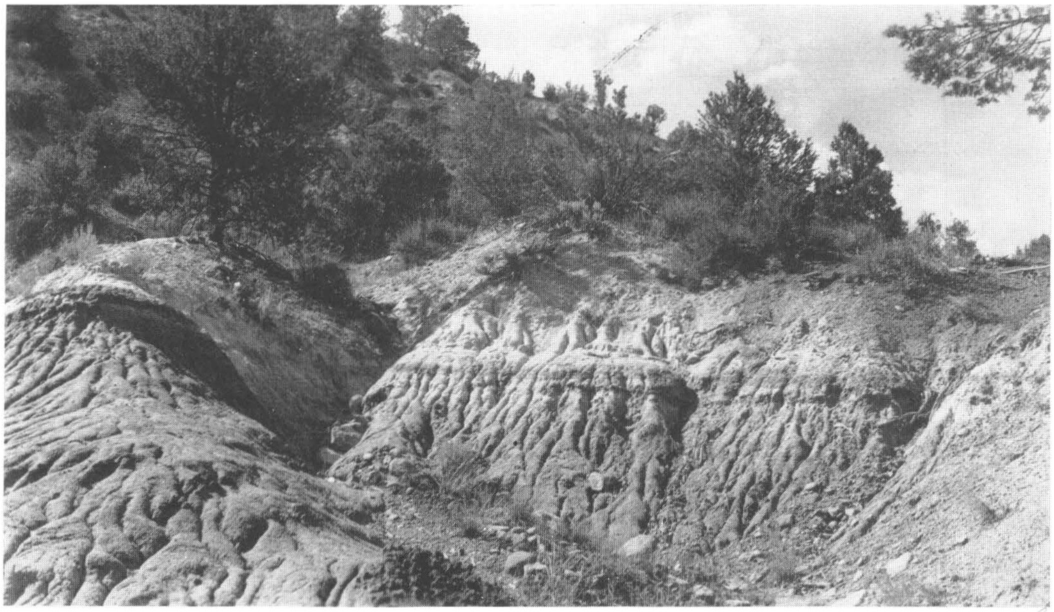

FIGURE 61.—Winsor formation, basal part of Muddy Creek, showing concretions and style of erosion.

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By the Powell Survey the Cretaceous formations were designated the "Gray Cliffs"—an appropriate regional term in a series that includes the Chocolate, the Vermilion, the White, and the Pink Cliffs. But as a unit they lack the color and form that give individual distinction to the great walls and platforms above and below. They are prevailingly gray and brown, though as a mass not somber in tone. As Dutton[99] remarks, "the platform immediately below the Pink Cliffs is picturesque rather than grand—the tones are very light and brilliant on the whole, the darker belts playing the part of a foil which augments rather than diminishes their luminosity."

The topography of the Cretaceous in the Zion Park region is unlike that of the Jurassic and Tertiary and also unlike that of the Cretaceous in regions to the east and north. There are few continuous long lines of cliffs hundreds of feet in height and few broad, flat terraces. In their place are innumerable low and high cliffs, flat-topped and round-topped ridges, and sloping hillsides. But the country is rough and difficult to traverse; it is cut by many gulches and in places dissected into badlands.

Because they contain beds of commercial coal the Cretaceous formations in the Zion Park region have received special attention, and their relations with comparable beds have many times been discussed. Howell[1] made the first regional correlation of the basal Upper Cretaceous and outlined the areas of Cretaceous shown on the maps of the Wheeler and Powell Surveys.

Gilbert[2] recorded 3,600 feet of Cretaceous in the Gray Cliffs along the upper Virgin River, below 1,200 feet of white and pink limestone and above gypsiferous shales.

Dutton[3] pictured the Cretaceous of southern Utah as parts of a once continuous expanse of sediments deposited in a sea that "south of the Unita Mountains covered 100,000 square miles.

Some 30 years after the regional reconnaissance surveys of Howell, Gilbert, and Dutton the Cretaceous of the Zion Park region was studied by Stanton[4] and by Richardson[5] and that of the adjoining region by Lee.[6]

[99] Dutton, C. E., Tertiary history of the Grand Canyon district: U. S. Geol. Survey Mon. 2, p. 31–32, 1882.

[1] Howell, E. E., U. S. Geog. and Geol. Surveys W. 100 Mer. Rept., vol. 3, pp. 278–279, 1875.

[2] Gilbert, G. K., U. S. Geog. and Geol. Surveys W. 100 Mer. Rept., vol. 3, pp. 158–159, 1875.

[3] Dutton, C. E., op. cit. pp. 212–214, 1882.

[4] Stanton, T. W., The Colorado formation and its invertebrate fauna: U. S. Geol. Survey Bull. 106, pp. 34–37, 1893.

[5] Richardson, G. B., The Harmony, Colob, and Kanab coal fields, southern Utah: U. S. Geol. Survey Bull. 341, pp. 379–400, 1909; The Upper Cretaceous section in the Colob Plateau, southwest Utah: Washington Acad. Sci. Jour., vol. 17, No. 18, pp. 464–475, 1927.

[6] Lee, W. T., The Iron County coal fields, Utah: U. S. Geol. Survey Bull. 316, pp. 359–375, 1907.

The report by Stanton is chiefly a faunal study, based on all available fossils including those collected by Walcott in 1882. It records for the first time the geologic age of the groups that make up the Cretaceous of southwestern Utah. Of the two reports by Richardson, which record observations made in 1908 and 1909, the first is strictly economic and deals with the coals everywhere present in the lowermost Cretaceous beds. The second, compiled by request as a contribution to the studies on which the present paper is based, includes measured sections and pertinent comments on the age and origin of the sediments on the Kolob and Skutumpah Terraces.

SUBDIVISIONS

In the Cretaceous of the High Plateaus Dutton[7] recognized a "lower division" equivalent to the Dakota (?), an undated middle division comprising "2,000 to 3,000 feet of sandstones and shales," and an "upper division averaging about 1,800 feet thick," equivalent to the Laramie. On faunal evidence Stanton[8] separated the Cretaceous in Walcott's Kanab sections (1882) into three divisions. He recognized the lower two divisions respectively 330 and 885 feet in thickness as lower Colorado and the upper 1,700 feet of stratia as Montana and Laramie.

Richardson[9] outlined a Colorado group 1,713 to 2,372 feet thick—a basal conglomerate followed upward in turn by shales and coal, and interbedded massive sandstone with shales of various composition. Separated by beds of conglomerate from the Colorado group of marine and brackish-water sediments he recognized a "Montana group," 340 to 826 feet thick, of buff sandstone and shale that contain fresh-water fossils.

As treated in this paper the Cretaceous of the Zion Park region comprises five subdivisions, the Dakota (?) sandstone, the Tropic formation, the Straight Cliffs sandstone, the Wahweap sandstone, and the Kaiparowits formation. (See pl. 5.) In the descriptions and on the geologic map the Straight Cliffs and the Wahweap are combined. As masses of bedded rock these formations possess distinctive features, but their regional and local variation is so great that much difficulty is experienced in fixing boundaries and establishing their relations with equivalent formations in eastern Utah, Colorado, Arizona, and New Mexico. Beds several hundreds of feet thick and essentially alike in lithology are of different age, and beds of the same age bear little resemblance to each other; the existing knowledge of the fossil fauna is sufficient only for approximate correlation.

[7] Dutton, C. E., Geology of the High Plateaus, p. 155, U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1880.

[8] Stanton, T. W., op. cit., p. 35.

[9] Richardson, G. B., The upper Cretaceous section in the Colorado Plateau: Washington Acad. Sci. Jour., vol. 17, p. 469, 1927.

CORRELATION AND AGE

All sections of the Cretaceous in the plateau country show three major divisions, each roughly consistent in composition, texture, and bedding though not everywhere of the same age. For the lowermost of these divisions the term "Dakota sandstone" was established some 60 years ago; for the succeeding formation the names "Mancos shale" and "Mesaverde formation," first applied in Geological Survey publications on southwestern Colorado, are widely used. Generally in the plateau country the divisions are readily recognized, as they are well exposed, are rather sharply bounded, have distinctive topographic expressions, and in color and arrangement are unlike the formations above and below. Typically the Dakota (?) is a hard gray conglomeratic sandstone that on erosion forms cliffs and platforms; the Mancos is a pile of drab and bluish-gray thin-bedded shales that form badland slopes and horizontally fluted cliffs; the Mesaverde consists of thick and thin, relatively fine-grained yellowish or buff-brown sandstones that stand in towering cliffs or as prominent ledges on steep slopes. Traced from Colorado westward across Utah these widespread prominent formations present marked changes in conditions of deposition and other stratigraphic relations. (See pl. 4.) As a distinctive group of beds the Dakota (?), 100 to 250 feet thick in southwestern Colorado, thins irregularly to an average of less than 50 feet in the Kaiparowits Plateau, and along tributaries to the Virgin River it is represented in places merely by thin streaks of poorly consolidated gravel. Likewise the shales in the Mancos thin westward from 2,000 feet in the Mancos Valley, Colo., to less than 800 feet in the Zion Park region. Along this line of measured sections, beds above the Dakota (?) show an irregularly increasing amount of sandstone, coal, and conglomerate, and west of the Hurricane Cliffs shales are conspicuously rare. This expression of the strata in southwestern Utah and some uncertainty regarding comparable age led to the adoption of the term "Tropic formation" for beds in the position of the lower Mancos. West of Glen Canyon beds comparable to those in the Mesaverde formation also assume marked differences from the type sections in topography, expression, and style of bedding. In place of the thick massive beds of sandstone inconspicuously interrupted by thinner beds that in the Mesa Verde National Park form nearly sheer cliffs 1,000 feet high, the strata above the Tropic in the Kaiparowits region, some 2,500 feet thick, are displayed as terraces banded by cliffs of variable heights, and though they include single sandstone units as much as 80 feet thick that outline long lines of cliffs, they include also many series of thin sandstone beds, together with argillaceous, gypsiferous, and carbonaceous shale. Farther west, in the Zion Park region, shalelike beds make up fully half of the interval. For outcrops west of Glen Canyon it was found impracticable to establish more than general correlation with the type section of the Mesaverde, and therefore the corresponding beds were recognized as two formations, the Straight Cliffs (lower) and the Wahweap, based on differences in composition, style of bedding, and topographic appearance, probable difference in origin, and possible difference in age. In two other respects the Cretaceous stratigraphy in the Zion Park region is not duplicated elsewhere in southern Utah. Instead of a clearly marked upper limit of the Dakota (?), the transition to the Tropic shale is made through a series of sandstones, shale, coal, and conglomerate, at no two places alike. Essentially the Dakota (?) gravel deposits are merely basal Tropic. Likewise west of the Paria River the division between the Straight Cliffs and the Wahweap formations is obscure. Though both are present and distinguishable in mass, their characteristic features seem intermingled in a belt as much as 500 feet wide. Therefore in measured sections the division line between the Dakota (?) and Mancos is in most places arbitrarily drawn, and the Straight Cliffs and Wahweap formations are mapped as one stratigraphic unit. The second feature of unlikeness is the presence in the Zion Park region and immediately adjoining areas of the distinctive Kaiparowits formation—the topmost of the Cretaceous beds.

These differences recorded in sections along a line extending eastward from Zion Park to Colorado are even more notable along a line extending northeastward. The Cretaceous in the Wasatch and Tavaputs Plateaus is nearly twice as thick as on the Kolob Terrace, and shows an arrangement of coal beds, sandstones, and conglomerates unknown in southwestern Utah. The great regional variations that in the absence of diagnostic fossils make correlations of formations somewhat speculative are matched by the variations within the formations.

In the field it was thought that, locally at least, the beds of fossiliferous sandstone might serve as guides, but they proved to be unreliable. Traced along the strike for a few hundred feet any of these beds may not only vary widely in thickness but change abruptly or gradually intergrade and interfinger into shale beds above, below or at the side.

The Cretaceous formations in the Zion Park region are confidently correlated with those in the Kaiparowits region. In tracing these formations westward from Paria Valley none of the formations was found to disappear, and no additional ones have been recognized. The relation of these formations to equivalent groups elsewhere in Utah and in Colorado, Wyoming, and New Mexico is that outlined in faunal studies by Reeside,[10] who shows that the Dakota (?) sandstone and the Tropic shale (pre-Carlile and Carlile fauna) may reasonably be correlated with the Bear River, Aspen, Frontier, and lower Hilliard formations of southwestern Wyoming, the Dakota (?) and lower Mancos including the Tununk sandstone member in the Henry Mountains, and the Dakota (?) and lower Mancos of Colorado; the Straight Cliffs sandstone (Niobrara fauna) with middle Hilliard in Wyoming, the lower part of the middle shale member of the Mancos in the Henry Mountains, and the middle Mancos in Colorado; the Wahweap sandstone (early Montana fauna) with part of the Hilliard in Wyoming, part of the Mancos shale including the Blue Gate sandstone member in the Henry Mountains, and the upper Mancos of Colorado; the Kaiparowits (Fruitland type fauna) with the Adaville in Wyoming and the Fruitland, Kirtland, and McDermott of Colorado and New Mexico.

A striking feature of recorded sections is the comparative thickness of the shale above the Dakota (?). In Colorado it is an undivided unit (the Mancos) some 2,000 feet thick. During the time represented by Mancos deposition not only shale (Tropic formation) but also great masses of coarser material were laid down west of the Colorado—the Straight Cliffs and Wahweap sandstones in southern Utah and the Ferron and Emery sandstone members of the Mancos in the eastern Wasatch plateau.

DAKOTA (?) SANDSTONE

The basal Cretaceous in the Zion Park region is classed as Dakota (?) because of its composition and its position in the stratigraphic column. Tracing along almost continuous outcrops leaves no doubt of its equivalence with the Dakota (?) of eastern Utah and northern Arizona and of its stratigraphic if not chronologic equivalence with the Dakota (?) of the Rocky Mountain region. (See pl. 4.) Locally, however, its topographic expression, its texture, and its contact with the underlying formations are exceptional. Generally in the plateau province the Dakota (?) is resistant to erosion; it caps innumerable cliffs and isolated mesas, forms the rim of miles of canyon, and is the bedrock of extensive plains. On the other hand, the Dakota (?) in southwestern Utah is extremely friable and takes little part in developing the rough topography; it forms no projecting ledges. On the talus it is represented by gravel as loose as that in nearby streams, and even in "gravel pits," exposed by removing the overburden of sandstone and shale, the rock may be quarried by shovel and used as road material without further treatment.

Regionally the contact of the Dakota (?) with the Morrison or other formations is an unconformity that plainly indicates a time interval during which the exposed surface was remodeled by vigorous streams. In the Zion Park region the Dakota (?) sandstone

[10] Reeside, J. B. Jr., Gregory, H. E., and More, R. C., The Kaiparowits region: U. S. Geol. Survey Prof. Paper 164, p. 111, 1931.

rests unconformably on the Winsor formation, of Jurassic age. In places west of the Parunuweap the underlying beds are slightly beveled, and in branches of Kanab Creek the dark-brown conglomerate of the Dakota (?) fills shallow channels in white friable, fine-grained sandstone. Here and there also the contact is marked by small slabs of shale and sandstone, clay, ironstone, and gypsum pellets, and ball-like aggregates of iron-cemented quartz grains. Commonly, however, there is no clearly marked discordance in bedding: for miles along canyon walls the Dakota (?) appears as a band of dark-colored gravel immediately in contact with apparently parallel beds of white Jurassic sandstone and is recognizable at a distance merely as a nearly black band in the midst of white, yellow, and gray sediments. (See fig. 62.) It is difficult to realize that a line on a cliff that separates rocks differing in color and texture but otherwise undistinguished represents a time interval of some millions of years during which all or most of the Lower Cretaceous sediments were deposited elsewhere.

In bedding, texture, and composition the Dakota (?) shows the considerable range common to near-shore deposits. In some outcrops the prevailing rock is coarse- or medium-grained sandstone irregularly or for short distances evenly deposited; in others sandstone and conglomerate are fitted together as wedges and strings of pebbles. The commonest pebbles in the conglomerate are rounded and subangular gray, brown, and red quartzite and massive or banded chert of various colors; more rare are pebbles of granite, vein quartz, and ironstone and slabs of compact clay, pitted limestone, and red sandstone. Among the constituents are earthy coal, macerated plant remains, and petrified wood—in Flume Canyon a log 3 feet in diameter—and limestone pebbles that contains Carboniferous fossils. It seems clear that the pebbles did not come from the rocks beneath. In southwestern Utah the San Rafael group, the Glen Canyon group, and the Chinle formation contain no original quartzites, vein quartz, or fossiliferous chert. The pebbles closely resemble those in the Shinarump, nearly 3,000 feet below, and like them must have come from distant sources. In a personal communication Prof. N. E. A. Hinds writes:

> The Shinarump and Dakota pebbles do not resemble any of the Algonkian rocks that I know nor any from the later Paleozoic section, but they are like certain pre-Algonkian quartzites which once were widely distributed through the Southwest. I think that this source for most of the quartzite pebbles cannot be questioned.

Unlike its lower contact the upper contact of the Dakota (?) has no persistent features. The conglomerate with its attendant sandstones grades irregularly upward into sandstones, shale, and coal of Colorado age. The beds overlap and interleave so unsystematically that separation into formations is impracticable. They are thought, however, to mark the beginning of the oscillation that during Upper Cretaceous time permitted the deposition of land, near-shore, and offshore sediments. The upper limit of the Dakota (?) was arbitrarily mapped just below the first fossiliferous bed in the overlying shale of the marine Tropic formation. As thus defined the formation in southwestern Utah ranges in thickness from 4 to 108 feet, averaging about 40 feet.

TROPIC FORMATION

GENERAL FEATURES

In the lower part of the Gray Cliffs the Tropic formation is continuously exposed across the Kolob Terrace from Kanarra Mountain to Orderville and eastward across the Skutumpah Terrace to the Paria River. In cliffs and steep slopes along La Verkin Creek, Oak Creek, Deep Creek, the Virgin River, Orderville Canyon, Muddy Creek, and elsewhere, it is conspicuous because of its dark color and its scant cover of vegetation. On flatter lands also it is conspicuous because it weathers into low mounds and ridges generally covered with fine, loose, porous débris, which makes walking difficult and even prevents traverse by horse.

However, in comparison with exposures east of the Paria River, where dark uniformly bedded fossiliferous shale lies between persistent sandstones and stands in cliffs several hundred feet high, the Tropic formation in the Zion Park region is neither prominent nor uniform. Though in mass it is unmistakable, its features are not clearly defined. The beds are arranged in no normal order; in number, thickness, length, and position they vary considerably in the same section and more in sections as little as a mile apart. Westward across the Kolob Terrace a dominantly shale zone is intertongued by sandstone beds, which increase in number and in thickness upward until in places they are indistinguishable from those in the overlying Straight Cliffs sandstones, and sandstone lenses within the otherwise unmodified shale become larger and more numerous. In sections of the Cretaceous measured in the Santa Clara Valley, 30 miles southwest of outcrops on the Kolob Terrace and at Iron Springs, on the north base of the Pine Valley Mountains, beds in the position of the Tropic are sandstones that include but a few thin beds of carbonaceous shale and macerated plant remains.

As shown in the stratigraphic sections the Tropic is an assemblage of coarse and fine tan, gray, drab, and black sandstone; arenaceous, carbonaceous, gypsiferous, and calcareous shale; earthy lignite; and coal.

The beds of sandstone, 2 to 20 feet thick, are of various kinds. Some are hard, massive, and so tightly cemented as to form rugged cliffs or so friable as to weather in rounded ledges and sand piles; others are thinly laminated or imbricated and form little steps separated by horizontal grooves. Some of the thicker beds retain their individuality for as much as 3 miles, but most of them are lenticular, and many of them split into shalelike beds within a few hundred feet. Cross bedding on a small scale is common, and some beds consist of wedges. In texture some of the sandstones are persistently fine grained, coarse grained, or conglomeratic, but when traced along the strike many beds range in composition from fine, well-rounded, and well-sorted quartz grains to coarse angular grains and to conglomerate, with pebbles of quartz, chert, and quartzite, and fossil wood, a quarter to half an inch in diameter. Concretionary balls of limestone, ironstone, and clay are irregularly distributed; a few dozen at Clear Creek Mountain include some about 2 inches in diameter. Iron is common as cement.

The dominant shale in the Tropic is the "drab," "blue-gray," "iron-gray," "steel-gray" rock, many times described as characteristic of the Tropic and also of the Mancos. Commonly this shale constitutes about half the formation and is thickest where it is present near the top. In places nearly all of it holds that position, but measured sections show it at the top, at the bottom, and in intermediate zones. Thus at Muddy Creek the lowermost three shale units have a combined thickness of less than 100 feet, the uppermost two units 425 feet. Near the head of La Verkin Creek series of drab shales 10 to 60 feet thick appear several times in the lower part of the section, and a unit 650 feet thick lies 180 feet from the top. (See fig. 63.) Everywhere shale beds a few inches to 3 feet thick and generally lenticular are incorporated in the sandstones at various altitudes. In contrast with this arrangement in the Zion Park region, sections of the Tropic formation at its type locality in the Paria Valley, and eastward across Utah into Colorado, show the thickest deposits of shale at the base, followed upward by increasing amounts of arenaceous materials. It would seem that the conditions that permitted the alternating deposition of marine mud and near-shore sand and gravel were longer-lived in southwestern Utah.

The typical drab shale in the Tropic is regularly bedded, thin-bedded, and as a whole uniform in composition. It consists of claylike material mingled with fine, thoroughly sorted, beautifully rounded grains of clear quartz, some crystalline gypsum, and calcite. But at all outcrops studied the beds of this kind are interstratified with thin sandstone, carbonaceous shale, earthy lignite, and nodular, fossiliferous, calcareous shale. Most of the fossils are in calcareous concretions, which are more abundant near the base. Coal is part of all sections measured, and though represented by thin lenses throughout the formation, most of it lies in a zone not far above the base and near the lowest prominent fossiliferous stratum, the well-known "oyster bed." (See fig. 64.) In most places the "coal zone" consists of three to seven beds, each less than 4 feet thick, interstratified with dense shales, fine sandstones, and layers of macerated plants. Mining has shown that the coal is thickest and commercially most valuable along the western edge of the Kolob Terrace. (See p. 192.)

FIGURE 62.—West face of Coal Hill. Winsor formation (*w*); Dakota(?) sandstone (*d*); Tropic shales (*t*). Photograph by J. C. Anderson.

Anderson, J. C. 117

AGE AND ORIGIN

As shown by the following list of fossils, identified by J. B. Reeside, Jr., the age of the Tropic formation in the Zion Canyon region is lower Colorado—the age of the Tropic at its type locality in the Paria Valley and that of the Mancos in Colorado and east-central Utah.

Fossils in the Tropic formation

Admetopsis subfusiformis Meek.
Anatina n. sp.
Anchura sp.
Baculites gracilis Shumard.
Barbatia micronema (Meek).
Camptonectes platessa White.
Cardium pauperculum Meek.
Corbula sp.
Corbula nematophora Meek.
Cyrena sp.
Cyrena securis Meek.
Eulimella? funicula Meek.
Exiteloceras pariense (White).
Fusus (Neptunea?) venenatus Stanton.
Inoceramus fragilis Hall and Meek.
Lima utahensis Stanton.
Liopistha elongata Stanton.
Lucina subundata Hall and Meek.
Lunatia concinna Hall and Meek.
Nemodon sulcatinus? (Evans and Shumard).
Placenticeras sp.
Serpula sp.
Sigaretus (Eunaticina?) textilis Stanton.
Tellina sp.
Tritonium kanabense Stanton.
Turritella? sp.
Turritella whitei Stanton.
Volsella multilinigera (Meek).
Volsella sp.

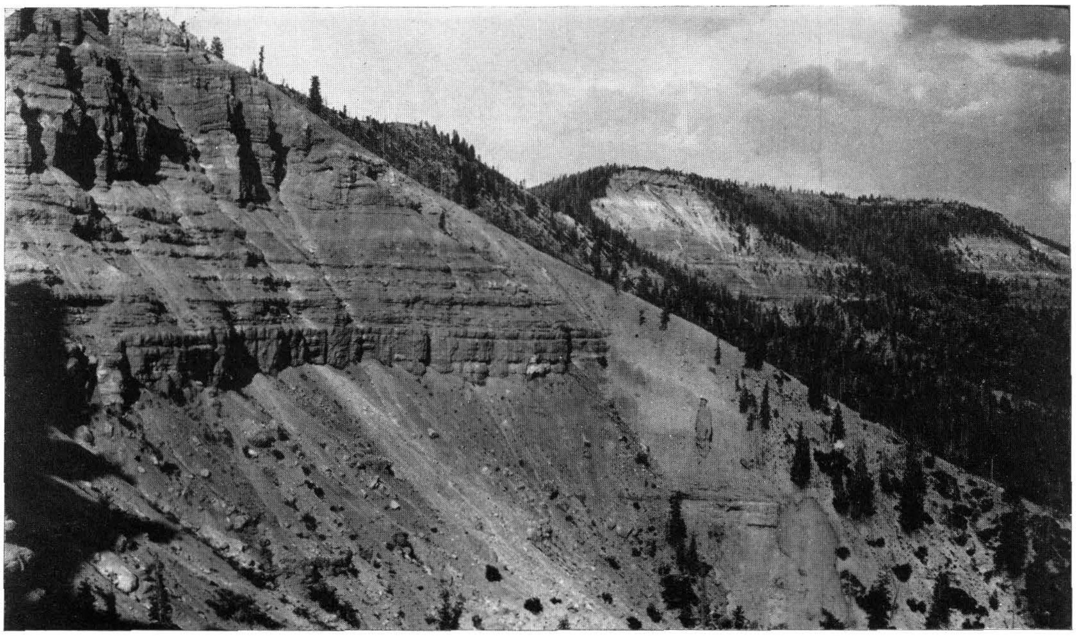

FIGURE 63.—Tropic formation, branch of La Verkin Creek. Photograph by G. B. Richardson, No. 185A.

Glauconia coalvillensis Meek.
Gryphaea newberryi Stanton.
Inoceramus sp.
Inoceramus labiatus Schlotheim.
Legumen sp.
Liopistha (Psilomya) meeki White.
Lucina? sp.
Lunatia n. sp.
Mactra sp.
Mactra utahensis Meek.
Metoicoceras whitei Hyatt.
Ostrea sp.
Ostrea prudentia (White).
Ostrea soleniscus Meek.
Plicatula hydrotheca White.

Stanton[11] lists the following species from Kanab Canyon:

Acanthoceras kanabense Stanton [*Neocardioceras septemseriatim Cragin*].
Anchura? prolabiata (White).
Anchura ruida (White).
Buchiceras [*Metoicoceras*] *swallovi* (Shumard).
Corbula kanabensis Stanton.
Helicoceras [*Exiteloceras*] *pariense* White.

[11] Stanton, T. W., The Colorado formation and its invertebrate fauna: U. S. Geol. Survey Bull. 106, p. 35, 1893.

None of the many plant fragments from the Tropic have as yet been specifically identified.

Though fossil wood and species of *Ostrea, Cardium* and *Corbula* are present in sandy beds from the top to the bottom of the formation, most species are roughly grouped with respect to age. Thus in the basal sandstones and shales of the Tropic the most abundant species are *Gryphaea newberryi* Stanton and species of *Ostrea*—in places veritable shell heaps and seemingly not associated with *Exogyra,* which is found at this horizon in most Cretaceous sections in the plateau country. The zone of coal-bearing beds is marked by the presence of *Cyrena securis* Meek, *Admetopsis subfusiformis* (Meek), *Ostrea soleniscus* Meek, *Corbula nematophora* Meek, *Mactra* sp., *Tellina* sp., *Volsella multilingera* (Meek) and *Barbatia micronema* (Meek). The collections from shales and sandstones in the upper part of the Tropic include *Cardium pauperculum* Meek, *Liopistha meekii* White, *Baculites gracilis* Shumard (in abundance), *Metoicoceras whitei* Hyatt, *Turritella whitei* Stanton, and *Serpula* sp.

The distribution of fossils in the Tropic formation illustrates the alternation of marine and terrestrial sediments characteristic of the upper Colorado sedimentation. The fauna in the basal beds is fresh water, brackish water, and marine; in the middle beds chiefly marine; and in the upper beds marine and fresh water. In places the alternation is closely spaced. Thus within a vertical distance of 200 feet at the Meadow Creek coal mines some lenses of sandy limestone contain marine fossils, others brackish-water fossils, and still others fresh-water forms.

STRAIGHT CLIFFS SANDSTONE

The Straight Cliffs sandstone, which overlies the Tropic formation, is exposed in the Zion Park region as a belt of cliffs that, except where offset by the Sevier fault between Mount Carmel and Glendale, extends almost continuously across southern Utah. As a feature in the landscape it is the most prominent part of the Cretaceous. (See figs. 65, 66.) In canyon walls and on the face of headlands that overlook exposures of Tropic shale its dominant beds of thick hard sandstone determine the topography of large areas between the Parunuweap and Hurricane Cliffs. Distant views give the impression of continuous walls, one above another, but when plotted on maps the lines of cliffs appear to separate the formation into definable parts and lose their identity. As regional topographic features they die out and are replaced by similar escarpments at somewhat higher or lower levels.

The Straight Cliffs sandstone derives its name from the Straight Cliffs in Escalante Valley, Utah, an unscalable wall of sandstone nearly 1,000 feet high, the beds regularly 10 to 60 feet thick, a few as much as 100 feet thick. Traced westward from its type locality the formation undergoes radical changes. Thus generally in the Kaiparowits Plateau it consists of massive, thick buff-gray sandstones, subordinate sandy shales (one-tenth to one-fifteenth of the total) and much coal, including beds 3 to 10 feet thick, of considerable commercial value. Westward along the base of the Paunsaugunt Plateau the number of thick sandstone beds decreases, the thin ones increase, and the coal beds decrease in number, thickness, and purity. In the Zion Park region sandstones more than 10 feet thick make up about 50 percent of the beds; thinner sandstone beds, 45 percent; calcareous and argillaceous shale, 5 percent; and coal is represented by inconspicuous earthy lignite or carbonaceous shale. Farther west in Santa Clara Valley both shale and coal are absent.

In composition the Straight Cliffs sandstone presents few persistent features. In the field it was thought that a score of complete sections and many partial sections would reveal some orderly arrangement, sufficient at least to define areal or stratigraphic groups. But when mapped, fine sandstone, coarse sandstone, conglomerate, limestone, and shales of various kinds found in one section were absent or their place occupied by different materials, in another section 1 to 3 miles, in places only half a mile, distant. Under these circumstances the result of the investigation is chiefly a description of the texture and composition of irregularly placed outcrops of sandstone, conglomerate, and shale.

The sandstones range in thickness from a few inches to 80 feet. Among the cliff makers, beds 10 to 40 feet are the most common; among the shaly sandstones, those 1 to 4 feet. Many beds are massive, and a few beds are regularly laminated or minutely im-

FIGURE 64.—*Tropic formation including coal beds, near highway bridge across Meadow Creek.*

bricated, but most of them, both thick and thin, are strongly lenticular, consisting of piles of overlapping slabs of various dimensions. Some beds are wavy and show poorly defined ripple marks; many are cross-bedded on a relatively small scale; in some the laminae are grouped as wedges. Of the sandstones about 90 percent consist of grains less in size than peas, 5 percent of coarser grains, and 5 percent of grains too small to be distinguished with the unaided eye. In some beds all the grains are spherical; in others all are angular. In places the sorting is complete, but commonly grains within a moderate range of size are not segregated; round and angular grains and small and large grains are intermingled. Fully 95 percent of the grains are quartz, most of it uncolored; feldspar, calcite, selenite, and magnetite are sparsely represented. The cement of most of the sandstone consists of lime and iron in varying proportions. In a few places silica cement has been sufficient to produce quartzite, and gypsum cement enough to give a taste to seepage water. Both lime and gypsum line cracks. Iron is abundantly represented, not only as a cement plastered to quartz grains, but as separate grains widely diffused. Ironstone concretions, in the form of bolt heads, balls, lozenges, and tubes, are fairly common. A feature of several sections is a layer of brown sandstone, 1 to 10 feet thick, so tightly cemented with iron as to form a projecting cornice on cliffs and a

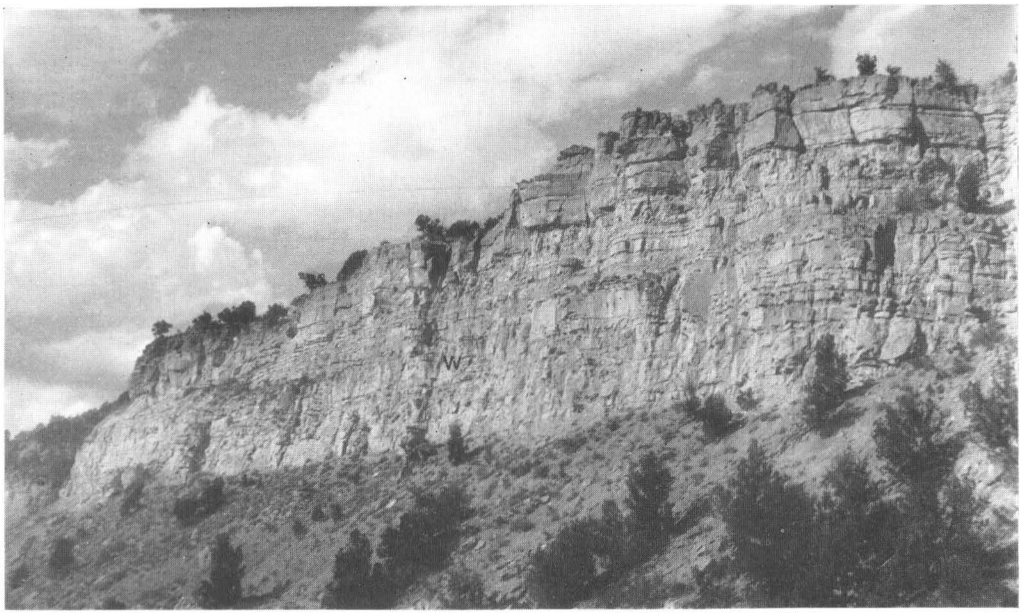

FIGURE 65.—Straight Cliffs sandstone in contact with Tropic formation (basal slope); branch of valley of Parunuweap River near Orderville. H. E. Gregory 866

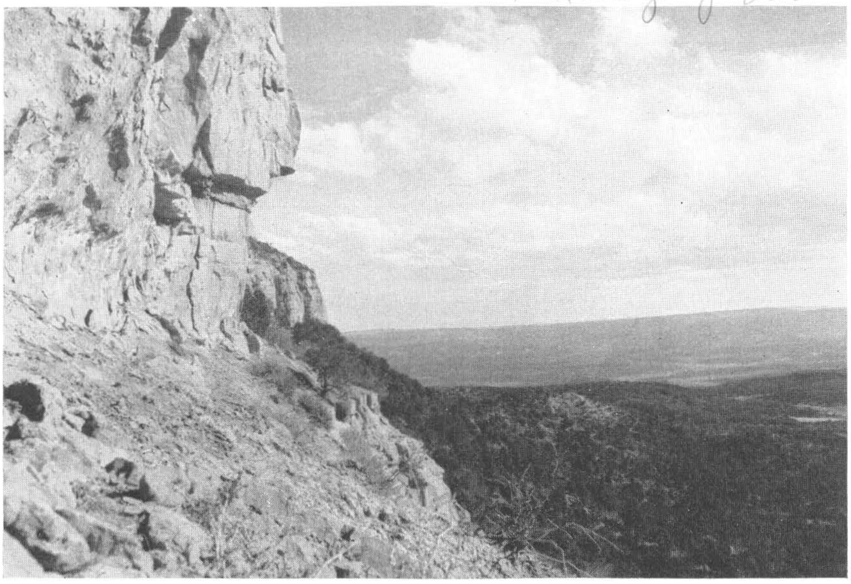

FIGURE 66.—Straight Cliffs sandstone, part of massive bed ±80 feet thick. Tropic formation below, at right. Clear Creek Mountain. Photograph by J. C. Anderson. 78

confining bed for ground water. Some of them include chunks of fossil wood, impressions of twigs and leaves, and worn vertebrate bones. On weathering the sandstone, in accordance with thickness, massiveness, and cement, produces vertical cliffs, box-headed canyons, benches, treads, and sand-covered steep slopes. Jointing, not everywhere present, gives rise to big angular talus blocks. Some beds have been stripped back of cliff faces, leaving a platform wide enough for wagons. Parts of some soft rocks are recessed at pits and shallow caves. In places the removal of lime and gypsum cement has produced a porous sugary rock that permits free flowage of ground water. The prevailing color of the sandstone is tan, buff, or yellow gray, but in places the rock is dark brown or red. Some dark rocks are spotted with white—the "salt and pepper rock" of notebooks. At various horizons thick beds and thin beds are separated by erosion surfaces of no great extent. These features of bedding, texture, composition, and topography are displayed so unsystematically along the strike and in vertical sequence and appear within areas so small that without much exaggeration they may be said to characterize single beds.

The conglomerate generally form lenses, 1 to 6 feet thick and 5 to 50 feet long. They consist of partly rounded and angular pebbles, mainly of quartz, quartzite, and chert, which range in size from a quarter of an inch to 1 inch; slabs of sandstone and shale; and less common limestone fragments. Here and there in the conglomerates and also scattered through the sandstones are sand balls, spheres, angular chunks of white, green, and drab shale, and concretionary aggregates of limestone 1 to 3 inches in diameter.

Like the sandstones the beds classed as argillaceous, arenaceous, gypsiferous, calcareous, and carboniferous shales and distinguished from "shaly sandstones" vary in texture, color, and composition and occupy no persistent positions in the stratigraphic column. They appear as series of considerable extent between massive sandstones, and as lenticular masses within the dominantly arenaceous beds. Most of the argillaceous shale, in units 3 to 8 feet thick, is regularly stratified, blue gray, and impervious to downward-seeping water. Some of it is soft gray-white or lavender amorphous clay, here and there arranged as pellets and disks. Gypsum in regular layers is very rare, but many arenaceous and argillaceous beds contain noticeable amounts; glistening particles lie on the talus, and seeps from these beds yield "bad water." Calcareous shales likewise are uncommon. Most of them are irregular lenses of lime silt and sand in which are embedded concretions and fragmentary shells. A short bed about 2 feet thick on Lydia Creek consists almost wholly of fossils. The carbonaceous shale, commonly associated with shales of other types, ranges in composition from sandy and clayey layers with specks of carbon and wood through earthy lignite to thin lenticular beds of bituminous coal. Most of the carbonaceous shale lies in the middle part of the formation, in about the same relative position as the thickest coal beds in the Escalante and Warm Creek-Wahweap coal fields of the Kaiparowits Plateau.

Fossils collected from the Straight Cliffs sandstone in the Zion Park region have received no detailed study. In a preliminary report J. B. Reeside, Jr., has identified the forms listed below. Some of them come from beds recorded in the field as "undifferentiated Straight Cliffs and Wahweap," and some listed as found in the Tropic formation (p. 102) doubtless should be included. The poorly defined division planes between the Wahweap and Straight Cliffs and between the Straight Cliffs and Tropic make more precise assignment uncertain. It seems worthy of note that in the collections so far examined several species recorded for the Straight Cliffs sandstone of the Kaiparowits region are lacking. Among them are *Barbatia micronema* Meek, *Cardium curtum* Meek and Hayden, *Gyrodes depressa* Meek, *Mactra arenaria* Meek, *Nucula coloradoensis* Stanton, *Ostrea prudentia* White, *Plicatula hydrotheca* White, *Turritella whitei* Stanton, *Volsello multilinigera* (Meek), and species of *Membranipora* and *Chemnitzia*. Particularly notable is the absence of the big thick-shelled *Inoceramus umbonatus* (of Niobrara age), which in the Kaiparowits region is conspicuous for number and range. Further comparison shows that brackish- and fresh-water species become progressively more numerous west of the Kaiparowits Plateau.

Fossils in the Straight Cliffs sandstone

Admetopsis subfusiformis Meek.
Anomia sp.
Campeloma? sp.
Cerithium? sp.
Corbula cf. *C. subtrigonalis* Meek and Hayden.
Cyrena sp.
Cyrena securis Meek.
Fusus cf. *F.* (*Neptunea?*) *venenatus* Stanton.
Glauconia coalvillensis Meek.
Neritina (*Velatella*) *bellatula* Meek.
Ostrea soleniscus Meek.
Physa sp., very large form, probably new.
Planorbis? sp.
Turbonilla? coalvillensis Meek.
Viviparus sp.
Viviparus cf. *V. panguitchensis* White.
Volsella multilinigera Meek.
Bones of vertebrates.
Petrified wood and casts of leaves.

WAHWEAP SANDSTONE

The Wahweap sandstone lies conformably above the Straight Cliffs sandstone and unconformably beneath the distinctive Kaiparowits formation. At the type locality of the Wahweap (Wahweap Creek, a tributary to Glen Canyon), the Wahweap and the Straight Cliffs are readily separated; they form separate lines of cliffs several miles apart and are characterized by differences in style of bedding and to a considerable degree in texture and kind of component materials. In the Zion Park region both formations are continuous parts of a cliff-benched regional slope that steepens upward because of topographic position rather than the number of resistant beds; both have thick massive and thin shaly sandstone beds, of like composition and remarkably variable in lithologic features. (See fig. 67.) The outstanding general differences are the rarity of carbonaceous, argillaceous, and calcareous shales and the high percentage of thin sandstones in the Wahweap. The absence of continuous guide beds and the scarcity of fossils in the Wahweap and the upper Straight Cliffs make it impracticable to draw a definite division line between the two formations. Almost identical beds and assemblages of beds range through an interval of as much as 500 feet. In fact, it seems possible that the upper part of the Straight Cliffs-Wahweap sequence in this region is but a Wahweaplike phase of the Straight Cliffs sandstone. (See p. 107.)

The most common beds in the Wahweap are sandstones 5 to 10 feet thick, irregularly laminated and lenticularly stratified with highly arenaceous shale. Some beds of considerable length are thick, uniformly massive, cross-bedded, and consist of coarse and fine rounded grains of quartz. Others combine to make a series of thin evenly or roughly stratified beds. Many sandstones change along the strike from solid beds of uniform composition and texture to beds that include shalelike layers and iron concretions and on into a series of "platy" beds of various dimensions—a sequence found many times repeated in tracing strata for long distances. Generally east of Deep Creek the topmost beds consist of thick massive sandstone that forms many vertical walls. At the head of Meadow Creek the formation terminates upward as three heavy ledges of sandstone with a combined thickness of 86 feet; at the head of Muddy Creek a massive resistant bed 26 feet thick overlies a bed 79 feet thick that includes eight groups of thin beds. In a section measured in Parunuweap Valley the topmost 100 feet is nearly all shale that rests on a cross-bedded massive ledge 25 feet thick and continuous for as much as 2 miles. In the sandstone angular grains are about as common as spherical grains, and coarse as common as fine. The chief cement is lime. Iron in small amounts is part of most rock beds and in places seems to bind the quartz grains securely together, producing exceptionally hard layers. At several places on the Kolob Terrace the ironstone that caps small mesas and ridges includes as much as 60 percent of iron. Though tan or light brown is the prevailing color, parts of many beds are yellow, cream, red, or spotted with minute fragments of black chert and white feldspar.

Strata that appropriately might be termed shale are conspicuously absent in the Wahweap of the Zion Park region. Specks of carbonized wood appear here and there, also gypsum crystals, and the rare beds of fossiliferous sandstone include considerable lime. Measured sections record much "shaly sandstone," "arenaceous shale," "mudstone," and "shale more massive than laminated," but little true argillaceous, calcareous, or gysiferous shale. At a few outcrops pink and lavender iron-bearing shale and drab clay shale are parts of long, thin lenses. In southwestern Utah the shale that in regions farther east lies in the lower and middle parts of the formation is largely replaced by sandstone, and the shale elsewhere present in the upper part seems to have been either not deposited or removed by post-Wahweap erosion. Fossils from unquestioned Wahweap strata include species of dinosaur (?) and turtle (?) bones, many well-preserved impressions of leaves, and *Neritina, Viviparus*, and *Physa*. Regarding *Neritina* Reeside remarks, "described from the uppermost Colorado beds at Coalville, Utah."

WAHWEAP-KAIPAROWITS EROSION INTERVAL

Everywhere observed the upper surface of the Wahweap is uneven. In places it is merely scoured and roughly striated, but commonly it is dissected into broad swales, rounded ridges, and narrow, even canyonlike trenches. Because of variation in bedding and the scarcity of fossils in the Wahweap sandstone, the extent and depth of erosion that produced this surface can merely be roughly estimated. In places the Wahweap seems to be nearly complete, but elsewhere its upper part, or all of it, was removed before younger beds were laid down. Thus in the Gray Cliffs along the northern edge of Kolob Terrace characteristic Straight Cliffs strata that contain marine fossils of Niobrara age lie less than 200 feet below fossiliferous Kaiparowits strata of Montana age. This rough surface of the Wahweap is coated with conglomerate, recorded in sections as ranging from 1 to 40 feet in thickness and averaging about 18 feet, composed chiefly of rounded and subangular pebbles of gray, white, and red quartzite and quartz, black chert, and fine-grained sandstone, a quarter of an inch to 2 inches in diameter. Angular chunks and concretionary balls of green-white clay, ironstone, and limestone are present in small amounts, but petrified wood, common elsewhere in Cretaceous conglomerate, is extremely rare.

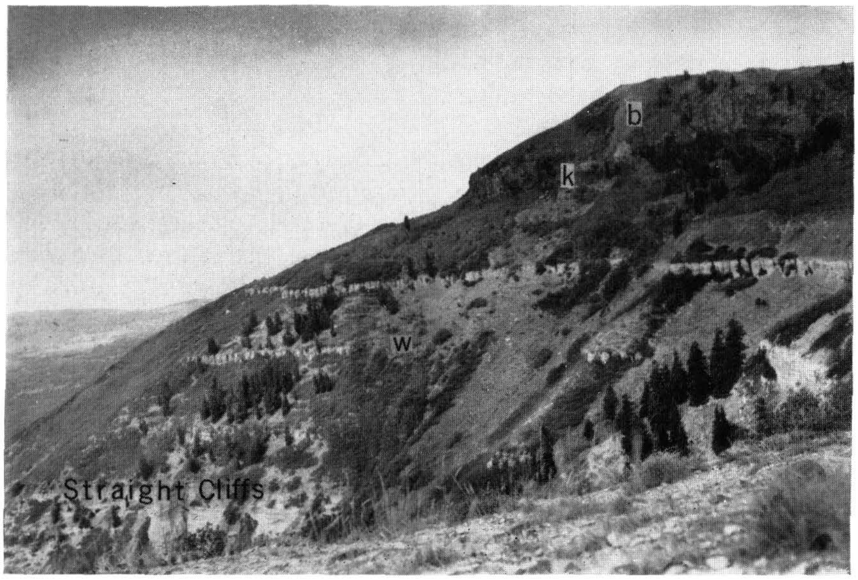

FIGURE 67.—Wahweap sandstone (*w*), Straight Cliffs sandstone (left bottom), Kaiparowits (*k*), basalt (*b*), at head of Oak Creek.

The hiatus in deposition represented by the unconformity at the top of the Wahweap has been traced for about 60 miles and is believed to have extended into regions where both the Wahweap and the Kaiparowits no longer remain. The interval may represent not only the youngest Wahweap sediments but also beds mapped in the Navajo country as "post Mesaverde" and in the San Juan Basin as "Lewis shale."

KAIPAROWITS FORMATION

In the Zion Park region the Kaiparowits formation forms part of the Gray Cliffs and is continually exposed across the Kolob and Skutumpah Terraces, where because of its prevailing dark color it is readily distinguished from the buff and yellow beds in the Wahweap and Straight Cliffs below and the pink beds in the Wasatch above. As a feature in the regional topography it formed gentle slopes broken by many gullies, or where protected from erosion by the overlying harder beds it forms steel slopes, rarely cliffs. (See fig. 67.) As a mass it is friable and roughly uniform in composition, and thus its exposures lack the benches and steps formed by the projecting ledges common to the other Cretaceous formations. Also, because it crumbles readily the rock is stripped of its weathered coating by recurrent rain-made rills, and the products of its disintegration accumulate about its lower border. (See fig. 68.) Even when carried forward by torrential rains and ephemeral streams the material retains its identity; at distances of as much as 4 miles from their source the black and greenish sands of the Kaiparowits are recognizable in stream beds.

In distant views the generally smooth surfaces of Kaiparowits outcrops suggest weakly cemented shales, but examination reveals the dominant rock as thin-bedded sandstone composed of quartz (50 to 90 percent), orthoclase, albite, mica, rare gypsum, and carbonaceous material. Few of the sandstone beds retain their individuality for as much as a mile; most of them die out within 100 feet. Evenly laminated beds composed of well-rounded and well-sorted grains form here and there ledges 5 to 10 feet thick, but disklike cross-bedded lenses, overlapping or abutting, are prevalent. Physical analyses of specimens considered typical for the finer sandstones show grain sizes of 0.25 to 0.50 millimeter. In a few beds the grains average 0.1 inch in diameter, but rock appropriately termed "coarse sandstone" is restricted to special places. In some sandstones spherical, partly rounded, and sharply angular grains, both fine and coarse, are intermingled like the components of rapidly built sand bars. Angular and concretionary fragments of chert, limestone, metamorphic rock, and igneous rocks, chips of clay, and pellets of sandstone appear as lenses and as widely dispersed individuals. The formation includes delicately stratified, hardened calcareous silt; limestone conglomerate that contains fossil shells; brown, red, and yellow hard sandy shales; and rare light-gray and bluish-gray shales. In order of abundance the cementing materials are lime, iron, and gypsum. Iron is the most effective cement in many of the harder beds and on weathering produces conspicuous blotches of yellow and the general "dirty, dark-green" tone of the entire formation. Notebooks record beds of ironstone as much as 2.5 feet thick

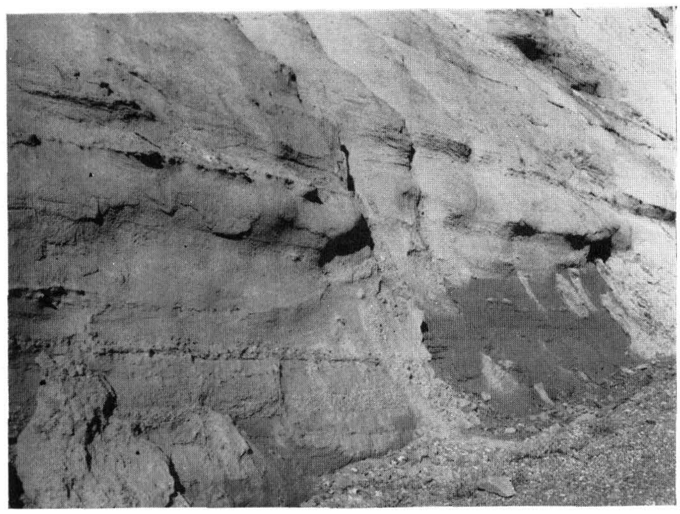

FIGURE 68.—Detail of Kaiparowits formation recently exposed in road cut near Lava Narrows, Parunuweap Valley.

and 60 feet long and concretionary balls, pancakes, and hollow tubes. A specimen from Shingle Canyon has the qualities of commercial limonite ore.

The style of bedding, the texture, and the composition of the formation suggest deposition by streams of moderate gradient flowing in poorly defined channels on a surface that included rivers, lagoons, and local shallow ponds. Consistent with the mode of origin are the many lateral unconformities and breaks in stratigraphic sequences, none of them of large dimensions.

The Kaiparowits formation contains an interesting terrestrial fauna and flora. Several species, not only of fresh-water mussels and land snails, turtles, and dinosaurs, but also of dicotyledons and gymnosperms, are represented in the collections. Commonly the invertebrate forms are grouped in colonies, but some gastropods are widely distributed as individuals. Some of the vertebrate fossils are partial skeletons, but most of them are isolated bones, worn by attrition or gnawing. The plants in the beds of fine-grained sandstone and shale have left fairly clear impressions of leaves; in coarser beds they are represented by twigs, bark, and fragments of tree trunks more carbonized than agatized. Some of the macerated leaves and splinters of lignite were found suitable for camp fires.

The fossils in the Kaiparowits are sufficient to determine the approximate age of the formation and the conditions under which its beds were laid down. As reported by J. B. Reeside, Jr., the invertebrate fossils are those commonly assigned to the Montana group. They are represented in the Kaiparowits at its type locality and are characteristic of the Fruitland formation of New Mexico. The vertebrate fossils, which await identification, include fragments of dinosaur and turtle bones and doubtless are generically at least representative of the forms listed below, which were described by C. W. Gilmore from equivalent beds along the base of Paunsaugunt and Kaiparowits Plateaus. Regarding this material Gilmore writes: "This collection of fragmentary specimens clearly indicates their Upper Cretaceous origin. This assemblage as a whole and especially the presence of *Baena nodosa* strongly suggests that the Kaiparowits formation is the equivalent of the Fruitland of New Mexico." Of the plant fossils not yet studied, the commonest are dicotyledons and cycads. As tentatively determined by Knowlton[12] plants from the lower part of the Kaiparowits formation on the west fork of Virgin River include *Dammarites caudatus?* Lesquereux, *Podozamites oblongus?* Lesquereux, *P. angustifolius?* (Eichwald) Schimper, *Platanus newberryana?* Heer, *Platanus* sp. cf. *P. primaeva* Lesquereux, *Betula* cf. *B. beatriciana* Lesquereux, *Menispermites ovalis?* Lesquereux, *Cinnamomum* sp., *Viburnum robustum* Lesquereux.

Fossils in the Kaiparowits formation

Invertebrate:
- *Campeloma?* sp.
- "*Helix*" sp.
- *Physa* cf. *P. reesidei* Stanton.
- *Planorbis?* n. sp.
- Unio sp., internal molds.
- *Unio* aff. *U. amarilloensis* Stanton.
- *Unio* sp., several internal molds.
- *Unio* cf. *U. danae* Meek and Hayden.
- *Unio* cf. *U. neomexicanae* Stanton.
- *Viviparus* cf. *V. leidyi* Meek and Hayden.
- *Viviparus* cf. *V. leai* (Meek and Hayden).
- *Viviparus panguitchensis* White.

Vertebrate:
- Hadrosauridea (duck-billed dinosaur).
- Nodosauridea (armored dinosaur).
- Theropod (carnivorous dinosaur).
- Crocodilia.
- Chelonia:
  - *Basilemys* sp.
  - *Adocus* sp.
  - *Baena* cf. *B. nodosa* Gilmore.
  - Trionychid turtle.

CRETACEOUS-TERTIARY EROSION INTERVAL

An unconformity that separates the Cretaceous from the Tertiary sediments is an outstanding feature in the stratigraphy and orogeny of southern Utah. It is plainly shown at the contact of the Kaiparowits (Cretaceous) and the Wasatch (Eocene) formations. In some places the hiatus is marked only by beds of conglomerate gravel and by abrupt change from dull-colored marine or fresh-water sandstone to pink or white fresh-water limestone. Commonly, however, the Kaiparowits was deeply eroded, in places all or nearly all removed before the earliest Wasatch sediments were laid down; in places the unconformity is a mature surface of erosion that is developed indiscriminately on flat-lying, tilted, and folded strata of different age and different composition.

Though for half a century this prominent hiatus has received attention, its implications are not well understood. To fix its date and extent involves a fuller knowledge of tectonic movements during Cretaceous time and of the fauna of the latest Cretaceous and earliest Tertiary time. In the Zion Park region the strata of the two systems seem nearly parallel, and some of the fossils in both the Kaiparowits and Wasatch formations suggest progressive deposition. On the other hand, the youngest Cretaceous beds represented elsewhere in Utah are lacking and likewise the Torrejon, Puerco, and Animas formations in southwestern Colorado, which contain a Paleocene fauna.

Evidence of various kinds shows that, in southern Utah, the pre-Wasatch erosion surface had considerable relief and that it included not only lowlands but also highlands that had stood above the general surface during much or all of Cretaceous time and other highlands produced by crustal movements in late Cretaceous or early Tertiary time. This newly made landscape of domes, long ridges, broad flats, and valleys provided conditions for lakes, and for swift and slow streams that had the sources in many different places where rocks of different kinds were exposed.

TERTIARY FORMATIONS

DISTRIBUTION AND TOPOGRAPHIC EXPRESSION

In southwestern Utah sedimentary rocks of Tertiary age are displayed in the Pink Cliffs—the longest and most continuous of the plateau escarpments and the most extensively and intricately carved. From most points in southern Utah this great wall is the sky line, and as the rim rock of the High Plateaus it may be traced eastward from Cedar City along the crenelated edge of the Markagunt and Paunsaugunt Plateaus and northward from the Paria Valley far into central Utah. Everywhere it is bold and impressive, and its grandeur is enhanced by strong, distinctive coloring and clear-cut architecture.

In the Zion Park region as here outlined the exposures of Tertiary rock are small in area and relatively thin. They merely mark the southern edge of sheets of rock that farther north and east cover thousands of square miles of plateau surface. But

[12] Knowlton, F. H., in Richardson, G. B., op. cit., p. 470.

though the outcrops cover but 50 square miles, their features are unmistakable. They are made of the same material and present the same attractive colors and forms as in adjoining regions. Some of the most pleasing views in Utah are the panels of bright-red and pink rock that terminate the dark-walled corridors through which flow the short streams tributary to the Parunuweap above Hidden Lake.

WASATCH FORMATION

BEDDING AND COMPOSITION

The Tertiary rocks in the Zion Park region are classed as the Wasatch formation, of Eocene age. In the topography they make up the Pink Cliffs. In fact, "Wasatch" and "Pink Cliffs" are nearly synonymous terms. (See fig. 69.) They include lacustrine and fluviatile sediments placed laterally, overlapping, or superposed, now represented by limestones, sandstones, and conglomerates which vary widely in amount, in style of bedding, composition, and stratigraphic position.

In general view the Wasatch seems fairly uniform, but traverses of its outcrops reveal somewhat surprising variations. In most places the dominant thick beds of massive light-red limestone are irregularly stratified with layers of hard thin shalelike limestone indifferently red, pink, or white and with sheets of gray sandstone and lenses of gravel, loosely or tightly cemented by lime. Firmly embedded in the limestone are concretionary masses and large isolated pebbles that on weathering produce a rough surface and give footholds for climbing the almost vertical cliffs. As shown in the section (p. 130) the base of the formation is generally a conglomerate of exotic material, the middle part sandstone and shale, and the upper part limestone.

The conglomerate consists of smoothly polished and partly rounded pebbles of gray, pink, and red quartzite, some of it banded; black chert; limestone; and many kinds of dense igneous rocks. Almost half of the pebbles have diameters of 1 to 3 inches, a few exceed 5 inches, and one smooth ball of gray quartzite measured 10½ inches. In places the conglomerate consists of closely packed pebbles in a matrix of calcareous silt, but generally the pebbles are scattered—a dozen or so in a cubic foot of coarse sandstone and brecciated limestone. In places the thickest conglomeratic beds lie some distance above the base. In tracing the Kaiparowits-Wasatch contact for 13 miles west of Lava Narrows the basal Wasatch beds were found to be even-grained calcareous sandstone at three places and thinly bedded argillaceous and calcareous shale at one place.

Of the sandstones some are evenly laminated layers of well-assorted coarse and fine spherical grains of quartz; others are roughly lenticular and include limestone, chert, manganese, and iron. Specimens from one dark very fine-grained bed, when examined under a microscope, consist almost entirely of chert embedded in a matrix of calcium carbonate. Most of the shale, perhaps more appropriately termed thin-bedded limestone, is soft, very fine grained, highly calcareous, and in part evenly laminated. In two fragments the microscope revealed bits of pink feldspar, angular quartz, mica, clay, and milky material (zeolitic?), in addition to the amorphous and crystalline calcite. The limestone is generally massive and roughly bedded. It includes in no regular order even-bedded and brecciated masses of nearly pure calcium carbonate and lenses of calcareous sandstone and shale. This limestone is dotted with cavities

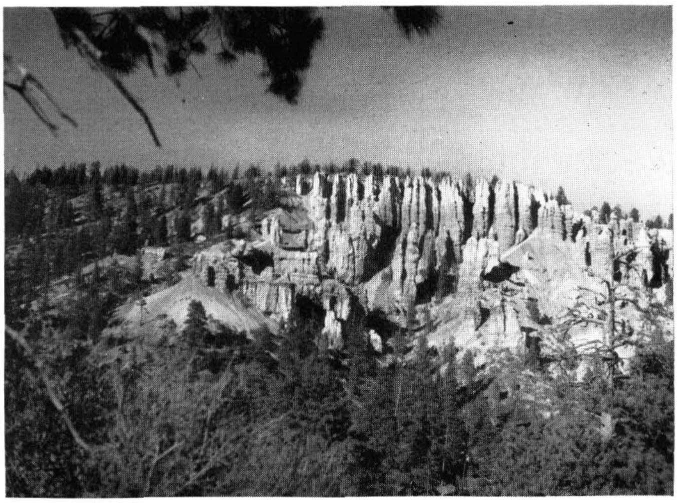

FIGURE 69.—General view of Pink Cliffs (Wasatch formation) near head of Virgin River. Photograph by G. B. Richardson.

lined with calcite crystals and in places is indented with shallow caves and long tubes. From it emerge some of the most freely flowing springs in the region, which have their source in sinkholes on the plateau above.

The general color of the unweathered limestone of the Wasatch is pale pink, red, or gray, in places nearly white, but weathering produces a strong pink tone, giving in distant views the remarkable appearance that has made these exposures famous. The coloring matter is chiefly iron oxide and, in small amounts, manganese-bearing carbonate, and the gradation from light pink to dark red represents the amount and state of oxidation of these metals. The rock thus records the amount of iron—the chief coloring matter in the sands and silts from which the beds were formed—and the chemical changes induced by weathering. Laboratory examination showed red ferric hydroxide as the most common coating of sand grains, particularly in the coarser rocks. Some thin lenses, a source of red paint for the Piutes, are nearly pure hematite and may be chemical precipitates. In the siltstones ferric oxide is abundant and mingled with clay and calcite gives rise to yellow and buff tones and various shades of pink, purple, and lavender. The manganese minerals occur commonly in aggregates 1 to 3 millimeters in diameter, sporadically distributed in beds of all classes. On weathering it combines with lime carbonates to produce a blue-gray paintlike material.

AGE AND ORIGIN

Invertebrate fossils in the Wasatch are sporadically distributed in the dense limestone beds, more rarely in the sandstone. Some of the shale beds contain fossil impressions of leaves. Most of the shells are crushed or worn fragments, and the best preserved are cuplike forms filled with lime silt. In the collections so far examined J. B. Reeside, Jr., recognized *Physa* sp. and *Bulinus* sp., "age undetermined by fossils"; "*Planorbis utahensis* Meek," "not reported below the Wasatch"; and structures "considered to be of algal origin." From beds at this horizon farther east W. H. Dall identified *Physa pleuromatis*, *P. bridgerensis*, and *Valvata?* or *Planorbis?*. Though the fossils and the stratigraphic relations leave little doubt that the Wasatch is of Eocene age, the evidence is insufficient to establish its place more definitely in the time scale or to correlate definitely beds in the Zion Park region with those better known in the adjoining region. The Wasatch in the cliffs of the Markagunt Plateau lacks beds that are present in sections measured on the Paunsaugunt Plateau, 20 miles northeast, resembles only in a general way the much thicker Tertiary deposits of the Aquarius Plateau, 50 miles east, and the Wasatch Plateau, 150 miles northeast, and is quite unlike the Tertiary of the Tushar Plateau, 40 miles north. In the Zion Park region the Wasatch formation is less than 500 feet thick; in the Aquarius Plateau, 1,000 feet; and in the Wasatch Plateau about 4,000 feet thick and including fresh-water limestone 800 to 1,000 feet thick. For these regions neither the lower, middle or upper beds of the Wasatch are lithologic equivalents. Some of this great range in thickness is obviously due to erosion of the upper beds and of the uneven floor of Cretaceous rocks on which the Tertiary sediments are deposited; but more of it doubtless records a longer lapse of time and different conditions of sedimentation. That the rocks are of terrestrial origin is shown by fresh-water fossils, by style of bedding, and by the distribution, kind, and regionally disproportionate amounts of limestone, sandstone, shale, and carbonaceous material—features that indicate separate basins of deposition, different in size and depth and here and there overlapping. The sediments seem to have been deposited as limy ooze and silt in shallow lakes, ponds, and bayous, and as sand and gravel in the beds and at the mouths of streams. Dutton's assumption that the limestones, shales, sandstones, and conglomerates making up the Tertiary of Utah were contemporaneously deposited in "an enormous Eocene lake twice that of Lake Superior" is out of accord with the field evidence. Neither the source, probably several sources, nor the mode of transportation of the materials in the Wasatch is yet known. It seems especially difficult to account for the presence of single pebbles 2 to 4 inches in diameter in 1,000 cubic feet of lacustrine silt.

QUATERNARY FORMATIONS

Deposits of Quaternary age are widely represented by alluvial fans, talus, landslides, slope covers, terraces, sand dunes, and lava flows. Here and there lacustrine silt, peat, and travertine are exposed. Because these materials are discontinuous, overlie the eroded surfaces of all the Paleozoic, Mesozoic, and Tertiary rocks, and contain no diagnostic fossils, their definite assignment to established epochs has been found impracticable. They are here treated as volcanic and physiographic features. (See pp. 133, 169.)

STRATIGRAPHIC SECTIONS

1. *Section in Timpoweap Canyon, beginning at La Verkin Hot Springs*

[Units 1–13 measured by Bronson Stringham]

	Feet
Moenkopi formation:	
15. Limestone, maroon to red at bottom; grades upward to buff and dark buff; predominantly thin-bedded and sandy, in places shaly; quartz grains 1 millimeter or less in diameter, more abundant near the top, weather out as small knobs. Veinlets of calcite, half an inch to 2 inches long, cut bedding planes at random; contain Triassic (?) fossils too fragmentary to be identified. A steep slope	25
14. Conglomerate, dark maroon red; massive, but with a few bedding planes; pebbles half an inch to 1 foot in diameter, of white chert, limestone, quartzite, and some shale; in a matrix of very fine calcareous, limy sand, in places micaceous; pebbles subangular, loosely packed together. A vertical cliff	45
Unconformity: pebbles in unit 13 strewn over truncated beds of unit 12.	
13. Conglomerate and shale, at base with red shale, very thin-bedded, highly argillaceous, considerably contorted; contains mica, gritty sand, and a few reddish calcareous beds of coarse sandstone; reddish conglomerate in middle and upper parts, composed of subangular pebbles of gray-blue limestone, dark-gray shale, quartzite, and chert, half an inch to 3 inches in diameter; appear to be long, thick lenses. Beds poorly exposed	58±
12. Limestone, gray to bluish cream, with hard, smooth, even texture; resembles lithographic stone; contains numerous gray and black chert pebbles with irregular outline, 1 to 3 inches in diameter; near the base includes brown calcareous sandstone in fairly regular compact beds. (This bed is reconizable at mouth of the canyon and at the Hurricane Dam)	45
Total Moenkopi formation measured	173

Unconformity: uneven surface; abrupt change in composition and bedding. *Feet*

Kaibab limestone:

11. Limestone, white to buff; in regular beds 6 inches to 10 feet thick; dense texture, hard in places; contains chert throughout, in places forming 25 to 30 percent of the rock; abundant Permian fossils including conspicuous brachiopods and crinoid stems. A series of beds monotonously similar, though individually distinct, that weather as round-edged steps on the canyon wall ---------- 224
10. Limestone, gray; generally thin, irregularly bedded; somewhat sandy; includes angular fragments of finely laminated limestone, 1 inch to 2 feet in diameter, embedded in buff dense shaly limestone; massive cherty limestone beds 3 feet thick, and soft gray calcareous claylike beds, 1 to 2 feet thick; the conglomeratic limestone changes abruptly along the strike to undisturbed shaly limestone that seems to be an intraformational feature. Steep slope, largely covered by talus ------ 52
9. Limestone, dense, gray to buff; lithographic; in massive beds, 1 to 3 feet thick; contains a very few chert nodules ---------------- 26
8. Limestone, bluish gray, coarsely crystalline; includes irregular lenses of gray and brown chert ------------------------------ 62
7. Limestone, bluish gray, massive, dense; contains chert ---------------------------- 5
6. Limestone, bluish gray; weathers to brown; nodular; generally dense but in places coarsely crystalline; chert fairly abundant; uppermost 5 feet contains small calcite and quartz geodes a quarter of an inch to 1 inch in diameter, which give the bed a rather distinctive appearance ------------------ 41
5. Limestone, gray; contains nodules of chert and of dense limestone; at bottom a bed of white, dense, finely crystalline gypsum about 3 feet thick. A slope, largely covered ----------- 11
4. Limestone, grayish blue, massive, coarsely crystalline, in beds 6 inches to 3 feet in thickness; slightly sandy; includes large calcite crystals and abundant crinoid stems -------------- 42

2–3. Limestone, buff, sandy, in places yellowish, even-grained, fine-grained, interbedded with sandstones; beds 1 to 2 feet thick; contains white chert that weathers to brown, irregular nodules; crinoid stems abundant ---------- 25

1. Limestone, buff to cream-colored, massive, in beds 6 inches to 1 foot thick, with some small quartz sand grains; uniformly dense ------ 48

Total Kaibab limestone -------------- 536

Bottom of river gorge.

2. *Section on west face of Little Creek Mountain, about 4 miles north of Utah-Arizona line*

[Measured by Bronson Stringham; descriptions revised with additions by Herbert E. Gregory]

Shinarump conglomerate.

Unconformity.

Moenkopi formation:

Upper redbeds: *Feet*

54. Shale and limestone, in alternating beds 1 to 3 feet thick. Shale, dark maroon, thinly laminated, sandy micaceous, in places concretionary. Limestone green blue, very hard, sandy, slightly micaceous; more abundant near the top; beds crossed by irregular fracture -------- 25

Moenkopi formation—*Continued* *Feet*

Upper redbeds—*Continued*

53. Sandstone, brown, micaceous; cemented with lime; a uniformly massive bed. A vertical cliff ------------------------ 15
52. Sandstone, dark red to maroon, shaly, micaceous, slightly cross-bedded. Weathers to a slope ----------------------- 8
51. Sandstone, brown, massive, composed of fine grains of quartz and a little mica and iron. A prominent cliff ----------- 20
50. Sandstone and shale, dark brown to maroon; at base micaceous, very shaly sandstone; extremely even-textured, grains 1 millimeter in diameter predominating; cross-bedded on small scale; near the center brown thinly laminated arenaceous shale; at the top thin-bedded sandy limestone, brown on weathered surface, bluish gray on fresh fracture. A steep slope poorly covered by talus-- 190
49. Sandstone, brown, evenly laminated; smooth, fine quartz grains; cross-bedded on small scale near the top; many thin layers of micaceous sandstone give the outcrop the appearance of shale, especially near the top, where the beds are half an inch to 1 inch thick; horizontal gypsum veinlets at base. Steep prominent cliff ------------------------ 56
48. Shale, dark brown, fine-grained, soft, micaceous, sandy; beds very thin; rock a much weathered slope protected by the sandstone cliff above --------------- 30
47. Shale, red to brown, thin-bedded, arenaceous; includes many thin lenses of dirty-white sandy limestone 1 to 2 inches thick, which contain nodules 1 to 2 millimeters in diameter composed principally of quartz and ferromagnesian minerals; cross-bedding laminae in limestone dip southwest ---------------- 15
46. Shale, reddish brown, sandy, thin-bedded; includes a few green calcareous lenses half an inch to 1 inch thick; very soft-- 3
45. Same as unit 47 ---------------------- 4
44. Same as unit 46 ---------------------- 4
43. Shale, brown-red, very thin bedded, sandy, in part cross-bedded; contains pale green-white thin hard lenses of calcareous material and in upper part soft dirty-white limestone in regular beds 1 to 2 inches thick; much disseminated gypsum. Weathers to slope ---------- 39

Total upper redbeds ------------ 409

Shnabkaib member:

42. Shale, calcareous, dense, irregularly fractured; in beds 1 to 3 inches thick; interstratified with red shale, producing red and white bands 3 to 6 feet wide; red more prominent toward top; much gypsum as grains and lining of seams; near

Moenkopi formation—*Continued* (Feet)

Shnabkaib member—*Continued*

bottom a few beds about 6 inches thick of white fine-grained alabaster 106

41. Limestone and gypsum interbedded; predominately white, redder toward the top. Limestone, white, marked with shallow ripples 2 inches across; nodular; oolitic concretions 0.5 to 2 millimeters in diameter, contain fragmentary shells (?). Gypsum massive, fine-grained, abundant near top; a short distance north beds are curved and slightly cross-bedded. Broken slope, largely covered 73
40. Limestone, white, dark gray on fresh fracture, thin-bedded, very dense, in part sandy; includes considerable clay and gypsum between beds; some compact beds show asymmetrical ripple marks three-quarters of an inch from crest to crest, extending southwest 76
39. Limestone and gypsum. Limestone, gray white, in beds 3 to 6 inches thick, very dense; gypsum massive, fine-grained, white, stained red on weathered surface; layer of red shale forms conspicuous band along the outcrop 15
38. Limestone and gypsum. Limestone very dense; breaks up into slabs 1 to 3 inches thick. Gypsum white, in beds 3 to 6 inches thick, massive, fine-grained 20

36–37. Limestone and gypsum. Limestone, white to light gray, in beds 3 to 6 inches thick; oolitic; weathers into nodules 1 to 2 millimeters in diameter. Gypsum, white, in compact dense beds 1 to 3 inches thick; near the bottom composes about half the outcrop; includes a little red shale that on weathering produces bands of pink.. 40

35. Shale, brown to red, calcareous and sandy, very thinly interbedded with white to pale-green impure limestone and gypsum. Weathers to a slope 6
34. Gypsum, white, massive, fine-grained; weathered surface stained red; continues as a single bed for as much as half a mile 2
33. Shale, green to white, finely laminated; contains lime and gypsum; cross-bedded on small scale. A much-weathered slope 30
32. Gypsum, white, massive, fine-grained; stained red on weathered surface. Forms steep cliff 5
31. Gypsum, pale green to white; with slightly cross-bedded calcareous shale, thinly laminated; has a shaly structure, continuous for a long distance 4

Total Shnabkaib member 377

Middle redbeds:

30. Shale, deep brown, sandy; very fine-textured; very thin-bedded; includes a few highly calcareous beds 3 to 6 inches thick, lenses of impure limestone, and many gypsum veinlets. A steep slope .. 49
29. Shale, brown, thin-bedded, interstratified with gray sandy limestone, in layers 2 to 6 inches thick, that weathers with splintery fracture; much gypsum in veinlets 17
28. Shale; lower part light green, resistant, calcareous, very thinly laminated; includes lenticular limestones; upper part red, soft, sandy, and slightly gypsiferous; near the center a 1-foot bed of red gypsum mingled with argillaceous material 11
27. Gypsum, thoroughly intermixed with red shale; a distinctive bed at least 100 yards long 2
26. Shale, reddish brown, with bands of light green 1 inch thick; very thin-bedded; gypsiferous; fractures across the bedding filled with gypsum 17
25. Gypsum, white to brown, in layers 2 to 4 inches thick, separated in places by thin bands of red-brown shale. Forms prominent cliff, visible along the outcrop for several miles 4
24. Shale, variegated white and pink, finely laminated, in groups of beds 2 to 4 feet thick; includes thin hard lenticular beds of pale-green and of brown gypsum that stand on the weathered slope as benches 60
23. Limestone, white, hard, very thin-bedded; grades upward into reddish-brown calcareous shale 2
22. Shale, reddish brown, calcareous, gypsiferous; very thin-bedded; beds of white gypsum 1 to 6 inches thick appear at intervals of 3 to 10 feet. Weathers to broad, much-dissected slopes, the white gypsum beds generally forming caps of small hills 107
21. Sandstone, gray to brown, imbricated, cross-bedded, fine-grained, well cemented; weathers into splinters 1 to 6 inches long; a conspicuous layer 1/25
20. Like unit 22, except that gypsum is absent in upper part 151
19. Limestone or calcareous sandstone, gray to white, fine-grained, in places coarsely crystalline, thin laminae, in places curved; contains some mica 7
18. Limestone, white to buff, sandy, coarsely crystalline, fossiliferous (?); splits into slabs half an inch to 2 inches thick. Forms conspicuous bench along contours for at least a mile 2
17. Shale, grayish brown; grades upward to deep brown; finely laminated but includes sandy beds 2 inches thick, in places ripple-marked and some gypsiferous shale beds near the top; bedding planes sprinkled with biotite and muscovite in flakes as much as 1 millimeter in diameter that lie flat on the bedding planes 32
16. Shale, dark purple to gray, micaceous, very finely laminated, somewhat concretionary; splits into extremely thin, hard fragments that weather to mud 6
15. Sandstone, gray, predominantly thin-bedded, calcareous; contains consider-

Moenkopi formation—*Continued* Feet

Middle redbeds—*Continued*

able muscovite and biotite; cross-bedded on a small scale; ripple marks of current origin asymmetrical to the southwest and about 1½ inches from crest to crest; top bed, 1 foot thick, is firmly cemented with lime and contains no mica. Forms a steep slope capped by a low cliff 25

13–14. Shale, gray, maroon, slightly sandy and micaceous, very soft; the basal 4 feet thinly laminated, chocolate brown, friable and contains considerable mica. Forms a nearly flat slope, largely covered. Contact with No. 12 gradational ... 23

Total middle redbeds 520

Virgin limestone member:

12. Limestone, brownish buff, massive, sandy; most of the quartz submegascopic in size; upon weathering breaks to thin angular chips 3½
11. Limestone, cream to white, shaly; many veinlets of brown silt on cross-bedding planes; includes laminae of pure shale; soft; weathers easily into spheroidal forms 2
10. Limestone, buff, coarsely crystalline, somewhat sandy; shaly structure; breaks into slabs 1 to 2 inches thick. Stands up in prominent cliff 2½

Total Virgin limestone member ... 8

Uncomformity: beds in unit 9 truncated.

Lower red beds:

9. Shale, dark reddish brown, gypsiferous, sandy, very thin bedded; contains lenticular seams half an inch to 2 inches thick of white to light-green impure limestone; near bottom several beds of light-gray gypsum 1 to 6 inches thick ... 118
8. Gypsum, white, red on weathered surfaces, fine-grained, massive, like alabaster; in places mixed with red shale ... 2
7. Shale, dark red, much like unit 9 ... 24
6. Limestone, light green, soft, sandy; shaly structure; contains selenite crystals ... 1–2
5. Shale, dark reddish brown, very thin-bedded; includes short lenses of gypsum about half an inch thick; some thicker layers show cross bedding. A steep ribbed slope; rests unevenly on unit 4 ... 74

Total lower redbeds 220

Timpoweap member:

4. Shale, yellow, calcareous and argillaceous (?); weathers easily 2
3. Limestone, gray, massive, hard, dense, in places shaly; contains tiny concretions and fragmentary fossils; breaks into hard slabs about 3 inches thick 2
2. Limestone, buff, very massive, crystalline; upper part contains concretions 1 millimeter to 1 inch in diameter. A prominent cliff. 200 feet along the strike contains small chert pebbles 4
1. Conglomerate, subrounded pebbles a quarter of an inch to 2 inches in diameter; white, gray, buff, brown, and black chert and quartz, angular fragments of gray limestone and brown and black shale; pebbles rather widely spaced within a matrix of sandy light-gray coarsely crystalline limestone; fewer and smaller near the top 5

Moenkopi formation—*Continued* Feet

Timpoweap member—*Continued*

Unconformity: discordant stratification.

Total Timpoweap member measured 13

Total Moenkopi formation measured 1547

It may be noted that in this section the Virgin limestone is remarkably thin. Here it lies in a channel about 700 feet wide and 70 feet deep. As shown in the following supplementary section measured less than half a mile distant it is ten times as thick.

Virgin limestone member:

3. Limestone, buff, somewhat sandy, coarsely crystalline, massive, extremely hard; breaks into large blocks; contains many Triassic pelecypods; weathered surface nodular. Caps a cliff 10
2. Limestone, gray to white, dense, with peculiar bedding; blocks 1 to 3 inches in diameter, square and oblong with rounded corners, are completely surrounded by shaly material not more than 1 inch thick, which appears like a stone wall of limestone blocks cemented with sand and clay. A steep overhanging cliff ... 47
1. Limestone, gray to blue, dense, richly fossilferous; breaks easily along bedding and at prominent vertical joints. Weathers to steep cliff ... 24

Total Virgin limestone number 81

Uncomformity.

Shale, red brown, sandy, gypsiferous.

3. *Section of the Belted Cliffs at Isom Wash, 2½ miles west of Virgin City*

[Measured with the assistance of J. C. Anderson and F. W. Christiansen. In the descriptions beds 5 to 8 combined with beds measured above the middle of Oil Seeps Wash]

Shinarump conglomerate: Feet

36. Sandstone and conglomerate, gray, ironstained, interbedded as lenses, wedges, and miscellaneous structures; rounded pebbles of quartzite (65 percent), quartz (10 per cent), chert (15 percent), and white clay pellets and sandstone fragments (10 per cent); contains blocks and chips of petrified wood; a regionally prominent cliff and the floor of a wide platform 129

Unconformity.

Moenkopi formation; dip 3½° NE.:

Upper redbeds:

35. Sandstone, red, white-spotted, and variegated shale; thins irregularly; interleaved 1–4
34. Sandstone, deep red and brown, in general regularly stratified as beds 1 to 4 feet thick; cement chiefly calcite and iron; a little gypsum; most beds shaly and

Moenkopi formation; dip 3½° NE.—*Continued* — *Feet*

Upper redbeds—*Continued*

friable at the base, massive and resistant above; along the strike the solid beds become laminated; includes thin, short lenses of calcareous and arenaceous shales; plasters of quartzite sands and scattered flakes of mica; forms steep, broken slope — 326

33. Sandstone or mudstone, red to chocolate-brown; evenly stratified as massive beds 2 to 3 feet thick, separated by thinner beds; fine, even-grained, in part micaceous; forms a ledge — 22

32. Shale, maroon, very thinly and evenly laminated; grains fine, round, well sorted; calcareous cement; many beds ripple-marked — 24

31. Shale and sandstone: shale deep red, sandy, calcareous, cemented with iron, fairly even-bedded, in part thinly laminated and ripple-marked; sandstone more abundant near the base, tan, massive beds 1 to 5 feet thick, cross-bedded by diagonal lines, composed of fine, well-rounded and sorted quartz grains, a little mica and gypsum; forms a steep slope — 132

30. Sandstone, red, massive, calcareous, fine-grained; a single bed that includes a few small, thin sheets of sandy shale — 10

29. Shale, maroon, streaked with white, evenly stratified; arenaceous, calcareous, and gypsiferous; interstratified with tan and white fine-grained sandstone in beds less than 1 foot thick; grades downward into red-white beds of No. 9 — 28

Total upper redbeds — 546

Shnabkaib member: prominent zone, banded red and white; three groups of closely spaced white bands with more widely spaced bands above and below; dominantly gray; gypsiferous; weathers as a slope broken by thin discontinuous ledges.

28. Shale and gypsum. Shale red, brown-chocolate, arenaceous, calcareous, and gypsiferous; most of it evenly, thinly laminated in groups a few inches to 3 feet thick; ripple-marked, mud-cracked. Gypsum white and gray green, some stained pink; in beds a quarter of an inch to 3 inches thick, grouped or separated by thin red shale; most of it sandy, some argillaceous, some pure; as secondary deposits fills joints; on talus appears as glistening specks. Section includes inconspicuous lenses of pure quartz sandstone, oolitic limestone, and quartz-lime conglomerate with fragmentary fossils — 92

27. Shale, chocolate brown, arenaceous; includes thin streaks of gypsum — 6–14

26. Gypsum (70± percent) and shale (30± percent). Gypsum impure, grades laterally into red arenaceous shale or extends as individual beds as much as 500 feet. Shale chocolate to red, in thin, even beds and imbricated, lenticular ripple-marked beds disposed as irregularly

Moenkopi formation; dip 3½° NE.—*Continued* — *Feet*

Shnabkaib member—*Continued*

placed layers dominantly arenaceous, argillaceous, or calcareous. Resembles No. 9 — 70

25. Shale (80± percent) and gypsum (20± percent), mainly red streaked with white, near the top yellow — 26

24. Gypsum, white, nearly pure, thinly laminated — 2

23. Shale, chocolate to red, sandy and calcareous; mainly in regular beds; includes three thin beds of gypsum, parting planes strewn with mica — 18

22. Gypsum (50± percent), shale (30± percent), and limestone (20± percent). Gypsum, gray and white, impure, in part lenticularly interleaved with sandy beds; some of the beds wrinkled and fractured on a small scale. Shale, gray, calcareous and gypsiferous, thinly laminated in lense-shaped beds. Limestone, in part oolitic, cherty, and conglomeratic, interleaved with gypsum along the strike; includes fragments of fossils like those in the Virgin limestone member. Constitutes the lowermost prominent white zone of the Shnabkaib — 40+

Total Shnabkaib member — 262

Middle redbeds:

21. Shale with subordinate sandstone, limestone, and gypsum. Shale, red to brown, evenly bedded, in part thinly laminated; most beds very arenaceous and might be termed thin impure sandstones; some beds ripple-marked, sun-cracked, and coated sparingly with fairly large quartz grains, bits of iron ore, calcite crystals, and mica. Sandstone, brown and gray, fine-grained, in large part earthy; in regular beds and lenses 6 inches to 2 feet thick; along the strike interleaves with shales and overlaps or underlies gypsum beds; parts stained green with hydrous iron, prospected for copper. Limestone in upper 100 feet, disposed as beds and as small lenses resting in local hollows; thin, compact, hard, sandy, in places oolitic and conglomeratic; contains fragmentary shells and bits of lignite. Gypsum in beds a quarter of an inch to 6 inches thick, white and gray, mostly sandy; thicker beds resistant enough to form ledges; fills joint cracks. Forms very steep slope — 368

20. Sandstone and shale. Sandstone, red and brown; thinly, evenly stratified; in part gypsiferous and calcareous. Shale, blue, green, red, argillaceous and calcareous; ripple-marked — 23

19. Shale and sandstone. Shale, red and green white; thinly, evenly stratified, ripple-marked, sun-cracked, some edges upturned; several beds carbonaceous and include macerated plants. Sandstone fine grained, lenticular, constitutes about one-fifth of the unit. Limestone lenticular, impure and unevenly bedded,

Moenkopi formation; dip 3½° NE.—*Continued* — *Feet*

Middle redbeds—*Continued*

sparingly near the base. All beds gypsiferous ---------- 45

Total middle redbeds ---------- 436

Virgin limestone member

18. Limestone, buff, massive, impure, interbedded with calcareous shales: forms cliff and broad platform, fossiliferous:
    - g. Limestone, firm, slablike masses that split along the strike into hard sheets as thin as cardboard, pastered over with crumpled red gypsiferous shale ---------- 3
    - f. Shale, reddish gray, calcareous, arenaceous, slightly gypsiferous, hard; breaks into angular blocks; some plant fragments; rare copper and zinc sulfide ---------- 12
    - e. Limestone, earthy; weathers as thin yellow slabs; uneven beds marked by ripples and aggregates of quartz and calcite grains; resistant; forms long cliff and platform ---------- 3
    - d. Shale, brown and blue gray, calcareous, arenaceous, and argillaceous; thinly laminated; some beds compact like indurated mud; a few thin lenses of limestone; tiny flakes of gypsum on weathered surfaces ---------- 27
    - c. Limestone, buff and gray, thin-bedded, in part regularly bedded; includes thin and thick stub-ended agglomerate lenses of stone, in disks, balls, and lozenges; some beds ripple-marked ---------- 18
    - b. Shale and limestone, thin, unevenly bedded. Shale, in part blue gray, argillaceous, and carbonaceous; includes nodular limestone conglomerates, thinly laminated almost pure quartz sand, and scattered flakes of gypsum ---------- 38
    - a. Limestone, buff, mottled with yellow; hard; in part crystalline; interbedded with blue-gray and brown calcareous and ferruginous shale; some beds ripple-marked and coated with coarse sand; rests on eroded surface of No. 17 ---------- 15

Total Virgin limestone member ---------- 116

Unconformity: eroded surface and change in sediments.

Lower redbeds:

17. Sandstone, red and gray, in uneven, slabby beds 1 to 2 inches thick; calcareous, irregularly interleaved with calcareous shale and gypsum ---------- 12
16. Shale, white, red, and green; argillaceous and calcareous, paper-thin, wavy sheets; weathers as knobs like mud balls ---------- 2
15. Shale (80 percent), sandstone (10 percent), and gypsum (10 percent). Shale, chocolate to red, thinly, fairly evenly laminated as individual sheets and as groups as much as 10 feet thick; in places broadly wavy or crinkled; some beds nodular and imbricated; locally friable and minutely interleaved with earthy gypsum; prevailingly arenaceous, much of it like the sandstone; includes several thin beds of blue and greenish-gray shale and rare lenses of conglomerates composed of limestone and dense, siliceous mudstone pebbles one-sixteenth to one-third inch in diameter in a matrix of crystalline calcite and fine sand. Sandstone chocolate to red, some of it conspicuously hard and white; even beds and long, thin lenses 3 inches to 2 feet thick; composed of small, well-rounded and well-sorted grains of quartz and quartzite, a little feldspar and biotite cemented with gypsum, iron, and lime; thinner beds, particularly near the base, ripple-marked on an extensive scale and showing rain prints, worm holes, and amphibian (?) tracks. Gypsum, white, pink, and greenish; more abundant toward the top; present as beds half an inch to 6 inches thick, as cement, as fillings of criss-cross joints, and as talus debris; the range of variation in bedding and composition much the same throughout; a 50-foot section taken at random might be considered typical. Forms a slope nearly vertical at the top ---------- 260
14. Shale, lower part red, upper part blue gray; minutely imbricated; includes lenses 3 to 6 inches thick of white sandstone, rounded mud balls, and scattered aggregates of calcite, iron, and coarse sand; gypsiferous alkali seeps at base; weathers to hard chips ---------- 4

Total lower redbeds ---------- 278

Timpoweap member:

13. Shale, yellow, composed chiefly of calcite and clear quartz grains cemented by limonite and gypsum; sandstone, calcareous, yellow, compact, in small sheets 2 to 6 inches thick; rare lozenges of clay, iron concretions, conglomerates containing fragmentary Triassic shells, disseminated pyrite; laterally interleaved with red shale and sandy argillaceous limestone; within 1 mile thickness ranges from 6 to 40± feet; to the south across the Virgin River includes conglomerate of angular quartz pebbles ---------- 22
12. Shale, brown, in paper-thin sheets, calcareous and gypsiferous; ripple marks and mud marks; alkali and sulphur seeps at base ---------- 6
11. Limestone and sandstone, white on weathered surface, nearly black within and on parting planes; top part nearly pure limestone, lower part sandy and gypsiferous; contains many fossils and cavities from which fossils have been rotted, now filled with asphaltic material; oil

Moenkopi formation—*Continued* — Feet

Timpoweap member—*Continued*

seeps from joints in the limestone. Forms tops of mesas — 6

10. Shale or thin-bedded, highly calcareous sandstone, yellow and gray, in places slightly brecciated; fragmentary fossils — 4
9. Limestone, gray, interbedded with calcereous sandstone and shale; extremely irregular in vertical and horizontal extent, color, arrangement of beds, and composition; includes lenses of pure limestone, of coquina, of clay, and of breccia made up of angular black chert, gray hard sandstone, and massive blue limestone; one layer fossiliferous; within 1,000 feet along the strike thickness 8 to 30 feet. Forms steps on steep slope — 28
8. Limestone, blue gray, on weathered surfaces tan; massive, somewhat wavy, resistant beds 6 inches to 4 feet thick, which resemble the "normal Kaibab"; includes some sandy yellow shale, friable sandy limestone, and a little chert; cavities filled with oily asphalt; abundant Lower Triassic fossils; forms rim of Timpoweap Canyon at highway bridge — 9–16
7. Limestone, mottled, in irregularly lenticular beds, 3 to 6 inches thick; hard, siliceous, unfossiliferous; along the strike thickness 0–8 feet — 8
6. Limestone, light red where purest; sandy, in beds 2 to 3 feet thick; slightly brecciated; weathers as pillows and balls; changes color and disappears (?) along the strike; forms a cliff — 0–20
5. Shale, tan, arenaceous, argillaceous, finely laminated; irregular mud plasters on uneven surface of No. 4 — ¼–8

Unconformity.

4. Breccia, gray; angular fragments of dense blue-gray limestone, white quartz, quartzite, hard gray sandstone, chert, and geodelike aggregates; largest fragments 2 by 4 feet; groundmass sandstone, quartz, calcite; rests on wavy, slightly eroded beds of No. 3; bottom of canyon near mouth of oil seeps wash — 3–8

Unconformity.

2–3. Sandstone and shale; irregularity bedded: a lens; average thickness — 12

Total Timpoweap member — 138

Total Moenkopi formation — 1,776

Unconformity.

Kaibab limestone:

1. Limestone, about half chert; abundant Permian fossils.

4. *Section near the mouth of Johnson Canyon, 3+ miles south of Fredonia, Ariz.*

[Measured by J. C. Anderson]

Moenkopi formation: — Feet

10. Sandstones, shales, and gypsum, interbedded, thinly laminated and crinkly; forms dissected slopes above cliffs of Virgin limestone, part exposed — 25+

Moenkopi formation—*Continued* — Feet

Virgin limestone member:

9. Limestone, tan to gray, stratified in thin laminae that overlap like shingles, hard, crystalline; bedding planes irregularly undulatory; laterally passes into a more massive, solid layer; contains Triassic fossils — 3
8. Shale, gray to greenish blue, gypsiferous, thinly laminated; forms slope; upper part red to brown, thinly laminated shale; some beds hard, calcareous — 27
7. Limestone, tan to cream-colored, stratified, crystalline, fossiliferous; in solid blocks, prominently jointed N.40°W. N.30°E. along vertical planes; locally thinly laminated and imbricated; some beds show mud cracks; a few hundred yards along the strike limestone changes from massive vertical ledge to two ledges, each about 3 feet thick, separated by calcareous and gypsiferous shale; Triassic fossils — 14–18

Total Virgin limestone member — 48

Unconformity; angular discordance of about 15° from the west to the east.

Lower redbeds:

6. Shales and mudstones; typical chocolate-colored cliffs; beds laminated, crinkly; in part lenticular; thicker beds weather into kidney-shaped knobs; ledge cut by veinlets of satin spar — 20
5. Sandstone and mudstone in beds 1 to 12 inches thick; gypsiferous, interbedded with thin layers of shale and gypsum; some cross-bedded and many ripple-marked — 70
4. Sandstone, brown, 2 inches to 3 feet thick, medium-grained, soft, in part cross-bedded; interstratified with shale and mudstone; calcareous and gypsiferous cement — 12
3. Shale and mudstone, thinly laminated, crinkly, chocolate-colored, gypsiferous, soft; interbedded with thin lenses of white to greenish blue — 3
2. Shale, gray, gypsiferous, calcareous, thinly laminated, grading downward to limestone — 2
1. Limestone, tan to light brown, massive, crystalline, fossiliferous, bedding planes irregular. A ledge that appears blocky or brecciated — 25+

Total Moenkopi formation measured — 205

5. *Section along Cottonwood Canyon 3 miles west of Fredonia, Ariz.*

[Measured by F. W. Christiansen]

Feet

Chinle formation: marls, shales, and conglomerates; contact with the Shinarump covered.

Shinarump conglomerate:

18. Sandstone and conglomerate. Sandstone, coarse, angular grains; upper part white, lower part yellow; massive, strongly cross-

Shinarump conglomerate—*Continued* *Feet*

bedded. Conglomerate in lenses and wedges; pebbles 1 to 1½ inches in diameter composed of quartzite (65 percent), chert (25 percent), and clay pellets (10 percent); includes petrified wood ---------- 39

17. Shale, light gray, arenaceous, lenticular, finely laminated; a lens about 200 feet long ------ 0–2
16. Sandstone, gray, iron-stained, lenticular; cross-bedded; grains poorly rounded and sorted; includes lenses of conglomerate ---------- 15
15. Sandstone, irregular-bedded, coarse-grained, pink to cream-colored; grains not well rounded or sorted; includes lenses of fine sandstone and decayed conglomerate; thin veins of secondary gypsum ---------- 4½

Total Shinarump formation ---------- 60

Unconformity: surface of erosion.

Moenkopi formation:

14. Sandstone, fine-grained, muddy, somewhat decomposed, white to gray, thinly laminated, soft, friable ---------- 2–5
13. Sandstone, thinly laminated; slope maker; slabs of evenly laminated sandstone strewn over slope; sandstone fine-grained, chocolate-colored; few lenses of cream-colored sandstone; ripple-marked; evenly stratified ---- 62
12. Sandstone, chocolate-colored; massive; ledge maker; evenly stratified; hard layers 3 to 8 feet thick, interbedded with thin layers of much softer sandstone ---------- 24
11. Conglomerate, fairly well rounded, finely banded pellets of sandy shale, cemented with fine-grained sandstone ---------- 2–3
10. Sandstone and shale, gray, interstratified, beautifully stratified, ledge maker; on weathering, the shale and softer sandstone produce corrugated ledge; white veins of secondary gypsum cut the layers in nearly every direction; most of the gypsum veins dip to the south and from a distance give the appearance of cross-bedding ---------- 25
9. Sandstone and shale, red to maroon, interbedded with very thin irregular sheets of gypsum; slope maker; includes beds of light-gray sandstone, evenly stratified, fine-grained, and finely laminated ---------- 45
8. Sandstone, fine-grained, red, ledge maker; grains fairly well sorted and rounded; joints filled with gypsum ---------- 13
7. Conglomerate of fairly well-rounded blue to gray sandy shale; the cementing material is a medium-grained sandstone with well-sorted subangular grains; some pellets of finely laminated shale; lenticular; pinches out laterally ---------- 1
6. Shale and sandstone, very thinly laminated; sandstone grades into irregularly bedded shale, grains not well rounded or sorted; brown, green, blue, yellow, and white ------ 3½
5. Sandstone, green, yellow to gray; thinly laminated, grades to shaly sandstone; grains well rounded and of uniform size ---------- 4
4. Sandstone, light gray, massive toward the top, evenly laminated near the base; fine-grained, soft, friable; steep slope maker; grains well rounded and sorted; lower part gypsiferous 28

Moenkopi formation—*Continued* *Feet*

3. Sandstone, very fine-grained, gypsiferous, light gray, thinly laminated; some gypsum layers are thick enough to form low cuestalike ridges and slopes; gentle slope maker; ripple-marked; some layers soft and friable, lower part covered ---------- 130
2. Sandstone, red, fine-grained; gypsiferous, in beds a quarter to half an inch thick; veins of secondary gypsum cut sandstone layers in all directions; interbeds of friable arenaceous shale as much as 4 inches thick; some thin beds of light-gray gypsiferous shale ------ 34
1. Conglomerate, small rounded pebbles of black chert, white clay, quartzite, and crystalline limestone; large sandstone slabs as much as 5 feet wide; well cemented with medium-grained sandstone; lower part porous—a spring horizon ----------6–10

Total Moenkopi formation measured--- 387

Unconformity.

Virgin limestone member (?).

6. *Section of beds between the mouth of the Parunuweap and the top of West Temple*

[Beds 15–18 measured in Pine Creek Canyon]

Feet

Navajo sandstone; massive, cross-bedded, banded at base; forms walls leading up to the top of West Temple and East Temple; thickness estimated ----2, 000

Kayenta formation:

18. Sandstone, red, in beds 6 inches to 3 feet thick that overlap irregularly within short distances; a series of lenses that vary much in composition and texture, but rock of different coarseness roughly segregated as in stream beds; upper 10± feet more evenly bedded; includes two layers of gray limestone conglomerate each about 1 foot thick; many foliation surfaces sun-baked and cracked; a few dinosaur tracks and fragmentary shells (unios?); microscopic examination by C. S. Ross of a representative sample of the red rock shows "fine-grained argillaceous sandstone; grains partly angular and variable in size; many grains bits of fine quartzite; groundmass clay and dolomite (?) grains coated with hematite; reduced in places to form white spots"; thickness, in part estimated ---------- 180±

Wingate sandstone:

17. Sandstone, gray, massive, even-grained, cross-bedded in curved and oblique lines, broken by joints into square blocks ---- 22

Chinle formation:

Upper sandstones:

16. Shale, red and purple, in part even-bedded, calcareous and sandy; two small thin plasters of limestone ---------- 16
15. Sandstone, red top, banded white and mauve; in overlapping and merging beds 1 to 8 feet thick in 100 feet along strike; dominantly fine, well-rounded, well-sorted grains but in part amorphous mudstone; about one-tenth of the unit arenaceous and shale irregularly dis-

Chinle formation—*Continued* — Feet

Upper sandstones—*Continued*

posed; a few lenses of white grits and plasters of siliceous limestone; forms cliff; some carbonaceous matter ______ 48

14. Shale and conglomerate, roughly lenticular; weathers as a groove in nearly vertical cliffs ______ 6

Inches

a. Mottled limestone, dense, thinly laminated, algae fossils ____ 6
b. Purple-brown, green, spotted sandstone, imbricated _____ 36
c. Gray limestone conglomerate of pellets, chunks, and saurian bones; includes thin sun-baked laminae ______ 8
d. Purple calcareous shales, ripple-marked and sun-baked _____ 3+
e. Gray and purple limestone conglomerate, unconformable on unit 13 ______ 18

13. Sandstone, brick red, in three massive beds incompletely separated by mud shales; coarser than No. 12; along the strike this unit thickness to 30 feet and thins to less than 10 feet ______ 15

12. Sandstone, red, streaked with white; upper two-thirds interbedded red and white in thin lenticular beds, many of them separated by patches of red or white shale; at the base 6 inches to 2 feet of variegated calcareous and arenaceous shale locally unconformable with unit 11; red beds friable, flaky, fine-grained mudstone that weathers as grooves; white beds very calcareous, hard, projecting as tiny ledges. Forms slope to steep to climb; thickness estimated ______ 250

Total upper sandstones ______ 357

Springdale sandstone member:

11. Sandstone, orange, red, and mauve, in massive, generally cross-bedded strata in uneven beds 3 to 8 feet, in places 10 to 15 feet thick; included in the sandstone are lenslike masses of red mud that weather as tiny curved flakes; between the beds are highly calcareous shale, siliceous limestone, white and red sandstone, and green clay disposed as fragments in conglomeratic lenses 10 to 500 feet long and 6 inches to 6 feet thick; basal beds dark brown carbonaceous shales, green flattened clay slabs, mud balls, and iron concretions; clays and conglomerates weather readily, leaving pits, grooves, and areas of porous rock through which water seeps; contains fossil fishes. Forms a very prominent vertical cliff. Thickness estimated _____ 70

Unconformity—eroded contact surface with a relief of as much as 15 feet in a distance of 1,000 feet.

Petrified Forest member:

10. Sandstone and subordinate shales; forming a slope with steps:

a. Sandstone, light red, very thin-bedded, imbricated, fine-grained; a few lenses of white coarse sandstone; gypsiferous, friable_ 120
b. Sandstone, red streaked with white, in beds 6 inches to 2 feet thick that split into thin shalelike layers; some beds separated by shale made of overlapping mud flakes; rests in hollows on surface of beds below ______ 40
c. Sandstone, blue white, imbricated, in paper-thin sheets, ripple-marked; includes plasters of calcareous shale, many light-green flakes, and disk-shaped pellets of mud ______ 9
d. Sandstone, red, thickest bed 3 feet, splits readily into slabs about a quarter of an inch thick with glistening surfaces; sandstone interbedded with lenses and sheets of green, white, and dark-red sandy and calcareous shales_ 42
e. Shale, green white, flaky, roughly interbedded with lenses and even beds 2 to 6 inches thick of sandstone that include flakes of green clay, conglomeratic masses of chert, limestone, and shale; some bedding planes sparsely coated with tiny grains of white, red, and yellow quartzite, garnet, and rotted feldspar; unconformable on beds below ______ 12
f. Sandstone, red, fine-grained, lenticular; splits readily into slabs about a quarter of an inch thick; many bedding planes strewn with green-white glauconitic sand; interbeds include cross-bedded conglomeratic lenses of limestone, chert, wood, and bones ______ 22
g. Shale, dark red, sandy; shows mud cracks, ripples, worm trails, and saurian tracks (?); in overlapping flakes; top bands of dark, earthy, macerated vegetable matter; weathers as a groove in cliffs ______ ½–2

9. Shales ("marls"), ash gray, red, and purple, gypsiferous; extremely irregular in composition, texture, bedding, and position of comparable units. Chief constituents, lenses of white coarse cross-bedded sandstone including strings of gravel; gray mottled "pepper and salt" sandstone; purple sandstone, criss-crossed with gypsum seams; gray conglomerate made of small slabs of sandy limestone, shale, chert, aggregates of quartz and iron, rare fossil wood, and saurian bones; clay pellets, "sand balls," and concretionary limestone. Subordinate beds, finely divided lacustrine (?) sands and clays in series 2 to 4 feet thick; lenses of sand-bar structure and low mounds with the curved cross bedding of dunes. From the bottom up-

Chinle formation—*Continued*

Petrified Forest member—*Continued* — *Feet*

ward becomes more red, more sandy, and more firmly cemented — 160

8. Sandstone, white, lenticular, cross-bedded; essentially a lens of two beds separated by shale; resembles No. 6 — 11

7. Shale, variegated, friable; includes lenses of white and red sandstone, limestone conglomerate, thin brown sandstone marked by worm trails and borings, and glistening rippled, arenaceous beds; resembles unit 5 — 110

6. Sandstone, white, cross-bedded, coarse-grained, hard; composed chiefly of quartz, a little feldspar, and aggregates of clay and lime; a series of lenses of variable thickness, position, and attitude; along the strike becomes browner, includes iron nodules, thickens to as much as 12 feet and thins to a few inches; some parting planes thinly coated with clay and limestone pellets; rests on eroded surface of unit 5; forms conspicuous projecting ledge — 6

5. Shales ("marls," "gumbos") and related beds; shades of red, blue, green white, lavender, and ash gray in bands, streaks, blotches, and circular areas, in part roughly color-banded; highly irregular in bedding, composition, and texture; most beds lenses 10 to 200 feet long, half an inch to 6 feet thick; a series of pure quartz, arkosic, and calcareous sandstone intermingled with siliceous limestone, limestone conglomerate, clay shale, bentonite, and finely laminated lacustrine silt; irregularly distributed aggregates of clay balls, coarse sand, chalcedony, and ironstone; gypsum common as part of the cement, the filling of joint cracks and as scattered crystals; petrified wood in chips and logs (no leaves or twigs); worn saurian bones and broken shells in the limestone conglomerates. Weathers to rounded knobs with spongy, powdery surface, locally called "clay hills" — 260

Total Petrified Forest member — 794

Lower sandstones:

4. Sandstone, brown, in beds about 2 feet thick alternating with shale much like No. 3; many beds ripple-marked; some sun-cracked; on some foliation surfaces the mud flakes are arranged like those in dried-up ponds — 15

3. Shale, lead-colored; overlapping flakes of arenaceous and calcareous material, splotched with gypsum; includes bits of carbonized plants — 3

2. Sandstone, green white, hard, in thin ripple-marked beds; chiefly fine-grained quartz cemented by calcite; scattered indurated clay chunks and coarse grains on foliation surfaces; weathers as square laminated blocks; along the strike becomes a lens of friable red

Chinle formation—*Continued*

Lower sandstones—*Continued* — *Feet*

sandstone as much as 16 feet thick and 200 feet long — 12

1. Sandstone, gray purple; seemingly a massive, resistant bed; weathering in places reveals its structure as tightly compressed layers, thin as cardboard. Composed of almost microscopic angular and subrounded grains of quartz (90+ percent), feldspar, mica, garnet, and clay, bound together with calcite — 13

Total lower sandstones — 43

Total Chinle formation — 1,264

Shinarump conglomerate: Sandstone, coarse, with wedges, lenses and strings of quartz, quartzite, limestone, chert, sandstone, and shale pebbles a quarter of an inch to 3 inches in diameter; chunks and logs of petrified wood; upper limit set at the wavy surface of the topmost conglomerate bed — 88

Unconformity, surface of erosion.

Moenkopi formation: Sandstone, red, thin, and shale, red-white streaked, topmost 1 to 4 feet green-white gypsiferous shale; part exposed — 20

This section (units 1–16) of the Chinle formation, considered representative for Zion National Park, is not duplicated in detail by sections measured at Shunes Creek, Eagle Crags, Smithsonian Butte, and Huber Wash, 2 to 4 miles distant, and includes units that assume quite different expression in sections as far west as North Creek and La Verkin Canyon. The purple bed (unit 1) and the Springdale sandstone member (unit 11) appear in all measured sections, and the groups of beds that make up the Petrified Forest member (units 5–10) and the upper sandstone series (unit 15) are likewise regionally persistent. Of the beds that include the "marls" or "gumbos," sections a few hundred feet apart are so unlike in arrangement and composition as to record only local features. Some of the descriptions are therefore generalized. In field notebooks subdivision 5 includes 46 units, 7, 14 units, and 9, 23 units. Of the formations above the Chinle the Navajo and the Carmel, where not removed by erosion, are typically exposed. The Wingate, not recorded at Shunes Creek, is represented at Smithsonian Butte by 5 feet of "white grit." Neither the Wingate nor the Kayenta is listed in sections measured west of Coalpits Wash.

7. Section of Vermilion Cliffs 2 miles west of Kanab, Utah

[Measured by F. W. Christiansen]

Wingate sandstone: — *Feet*

27. Sandstone, massive, white, cross-bedded; ledge maker; sand grains well rounded and sorted; thickness exposed — 35+

Unconformity: not prominent, cross-bedded sandstone rests on a fairly even surface of stratified red beds.

Chinle formation:

26. Sandstone and sandy shale, red; ledge maker; massive layers interbedded with soft sandy shale; sandstone finer-grained than the Wingate in beds 1

Chinle formation—*Continued*	Feet
foot to 16 feet thick; shale beds 1 to 12 inches thick	78
25. Sandstone interbedded with sandy shale, red, steep slope maker; sandstone fine-grained, not well sorted or rounded; small cross-bedding in some beds; mostly covered	85
24. Sandstone, red, massive; ledge maker; small cross bedding; sand grains well cemented with lime; grains well sorted and rounded	32
23. Sandstone and shale, light red, interbedded; steep slope maker; sandstone grains well rounded and sorted; some members cross-bedded; shale layers thinly laminated, red to gray, well stratified, some deeper red than the sandstone	59
22. Sandstone and conglomerate. Sandstone red, massive, irregular-bedded, cross-bedded; ledge maker; lenses 2 to 3 feet thick of sandstone and limestone; other lenses of rounded fragments of shale and clay; locally very hard sandstone cemented with calcite; small fractures filled with calcite crystals	42
21. Conglomerate, well-rounded pebbles half an inch to 2 inches in diameter of calcareous sandstone and limestone in a sandy matrix; also pellets of dark-blue shale, fragments of hard clay, and iron nodules; lenticular	0–4
Unconformity (?).	
20. Sandstone (Sprindale member), massive, thick-bedded, slightly cross-bedded; ledge maker; grains well sorted and rounded; local lenses of coarse sandstone with pebbles a quarter to half an inch in diameter; also fragments of red shale and limestone scattered through the buff coarse sandstone	57
19. Conglomerate, lenticular; partly decomposed; gray, red, yellow, and tan; pebbles half an inch to 3 inches in diameter, composed of sandstone and limestone; some fragments well rounded; the interpebble material is sandstone cemented with calcium carbonate	0–4
Unconformity (?).	
Petrified Forest member:	
18. Sandstone, thinly laminated, interbedded and locally merged with shale, irregular	21
17. Sandstone, red, massive, in part cream-colored and thinly laminated; ledge maker; cross-bedded; soft, friable; local brown iron-cemented areas of various shapes, much harder and standing out in relief	18
16. Sandstone, irregular lenticular beds; slope maker; gray to yellow, friable; lenses of fairly hard calcareous sandstone and of angular fragments of red finely laminated fine-grained sandstone; lenses of conglomerate include pebbles of dark-blue to maroon calcareous shale, fine-grained sandstone, and concretionary limestone a quarter of an inch to 3 inches in diameter; some of the sandstone fragments are thinly laminated and color banded	8
15. Shale and sandstone, pink, lavender, yellow, and gray green, interbedded, unevenly stratified; lower part thinly laminated, upper part a more massive wedge-shaped red bed 2 to 8 feet thick; locally the sandstone is a conglomerate of sandstone and shale fragments; the shaly layers seem firmly cemented and weather with a nodular surface	29
14. Sandstone and shale, red, interbedded; ledge maker; shale contains numerous streaks of white sandstone; fine-grained, well rounded, and well sorted; laterally the sandstone members thicken and thin capriciously	34
13. Shale and sandstone, interbedded, well stratified, white, red, yellow, and lavender; sandstone fine, in layers 1 inch to 1 foot thick, grains well rounded and sorted; shale soft, thinly laminated; slope maker	28
12. Sandstone, steep slope maker, fine-grained, gray, with lenses of red, maroon, brown, lavender, and light blue; hard and soft layers interstratified; small cross bedding; some beds thinly laminated; sandstone grains well rounded and sorted	59
11. Sandstone (lower part) and shale. Sandstone brown to maroon, fine, even-grained; soft, friable; includes lenses of mottled hard sandstone. Shale in thin, uneven beds, arenaceous and calcareous; includes lenses of hard white sandstone	58
10. Shale, thinly laminated, bluish gray, well stratified; slope maker; gypsiferous; some thin lenses of pure gypsum	3
9. Sandstone, very fine-grained, blue to gray, thinly laminated, ripple-marked; ledge maker	2
8. Sandstone, fine, well-rounded grains, light gray to red; some layers mottled red and white; friable; lenses of coarse-grained sandstone, well rounded but not well sorted; gypsum lenses and nodules scattered through sandstone; some of the gypsiferous sandstone hard, cropping out as low ledges; weathers to low rolling hills	59
7. Sandy slope, little rock exposed; fragments of gypsum strewn over the surface; soil red, maroon, gray, and lavender	113
6. "Marl," loose, lumpy, variegated, claylike material that includes gypsum and dirty black limestone; coats the surface of mounds and ridges to depths of 8 to 10 inches; in the ledge appears as amorphous gypsiferous marl that weathers into small angular chunks	28
5. Long slope covered; probably like No. 6	442
Total Chinle formation	1,263
Shinarump conglomerate:	
4. Sandstone, coarse-grained, cross-bedded, light gray; grains fairly well sorted and rounded; irregularly bedded	14

Shinarump conglomerate—*Continued* *Feet*

3. Conglomerate, massive, well cemented; pebbles well rounded; contains petrified logs 2 by 8 feet; irregular lenses of smaller pebbles in more massive conglomerate, composed of quartz, quartzite, chert, silicified igneous fragments, white clay pellets, and sandstone ---- 4–12
2. Conglomerate, iron-stained and cemented; pebbles not larger than 2 inches in diameter, lenses of brown to black iron concretionary layers at base ---- 1½

Part of Shinarump exposed ---- 27½

Unconformity.

Moenkopi formation:

1. Sandy clay shale, decomposed; light gray to white; irregular-bedded, lenticular; grades downward to the sandstone and shale of the Chocolate Cliffs.

8. *Section of Vermilion Cliffs 1 mile east of Kanab*

Chinle formation: *Feet*

27. Sandstone, white, firmly cemented with lime; chiefly quartz in subrounded grains, 0.1 to 0.5 millimeter in diameter; includes rare garnet, tourmaline, and considerable colorless pyroxene; forms a conspicuous bench at top of the Kanab Cliffs. On the back slope of the cliffs at a horizon about 250 feet above No. 1 the Wingate sandstone forms prominent mesas ---- 2
26. Sandstone, red, thick-bedded, cross-bedded, uneven ---- 30
25. Shale, dark red, argillaceous, arenaceous, and calcareous; lumpy overlapping beds; includes "sand balls" ---- 2
24. Shale and thin-bedded sandstone; parts of the sandstone extremely fine-grained; some worm borings and carbonaceous matter; friable, largely concealed by sand talus ---- 53
23. Sandstone, red, fine-grained, lenticular; includes thin lenses of limestone conglomerate 2 inches to 6 feet wide, 5 to 100+ feet long, and discontinuous beds of clean-washed microscopically fine pure quartz; resembles No. 7 ---- 30
22. Sandstone, red and drab, in thin irregular layers alternating with clay shale that contains fish teeth and scales; friable; largely concealed ---- 25

Springdale sandstone member:

21. Sandstone, orange red, streaked and mottled with green, white, and purple; on cliff faces appear as a single ledge of indefinite extent; in reality composed of even-grained cross-bedded strata 3 to 10 feet or more thick; bedding made irregular by lenses, lumps, and slablike masses of conglomerate composed of limestone, shale, and sandstone fragments, consolidated clay and silt, rare bones and wood. Weathering of the less resistant subordinate beds has produced shallow caves and "owl holes" ---- 65

Chinle formation—*Continued* *Feet*

Zone of unconformity; lenticular aggregates of limestone conglomerate, shale, green clay pellets, subangular grains of quartz, calcite, and dolomite; rare fossil wood and saurian bones; rests unevenly on No. 20 ---- 1–4

Petrified Forest member:

20. Shale; parts of it essentially accumulations of fish and other organic remains. Traced along the strike this bed, together with beds 21 and 19, is seen to occupy a shallow depression ---- 1–7
19. Sandstone, shaly, light red, very fine-grained, thinly, evenly laminated like lacustrine deposits ---- 2–5
18. Shale, brown, red, and purple, argillaceous; includes calcareous and arenaceous beds 8 inches thick in which scales of fish are thickly embedded ---- 1–4
17. Sandstone, alternating red and green white, in part lenticular and platy; weathers into hard slabs ---- 9
16. Sandstone, red; single massive bed; fine-grained except for plasters of gravel ---- 5
15. Sandstone, like No. 16 ---- 28
14. Sandstone, light red, thick-bedded ---- 20
13. Sandstone, reddish brown and green white, in alternating beds 1 to 4 feet thick, inconspicuously subdivided into laminae less than 1 inch thick; irregularly bedded, in part cross-bedded; lime cement; very compact; spalls as micalike chips; includes clay balls and small conglomeratic aggregates of shale, limestone, and sandstone ---- 33
12. Shale, light red, sandy, in part highly calcareous; extremely irregular in bedding; includes thin limestone conglomerates, green mud lumps, and pellets and aggregates of calcite ---- 38
11. Sandstone, red and white streaked; thin irregular beds so tightly compacted as to form a seemingly massive ledge; includes lenses of fully laminated, imbricated, ripple-marked shales ---- 55
10. Shale, light red mottled with white, calcareous, irregularly interbedded with white sandstone; some shale rippled and worm-marked; much of the sandstone has sand-bar structure and includes mud lumps and strings of coarse quartz grains; one hard bed of regularly imbricated sheets like tile roofing ---- 29
9. Sandstone, red striated with green white, thin-bedded, friable ---- 5
8. Shale, variegated red, green, and white; paper-thin, lenticular beds; gypsiferous; crumbles readily ---- 22
7. Sandstone, light red with white band at top, bedded like sand bars ---- 7
6. Shale, light red streaked with white; intertonguing ridges and sheets; fine-grained; resembles consolidated quicksands; masses of sand fill some pockets ---- 35
5. Sandy, banded red (90 percent) and white (10 percent); overlapping, platelike lenses ---- 6
4. Shale, light red, sandy, in beds as thin as cardboard; calcareous cement ---- 20

	Feet
Chinle formation—*Continued*	
Petrified Forest member—*Continued*	
3. Shale, light red, imbricated, irregularly interbedded with six thin sheets of hard gray lenticular sandstone; at the base a half-inch bed of sandy limestone	20
2. Shale, purple red, crisscrossed by seams of white gypsum; in part even-bedded; includes calcareous conglomerates	6
1. Shale, "marls," sandstone, limestone and bentonites, a few knobs exposed on a plain otherwise coated with debris that overlies the Shinarump conglomerate. Thickness estimated	700
Part of Chinle measured	1, 260

This section is probably not far from that measured by Walcott (1879), who first described the "Kanab Valley fish bed." (See p. 72.) Walcott recorded 1,415 feet of strata here classed as Chinle, including 490 feet of sandstone and shale between the fossiliferous shale and the "massive gray sandstone, cross-bedded—310 feet thick" (Wingate sandstone).

9. *Section in Kanab Canyon near the mouth of Cave Lakes Canyon*

	Feet
Navajo sandstone, light red, massive, strongly cross-bedded.	
Kayenta formation:	
15. Sandstone, red brown; a series of lenses of coarse and fine sands that include lenticular aggregates of ferruginous sand; contact with Navajo sandstone marked by abrupt change in sedimentation and by streaks of black and yellow iron and carbonaceous material that suggest decomposition on exposure to weathering	12
14. Sandstone and irregularly bedded shale, red, massive; weathers into curved flakes; shaly parts recessed	12
13. Sandstone, dark brown, flaky, much like No. 14; white band at top	8
12. Limestone, purple brown, white-blotched, arenaceous	1
11. Shale, red, flaky, like parts of No. 14	4
10. Sandstone, red, nodular, and otherwise irregularly bedded, firmly cemented, fairly coarse; forms cliff	4
9. Sandstone, red, coarse and fine, unevenly bedded, hard; weathers as slabs	12
8. Sandstone, red, white-blotched, very calcareous; top spotted with tiny holes that extend downward for a foot or more and suggest worm holes or root marks; forms ledge	2
7. Mudstone, red, much disseminated iron; crumbles to shale slope	14
6. Sandstone, white, red-blotched, very calcareous, hard; forms a ledge	1½
5. Mudstone, in thin lenses and beds that resemble shale flakes	15
4. Mudstone, red brown, indefinite in bedding and in erosion forms; intermingled discontinous beds of sand flakes, of hard limy lumps, and of white sandstone in bands and lenses; all highly calcareous, forms low cliff	28
Kayenta formation—*Continued*	
3. Limestone, white, especially dense, brittle, tends to split in thin chips and flakes	1–1½
2. Limestone, purple brown in paper-thin beds; dense, firm; combines with No. 13 in protecting No. 1 from erosion	0–2
Total Kayenta formation	117
Unconformity (?); contact wavy; sharp change in type of sediments.	
Wingate sandstone:	
1. Sandstone, massive, intricately cross-bedded, kneaded; includes thin, short limestone beds; traversed by joints and faults of few inches to few feet throw; part exposed	80

10. *Section in Kanab Canyon between the mouth of Hog Canyon and the White Cliffs*

[Measured in cooperation with L. F. Noble, in 1922]

	Feet
Navajo sandstone:	
27. Sandstone, white, cross-bedded; forms the White Cliffs; thickness estimated	800
26. Sandstone, orange red, cross-bedded, forming low hills coated with a peculiar orange-red soil (sand) on a bench that extends 8 miles southward from the base of the White Cliffs. About 160 feet from the base a resistant lens of conglomerate 1± feet thick consisting of subangular fragments of blue-gray and purple crystalline limestone averaging half an inch in diameter, calcareous and siliceous clays, in a matrix of fine sand. Contact with No. 25 concealed; thickness estimated	410
Total Navajo sandstone	1, 210
Kayenta formation; alternating beds of red sandstone and red shale forming slopes broken by small cliffs:	
25. Sandstone, irregularly bedded; some beds evenly laminated; others lenticular and gnarly; includes thin lenses of shale and stringers of coarse sandstone	24
24. Shale, fine-grained, soft, sandy; resembles Hermit shale of the Grand Canyon district	12
23. Sandstone, fine-grained, buff, cross-bedded, stained red on surface	2
22. Shale, like unit 24	5
21. Sandstone, like unit 19	1
20. Shale, like unit 24	6
19. Sandstone, massive, irregularly bedded, fine-grained, buff or greenish white on fresh surfaces, but stained red on weathered surfaces	13
18. Shale, like unit 24	12
17. Sandstone, like unit 19	1
16. Shale, like unit 24	9
15. Sandstone, like unit 19	2
14. Shale, like unit 24; rests on uneven surface of unit 13	6
Total Kayenta formation	93
Wingate sandstone:	
13. Sandstone, grayish white, fine-grained, violently and persistently cross-bedded, beautiful tangential cross bedding common; closely resembles the Navajo sandstone in structure, texture, and charac-	

Wingate sandstone—*Continued*	Feet
ter of component materials; some beds weather into pellets; forms cliffs that weather into knobs and pinnacles	290
12. Limestone or highly calcareous fine-grained sandstone; dull yellow and purplish; in places along the strike passes into conglomerate like the "Saurian conglomerate" in the Chinle and the Devonian fish beds in Grand Canyon; gnarly, but not cross-bedded; here and there contains lumps of chert, scattered quartz grains, and fragments of siliceous clay; some of the chert forms hollow ring-shaped masses as much as 3 feet in diameter and includes wormlike aggregates (fresh-water algae?); two irregular beds each about 2 feet thick separated by gnarly red sandstone; forms a wide shelf	4
11. Sandstone, like unit 13	100
10. Sandstone, gnarly, mottled red and white; a curious gnarly bed; appears like partly consolidated sand churned up with an egg beater. Weathers as alcoves under the cliffs of unit 11	12
Total Wingate sandstone	406
Chinle formation; reddish shale and sandstone in alternating beds forming slopes broken by small cliffs:	
9. Sandstone, massive, irregularly bedded, variable along strike; resembles unit 7	13
8. Shale, reddish, sandy; unevenly bedded; near the top beds composed of elongated greenish white mud pellets averaging a quarter of an inch in thickness	23
7. Sandstone, massive, fine-grained, buff or greenish white on fresh surface, but stained red on weathered surfaces; contains lenticular beds of red sandy shale; beds 2 to 4 feet thick, very irregular, wavy, in places gnarly	21
6. Shale, red, sandy, like units 4 and 2; shows greenish streaks and spots and includes considerable slabby sandstone; forms talus of slabs	27
5. Sandstone, like unit 3	6
4. Shale, red, soft, sandy, like unit 2; greenish zones averaging 1 foot in thickness alternate with red zones averaging 3 feet, but neither conform with the bedding; greenish-white spots and streaks common	54
3. Sandstone, fine-grained, cross-bedded, whitish in upper part, reddish below; contains fragments of mud, lenses of arenaceous and calcareous shale, and irregular aggregates of coarse sand; in places weathers into pellets	7
2. Shale, red, fine-grained, soft; resembles Hermit shale of Grand Canyon. Very irregular beds, includes thin hard lenses of red and white sandstones, and of calcareous conglomerates	32
Springdale sandstone member:	
1. Sandstone, thick-bedded, in part cross-bedded, a prominent cliff, not measured.	
Part of Chinle exposed	183

11. *Section in Orderville Canyon*

[Measured by F. W. Christiansen]

Straight Cliffs sandstone: Sandstone, irregularly bedded; ledge maker; medium- to coarse-grained.

Tropic formation:	Feet
31. Covered, sandy slope	317
30. Sandstone, white to cream colored, medium-grained, cross-bedded; steep slope with shelf at top	21
29. Sandstone, thin and thick beds; slope mostly covered	39
28. Shale, dark gray, carbonaceous	2
27. Coal	3
26. Shale and mudstone, blue to gray; fossiliferous, carbonaceous; white fragments of shells strewn over slope	5
25. Sandstone, buff, laminated, medium- to fine-grained	15
24. Sandstone, gray to cream-colored, soft, fine-grained; steep slope covered; no bedding exposed	99
23. Shale, carbonaceous, gypsiferous; interbedded with coal seams; slope partly covered	25
22. Shale and mudstone, gray to nearly black, arenaceous; slopes partly covered	22
21. Shale and mudstone, blue to gray, arenaceous, carbonaceous, gypsiferous; slope mostly covered	428
20. Shale and mudstone, blue to gray, carbonaceous; includes seams of coal; slope mostly covered	16
Total Tropic formation	992
Dakota (?) sandstone:	
19. Conglomerate and coarse sandstone, irregularly bedded, cross-bedded; well-rounded pebbles of black chert, gray quartzite, and brown sandstone; abundant petrified wood	44
Winsor formation:	
18. Sandstone, cream-colored to gray, with bands of red, fine-grained, evenly bedded; grades upward to coarse gray sandstone	68
17. Sandstone, red, fine-grained, very thinly, evenly bedded; few thin lenses of fine conglomerate in which igneous pebbles predominate; steep slope, mostly covered	120
Total Winsor formation	188
Unconformity; uneven surface, abrupt change in composition and bedding.	
Curtis formation:	
16. Limestone, gray, thinly laminated, fossiliferous; shelf maker	3–4
15. Sandstone, light gray, fine-grained, calcareous; interbedded with arenaceous muddy limestone	18
14. Gypsum, white alabaster; ledge maker	30
13. Limestone, gray to cream-colored, thin-bedded	7
Total Curtis formation	59
Entrada sandstone:	
12. Sandstone, red to gray, fine-grained, even-bedded, slightly gypsiferous, very friable; steep slope, mostly covered with fine sand	170

Carmel formation:	Feet
11. Limestone, in three beds, cream colored on weathered surfaces, gray on fresh surfaces, hard, fossiliferous; forms a cliff	10
10. Limestone, gray, muddy, thinly laminated; forms smooth slope	30
9. Limestone, gray, massive, fossiliferous, oolitic, ripple-marked; upper 6 inches mostly fragmentary fossils	9
8. Limestone, blue, gray, and tan on weathered surfaces, thin-bedded; talus slope covered by plates and fragments of hard limestone	52
7. Mudstone, gray to red, calcareous, thinly laminated; slope maker	29
6. Limestone, pink gray, massive; ledge maker	5
5. Mudstone, gray, thinly laminated, crinkly; slope maker	6
4. Shale, calcareous, and compact mudstone irregularly interstratified with white and pink gypsum in beds 1 to 6 inches thick; one short lens of white alabaster nearly 5 feet thick	23
3. Limestone, gray, muddy, thinly laminated; abundant biotite(?) flakes in rock; slope maker	20
2. Limestone, cream-colored and gray, in beds 6 inches to 3 feet thick, ripple-marked, oolitic; many vertical joints	30
1. Sandstone or sandy calcareous shale. Shale red and gray in fairly regular layers, fine-grained, alternately hard and soft. Sandstone red, muddy, fine-grained; grades upward into compact limestone	23
Total Carmel formation	237

Unconformity; eroded surface.
Navajo sandstone; Typical tan, cross-bedded, cliff-making sandstone.

12. *Section in Meadow Creek Canyon, below Highway Bridge*

Dakota (?) sandstone.
Unconformity.

Winsor formation:	Feet
10. Sandstone, upper ⅔ yellow white, lower ⅓ light red banded with white; thin beds, very friable; thickness estimated	240
Curtis formation:	
9. Conglomerate of sandstone, limestone, and shale fragments embedded in coarse lenticular sandstone; varies much in thickness and composition	3–8
Unconformity.	
8. Gypsum, white, lumpy, lower part inconspicuously bedded, otherwise massive. Conspicuous band everywhere within range of vision	30
Total Curtis formation	38

Unconformity: gypsum, mingled with coarse sand; rests on slightly eroded surface of unit 7.

Entrada sandstone:	
7. Sandstone, red and brown, banded with white; most of it in regular beds 1 inch to 3 feet thick; weakly cemented with Gypsum, crumbles easily where not protected by unit 8	220

Carmel formation:	Feet
6. Limestone, blue gray; weathers tan; beds average about 1 foot in thickness; include near top a 6-foot bed; fossiliferous; forms persistent cliff	77
5. Limestone in beds a few inches thick, arenaceous, fossiliferous; forms slope; includes some shaly beds	96
4. Limestone, massive, in three beds; forms cliff	5
3. Limestone, in shalelike beds half an inch to 2 inches thick; regularity of bedding interrupted by lenticular sheets of calcareous sandstone and shale and aggregates of calcite crystals; forms slope	66
2. Limestone, cream-colored, firm, in beds 1 to 4 feet thick, which interleave along the strike; thinner beds brittle, break into hard chips. forms cliffs at waterfalls; thickness estimated	40
1. Shale pellets and red quartz grains in discontinuous patches	1–2
Total Carmel formation	286

Unconformity.
Navajo sandstone, massive, moderately cross-bedded.

13. *Section on a north-south line from the head of Parunuweap Canyon to Muddy Creek*

[Beds 1 to 5 measured by L. F. Noble. Reproduced, slightly revised, from Gregory, H. E., and Moore, R. C., The Kaiparowits region: U.S. Geol. Survey Prof. Paper 164, pp. 73–74, 1931]

Dakota (?) sandstone.
Unconformity; surface of erosion.

Winsor formation:	Feet
26. Sandstone, white, generally fine-grained, evenly bedded; includes overlapping and interleaving thin sheets of hard calcareous sandstone and lenses of green shale, limestone, and concretionary conglomerate; disintegrates readily; a steep slope beneath an overhanging ledge of conglomerate of the Dakota (?); thickness estimated	50
25. Sandstone, banded alternately pale red and white; thin regular beds; fine subangular grains of quartz; rare biotite and magnitite; calcareous cement; weakly consolidated	130
Total Winsor formation	180

Unconformity.

Curtis formation:	
24. Limestone, gray, sandy, oolitic in part, a conglomerate lens more than 30 feet long; fragments of *Trigonia, Ostrea,* and *Dosinia*	⅓
23. Sandstone, banded pale red and white, fine-grained, friable	13
22. Gypsum, white, lumpy; absent 120 feet distant along the strike	3
21. Sandstone, red and green, white-banded; in composition like unit 23	12
20. Gypsum, white green, kneaded into masses like gristle in bacon	16
19. Shale, white, gypsiferous and arenaceous	2
18. Gypsum, white and green, with pink lenses near top; evenly bedded, breaks into sheets about 1 inch thick	4
Total Curtis formation	50

Curtis formation—*Continued* — Feet

17. Unconformity; pockets in eroded surface are filled with gravel that consists of pebbles and fragments of quartz, green mud shale, and red shale.

Entrada sandstone:

16. Sandstone beds 4 inches to 6 feet thick; lower 36 feet alternately banded white and pale red, with some bright-red and green streaks; upper part has yellow cast; many beds very uneven and include thin, short lenses of contorted lumpy calcareous mud, green lime shale, and buff platy limestone; beds crisscrossed with streaks of white; abundantly gypsiferous; very friable; some beds unconformable; at base conglomerate patches of limestone, green shale, and red sandstone — 168

Carmel formation:

15. Limestone, light gray to cream-colored, dense, brittle, hard; lower part in beds 3 to 5 feet thick; upper part splits into slabs 1 to 3 inches thick; topmost bed made porous by removal of clay nodules; foliation surfaces profusely ripple-marked; contains *Trigonia quadrangularis* Hall and Whitfield, *Dosinia jurassica* Whitfield, and undetermined gastropods; forms caps of mesas — 28
14. Shale, gray to buff in paper-thin overlapping beds, calcareous; foliation surfaces smooth and glistening — 10
13. Limestone, cream-colored, dense, hard, siliceous, with thin lenses and seams of chert; breaks with conchoidal fracture — 1½
12. Shale like unit 10; forms slope on all mesas in this vicinity — 35
11. Limestone, buff, earthy, one massive bed; top consists largely of broken shells — 2
10. Shale, calcareous and arenaceous, and thin earthy limestone, gray to cream-colored, flaky, friable, in discontinuous beds; fossils abundant, including *Ostrea strigilecula* White and *Lima occidentalis* Hall and Whitfield — 22
9. Sandstone, gray to buff, very calcareous; top few inches coated with beautifully preserved stem joints of *Pentacrinus asteriscus* Meek and Hayden — 4
8. Shale, buff, calcareous and arenaceous — 12
7. Limestone, hard, platy, in wavy, paper-thin laminae, ripple marks — 5
6. Shale, buff gray, argillaceous, calcareous, and arenaceous; a few beds 1 to 2 feet thick; firm sandy limestone; some beds corrugated — 18
5. Shale and limestone making a steep, ledgy slope:
   - e. Limestone, buff, single massive bed; contains many fragments of small shells — 1–1½
   - d. Shale, buff, sandy — 10
   - c. Limestone, buff, sandy, sparingly fossiliferous — 3
   - b. Shale, buff, sandy — 5
   - a. Sandstone, buff to purple, calcareous, platy; contains several beds made largely of shell fragments — 5
4. Shale, buff, sandy, in paper-thin laminae; contains a few beds of platy calcareous shale — 20

Carmel formation—*Continued* — Feet

3. Limestone, forming cliffs:
   - d. Limestone, sandy, made up almost entirely of small fragments of shell; a very conspicuous fossiliferous bed — ½
   - c. Limestone, cherty, in beds averaging 6 inches thick, alternating with beds of buff arenaceous platy limestone averaging 4 feet thick — 17
   - b. Limestone, buff, in beds about a quarter of an inch thick, mottled with many small masses of white chalcedony or chert, fossiliferous; weathers with a rubbly surface; bedding wavy — 1
   - a. Limestone, buff, dense, crystalline, somewhat arenaceous; breaks with a conchoidal fracture and in outcrops appears massive, forming solid beds 6 to 10 feet in thickness, but weathered exposures show it to consist of laminae less than half an inch thick; basal 5 feet of limestone purplish and more sandy — 17
2. Shale, reddish or purplish, soft, sandy and thinly laminated; lower part kaolinitic; upper part calcareous; along the strike includes beds of brick-red and pink hard shale that breaks into chips; forms a slope — 4–12
1. Sandstone, green white, gray, and pink, in places conglomeratic with red quartz grains, green mud pellets, and shale fragments; along the strike this bed thickens, thins, or disappears — 6

Total Carmel formation — 235

Unconformity.

Navajo sandstone (Temple cap member): White, fine-grained sandstone, cross-bedded on a huge scale.

14. *Section near the mouth of Threemile Hollow, tributary to Kanab Creek*

[Measured in cooperation with Levi F. Noble, in 1922]

Curtis (?) formation: — Feet

9. Conglomerate, calcareous, composed chiefly of fragments of sandstone, shale, and limestone and aggregates of quartz and calcite grains; rare shell fragments; only the basal beds exposed; thickness estimated — 15
8. Gypsum, white, massive, part of it waxy like alabaster; near the base some interbedded thin white, red, and green shales — 28

Total Curtis (?) formation — 43

Unconformity (?).

Entrada (?) sandstone:

7. Sandstone, red, with many white bands, fine-grained, regularly bedded, very friable; nearly pure quartz in round and lentiform grains; gypsum abundant as cement and thin sheets; includes lenses of conglomerate, sand concretions, and hard gray sandstone; weathers as "badlands" — 180

Carmel formation:

6. Limestone, a steep slope with projecting ledges:
   - f. Limestone, massive, dense, hard, gray, crystalline, in beds averaging 18 inches

Carmel formation—*Continued* — *Feet*

thick; fossils (chiefly lamellibranchs) abundant but poorly preserved 9

e. Limestone, gray, in irregular, wavy beds averaging 2 inches thick 13

d. Limestone, gray, thin-bedded, argillaceous, ripple-marked 5

c. Limestone, massive, buff to gray, crystalline, beds range in thickness from a fraction of an inch to 1 foot; fossil *Trigonia, Camptonectes, Ostrea,* and *Pentacrinus* abundant 7

b. Limestone, gray, crystalline, thinly laminated; many thin shaly beds ripple-marked 11

a. Limestone, gray, crystalline, a single resistant bed 1

5. Shale, buff, platy, calcareous and argillaceous; most laminae as thin as cardboard; many corrugated and irregular; in upper part of a few beds of firm limestone 3 to 5 inches thick; much decomposed; forms a slope 80

4. Limestone and calcareous shale; form a series of weak cliffs and gentle slopes:

e. Limestone, gray, massive, in beds 3 inches to 2 feet thick; texture entirely crystalline; rock contains obscure fossils of various species, mostly lamellibranchs 15

d. Shale, greenish, bluish, and buff, calcareous, in wavy laminae as thin as cardboard; forms slope 6

c. Limestone, gray, in wavy, lenticular beds averaging 1 inch in thickness ... 2

b. Shale, calcareous, ripple-marked 4

a. Limestone, gray, massive, crystalline; in beds a few inches to 2 feet thick 5

3. Shale, gray, calcareous; very thinly laminated; ripple-marked; near the base a few thin lenses of limestone conglomerate composed of flattened and subangular pebbles and chips of limestone and siliceous material less than 1 inch in diameter: contains calcite aggregates that may represent fossils; forms a slope ... 37

2. Limestone, hard, massive; beds in upper part a few inches to 4 feet thick, in lower part less than 3 inches thick; somewhat argillaceous; contains fossils poorly preserved; forms a cliff 29

1. Shale, brown, greenish, and buff, soft, sandy; in wavy laminae as thin as cardboard; weathers as a recess alcove under cliffs. Rests on an even surface that truncates the inclined wedges of the underlying sandstone 1

Total Carmel formation 225

Unconformity.

Navajo sandstone; white, fine-grained, cross-bedded on a huge scale.

15. *Section along Meadow Creek (Nos. 1–30) and north of Clear Creek Mountain*

[Dip 1½°. NE. Measured by J. C. Anderson; revised with additions from nearby sections by Herbert E. Gregory]

Wasatch formation.

Unconformity. Contact not exposed; on the slope are pebbles of quartzite, chert, and limestone.

Kaiparowitz formation: — *Feet*

61. Sandstone, gray green, in thin friable, fairly regular beds composed of rounded and angular grains of quartz and some feldspar, gypsum, lime, and clay; includes resistant lenses of black chert pebbles about a quarter of an inch in diameter embedded in clear quartz sand; a little feldspar and gypsum; at the top three ledges of hard sandstone specked buff and black; talus-covered slope terminating in a cliff 86

60. Sandstone, buff red, in beds 1 to 4 feet thick; some soft, weakly cemented by lime; others hard, firmly cemented by iron; at the top a lens 6 feet thick of almost pure iron; bedding wavy; fossil bones and wood and some black chert nodules 46

59. Sandstone, gray green speckled black and white with chert and feldspar; soft, coarse, 12 feet; gray shale, 20 feet; platy black iron-cemented "pepper and salt" sandstone in beds 1 to 4 inches thick, 10 feet 42

58. Shale, gray, very sandy in places; capped by 8 feet of hard clinkery sandstone 48

57. Sandstone, buff, medium- and fine-grained, iron-cemented; grades into black and white speckled material in wavy beds 26

56. Sandstone, speckled white and black; thin layers, separated by shale 49

55. Sandstone, thin beds alternating with fine-grained impure grit; uneven beds; fossil bones, coiled gastropods near the top 108

54. Sandstone, yellow, brown, and dark gray; regularly bedded; sandy gray shale disposed as lenses; includes banded and concretionary masses of ironstone, limestone, and barite and chunks of hardened clay; forms slope broken by benches 147

53. Sandstone, dark gray, blotched with brown, red, and yellow; forms thin ledges on a slope of extremely friable shalelike beds that includes bits of weathered feldspar, limonite, calcite, and gypsum, ironstone nodules, calcareous concretions, and fragmentary shells, mostly unios; slope thickly coated with talus 60

52. Sandstone, brown, of fine well-rounded grains of clear quartz firmly cemented by iron 24

51 (field unit 33). Sandstone, light gray, some of it nearly white, stained yellow by iron and dotted with minute black and white grains (chert ? and feldspar ?); upper part includes many thin shaly beds 40

Total Kaiparowits formation 676

Straight Cliffs and Wahweap sandstones undifferentiated:

50. Sandstone and shale, fine-grained, in thin, regularly alternating layers 44

49. Sandstone, brown, dense, fine-grained, concretionary, cross-bedded and massive; small round concretions of lime and sand weather out into balls, peanuts, and other odd shapes, arranged in zigzag fashion; iron concretions near the top 28

48. Sandstone, soft, coarse, peppery; grains angular, composed chiefly of white, black, and brown quartz; includes cherty nodules; layers gray shale at the top and bottom 31

Straight Cliffs and Wahweap sandstones undifferentiated—*Continued*	Feet
47 (field unit 30). Sandstone, buff with a very white band 5 feet thick about 75 feet from base; medium- and fine-grained; indurated shale, irregularly bedded peppery sandstone, and concretionary iron about 40 feet from base; some leaf casts and carbon fragments; oyster casts and other fossils in uppermost 20 feet	98
46. Shale, gray, and three thin sandstone layers	30
45. Sandstone, buff, medium-grained, calcareous; 2 feet of carbonaceous shale about halfway up; forms heavy ledge	84
44. Sandstone, fine-grained, angular, in puckered or undulating beds, strongly cross-bedded; gray shale, coarse, gritty, at bottom and top	39
43. Sandstone, coarse, thick-bedded and shale, thin-bedded, sandy; toward middle sand becomes conglomeratic with a mixture of white, gray, black, and brown banded pebbles, one-sixteenth to one-half inch in diameter, embedded in impure sandstone; pellets of gray-green shale and concretionary limestone; a few fossil shells; 30 feet from the top a conglomerate of small poorly rounded pebbles rests in pockets worn into thin gritty blue shale; beds change radically within a few feet	118
42. Shale and sandstone, alternating thin layers; four low ledges; slope largely covered	146
41. Shale, gray, sandy, capped by a 6-foot ledge of hard iron-cemented quartz sandstone	26
40. Sandstone, buff, cross-bedded, medium- to fine-grained; lenses of sandy shale; weathers into long slope	60
39. Shale and thin lenses of sandstone	13
38. Sandstone, buff, platy beds, peppered with iron rust	48
37. Shale, blue, gray, to lilac	18
36. Sandstone, buff, in massive medium-grained grained beds and evenly stratified fine-grained beds 4 to 8 feet thick; blue-gray and reddish shale in regular beds as much as 200 feet long and in lenticular masses serves to break the steep slope into benches	67
35. Sandstone, coarse-grained, platy beds 1 to 2 inches thick; thin shaly beds at the top	25
34. Shale, light lavender; cement, iron and lime	15
33. Sandstone, cross-bedded; very coarse- to medium-grained beds 5 to 30 feet thick; includes conglomeratic masses and scattered pebbles one-sixteenth to three-quarters inch in diameter; a few lenses of blue shale; weathers in alternate hard and soft layers; grades upward into unit 34	150
32. Shale, white, blue, lilac, and gray; calcareous and sandy	12
31. Sandstone and conglomerate, buff on weathered surfaces, cross-bedded; coarse, angular grains, chiefly of quartz and chert one-eighth to one-quarter inch in diameter, cemented by lime; a single bed 24 feet thick; just above the thick bed is 2 feet of fine-grained sandstone tightly cemented by iron and lime; just below is 3 feet of blue-gray calcareous and slightly carbonaceous shale	37
30. Sandstone, buff on weathered surface, gray on fresh fractures, massive, coarse, angular, slightly worn grains, mostly clear quartz; some pebbles as much as a quarter of an inch in diameter; lime-cemented; some small black grains of chert and rare feldspar; a prominent ledge	12
29. Shale, blue, argillaceous, sandy	4
28. Sandstone, buff, speckled with grains of iron	18
27. Shale, black, fossiliferous; some earthy lignite	5
26. Sandstone, cross-bedded in sets of regular layers in wedges	42
25. Sandstone, even-bedded, very fine and hard; numerous iron specks; includes a lenticular bed 8 feet thick of broken shells mostly of oysters, embedded in sand and clay; a cliff of beds 6 to 40 feet thick	134
24. Sandstone, gray, very fine-grained, massive, fossiliferous; many specks of oxidized iron	12
23. Shale, blue gray, very soft; makes small shelf on cliff	6
22 (field unit 10). Sandstone, buff on exposed surface, gray underneath; fine quartz grains; *Ostrea solenensis*, *Admetopsis*, *Anonia*, and other fossil shells scattered throughout; numerous roughly lenticular layers of very hard silica-cemented sandstone weather as blocklike shelves; forms a cliff continuous for about a mile	84
Total Straight Cliffs and Wahweap sandstones	1,406

Tropic formation:	Feet
21. Shale, grayish blue, argillaceous, calcareous, slightly carbonaceous; includes a few thin platy layers of sandstone, one of them, 260 feet from top, highly gypsiferous; many mushroom calcareous, fossiliferous concretions near the base and iron concretions near the top; the uppermost 13 feet chiefly of blue shale eroded into channels filled with fossiliferous sands of unit 22; ends abruptly at base of ledge; a steep slope, broken by low discontinuous benches	573
20. Sand, buff, in thin irregular beds; small amount of gray shale; slope largely covered by débris	90
19. Sandstone, buff, yellow gray; beds 2 to 20 feet thick, very irregular in composition, texture, and length, in part cross-bedded; includes wedgelike masses of conglomerate with pebbles of quartz and quartzite, one-eighth to one-quarter inch in diameter, sand and clay aggregates, fragmentary shells, and lenses of calcareous and iron-stained shale	138
18. Covered slope	42
17. Gray gritty shale	10
16. Sandstone, buff, fine-grained, massive	4
15. Shale, brown, generally sandy, calcareous, irregularly bedded	18
14. Shale, gray, sandy, carbonaceous, argillaceous; thin seams of coal, good quality	6
13. Shale, brown, interbedded with layers of hard, lime-cemented sandstone 2 to 4 inches thick; coal, earthy, gypsiferous; at the bottom 2 feet of drab argillaceous shale	14
12. Sandstone, like unit 5	42

Tropic formation—*Continued*

	Feet
11. Lignite, brown; layers of macerated leaves and twigs mingled with sand and mud	3
10. Sandstone or grit, dirty gray; thin, markedly lenticular beds which overlap or merge with sandy shale of various composition; fine rounded grains (about 30 percent), medium and coarse angular grains of quartz; rare carbonaceous and calcareous shale and fragments of carbonized wood; a slope broken by poorly defined ledges	210
9. Shale, blue, sandy; some lenticles of clay and lime concretions	4
8. Sandstone, gray, buff, fine-grained, in thick massive beds; some cross bedding near top	20
7. Shale, blue, gray, and black; includes bed 1 foot thick of good coal, which breaks into cubes with bright conchoidal fracture	14
6. Sandstone, buff, very fine-grained, well laminated	6
5. Sandstone, buff, very fine-grained, irregularly bedded; capped by a bed 10 inches thick of hard iron-cemented sandstone	24
4. Shale, carbonaceous, gypsiferous, irregularly interbedded with coal; much of the coal earthy in thin beds, some of it of good quality and thick enough to mine; friable; outcrop poorly exposed; rests unconformably on unit 3 and grades into unit 5	30
Total Tropic formation	1,248

Dakota (?) sandstone:

	Feet
3. Shale, gray, gritty; a few thin lenses of conglomerate in the middle and at the top; grains visible are all pure quartz	18
2. Sandstone, white, coarse, angular and subangular; a few grains of white quartz, quartzite, and black chert	4
1a. Sandstone and conglomerate in alternating beds, cross-bedded, lenticular; at the top a 10 inch layer of jet black shale	10
1. Conglomerate and sandstone in overlapping and interfingering wedges; pebbles of quartz, quartzite, ironstone, limestone, clay, and fossil wood a quarter of an inch to 10 inches in diameter; very friable in the ledges; weathers to gravel	6
Total Dakota (?) sandstone	38

Unconformity.

Winsor formation, white, fine-grained, evenly stratified quartz sand.

16. *Section from Flume Canyon ("Dry Wash"), 3 miles northeast of Glendale, northward 10 miles across the head of Parunuweap Valley*

[Dip 2° NE. Measured by F. W. Christiansen; revised with additions by Herbert E. Gregory]

Tertiary:

Wasatch formation:

	Feet
Limestone, calcareous sandstone, and conglomerates of various composition and color. In this locality the usual high wall of the Pink Cliffs has been removed by erosion.	
66. Limestone, pink to gray, massive, crystalline near base	12
65. Conglomerate, essentially cross-bedded calcareous sandstone in which are embedded small well-rounded pebbles of quartzite and hard sandstone; forms a cliff	8
64. Sandstone, pink to gray, calcareous, irregularly bedded, includes lenses of massive limestone and conglomerate; weathers to talus-covered slope	54
63. Conglomerate, gray except where stained with red mud from the rocks above; composed of fairly well-rounded pebbles one-sixteenth to three-quarters inch in diameter, chiefly gray and brown hard sandstone, black chert, quartzite, and quartz embedded in a calcareous sand; a lens about 200 feet long between beds of finer-grained sandstone	3–10
62. Sandstone, gray pink, calcareous, cross-bedded and irregularly coarse at base, passing upward to even-bedded fine-grained rock; contains isolated pebbles of quartzite and fossil *Physa* and *Planorbis?*	22
61. Conglomerate, composed chiefly of smooth well-rounded pebbles of red, gray, and black massive and banded quartzite, black chert, quartz, and limestone, ranging from a quarter of an inch to 8 inches in diameter, embedded in sand and weakly cemented by lime	2–5
Total Wasatch formation measured	111

Unconformity; a deeply eroded surface.

Cretaceous:

Kaiparowits formation:

	Feet
60. Sandstone, dark gray, yellow green, generally massive, cross-bedded, and uniform in texture; most grains fairly well rounded; the upper part consists of coarse spherical and subangular grains of glistening white quartz (65 percent), iron-stained black and brown grains (30 percent), and small amounts of feldspar and clay; near the top are long lenses of concretionary, conglomeratic ironstone separated from each other by friable cross-bedded fine-grained sandstone; isolated iron nodules are common; friable; weathers as sand-coated slope	39
59. Sandstone, nearly white; grains of medium size, fairly well sorted, most of them somewhat angular, fully 70 percent pure quartz; cement chiefly lime; interbedded with the generally friable white rock are thin layers of yellow sandstone cemented with limonite and so resistant as to form ledges on an otherwise even steep slope	38
57–58. Sandstone, buff, massive, medium-grained; fairly well sorted and rounded; at its base a lenticular layer of concretionary ironstone, nearly 2 feet thick	8–10
56. Sandstone, dark gray, generally massive and cross-bedded; grains well sorted and rounded; about 85 percent are white, pure quartz, 10 percent brown iron-stained, and 5 percent black; many lenses of conglomerate composed largely	

Cretaceous—*Continued* | Feet

Kaiparowits formation—*Continued*

of angular fragments of very fine-grained hard sandstone as much as 3 inches in diameter and smaller rounded pebbles of ironstone, white clay, and calcareous mud; includes a layer, 1 foot thick, of blue-white dense nodular sandy limestone; also concretionary masses of iron, some feldspar, gypsum crystals, and fragments of wood and bone (dinosaur?). Forms a cliff capped with a layer of nearly black resistant iron-cemented sandstone ---------------------------- 92

55. Sandstone, dark gray, stratified in alternately thick and thin, hard and soft, medium-grained layers; generally cross-bedded; grains fairly well rounded and sorted. Forms a slope --------------- 55
54. Sandstone, light gray, massive, composed largely of poorly sorted, fairly well rounded grains of pure quartz, iron, and rarely feldspar; cemented with limonite --------------------------- 15
53. Sandstone, massive, cross-bedded; medium-sized grains tightly cemented with lime; about 50 percent of the grains are gray, 25 percent brown, 13 percent white, and 12 percent black. Forms a cliff ---------------------------------- 9
52. Slope thickly covered with fine sand grains and fragments of concretionary ironstone ------------------------------- 96
51. Sandstone, dark gray, hard, massive; grains fine, well sorted and rounded--- 11
50. Slope covered -------------------------- 69
49. Sandstone, thin, dark-gray, soft, fine-grained layers, unevenly interstratified with layers of red, hard, iron-cemented layers composed of coarse, poorly sorted, subangular grains of white quartz and black ferruginous material ---------- 33
48. Shale and sandstone, irregularly interstratified. Shale nearly white, sandy, very soft, calcareous; contains fossil shells (*Unio*, *Viviparus?*) and wood. Sandstone yellow to buff, in beds 1 to 3 feet thick; topmost beds of fine, round grains, evenly stratified; lower half medium-grained, poorly rounded and sorted; beds are prominent on weathered slopes --------------------------- 91
47. Sandstone, brown to yellow, massive, cross-bedded on small scale; grains medium, fairly well rounded and sorted, 90 percent of grains clear white quartz, 10 percent black and brown; includes thin, short, hard, lenticular conglomerate layers composed of light-colored angular fragments of sandstone; fractures in the massive sandstone filled with calcite. Forms a cliff continuous for at least half a mile ---------------------------- 18
46. Sandstone; a series of soft shalelike beds composed chiefly of subangular, poorly sorted quartz grains; much of the sandstone is porous; a slope capped with hard, iron-cemented, ledge-making bed; outcrop not well exposed ------------- 39
45. Shale or thin, soft, irregularly bedded sandstone; well rounded and sorted; lime cement; among the grains are much decomposed calcite, some feldspar, gypsum, and other material; includes fragmentary shells; friable rock, protected from erosion by a 3-foot cap of hard buff iron-cemented sandstone; grains fine. Largely concealed -------------- 18
44. Sandstone, buff, massive, cross-bedded, soft; weakly cemented with lime; grains fairly well sorted and rounded; very porous; about 65 percent of the grains are pure quartz, 30 percent stained by iron oxide, 5 percent black and brown-- 39
43. Sandstone; at the base an 8-foot massive bed of fine-grained friable brown sandstone, strongly cross-bedded and composed of poorly sorted subangular grains; next above, 15 feet of white to brown-yellow soft shalelike beds; at the top 5 feet of dark-gray cross-bedded medium-grained sandstone, stained with limonite. Form a slope -------------- 28
42. Sandstone, yellow to cream-colored; very friable, grains fairly well rounded and uniform in size; cross-bedded; includes lenses composed of angular fragments of sandstone, clay, and concretionary cherty limestone, thin lenses of conglomerate and short, thin beds of dark-gray well-cemented sandstone; topmost 8 feet a massive layer of tan to yellow, fairly coarse sandstone in which the grains are not well sorted or rounded and in which most of them are stained with iron oxides --------------------- 35
41. Conglomerates; well-rounded pebbles, a quarter of an inch to 2 inches in diameter, of quartz, chert, fine-grained sandstone, quartzite, clay nodules, and concretionary limestone; includes very soft, friable lenses of coarse and fine sandstone in which the grains are well sorted, about 90 percent of them brown, light yellow, and white quartz. Form low rugged cliff ------------------------ 2–8

Total Kaiparowits formation ----- 743

Unconformity; maturely eroded surface.

Straight Cliffs and Wahweap sandstones undifferentiated:

40. Shale, lavender to gray; arenaceous, more massive than laminated; generally friable but includes lenses of yellow thin sandy shale, resistant enough to form ledges; upper 38 feet covered with sandstone boulders ---------------------- 72
39. Sandstone, buff, massive, evenly stratified toward the base, irregularly bedded and cross-bedded above; relatively soft; composed of angular grains, fairly well sorted; cement lime and iron; about 40 percent pure quartz angular grains; 25 percent iron and other black and brown grains and 35 percent material too fine to analyze; numerous spots of white soft material (kaolin?); weathers into knobs and cavities of various shapes -------- 25

Cretaceous—*Continued*

Straight Cliffs and Wahweap sandstones undifferentiated—*Continued* — Feet

38. Shale and thin impure sandstone, lavender to blue gray; evenly stratified; includes sheets of pure quartz sandstone; slope, partly covered ---------------------- 45
37. Sandstone and sandy shale, yellow to dark gray; the lower part in layers 1 to 12 inches thick, fairly resistant; most of the grains coated by brown iron oxides; many beds in the upper part are thin and friable, some well laminated and grade into more massive beds composed of coarse well-sorted subangular quartz grains and including scattered fragments of clay, hard sandstone, and limestone; the topmost bed, 4 feet thick, is hard well-cemented sandstone of angular grains, 65 percent of them clear quartz and much of the remainder quartz stained black and brown; calcite and decomposed feldspar mingled with the dark grains give a salt-and-pepper appearance; the fractures are filled with calcite; form broken slope ----------- 73
36. Sandstone or mudstone, generally light gray, soft; includes concretions of hard, iron-cemented fine-grained sandstone; grains in much of the rock too small to be identified; in the yellow and brown beds they are obscured by iron stain; those in the coarser parts unassorted and angular, 75 percent gray quartz, 15 percent decomposed material and black grains, and 10 percent black iron grains; distributed through the mass are thin lenses of subangular pebbles about half an inch in diameter; broken slope, partly exposed ----------------------------- 57
35. Shale and sandstone; basal beds of drab, finely laminated arenaceous shale, grade upward into blue-gray to yellow massive soft fine-grained sandstone; and in individual beds fine-grained sandstone grades vertically and laterally into well-stratified coarse-grained sandstone with poorly rounded, sorted grains; forms a slope -------------------------------- 22
34. Sandstone, buff, light gray; massive; lower part cross-bedded and upper part stratified; ranges vertically and laterally from a uniformly fine-grained sandstone to a coarse-grained or even conglomeratic rock, roughly bedded and composed of poorly sorted and rounded grains; on weathered surface concretionary masses and lenses of iron-stained sandstone stand in relief; iron and limestone nodules and masses of angular sandstone fragments are common. A prominent cliff capped by a 10-inch layer of resistant iron-cemented sandstone ------ 41
33. Sandstone, buff, interbedded with blue to gray friable sandy calcareous mud. Sandstone near the base is roughly bedded, cross-bedded, and composed of coarse, slightly sorted, subangular grains of light-gray, brown, and black quartz and includes stringers of nearly black carbonaceous shale; the upper sandstone forms a series of overlapping lenses, coarse, fine, and conglomeratic, which contain iron concretions, mud balls, and slabs of sandstone and shale. Shale thin-bedded, in groups 3 to 4 feet thick; calcareous, argillaceous, and carbonaceous but contains much sand; the rock weathers into irregular grooves and rounded knobs on the face of a cliff- 35
32. Sandstone, buff, slightly cross-bedded, relatively soft, porous; coarse and fine grains not well sorted or rounded; loosely compacted; 75 percent of white quartz grains, 20 percent brown or yellow, 5 percent black or dark gray; forms a cliff ------------------------------ 18
31. Sandstone, buff; a series of thick, poorly stratified, in part cross-bedded lenses, coarse-grained, fine-grained, and conglomeratic; grains not well sorted or rounded; conglomerate composed of rounded and angular pebbles of chert, quartz, quartzite, and sandstone, averaging about 1 inch in diameter; nodules of ironstone project from ledge; patches of iron-stained sandstone and pieces of black charcoal are common; grades laterally into regularly bedded massive sandstone; forms ledges ------------- 38
30. Coal, earthy, interbedded with black sandy shale ----------------------------- 8
29. Shale, gray buff, sandy, carbonaceous, calcareous, irregularly interbedded with fine-grained fossiliferous sandstone; includes a lenticular bed of hard limestone 18 inches thick, packed with gastropod and pelecypod shells ---------------- 12

27–28. Shale, dark, carbonaceous, and coal, interbedded with thinly laminated sandy shale; slope largely covered ---------- 28

26. Sandstone, massive, thick-bedded; medium grains, not well sorted or rounded; in large part evenly stratified; little cross bedding; includes several groups of thin resistant layers, tightly cemented with lime. A series of superposed strong cliffs between narrow platforms; weathers into arches, caves, and "owl holes" ---- 213
25. Sandstone, buff, fine-grained, thinly laminated; includes lenses of coarse sandstone, containing pebbles of chert and quartz; and of sandy shale 1 to 3 inches thick ----------------------------- 13
24. Sandstone, yellow gray, fine-grained, evenly laminated, loosely consolidated; includes beds of carbonaceous shale and some coal ------------------------- 6
23. Shale, gray, sandy; grains not well rounded or sorted; many disseminated specks of organic matter ------------- 4
22. Sandstone, brown, medium-grained, massive ------------------------------- 3
21. Shale, sandy and calcareous, with thin layers of interstratified sandstone;

Cretaceous—*Continued*

Straight Cliffs and Wahweap sandstones undifferentiated—*Continued*

	Feet
grains of uniform size, fairly well rounded and sorted	12
20. Slope covered	15
19. Conglomerate, a local lens of well-rounded pebbles, a quarter of an inch to 2 inches in diameter, of black chert, brown, red, and gray quartzite, white quartz, and brown sandstone	2–6
Total Straight Cliffs and Wahweap sandstones	746

Tropic formation:

	Feet
18. Shale, drab, calcareous and argillaceous; thin beds of gray sandstone, numerous in upper part	43
17. Shale and sandstone interbedded; sandstone dense, fine-grained, in beds 1 inch to several feet thick; shale blue gray, arenaceous, calcareous, and carbonaceous. Forms a broken slope	34
16. Sandstone, drab gray, very fine, well-rounded grains, massive, friable; no surface indication of stratification. A ledge	14
15. Shale, mudstone, and sandstone. Shale drab, sandy, argillaceous and carbonaceous in uneven layers, stratified with finely laminated clay mudstone. Sandstone yellow to gray, in beds 1 to 12 inches thick; the thicker layers not so finely laminated as the thinner layers, which are evenly laminated and composed of fine, fairly well sorted and rounded gray and black grains and which have the appearance of a mixture of salt and pepper; the thicker, more massive beds, light brown, are roughly laminated, somewhat porous, and consist of small round grains of uniform size, many of them coated with iron. An irregular slope	85
14. Shale and mudstone, interbedded with sandstone. Shale sandy, calcareous, in layers less than a quarter of an inch thick, minutely laminated, in part concretionary, interstratified with sandstones 1 to 12 inches thick, assorted into round fine and medium-sized grains; the larger grains are subangular and include pellets of dark mud. Mudstone is a blue-gray compact mass of argillaceous calcareous materials that show irregular conchoidal fractures and break off in concentric egglike masses. A fairly smooth slope	83

Cretaceous—*Continued*

Tropic formation—*Continued*

	Feet
13. Shale or mudstone, blue to gray, interbedded with layers of fine-grained well-cemented sandstone in layers about 12 inches thick	8
12. Coal, in lenses 1 to 10 feet thick, irregularly interbedded with sandy gypsiferous shale and friable fine-grained sandstone	12
11. Sandstone, light buff, lenticularly interbedded with fossiliferous shale and seams of impure coal; the shale contains concretionary boulders of limestone, some of them crushed; fractures are filled with calcite and gypsum	13
10. Sandstone, buff, thinly laminated; irregular layers of medium-sized, well-sorted and rounded quartz grains; includes some soft shalelike material	6
9. Shale, dark, arenaceous, calcareous, and carbonaceous, compact, interbedded with layers of fine-grained sandstone; contains small lenses of soft gypsiferous sandstone and scattered clay pellets	24
8. Sandstone, cross-bedded, friable; irregular beds of medium-sized well-rounded quartz grains	3
7. Shale, brown to black, thinly laminated, arenaceous, lenticular, and carbonaceous	2–3
6. Sandstone, buff to cream, cross-bedded; composed of spherical, glistening white quartz grains and a few black carbonaceous grains; friable; porous. Forms a cliff	38
5. Shale, dark gray to black, carbonaceous, gypsiferous	13
4. Coal, earthy, grading above and below into dark argillaceous and calcareous shale	3–6
3. Shale, gray to black; carbonaceous and calcareous; gypsum crystals strewn over the surface. Lies unevenly on No. 2	3–4
Total Tropic formation	389

Dakota (?) sandstone:

	Feet
1–2. Conglomerate; well-rounded, polished pebbles of quartzite, quartz, chert, and dense sandstone, half an inch to 4 inches in diameter; includes petrified wood in chips and logs as much as 3 feet in diameter and 6 feet long; aggregates of limonite and bright-yellow lenses of coarse sandstone are conspicuous in the generally dark-brown and gray rock; poorly consolidated; weathers to slope	5–14

Cretaceous or Jurassic:

Winsor formation: Sandstone, tan to white, evenly bedded, friable.

IGNEOUS ROCKS

GENERAL FEATURES AND RELATIONS

In the Zion Park region extrusive igneous rocks are represented by volcanic cones and by streams and patches of lava; the intrusives by a few dikes. Most of the exposures are topographically prominent and readily accessible. Along the approach road to Zion Park through Virgin the lavas in North Creek, Dalton Wash, and Coalpits Wash are in plain sight. The road from Hurricane to Short Creek follows a lava flow for 3 miles and passes the volcanic Gray Knoll, and the branch road to Antelope Springs follows and crosses flows and a dike and brings into view the conspicuous lava-capped mesas that overlook the Hurricane Cliffs. Lava appears as patches on the west wall in the Parunuweap Valley and as sheets on the east wall above Hidden Lake, while at Lava Narrows it forms both walls. In Kanab Valley the highway from Glendale to Skutumpah crosses a lava flow and on the Kolob Plateau such craters as Firepit Knoll and Spendlove Knoll are as prominent as the buttes and walls made of Navajo sandstone.

Along the western and southern borders of the Zion Park region igneous rocks are likewise common. Thick sheets of trachyte porphyry (?) form the top of Pine Valley Mountain, and basalt flows heading in well-defined cones are prominent features in the topography about Toquerville, Hurricane, St. George, and Santa Clara. (See fig. 13.) On the Uinkaret Plateau Mount Trumbull and its scores of associated cones and flows form a volcanic area comparable in dimensions with the San Francisco Mountains, south of the Grand Canyon. East of the Zion Park region no lavas and only two dikes have been mapped between Johnson Canyon and the Colorado River.

As features in the topography the cones and flows are distributed in seemingly haphazard fashion. They lie on plateau and mesa tops, on slopes, and in valley bottoms and are bordered by rocks of Triassic, Jurassic, and Cretaceous age. They also seem to be unrelated to tectonic structures. The distribution of the cones and flows as recorded in recent mapping gives little support to the statements of Dutton[13]:

> It is a notable fact that by far the greater portion of them occur upon the uplifted side of this great displacement [Hurricane fault]; * * * indeed, those upon the thrown side are comparatively trivial. * * * [This arrangement] is, moreover, so strongly emphasized, that it suggests the possibility of a correlation between the basaltic eruptions and the greater upward displacements.

In the Zion Park region, on the upthrown side of the Hurricane fault, the flows from existing cones and those from sources not determined are no greater in mass or in number than those in Ash Creek, Virgin, and Santa Clara Valleys, on the downthrown side.

In a broad sense the Zion Park region is a volcanic province distinct from central Utah. North of the Markagunt Plateau most of the volcanic cones have lost their initial forms, many have completely vanished, and few of the sheet lavas are recognizable as flows from known sources. Generally in central Utah the craters and flows are old enough to have been features in the topography when the plateau lands were raised to their present position and the present cycle of erosion began. South of the Markagunt the cones and their summit craters retain much of their original form, and the streams of lava are clearly defined. They were poured out on surfaces essentially like those of today; in fact, their form and position have been determined by the present topography. On the flat lands of Kolob Plateau and Little Creek Mountain broad, thick flows lie near their source; in Little Creek, North Creek, Parunuweap, Kanab, and Johnson Valleys thin, narrow flows follow the stream beds for several miles. Regional differences are also expressed in the composition of the lavas. In central Utah the dominant and for large areas the only volcanic rocks are reported by Dutton as "rhyolite" and "trachyte", and by Callaghan[14] as "latite and rhyolite". South of the Markagunt plateau all the lavas examined are basalts—most of them olivine basalts.

In the absence of stratigraphic time markers more recent than the Wasatch formation (Eocene), the geologic date of the volcanic eruptions in the Zion Park region is known only with reference to tectonic movements and physiographic cycles, and these have no recognized place in Miocene, Pliocene, Pleistocene, and Recent epochs.

Dutton treated the basalts of the Markagunt Plateau and adjoining regions as marking the last of five periods of eruption that began with the Eocene. Like Howell, Gilbert, and Holmes he stressed the recency of the cones and flows about Hurricane and St. George, and on the Uinkaret Plateau. Huntington and Goldthwait[15] concluded that the oldest lavas along the Hurricane fault date from Eocene or early Miocene time, "when as yet erosion had made no noticeable impression upon the strata of our area and perhaps even while they were still under water * * *"; and that later lavas were extruded at various times during the "interfault cycle" that preceded the most recent faulting.

Obviously no great length of time has elapsed since volcanism was last active. Most of the cones, though scored by tiny rills and superficially weathered, have the slopes normal for materials near vents—slopes that terminate in craters strewn with bombs and blocks. Many of the lava flows likewise are remarkably fresh—they retain their slaggy surfaces and tubes, their local mounds produced by gas expansion, and their division into streams where the underlying surface is irregular. The flows in Little Creek Valley, in Kanab Canyon, and on the Kolob Terrace are so like those from volcanoes now active that it is difficult to think of them as more than a few centuries old. On the other hand, the Parunuweap at Lava Narrows, Little Creek at Gould Spring and Gray Knoll, and North Creek above Mountain Dell have cut deep trenches through the latest flows, and in many places erosion has left patches of lava high on valley walls. Kanab Creek, blocked by lavas from Corral Knoll, has cut a deep new channel around the edge of the flows.

The existing cones are believed to be of about the same age and their unequal erosion to be due to different rates of weathering resulting from different local climates and different topographic positions, which determine differences in strength of eroding streams. There is evidence, however, that from vents in the position of present cones lava emerged at more than one time and that still earlier lavas came from

[13] Dutton, C. E., Geology of the High Plateaus of Utah, p. 202, U. S. Geog. and Geol. Survey Rocky Mtn. Region 1880.

[14] Callaghan, Eugene, Preliminary report on the alunite deposits of the Marysville region, Utah: U. S. Geol. Survey Bull. 886, pp. 149–159, 1938.

[15] Huntington, Ellsworth, and Goldthwait, J. W., The Hurricane fault in the Toquerville district, Utah: Harvard Coll. Mus. Comp. Zoology Bull., vol. 41, pp. 217–218, 1904.

vents not now known. Thus the gravel deposits and assemblages of boulders that underlie several of the flows and include basalt and ash like those in the present cones and also igneous material of different composition are records of ancient eruptions. The weathered lavas that form the top of Sugar Loaf and other high mesas south of Hurricane are clearly older than the remarkably fresh rocks at Rattlesnake Spring in nearby Little Creek Valley, 600 feet below, and a dike, near Alton on the floor of Kanab Valley, doubtless gave rise to flows now entirely erased by erosion. Also, the volcanic ash embedded in the Wasatch formation must have come from vents that long predated those giving rise to the lavas on its maturely eroded surface.

The oldest lavas were contemporary with or even earlier than the earliest regional faulting, and some of the later lavas, perhaps most of them, were poured out before the latest faulting occurred.

The lava cap of Sugar Loaf and of adjoining mesas is believed to be part of the extensive sheet that now lies at the base of the Hurricane Cliffs, some 1,500 feet below. Thus since this sheet was poured out from some source not now exposed it has been faulted, and the part on the upthrown block has been almost entirely destroyed by erosion, which has isolated the remnants and also removed some 600 feet of Moenkopi strata about their base. At La Verkin Hot Springs a sheet covers an old fault and is broken by one of later age. In Sunset Cliffs north of the mapped area fresh-looking lava has been fractured by a late movement along the Sevier fault and on Kolob Terrace by local faults of small displacement.

It seems interesting to note that four meteorites weighing 2 to 8 pounds each were found on bare-rock surfaces of Moccasin and Wygaret Terraces and considerable meteorite dust in the stream sands. One fragment analyzed by Prof. S. S. Ballard, of the University of Hawaii, contains iron, 90± percent, silicon 8+ percent, nickel 1± percent, and traces of copper, manganese, calcium, magnesium, cobalt, zinc, sodium, molybdenum, and barium.

During the present survey the igneous rocks in the Zion Park region were not studied in detail. Only their distribution and their outstanding characteristics are here recorded.

VOLCANIC AREAS

HURRICANE CLIFFS

Along the Hurricane Cliffs remnant lava flows from the topmost rocks east of Midway and Pintura, at Toquerville, and at the mouth of Timpoweap Canyon, and cap five mesas south of Hurricane. At the west base of the cliffs they are almost continuously exposed in the valley of Ash Creek and southward across the Virgin River. The flows north of Little Creek Canyon appear to be edges of sheets of lava that had their source in regions west of the Hurricane Cliffs and owe their position to the faulting that initiated the escarpment. They are not closely associated with cones, and the position of their feeding dikes is unknown. They appear to be all of the same age and to have the same relation to the sedimentary beds below. The lavas that now form the tops of Sugar Loaf, Three Brothers, White Face, and "The Wart," south of Little Creek, have a less simple history. Though probably from the same source, they are parts of at least two flows, rest on beds of different age, and differ in composition. (See figs. 70, 71.)

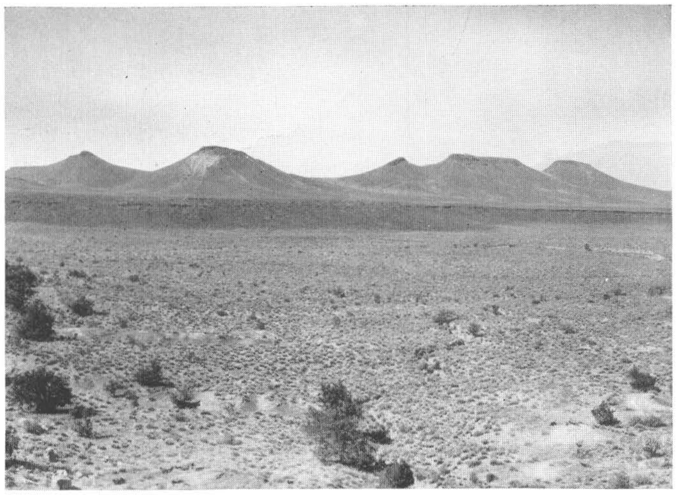

FIGURE 70.—Lava-capped mesas near crest of Hurricane Cliffs south of Gould Canyon. View west from Workman Wash. More recent lava flows in middle distance. Beds of middle Moenkopi form mesas and underlie alluvium in foreground. (See fig. 71.)

Sugar Loaf is a historic landmark. It stands near the crest of the Hurricane Cliffs as an isolated mesa about 400 feet high, bordered by steep slopes of shale of the Moenkopi formation and capped by a thick sheet of lava—a remnant of one of the oldest flows in southern Utah. In composition and texture it is unlike other igneous rocks so far studied in the Zion Park region. It is a coarse-grained olivine diabase which lacks the usual augite. Microscopic examination shows its chief component to be elongated lath-shaped, coarsely twinned labradorite crystals, distributed and oriented at random. Olivine is conspicuous as large crystals and granular aggregates in the groundmass. Magnetite is represented by small isometric crystals grouped in places. A minute, slender, needlelike mineral was not identified. The rock seems to have been formed at a late stage in crystallization.

In contrast with the lavas of Sugar Loaf, those that cap the adjoining mesas on the edge of the Hurricane Cliffs are basalts of the type common to southern Utah. They consist of labradorite, olivine, magnetite, and augite crystals in a groundmass chiefly of augite and olivine. (See fig. 72.) These remnant lavas may once have been parts of flows extending westward into the sheets that in consequence of faulting now lie at the base of the Hurricane Cliffs, 1,400 feet below.

The Divide dike, about 1,300 feet long and 6 to 12 feet wide, is the resistant core of a steep-sided ridge that separates the drainage basins of Little Creek and Short Creek at the west base of Little Creek Mountain. (See fig. 73.) The center of the dike is black and finely crystalline; its edges are generally dense, but vesicles are fairly common. In places columnar structure has been developed. At its contact with the bordering shales of the Moenkopi formation the dike rock is in places glassy, but more commonly spongy, and includes fragments of quartz and quartzite and slabs and irregular, slightly metamorphosed chunks of the shale and limestone. The country rock close to the dike is baked and furrowed by vertical grooves. Viewed under the microscope the core rock is seen to consist essentially of plagioclase feldspar, considerable olivine and augite, and some magnetite, all in well-formed crystals.

The vesicular texture of much of the dike, the lack of gradation in completeness of crystallization from the center outward, and the unmodified condition of many limestone inclusions suggests that the igneous mass now exposed was formed near the surface, where steam and other gases could readily escape. An upward extension of about 200 feet would bring it to the base of the remnant lavas on the adjoining mesas. In fact, the composition and topographic relations of the dike suggest that it was the source of the lava streams in Workman Wash and that it may have been the feeding dike for some of the lavas west of the wash.

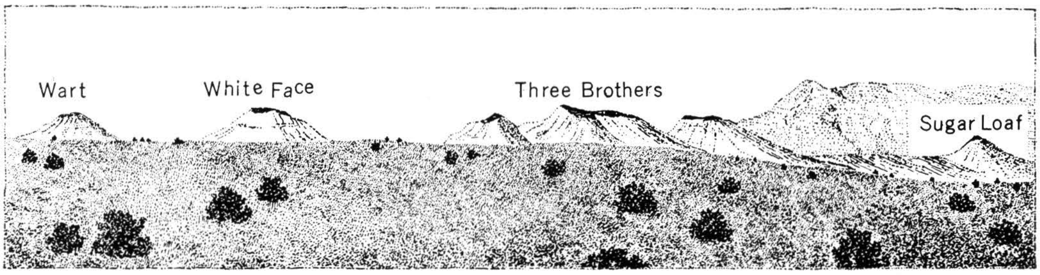

FIGURE 71.—Sketch showing form and position of basalt-capped mesas on back slope of Hurricane Cliffs south of Gould Canyon. Slopes beneath lava and in foreground are developed on Moenkopi strata. Pine Valley Mountains in background (upper right). Sketch by Elinor Stromberg.

WORKMAN WASH

Heading near the Divide dike a lava field half a mile to a mile wide extends northward down Workman Wash to Gould Spring, a distance of about 5 miles. On the west it terminates in a sinuous line along the eastward-dipping back slope of the Hurricane escarpment or as tongues that extend down valleys. On the east it is rather abruptly cut off by Workman Wash and its consequent tributaries and for a long distance stands as the top of a cliff of Moenkopi sedimentary rocks, as much as 150 feet above the floor of the wash. The lava surface retains much of its original roughness, expressed in low domes, upturned blocks, and coalescing strands, and near its south end rise two knolls (spatter cones?) about 200 feet high, composed of spongy vesicular lava and some clinkers and cinders. In composition the rock is a black dense basalt that includes olivine phenocrysts large enough to be recognized by the unaided eye.

Near the head of Gould Canyon the black lavas in Workman Wash are overlain by white beds 2 to 10 feet thick that superficially have the appearance of volcanic ash, for which, in fact, they have been mistaken. Microscopic analysis revealed the material as essentially gypsum that includes cloudlike areas of fine granular secondary calcite—the sort of material that results from the erosion of the more richly gypsiferous parts of the Moenkopi formation. These white beds, some of them well stratified, are interpreted as lacustrine deposits laid down during the time when streams in the wash were blocked by lava that filled to the brim the outlet channel below.

LITTLE CREEK VALLEY

In the lower Little Creek Valley a symmetrical volcanic cone has given rise to lava flows that, spread out on the valley floor, extend westward about 4 miles into Gould Canyon and end about 2 miles from the Hurricane Cliffs, where they come into contact with the younger (?) flows from Workman Wash. The lavas rest on talus, gravel, and Moenkopi sedimentary rocks in the bed of an ancient streamway. Differences in distribution, texture, and degree of weathering distinguish two flows from the same cone; the later one, larger in area, rests in places on the earlier flow and elsewhere overruns its edge, causing Little Creek and its tributaries to readjust their courses. Where exposed in Gould Canyon the earlier flow is lighter colored, more compact, much less fractured, and not separated into sheets. (See fig. 74.) It includes many large angular masses of very dense black rocks, chiefly thoroughly baked shale. The later flow is a series of superposed sheets, scoriaceous at their tops. Both flows are olivine basalts, in which C. S. Ross found "no very essential difference * * * microscopically [No. 3] earlier flow is a little coarser-grained and contains a little more olivine in larger phenocrysts. Both contain the same type of interstitial plagioclase and augite in small granular crystals." The cone and flows in Little Creek Valley obviously post-date all but very recent topography. However, recent streams have buried the edges of the lava with gravel, cut shallow narrow channels through it, and in Gould Canyon have re-excavated the lava-filled channel to a depth of 25 feet.

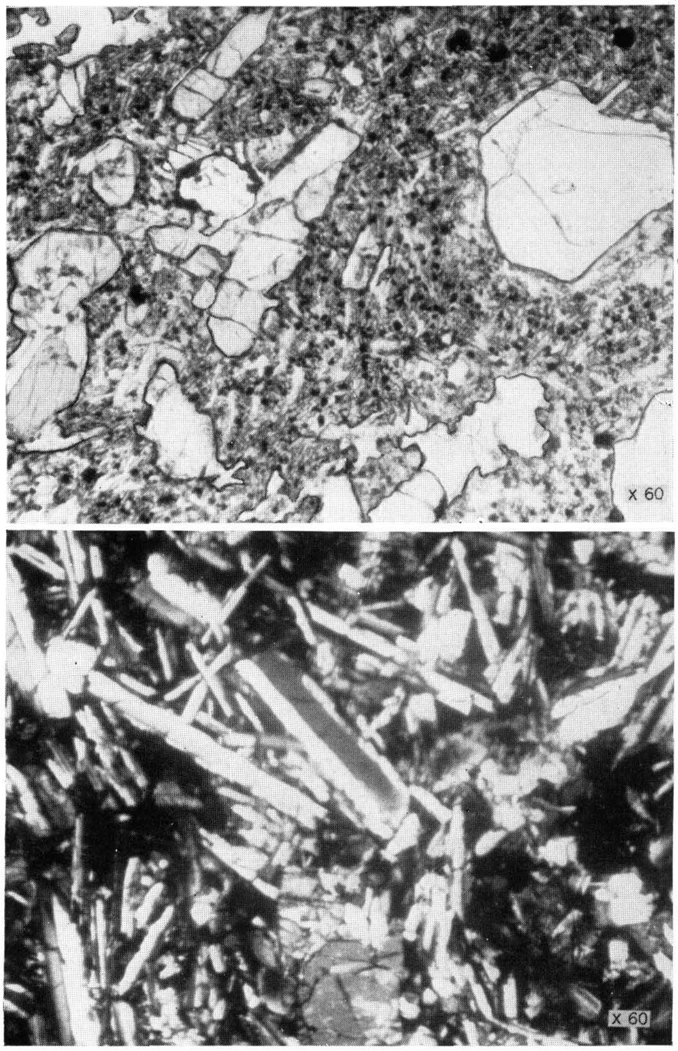

FIGURE 72.—Photomicrographs of lavas, X60. *A*, Gould Canyon. Porphyritic basalt: crystals of olivine (center and lower left) and augite (upper right) in a groundmass of augite prisms, labradorite laths, and magnetite grains; includes vescicles. *B*, Sugar Loaf mesa. Basalt: lath-shaped twinned crystals of labradorite olivine (lower center) and magnetite (dark areas) in groundmass of granular olivine and magnetite; augite absent. Photographs by Bronson Stringham.

LITTLE CREEK MOUNTAIN

On Little Creek Mountain a series of volcanic vents with associated lava flows extends from the cliffs above Rattlesnake Spring southeastward for about 2 miles down the dip slope of beds of Shinarump conglomerate. In the topography the igneous rock is represented by a low, discontinuous, irregularly bounded black ridge 10 to 50 feet high and 40 to 1,200 feet wide, which terminates in the prominent Gray Knoll near the head of Little Creek. The vents are in line, and though no feeding dike is exposed the immediately adjoining country rock is traversed by a series of strong joints, some of them open as much as a foot, that parallel a line through the vents. Some of the vents are merely knobs with summit cracks from which enough scoriacecous lava emerged to cover a few acres. Others are little-modified craters from which clastic material but no lava was extruded, and still others gave rise to both clastic volcanic rocks and flows. The field relations suggest that quiet upwelling of lava from cracks preceded the explosive eruption of bombs, lapilli, and blocks.

The summit crater of a cone 150 feet high on the cliffs above Trough Spring is floored with slag, which grades into dense, partly crystalline material about the rim. Its outer slopes are strewn with bombs and lapilli. In a small isolated crater about half a mile farther west blocks of Shinarump conglomerate are mingled with the clastic volcanics both inside and outside of the cone, which is entirely surrounded with sedimentary rock. The adjoining knobs likewise are wholly fragmental, but patches of lava lie nearby. A cone still farther northwest gave rise to lava which flowed westward about 200 feet on the flat surface and eastward considerably farther down the dip slope. Gray Knoll, the most prominent of the group of craters, is a symmetrical cone 300 feet high and about 2,000 feet in diameter at its base. Its sides are worn by rainwash, and its crater is nearly filled with debris from the rim. Weathering has produced a general dark-gray tone that contrasts strongly with the black of the adjacent lavas and the light gray of the sandstones. The outer slopes of the cone are thickly strewn with lapilli and ropy, twisted bombs a few inches to 4 feet in diameter, and coarse cinders and ash are abundant in the materials about its base. Southeast and west of the cone the fragmental material lies on lava flows 25 to 40 feet thick. This lava,

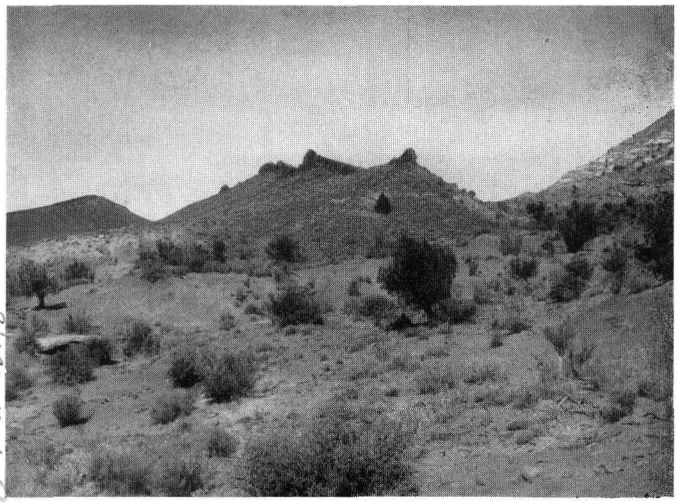

FIGURE 73.—Divide dike at head of Workman Wash; protrudes from Moenkopi shales.

in part dense, massive, and conspicuously jointed, in part scoriaceous and amygdaloidal, seems to have been poured from the vent which later gave rise to the clastic deposits of Gray Knoll. The coarsely crystalline, scoriaceous, glassy, and clastic rock in all the flows and craters of the Rattlesnake Spring area is essentially uniform in composition and is classed as olivine basalt in various stages of crystallization. In a groundmass of plagioclase feldspar and subordinate

FIGURE 74.—Basalt, recent flow (cliff) and older flow (platform) near head of Gould Canyon. Both cut by Little Creek.

augite and granular olivine are set phenocrysts of olivine 0.5 to 2 millimeters in diameter.

The igneous activity on Little Creek Mountain is of recent date. Most of the lavas retain substantially their original texture and superficial form, and since they were poured out the adjoining flatlands have suffered little erosion. However, where the flows reached the edge of cliffs they have been undercut by seepage and broken by landslides, and at Trough Spring a flow and its supporting rock have been trenched to a depth of 75 feet.

The cones and flows in Workman Wash, in Little Creek Valley, and on Little Creek Mountain are almost identical in composition, in range of texture, and in type of clastic material. They are probably of the same age and may have come from a common deep-seated source. The relatively greater erosion of the Workman Wash flow is seemingly due to its position on steep slopes.

NORTH CREEK, DALTON WASH, AND COALPITS WASH

In North Creek valley the lavas on the floor are the ends of typical basalt flows that extend up tributary valleys to their source on the Kolob Terrace. Those that cap the prominent Black Ridge (fig. 75) on the east side of the valley are remnants of an earlier flow whose source has not been determined.

The lava and volcanic agglomerate that cap the cliffs along the Virgin River between Dalton and Coalpits Washes are the edges of sheets that farther north form benches ½ to 3 miles wide. Where its base is exposed the lava rests indifferently on gravel beds of ancient streams, on accumulations of lava boulders cemented with calichelike material, on sandstones of the Shinarump conglomerate, and on shales of the Moenkopi. In consequence of the flows the former rough topography developed in tilted beds has been transformed into fairly level surfaces which locally are marked by roughly circular mounds 20 to 30 feet high and shallow craterlike depressions. The field relations show that the lavas are of at least two ages and came from more than one source. For the flows exposed between Dalton Wash and Grafton a vent may have been near the road 3 miles west of Grafton, where the igneous mass, 200 feet thick, is broken into columns tilted toward the top and bordered by fractured masses of country rock and agglomerate. (See fig. 76.) Still earlier flows from unknown sources must have supplied the rounded and angular igneous boulders on which the basalt rests. The youngest volcanic rocks came from Crater Hill, a cone that stands 600 feet above a platform of sedimentary conglomerate, near the western edge of Coalpits Wash. The crater rim of this symmetrical cone consists mainly of clastic material, and its slopes are strewn with lapilli, fragments of scoriaceous lava, and bombs. From breaches in the cone lava emerges and flows eastward over the sandstone wall of Coalpits Wash and southward over the lavas from earlier eruptions. As at Gray Knoll, the vent at Crater Hill produced lava and, as the final stage of eruption, clastic materials. The intermingling of ash and basalt suggests the possibility of alternation in periods of quiet and of explosive eruption.

KOLOB TERRACE

On Kolob Terrace volcanism has been particularly active. For fully 20 miles, from Virgin over the highlands to Cedar City, the traillike road runs on lava. Sheets of lava are cut by tributaries of Kolob Creek, and more than half of the surface west of Wildcat Canyon and Blue Creek is covered with lava. Cones 200 to 300 feet high are prominent landmarks. Suc-

EXPLANATION OF FIGURE 75

Black Ridge between North Creek and Dalton Wash, part of a larger flow from the northeast, overlies eroded Moenkopi strata. At top, basalt. Photograph, National Park Service No. Z256.

cessive flows from such high vents as Firepit Knoll (fig. 78), and Spendlove Knoll, and from many less prominent sources have spread widely over flatlands and have filled the original valley to depths of 20 to 100 feet. Continuous streams of basalt extend for about 10 miles down Grapevine Wash and North Creek and 4 to 6 miles down Pine Springs Wash. In places the lava has cascaded over cliffs. (See fig. 77.) Preliminary examination of the Kolob volcanic field revealed features similar to those in the Little Creek and Virgin River Valleys. About the cones are strewn lapilli, bombs, and inclusions and broken slabs of dense and scoriaceous lava. The flows constitute a series of overlapping sheets of olivine basalt, the upper ones little affected by weathering. All those observed are younger than the prominent cliffs and canyons, but some, perhaps all, are old enough to have been trenched by recent erosion. The sources of the individual streams, their age, and the relation of the lavas on the floor of the North Creek Valley to those on the adjacent high cliffs merit much fuller investigations.

PARUNUWEAP VALLEY

In the Parunuweap Valley patches of lava lie on the cliffs southwest and north of Glendale, and at Lava Narrows Highway 89 passes between close-spaced vertical walls of black basalt 30 feet high. Traverses of the areas covered by lava revealed no source craters and no localized clastic igneous material. The most probable center of eruption is near Flax Lakes, where the lava is thickest and least uniform in composition and texture. Here the generally amygdaloidal mass, broken into vertical sheets by strong joints parallel with those in the adjoining Cretaceous sandstone, includes dense masses characterized by flow structure and slightly metamorphosed fragments of sandstone and shale. It seems probable that from fissure vents just west of the Flax Lakes the molten rock flowed westward down a narrow wash for about a mile, then spread to a width of about 2 miles. On reaching the Parunuweap most of it dropped over the canyon walls and flowed downstream. At the Narrows it completely filled the canyon and extended about half a mile beyond. At present the thick central mass of vesicular and dense basalt rests on a surface of erosion which is cut by the Sevier fault and at its eastern edge terminates abruptly in a cliff roughened by landslides.

A representative specimen from the flow is described by C. S. Ross as "typical basalt with large phenocrysts of olivine in a fine-grained groundmass of plagioclase, augite, and an unusual proportion of magnetite."

KANAB VALLEY

In Kanab Valley volcanic rocks are represented by Buck and Corral Knolls, and by long flows. Buck

FIGURE 76.—Basalt, north side of valley of Virgin River west of Grafton. Possible center of eruption.

Knoll, about 7 miles south of Alton, is a volcanic cone 250 feet high, which stands against a cliff of Cretaceous sandstone of the same height and therefore is not topographically prominent. Its crater is about 300 feet in diameter and 50 feet deep and inside and outside is strewn with lapilli, bombs, and fragments of scoriaceous lava.

Corral Knoll is a volcanic cone conspicuously because of its position on flatlands near the juncture of

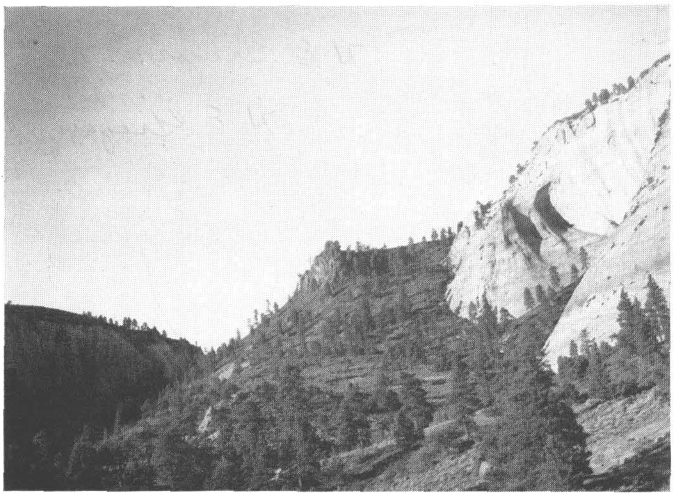

FIGURE 77.—Basalt flow (center) passing over a cliff of Navajo sandstone southwest of Pine Spring on Kolob Terrace. Photograph by J. C. Anderson.

Sink Valley and Kanab Valley. In composition and structure it closely resembles Buck Knoll but is less symmetrical and may be older. Its crater is largely filled, its sides are deeply scoured, and talus is thickly piled at its base. (See fig. 79.)

Between the two large knolls a mound 12 feet high and 8 to 10 feet in diameter rests on the lava from Buck Knoll. The well-preserved vent at its top is partly filled with vesicular slag that grades outward into dense crystalline rock marked by hexagonal joints perpendicular to a circular wall. This little crater may have been the last expression of volcanic activity in Kanab Valley. The lava from these three craters is spread about their bases and in places overlaps. In unknown amounts it combined to form the molten streams that flowed down Kanab Valley 14 miles and in places completely filled the canyon. Some of the lava seems remarkably fresh, but much of it is weathered a rusty red and, in particular that near Corral Knoll, is so broken into talus blocks that its

FIGURE 78.—Firepit Knoll crater on Kolob Terrace. Lava flow (foreground), Navajo sandstone and Carmel formation (cliffs, background).

original surface is obscured. Since the lavas were poured out the Kanab has had time to readjust its course, first by detours and later by trenching the lava itself. Downstream the Kanab has removed much of the obstruction, leaving the lava in thin isolated patches in the narrow defile through the White Cliffs. Examination by microscope shows that both the dense even-grained crystalline parts and the vesicular parts of the rock from Buck Knoll and Corral Knoll are olivine basalt. In some specimens magnetite is unusually abundant.

STRUCTURE

REGIONAL FEATURES

Of the large-scale structural features that characterize the Colorado Plateau province only faults and volcanoes are represented in the Zion Park region. In the sedimentary rocks prominent displacements, like the Kaibab and Monument Valley upwarps, the Tusayan, Sage Plain, and Kaiparowits downwarps, and the Echo and Waterpocket monoclines, are absent. The igneous rocks include no laccolithic masses like Navajo, Henry, Abajo, and Carrizo Mountains and no volcano necks like those in the Navajo Country. In the Zion Park region the outstanding regional features are the Hurricane and Sevier faults, which outline the enormous Markagunt and Paunsaugunt earth blocks and break the continuity of all the rocks exposed, Perinian to Eocene; the prevailing northeasterly dip of surface and deep-seated rocks alike; and the volcanic cones which rise above the general surface.

As elsewhere in the plateau country the master faults and most of the minor faults have a general northerly trend. In a few places short parallel fractures outline narrow blocks or slivers that dip from the major fault at steep angles. All the small faults observed and, for long stretches, the great Hurricane and Sevier faults, are vertical or inclined at angles exceeding 75 degrees. Generally they are clean-cut fractures accompanied by little fault breccia and because they traverse friable rocks fault striae are poorly preserved. In other words, the faults in the Zion Park region are normal breaks incident to the regional uplift of a series of widely extended sedimentary beds. (See pl. 2.)

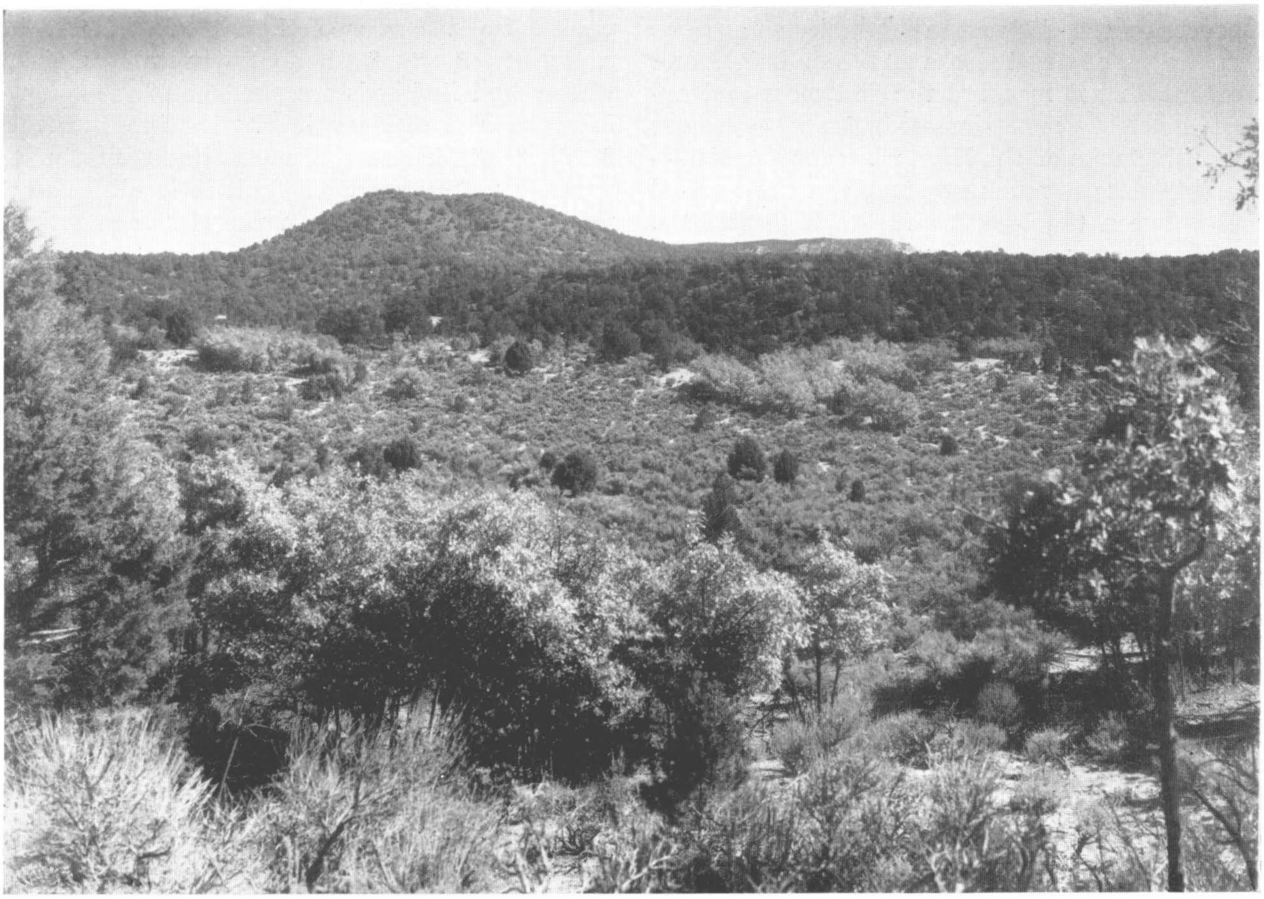

FIGURE 79.—Corral Knoll, volcanic cone at junction of Kanab Canyon and Sink Creek. Lava in foreground; Cretaceous strata, upper right.

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The regional inclination of the strata is remarkably regular. Where accurate maps are available, structure contours drawn in Zion National Park are for long distances nearly parallel and elsewhere show no great divergence. As shown by scores of measurements the rocks that form the plateaus and terraces dip east, east-northeast, northeast, north-northeast, or north—a computed average of north 36° east—and the angle of inclination is monotonously 0°, ½°, 1°, 1½°, 2°, or 2½°. Here and there the northeasterly dips measure 3°, 4°, 5°, and 6°, but only immediately along the major faults and local synclines do dips exceed 10° and even in these positions dips as high as 30° are very rare. Over large areas the beds are nearly horizontal.

The eastern component of the regional northeast dip is in some places greater than the northern component. Thus eastward down the back slope of the tilted earth block that lies between the Hurricane and the Sevier faults the dip averages more than 2°, whereas northward across the area it is less than 1½°. Dutton estimated the northward dip of the beds in the Markagunt plateau south of the Pink Cliffs as 40′—the average of measurements ranging from 0° to 3°—and noted that the dips at the crests of the long Vermilion and White cliffs were generally somewhat steeper than on the terraces farther back, suggesting to him the possibility that release of weight has permitted the rise of a stratum elsewhere held down by overlying sediments.

This northward inclination of the strata, though slight, is regionally of large importance. In the existing topography the cliffs and the platforms are the truncated edges of tilted strata and their height and areal extent do not measure the thickness and expanse of the strata that compose them. Everywhere on the south flanks of the High Plateaus the stratigraphic thickness is much greater than the vertical interval between the lowest and the highest beds. Thus if the strata were horizontal the Eocene beds in the Paunsaugunt and Markagunt plateaus would lie some 2 miles above the Permian beds on the Kanab and Uinkaret plateaus but because of the northern dip the topmost Wasatch strata are only about 4,000 feet higher than the Kaibab, and southward on the Kaibab plateau the Permian limestone is as high as the Eocene of Paunsaugunt plateau. Likewise because of the eastern component of the regional northeast dip, limestone of the Carmel formation in Block Mesas, lies but 2,100 feet above the Kaibab in Timpoweap Canyon, an interval occupied by 3,300 feet of Triassic and Jurassic strata. It is interesting to note that the inclination of the beds is out of accord with the drainage pattern. The large canyons and most of the small valleys trend south or southwest—directions opposite to the regional dip. (See p. 156.)

The structural features in southern Utah and northern Arizona illustrate the geologic unity of the plateau country and reveal the absence of local tectonic disturbances during long periods of time. From the Devonian to the Tertiary, sediments were laid down in the sea and on land, intermittently uplifted, eroded, and depressed in terms of hundreds, perhaps thousands of feet, but except for the broad bowing and the slight tilts involved in regional uplift the large-scale tectonic features are post-Cretaceous in age. Slight local disturbances during Permian, Triassic, and Cretaceous times are recorded in the sedimentary beds and during the period from the Cretaceous through the Eocene most of the plateau region witnessed disturbances of large proportions; the eroded edges of upturned rocks of Cretaceous age lie beneath nearly horizontal Eocene beds. The major structural features that have affected the present topography of the Zion Park region—the two great faults, and most, perhaps all, of the minor faults and the folds—are, so far as known, post-Eocene. Certainly the period during which the sedimentary beds were disturbed by local tectonic movements was many times shorter than the period of relative stability which preceded it.

The recency of faulting in the plateau country and its expression in the present topography is repeatedly emphasized by the geologists of the Wheeler and the Powell surveys in terms similar to those used by Dutton.[16] "Every fault in the district is accompanied by a corresponding break in the topography * * * * I do not recall an instance where the lifted beds are planed off by erosion so as to make a continuous level with the thrown beds * * * * These characteristic breaks in the topography often betray a fault in localities where it would otherwise have been passed over unnoticed and unsuspected."

Recent studies show that Dutton's generalizations are too broad. Though in places the great faults are marked by great cliffs, in other places they are unexpressed in the topography. The field evidence leads to the conclusion that the greater part of the displacement along the major faults was accomplished before, rather than after, the "great denudation"; that the faults are features of the regional uplift that made possible the spectacular erosion of the present canyon cycles; and that along the same general lines the original faulting has been followed in places by later faulting of considerable amount. The antiquity of the pre-canyon faults is roughly measured by the changes in their present topographic appearance, as produced by erosion. Along the Sevier fault between Alton and Glendale the upthrown block has been erased and at one place the resulting post-maturity surface is covered by lava of considerable age. In the vicinity of Pipe Spring the landscape produced by faulting has been completely remodeled and as shown by Davis the present topography is entirely inconsistent with the assumption of recent faulting. (See p. 147.) Likewise, along the Hurricane fault the features produced during the original fauting have been largely removed by erosion. The present cliffs represent the upthrown blocks of a more recent fault.

Though not widely separated in time the movements along the various faults were not contemporaneous and in each major fault activity was interrupted by intervals of repose. Both the Hurricane and the Sevier fault zones include fractures additional to the major displacements, some of them with dif-

[16] Dutton, C. E., The physical history of the Grand Canyon district; U. S. Geol. Survey 2d Ann. Rept., p. 134, 1882.

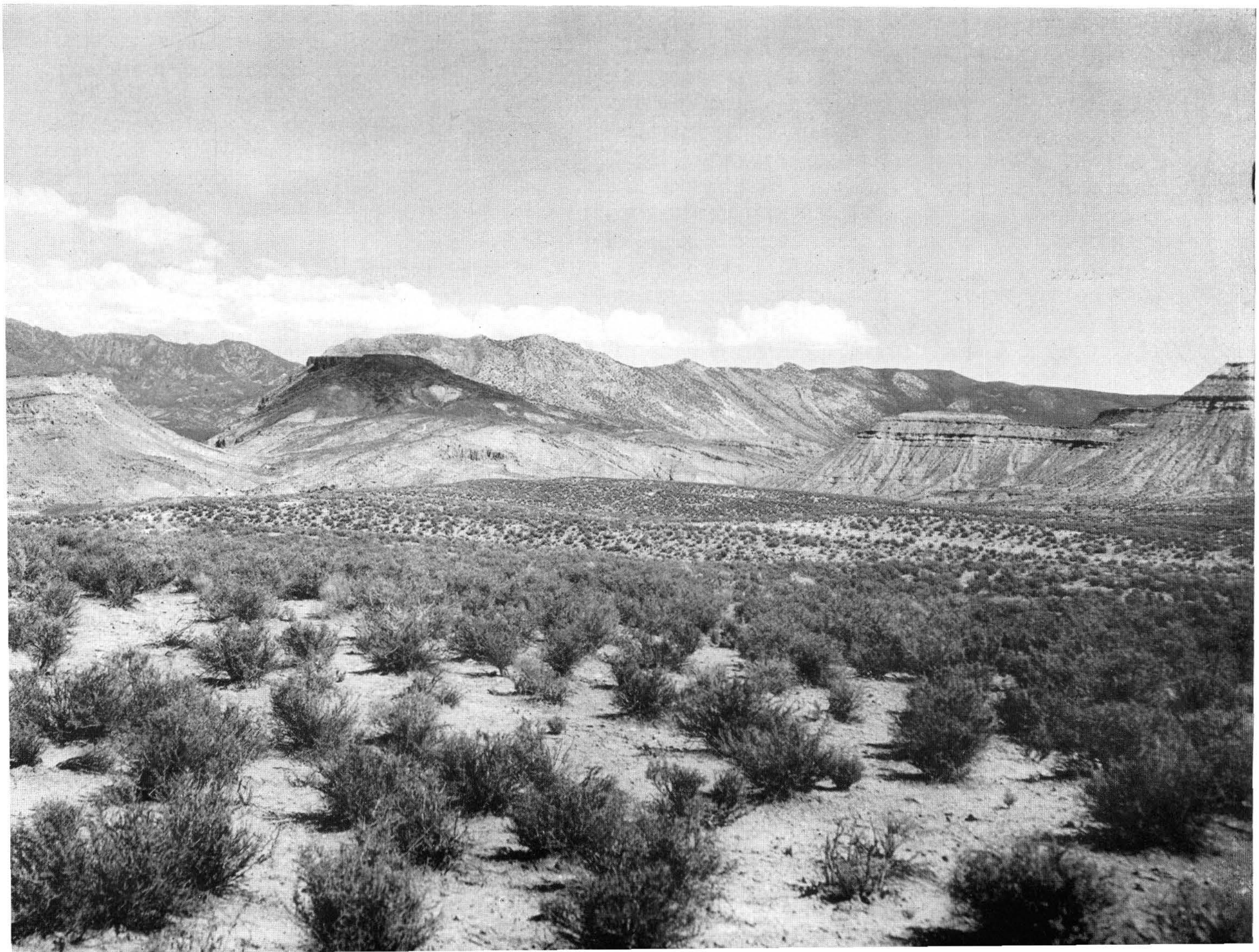
EXPLANATION OF FIGURE 80

View northwest toward mouth of La Verkin Canyon. Kaibab strata on steep back slope of Hurricane Cliffs (top center) become nearly horizontal and pass beneath the Moenkopi (right). Hurricane fault, here branched, passes the lava-capped Toquerville hill (left center) and extends northward between Hurricane Cliffs and Pine Valley Mountain (top left). Photograph by National Park Service, No. Z202.

ferent trends. That the latest faulting is geologically recent is abundantly shown by the newness of the present topography. High cliffs stand very near the fault lines—some of them in fact are but the slightly modified faces of upthrown blocks—the drainage channels are youthful, and the streams are adjusting themselves to uplifts that seem to be still in progress. In Johnson Canyon the alluvial fill is broken by a fault that extends downward to a crack in the rock on which slickensides are brightly marked. Near Parowan a fault crosses outwash gravels. Since the Zion Park region was settled in 1851 several earthquakes have been recorded. Those at Kanab in 1885 and 1891, at Tropic, Glendale, and Panguitch in 1902, 1924, 1930, and 1931 were of special note.

HURRICANE FAULT

Hurricane fault is the most prominent structural feature in the Zion Park region—in fact, one of the longest and the most conspicuous lines of displacement in the whole Plateau province. It marks the position of the Hurricane Cliffs—the escarpment, which, beginning south of the Colorado River and extending northward about 180 miles at least to Paragonah, forms the western edge of the Uinkaret and Markagunt plateaus and the intervening Kolob Terrace. South of the Virgin River this great fault has the appearance of a single continuous fracture expressed in the topography by nearly vertical cliffs, 1,000 to 1,400 feet high, made of Kaibab, Coconino (?), and Supai (?) strata, capped in places by Moenkopi shales and by lava. For 3 miles north of the Virgin the displacement incident to faulting rapidly decreases in amount and the usual cliffs are represented by ridges of tilted Triassic and Jurassic rock that culminate in the lava-capped Toquerville Hill—parts of a faulted anticline. (See fig. 80.) North of Toquerville the fault resumes its large displacement and its associated cliff is prominent as Black Ridge (Belevue Ridge), a wall rising 1,500 feet above the bed of Ash Creek at its base. Still further north the major fault is associated with other faults in a somewhat complex relationship. Throughout most of its length the Hurricane fault reveals at least two uplifts with the same general trend and position. The topographic features produced by the earlier fault were largely obliterated before the later faulting, expressed in the present cliffs, occurred. Generally the evidence of the first fault, much the larger in displacement, is stratigraphic; that of the second, stratigraphic and topographic. Thus near the mouth of Timpoweap Canyon the Moenkopi and younger strata on the downthrown (western) side of the earlier fault dip westward at angles of 30 to 60 degrees; on the



upthrown side Kaibab and Moenkopi limestones dip eastward at an average angle of about 3°. Here the latest fault has broken sheets of lava poured out during an interfault cycle and its position is marked by a cliff 250 to 300 feet high. North of Toquerville the escarpment along the more recent fault is 1,200 to 1,500 feet high. The stratigraphic displacement by the two faults combined is least along the west border of the Uinkaret plateau and most along the base of the Kolob Terrace. At Virgin River, where the upper shales of the Moenkopi and the Shinarump conglomerate abut against Kaibab limestone, and near the mouth of Ash Creek, where upper Jurassic and Cretaceous beds are exposed on the downthrown side, the displacement exceeds 5,000 feet. Farther north near Kanarraville the displacement attains its maximum of about 8,000 feet. These figures, however, are estimates, because lava flows in Ash Valley canyons, thick sheets of alluvial gravel on La Verkin bench, and local folds all prevent continuous tracing of structural features.

The prominent Hurricane fault was described in reports by the geologists of the Wheeler and Powell surveys, and has attracted the attention of many later students of earth science. Howell and Gilbert, who worked at a time when monoclinal folds and enormous earth blocks, broken by faults but otherwise little deformed, were considered stages of development in structures that began as simple anticlines, thought of the Hurricane cliffs as the locus of a fold, in places faulted and eroded on its western side. Dutton[17] considered the Hurricane fracture as a normal fault, the result of a single uplift; it "nowhere appears to take on the true monoclinal form." Huntington and Goldthwaite[18] concluded that instead of a simple fracture or fold modified by erosion the Hurricane fault and associated cliffs record a series of events in which two periods of faulting are involved, that true faults south of Toquerville and broken flexures farther north break pre-existing folds.

Because the Hurricane fault crosses coal beds and structures that may contain oil, it has in recent years received considerable attention. Lee[19] noted a difference in elevation of 4,000 feet on the two sides of the Hurricane fault south of Cedar City. Though he saw "little evidence of the existence of a fold" he was "impressed with the profound faults and tilted blocks plainly to be seen near the edge of the plateau." Richardson[20] found that along the west base of the Kolob Terrace "the structure is complex and the strata highly tilted" and that in consequence of faulting "the coal in the Colob field occurs about 2,000 feet higher than that in the New Harmony field."

Dobbin[21] estimated the displacement along the fault as not less than 7,800 feet where it crosses Virgin River and not less than 15,000 at Bellevue ridge, 1,400 feet of it produced by the most recent faults. Johnson[22] reached the conclusion that though the Hurricane displacement "has the indication of a fault —it proves to be only a sharply folded anticline, foreshortened on the west."

SEVIER FAULT

The Sevier fault is an outstanding feature in the structure of the Plateau Province. In length and amount of displacement and in its influence in modeling the landscape it ranks with the Hurricane fault, the Paunsaugunt fault, the Kaibab uplift, the Waterpocket fold, and the Echo monocline. Across the Zion Park region it is a strongly marked continuous line of displacements—the division plane between the Kolob and the Skutumpah, the Wygaret and the Moccasin Terraces. South of the region treated in the present report the fault is clearly shown for about 5 miles where it is lost to view in the débris-covered Moenkopi strata, on the Uinkaret Plateau. Though it may not continue farther, it probably is represented by the fault that crosses Grand Canyon at Toroweap. Northward the fault extends far into central Utah along the Sevier River Valley, from which it derives its name. Throughout much of its length of about 200 miles the position of the fault is readily recognizable in the topography; the alinement of the fault is also that of cliffs. Such lofty escarpments as the Elkheart Cliffs in the Parunuweap valley, and the Sunset Cliffs in the Sevier valley, stand on the upthrown side and overlook extensive lowlands.

For long stretches the fault is a single normal fracture, a sheer cut through rocks otherwise little disturbed, but in places it is accompanied by two or more roughly parallel faults that outline slivers of various dimensions and attitudes, and in other places it branches along curved lines that return to the master fault or die out in the adjoining rocks. The measured displacement along the fault ranges from about 100 feet to as much as 2,000 feet.

Although nowhere has the discordance of strata been produced entirely by simple or compound folds, at several places the beds are arched and at the steeply tilted fault plane the inclination of the beds varies from horizontal to almost vertical. In accord with the unequal uplift on one plane or on several parallel planes, the height of the original fault cliffs, and the form, attitude, and dimensions of their rem-

[17] Dutton, C. E., Tertiary History of the Grand Canyon District; U. S. Geol. Survey Mon. 2, pp. 20, 113, 1882.

[18] Huntington, Ellsworth and Goldthwaite, J. W., The Hurricane fault in the Toquerville District, Utah: Harvard Coll. Mus. Comp. Zoology Bull., vol. 42, pp. 199–259, 1904.

[19] Lee, W. T., The Iron County coal field; U. S. Geol. Survey Bull. 316, p. 366, 1927.

[20] Richardson, G. B., The Harmony, Colob and Kanab Coal fields, Utah; U. S. Geol. Survey Bull. 341, p. 383, 1909.

[21] Dobbin, C. E., The Oil reserve in southern Utah (manuscript on file, U. S. Geol. Survey).

[22] Johnson, L. Z., Report to the Escalante Exploration Company (manuscript on file, U. S. Geol. Survey).

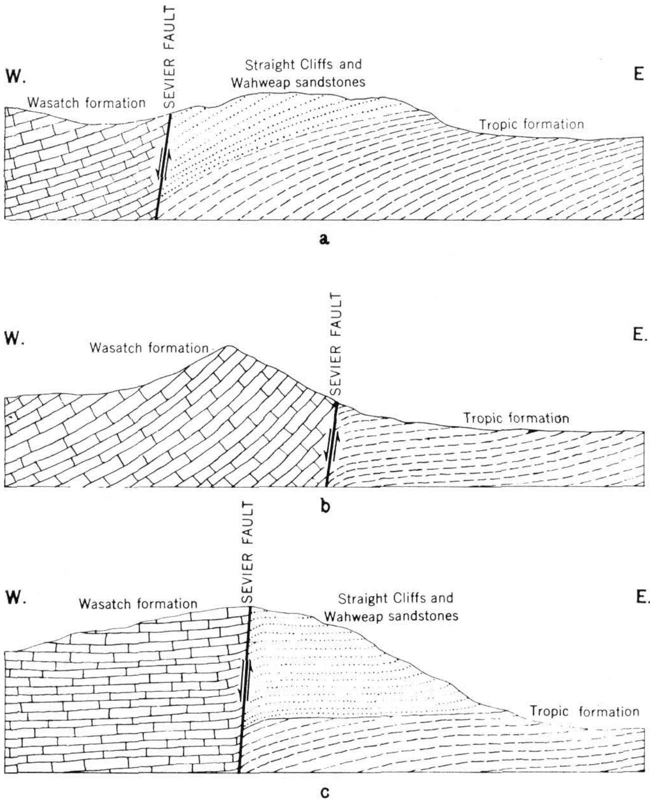


FIGURE 81.—Cross sections snowing Sevier fault near Alton. *A*, 1½ miles north; *B*, 1 miles northwest; *C*, 3± miles southwest. Estimated maximum displacement, 800 feet. Bases of Wasatch and Tropic formation not exposed.

nants differ widely. In places the faulting is clearly reflected in the present topography, in other places all the cliffs and ridges produced by faults have been worn to a common surface and in still other places the topography of cliffs, highlands, and lowlands is the reverse of that produced by the fault. The arrangements of strata along Sevier fault might be termed local features. Selected sections along the line of fault are shown in figures 81 to 85.

In the development of the present topography, the effect of the faulting is especially well shown in the high cliffs where the strata are horizontally and vertically discordant and prominent headlands seem out of place. In the Vermilion Cliffs differential erosion of the northeasterly dipping Moenkopi, Shinarump, and Chinle beds along the fault has produced an offset of 9 miles; in the White Cliffs, between Heaton Point on the Elkheart Cliffs and Esplin Point on the Block Mesas, the Navajo sandstone is offset 8 miles; and in Parunuweap Valley the otherwise continuous Cretaceous cliffs are offset nearly 10 miles. Such breaks in the continuity of the escarpments are unique features in a topography otherwise in general accord with the composition and attitude of the sedimentary rocks.

Tracing of the Sevier fault from the rugged hills at Alton to the flatlands about Pipe Spring National Monument reveals its varied characters and the form and position of its related topographic features. (See figs. 81, 82, 83, 84, 85, 86, 87, 88, 89, 90.) In the vicinity of Alton the fault is not associated with the usual cliffs; it traverses mounds and ridges on the divide between the Parunuweap and Kanab Valleys where its position is determined almost wholly by stratigraphic discordance. Here the displacement of 500 to 800 feet is interpretd as a simple fracture nearly vertical, which, as Gilbert[23] surmised, may have followed or been accompanied by a flexure. (See fig. 81.) As far south as Flax Lakes the fault traverses a gently undulating surface thickly coated with the products of weathering and appears in plain view only in the narrow, shallow valleys. At Flax Lakes it passes for about 500 yards beneath a thick sheet of basalt. (See fig. 82.)

From Flume Canyon southward along the base of the Elkheart Cliffs past Orderville and Mount Carmel to Heaton Point the fault zone assumes special prominence. (See figs. 83, 86, 87.) It includes the master fault, branch faults, and minor parallel faults and along it upturned blocks and small slivers mark the zone of greatest movement. Along the major fault in Flume Canyon rocks of the Tropic formation abut against limestone of the Carmel formation and minor

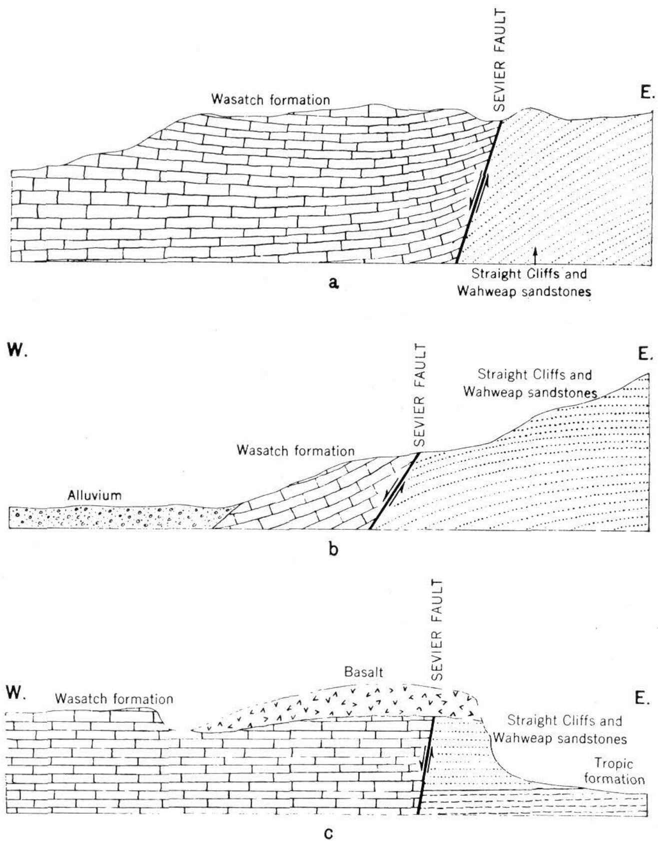


FIGURE 82.—Cross sections showing Sevier fault in vicinity of Flax Lakes. *a*, Head of McDonald Wash; *b*, About 1 mile north of Flax Lakes; *C*, Lava ridge above Flax Lake. Estimated displacement, 700 feet.

[23] Gilbert, G. K., in Wheeler, U. S. Geog. and Geol. Surveys W. 100th Mer., vol. 3, Geology, pp. 49, 50, fig. 25, 1875.

faults break the continuity of the Carmel, the Entrada, and the Curtis formations. South of Glendale the displacement along the Sevier fault increases, the belt of broken rock becomes wider, and due to post-

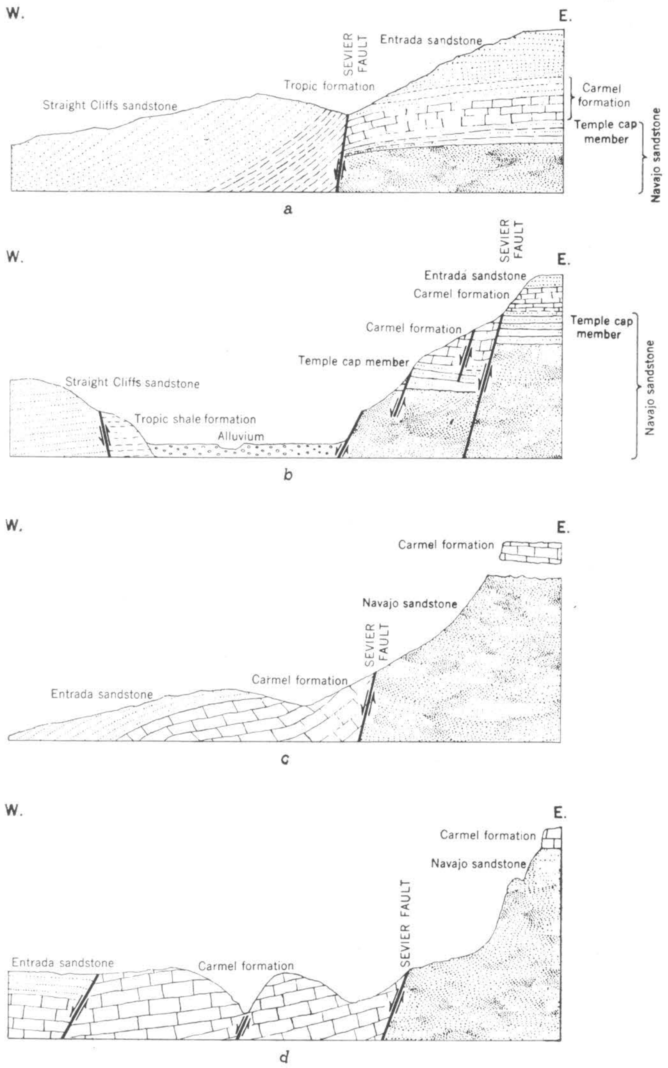


FIGURE 83.—Cross sections showing Sevier fault along base of Elkheart Cliffs. *A*, In Flume Canyon—strike of beds in Carmel formation N. 45°–50° E., in Straight Cliffs N. 40° E., estimated displacement 450 feet; *B*, 1 mile south of Glendale, dip of fault plane 75°–80° NW., estimated displacement 380 feet; *C*, 1 mile north of Orderville, fault plane strikes N. 23° E., dips 77° W., estimated displacement 900 feet, strike of Carmel formation N. 22° E., dip N. 28° W.; *D*, East of Mount Carmel Junction, strike of fault plane N. 35° E., dip 75°–80° NW., measured displacement 1,680 feet.

fault erosion the downthrown side in places overlooks the upthrown side. Between Glendale and Orderville a fault about 2 miles long and parallel with the main fault traverses Cretaceous sandstone. In the depressed area between the two faults the Parunuweap River has established its course. From the stream bed a great slab of Upper Jurassic rock slopes upward to the plane of the major fault where it seems to be hinged to the vertical wall. (See fig. 84.) In short canyons leading to the Parunuweap southeast of Mount Carmel the displacement is expressed as a zone 30 to 200 feet wide which includes the major fault—a clean fracture typically shown as the face of a low vertical cliff of Navajo sandstone. In places the downthrown strata dip downward toward the fault, in other places they are horizontal or dip upward as if dragged by the uplifted block. In the Levenger mine near Glendale Cretaceous coal beds that dip eastward at an angle of 6 degrees abut against Navajo sandstone. Unlike the topographic features at Alton and Flax Lakes those about Mount Carmel are clearly initiated by faulting. On the upthrown side stand the lofty Elkheart Cliffs, a vertical wall close to the fault plane; on the downthrown side broad benches and disorderly mounds form the surface dissected by tributaries of the Parunuweap River. On the upthrown block the cap rock is limestone of the Carmel formation; on the downthrown side the youngest rocks exposed are shales of the Tropic formation and, where these have been worn away, the Winsor, Curtis, Entrada, or Carmel. Instrumental measurements show that the basal bed of the Carmel formation lies 1,520 feet below its counterpart at the top of Elkheart Cliffs. For about 2 miles south of Heaton Point the fault is marked by slabs of Navajo sandstone and limestone of the Carmel formation tilted against the upthrown block. Farther on its features are lost to view beneath the alluvial fill of Yellow Jacket Valley and are generally indistinct on the dun-covered land east of Esplin Point, but are again plainly expressed at Chris Spring near the head of Sand Canyon. The exposed Carmel and upper Navajo strata in Block Mesas dip eastward toward the fault and doubtless beneath the surface meet horizontal beds in the lower part of the Navajo sandstone. At Chris Spring where the fault is a clean-cut simple fracture, the Wingate sandstone is brought to the position of the Navajo sandstone, normally about 300 feet higher. Here the fault branches and continuing southward presents unusual features of alinement and displacement. (See figs. 85, 90.) One

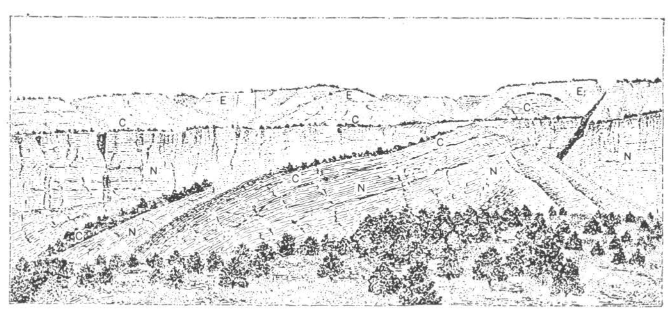


FIGURE 84.—Elkheart Cliffs at Orderville showing a "rock sliver" torn from cliffs at plane of Sevier fault on Entrada, Carmel, and Navajo strata.

branch with a throw of 75 to 100 feet is traceable for about a mile along the base of a high mesa. Of the other two branches the eastern passes beneath the landslides and jumbled talus on the west side of Sand Creek Valley, rounds Indian Point, and continues beneath the alluvial flats of Two Mile Creek to the base of moundlike hills west of the Kaibab Indian School. Along the line of greatest displacement about a mile north of Indian Point the middle Chinle beds have been raised nearly to the base of the Navajo, recording an uplift of about 500 feet.

The western branch of the fault with a throw of 60 to 180 (?) feet and associated with minor faults and close-spaced joints passes southwestward through a sag in the Vermilion Cliffs and along the ing eastward to Fredonia, and the Navajo and Chinle formations, which make up the cliffs, are replaced by Moenkopi strata that for many square miles form the surface of Uinkaret Plateau. Because the Navajo sandstone curves downward and is progressively beveled as it approaches the fault, the actual zone of fracture lies on a broken slope and is largely concealed

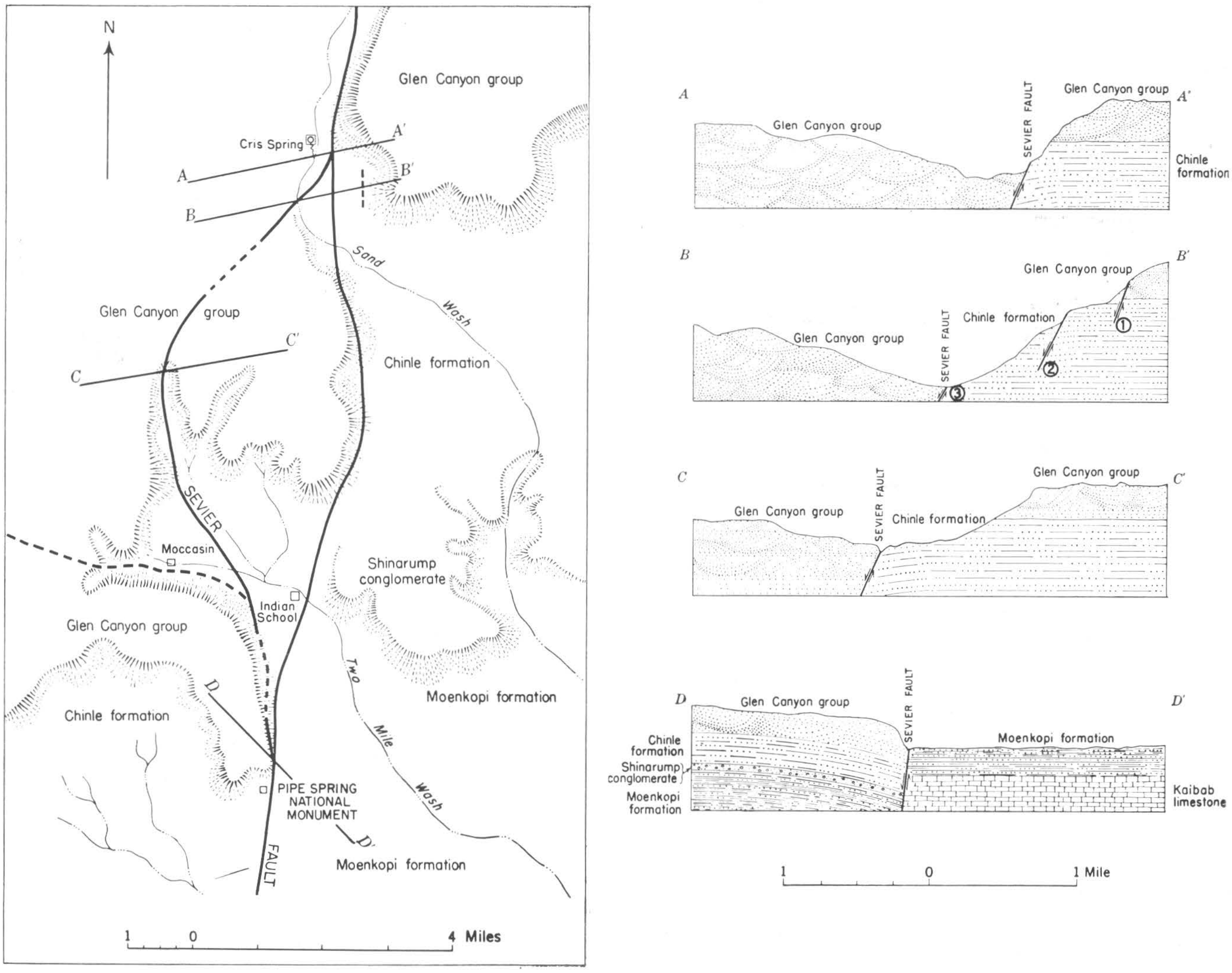


FIGURE 85.—Generalized geologic map and sections showing position of Sevier fault in Vermilion Cliffs. Section A–A′, at head of Sand Canyon; along a simple fracture the Chinle formation has been raised 200 feet with respect to Navajo sandstone. Section *B–B′*, about 1 mile south of Chris Spring, showing three branch faults; displacement in fault 1 is 75–100 feet; in fault 2, 250–300 feet; in fault 3 (estimated), 500 feet. Section *C–C′*, in cliffs north of Moccasin, estimated maximum throw, 180 feet. Section *D–D′*, Pipe Spring, an uplift on east side of fault has brought middle Moenkopi shales to level of sandstone of Glen Canyon group, a displacement of about 2,000 feet.

base of a sandstone wall to a junction with the eastern branch. In the cliffs north of Moccasin it lies in a belt of shattered rock, about 400 feet wide, where slabs of Chinle shale and sandstone tilted at various angles form walls between which the trail winds in and out. At least three of the springs at Moccasin emerge at the fault line, others along minor faults.

At Pipe Spring the Sevier fault marks a sharp break in the topography and an equally sharp break in the continuity of the sedimentary strata. Coming from the west the rugged Vermilion Cliffs, which at Short Creek and Cane Beds attain heights exceeding 1,000 feet, are abruptly replaced by flatlands extend- by talus and stream wash, but the relations are evident—the basal Navajo sandstone abuts against the gypsiferous shales characteristic of the middle Moenkopi formation. The stratigraphic displacement is therefore at least 1,800 feet. Taking into account the local and regional dips and assuming various thicknesses for the Triassic and Jurassic strata originally in place, the calculated displacement is 1,850 to 2,380 feet.

It is conceivable that for long periods of time the topography initiated by faulting in the Pipe Spring region was as rugged as that along the Hurricane fault at Toquerville and the Sevier fault at Mount

Carmel. But the features associated with the original disturbance no longer remain. In consequence of profound erosion the Tertiary, Cretaceous, and Upper Jurassic strata have been removed from both sides of the fault and in addition the thick Navajo sandstone, the Chinle, the Shinarump, and the upper Moenkopi formations have been stripped from the

FIGURE 86.—Sevier fault at Orderville. In gap just north of village the fault separates the Straight Cliffs sandstone (SC) and Tropic formation (T), at left, from upper part of Navajo sandstone (N) and Carmel (C) in Elkheart Cliffs, at right. Photograph by G. B. Richardson No. 191.

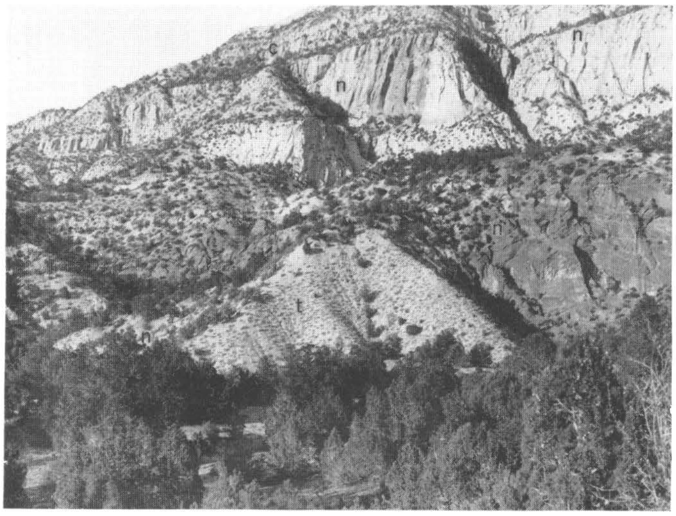


FIGURE 87.—Sevier fault, along face of Elkheart Cliffs (at top) near Heaton Point. Tropic formation (T)—slope in foreground—rests against a nearly vertical wall of Navajo (N) sandstone (in right center). Photograph by J. C. Anderson, No. 11 in Geological Survey files.

upthrown block. The downthrown block now stands higher than the upthrown block and across the fault trace a plain of erosion permits the unobstructed passage of streams. (See p. 180.)

MINOR FAULTS AND FOLDS

In addition to the great Hurricane and Sevier faults that cross the Zion Park region and extend beyond its borders, many short faults of small displacement and a few low folds interrupt the continuity of the extensive sedimentary beds. Because these minor fractures, upwarps, and downwarps are small-scale representatives of the class to which the larger structural features belong, only the few here listed were examined. Detailed mapping undoubtedly would reveal many small anticlines, synclines, and faults and perhaps broad regional upwarps and downwarps not recognized during the present survey.

La Verkin Canyon.—In crossing La Verkin Valley, where the usual conspicuous fault scarp is lacking, the disturbance caused by the Hurricane fault is recorded in several short strike faults and by folds of small dimensions. These structures appear to be local features of the major fault, which passes west of Toquerville Hill and along the base of Black Ridge. Toquerville Hill is essentially an anticline from whose faulted and eroded crest the beds dip southwestward and northeastward. Down the east flank of the fold the dip of a key bed of limestone in the Moenkopi decreases within 500 feet from 16° to 4° and 1,000

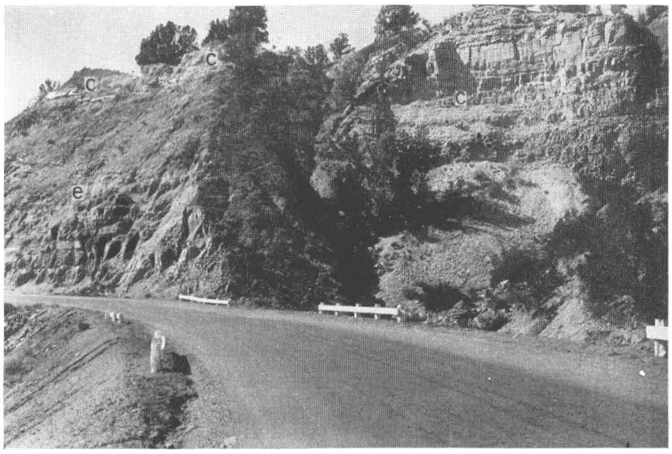


FIGURE 88.—Fault in San Rafael group near Mount Carmel Junction. Entrada and Curtis formations (left), Carmel formation (right), throw 120± feet. Photograph by C. H. Wegemann. Gregory, H.E. 1285

feet farther downslope to 2°—the regional dip. At this place the La Verkin Creek has shifted its course from the steep structural slope onto slightly tilted rocks that form the high eastern wall of its canyon. For a short distance in a nearby tributary the Kaibab limestone, crushed and minutely faulted, is curved upward and flanked by sandstone of the Moenkopi dipping east and west—a fold from which the beds above the Permian have been eroded. Northward for about 15 miles along the back slope of the Hurricane Cliffs the steeply dipping stratia are unbroken, but near the head of the La Verkin a fault with an estimated displacement of 700 feet crosses the Navajo sandstone.

Folds and Faults near Grafton.—From near the head of South Wash northward across Virgin River into Coalpits Wash the Moenkopi strata are bent upward into a low narrow north-south trending anticline, locally known as the Grafton fold. Through most of its course the structure has been destroyed by erosion and is now represented by a band of crumbled gypsiferous shales, which separate mesas composed of essentially flat-lying strata. The fold is

FIGURE 89.—Fault in Carmel formation near head of Parunuweap Canyon. (See also fig. 54.)

FIGURE 90.—Headquarters of Kaibab Indian Reservation, Ariz. West branch of Sevier fault passes through flatlands (upper left) between Navajo sandstone (left) and Chinle (right). East branch passes between Indian Point (top center) and Lamb Point (top right). (See also fig. 85.)

most complete about 1½ miles south of the village of Grafton, where from its rounded crest the beds dip, eastward into the valley wall at an angle of about 7° and westward into a syncline about 6 feet deep, and then rise with slight inclination to a nearly horizontal position. This anticline is the largest of many folds, 2 to 10 feet high and 100 to 1,000 feet long, that, in the Virgin River Valley below Rockville and also in North Creek, Little Creek, and Short Creek valleys, modify the surface of the exposed Moenkopi formation. About these inconspicuous features the regional northeast dip of 1° to 2° changes to 6° to 8° northwest, southeast, or south. All of those mapped have the approximate trend of the Hurricane fault and probably are closely related to it in age and origin. In the hope of obtaining oil, wells have been drilled in these anticlines near Grafton, Virgin, and Antelope Springs. (See p. 192.)

Associated with the Grafton anticline three normal faults break the continuity of the Triassic sediments by raising the strata on the east, thus forming sharply bounded cliffs in the harder beds. Their trend is roughly parallel with the axis of the anticline, and they seem to be features of a disturbance that produced both the faults and the folds that have affected the Moenkopi, the Kaibab, and perhaps formations below, and the Triassic and Jurassic beds now removed by erosion. One of the faults breaks the crest of the Grafton anticline in Coalpits Wash and a mile east of the north end of the anticline another fault of small throw crosses Scroggs Wash. The largest fault of the series traverses the mesa between South Wash and Grafton Wash about a mile west of the south end of the Grafton anticline. In the cliffs that face the Virgin River this zone of disturbance is represented by a group of joint cracks along which slight movement has taken place. Farther south the rocks are torn apart with increasing displacement until in the southwest corner of sec. 16, T. 42 S., R. 11 W., the Shinarump conglomerate and topmost Moenkopi strata east of the fault lie more than 250 feet above corresponding beds on the west. As the fault is not noticeable in Gooseberry Mountain, about a mile south of the point of greatest measured downthrow, it is believed to end beneath the thick talus on the rough land west of Smithsonian Butte.

Back slope of Hurricane Cliffs.—Generally on the upthrown side of the Hurricane fault the strata have easterly dips of 5° to 20°—greatly exceeding the regional easterly dips—and in many places are disturbed by inconspicuous folds and faults. About 2 miles southeast of Antelope Springs the Moenkopi strata are uplifted in an anticline about 2 miles long in which the beds dip 1° to 2° northeast, rise to a nearly flat crest, and then dip southwest at angles of 1° to 4°. At the head of Rock Canyon, Short Creek crosses an anticline, composed of Permian and Triassic strata steeply inclined, and broken small-scale faults. (See fig. 91.)

In Little Creek and Virgin River Valleys surface rocks are locally unwarped, and in Alkali Wash and Timpoweap Canyon the lowermost shales in the Moenkopi are broadly wrinkled, the underlying limestones and sandstones being undisturbed. It would seem that here the stresses incident to the uplift that produced the Markagunt fault block were adequate to buckle and squeeze the weak gypsiferous shales but not the massive limestones and tightly cemented conglomerates. This belt of disconnected low anticlines, here and there broken by faults of very small throw, is approximately parallel with the Hurricane fault 3 to 4 miles west and is thought to be closely related to it in origin and age.

Cougar Mountain.—On the east side of Cougar Mountain the cliffs of Navajo sandstone are offset by a fault that also crosses the mountain through a sag between mesas. At its point of probable greatest displacement the measured downthrow is 480 feet, bringing the Navajo sandstone in horizontal contact with the upper sandstones of the Chinle formation. (See fig. 92.) Southeastward across North Creek the fault continues with decreasing throw for at least 6 miles and may be represented by the inconspicuous fracture that disturbs Chinle and Shinarump beds in Scroggs Wash above its junction with Coalpits Wash and dies out in the gravel-capped mesa near the Virgin River. About 2 miles west of the Cougar Mountain fault a parallel fracture breaks the walls of North Creek Canyon.

White Cliffs and Vermilion Cliffs.—In the Navajo and Carmel formations making up the White Cliffs, faults of small throw are traceable on the surface back of the crests and are relatively conspicuous at cliff re-entrances where they have determined the position of streams. At Jos Creek on the south face of Block Mesas a fault with an upthrow of about 200 feet on the east brings the Navajo sandstone into horizontal contact with Carmel. The fault and adjoining fractures have determined the position of the ephemeral stream on the top of the mesa and of the spring in the box-headed canyon at its base. In a canyon near the east entrance to Zion Park the Temple cap member of the Navajo sandstone and limestone of the Carmel formation above it are broken by a curving fault that trends N-S to N 15°W and along which the displacement in a distance of about half a mile measures 32 to 54 feet. A short parallel fault has an upthrow on the west of about 12 feet. Likewise along the face of the Vermilion Cliffs faults disturb the Chinle and overlying beds at several places. The throw of few of them exceeds 5 feet; most of them are merely zones of strong jointing along which slight movement has taken place and they would attract little attention were it not for their influence in determining the position of drainage lines.

Zion Park Junction.—In the vicinity of Zion Park Junction the Jurassic strata are cut by numerous faults, most of which have very small throw, die out within a few hundred feet, and are restricted to the formation in which they appear. Thus of 8 faults with throws of 6 inches to 4 feet in the Carmel formation, 5 affect neither the Entrada above nor the Navajo below, and of the scores of tiny faults noted in the Entrada only 6 could be definitely traced upward into the Curtis formation and only 2 downward into the Carmel. (See fig. 53.) On the other hand a fault crossed by the Zion-Mount Carmel highway about half a mile west of its junction with the Orderville-Kanab road is at least a mile long and breaks all the formations of the San Rafael group (See fig. 88.) Along the fault plane that trends N 10°W the Carmel formation on the east side is raised to the level of the upper Entrada by an upthrow of about 120 feet. About half a mile south of the Junction a possible extension of this fault reaches the Parunuweap River and again brings the Entrada and the Carmel to a common height. Across the river it is represented by a belt of disturbed rock in which at favorable places three parallel faults are recognizable. (See fig. 89.) Two of them define a graben about 30 feet deep and 60 feet wide. The faults in this area trend in various directions but most of them are roughly parallel with the Sevier fault that 2 miles east cuts all the formations exposed. (See figs. 83, 87, 88.)

Cave Lakes Canyon.—In Cave Lakes Canyon near its junction with Three Lakes Canyon, a fault with a throw of 10 to 60 feet and as much as half a mile long breaks the continuity of the Jurassic beds. At the point of maximum displacement the Kayenta formation is in horizontal contact with the Wingate. In a nearby canyon a fault with a throw of 12 feet breaks the Navajo sandstone. Similar faults trending generally about N 15°W and of less displacement are common along other western tributaries to the Kanab, and discordance in bedding suggests the presence of a fracture directed east-west beneath the thick alluvial fill of Cave Lakes Canyon. Some of these faults are parts of fracture zones 1 to 5 feet wide in which the beds, particularly the Wingate sandstones, are fantastically buckled and cracked. (See figs. 43, 44.)

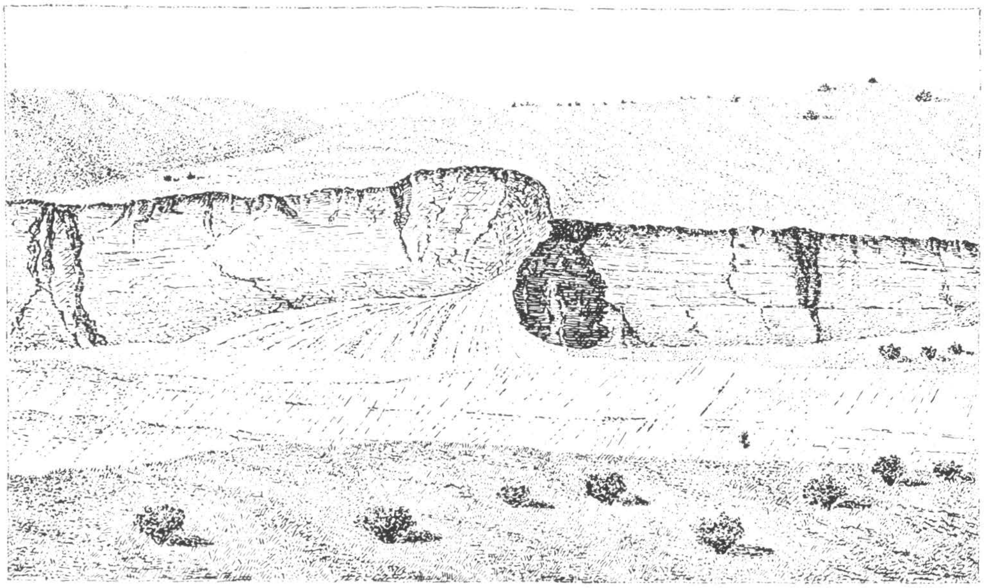


FIGURE 91.—Fault in Moenkopi formation at head of Rock Canyon. Sketch by Elinor Stromberg.

Johnson Canyon.—Through the White Cliffs Johnson Creek occupies a canyon cut into Navajo sandstone which shows no structural disturbances other than its northeastern dip. Farther downstream the west side of the canyon is traversed by a fault, for short stretches by two faults, that bring the Wingate sandstone to the level of the Kayenta formation—a measured upthrow on the east of 100+ feet. (See fig. 93.) Though no other faults were found along the canyon, the discordance of strata on opposite walls seems to require the assumption that the rocks beneath the alluvial floor of the valley are also displaced. For a distance of about 5 miles above the village of Johnson, despite an easterly dip of 2°, the strata on the east side of the canyon are 100 to 200 feet higher than corresponding strata in the west side. Additional evidence of displacement is a "shatter belt," produced by tiny faults at one of the few places where streams have cut to bed rock. This assumed fault, now concealed by valley fill, probably dies out southward before reaching the face of the Vermilion Cliffs. Near the mouth of Johnson Canyon comparable strata continue to occupy higher positions on the east but on the canyon floor appear to be unbroken. In the absence of a topographic map of suitable scale the exact arrangement of the beds in Johnson Canyon was not recorded, but the structural features observed suggest that its mouth lies on the west flank of an anticline and that for some miles farther north and south it is located on a low broad upwarp faulted on its western flank.

Kanab Canyon.—Kanab Canyon like Johnson Canyon exhibits structural features not easy to define, particularly where its course lies in unstratified sandstone. In its course across Skutumpah Terrace, faults of small displacement are shown in the Dakota (?), the Curtis, and the Carmel formations and below the mouth of John R. Valley short faults with upthrows of 3 to 15 feet traverse the west wall of the canyon. However, the combined displacements of the faults observed is insufficient to account for the fact that though the strata dip generally northeastward, the eastern outcrops of corresponding beds lie higher than the western, that across a canyon less than half a mile wide the discordance in position of an individual stratum is 80 to 250 feet. It therefore seems reasonable to suppose that displacements of considerable amounts are recorded in the bedrock now deeply buried by alluvium. Support for this assumption appears in the faults that break the Shinarump conglomerate, which crosses Kanab Valley south of Vermilion Cliffs. Though the observed and the conjectured faults seem to explain the structural features of Kanab Valley the information is too meager to justify wholly discarding the possibility that the displacement involved both folding and faulting.

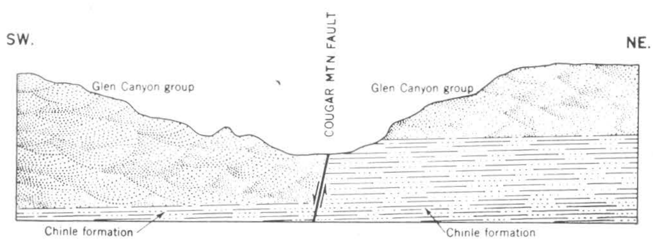


FIGURE 92.—Cougar Mountain fault at a point in divide between Left Fork and Right Fork of North Creek, displacement 480± feet.

JOINTS

In the rocks of the Zion Park region joints are common and in places unusually prominent. They include not only the short, irregularly spaced, tight cracks that everywhere result from the consolidation of sedimentary deposits, the radial "sun symbols" in limestone and hexagonal outlines in sandstones, but also cracks that extend for miles. Some of them are wide open, some closed, some filled with extraneous material, and some lined with cemented bits of bordering rock. Along the cracks and zones of jointing in the Jurassic and Cretaceous sandstones small-scale faulting is fairly common, and displacements of a few inches or feet are characteristic features of many canyon walls and faces of detached mesas; and though most of these joints affect only a single formation and are too small to be expressed in the topography, they have determined to a large degree the form of cliffs, the alinement of tributary streams, and the position of springs and seeps. (See p. 196.) As an example of their kind and arrangement in the thick-bedded sandstones of the Zion Park region the joints were mapped in the Pine Creek Canyon, where they concern the stability of the highway tunnel bored through Bridge Mountain.[24] Here within a distance of half a mile the massive, fine, even-grained Navajo sandstone and the underlying sandstones and shales are traversed by more than 200 joints, widely spaced or grouped as fracture zones 6 to 20 feet wide and including 4 to 30 joints. Most of the joints are vertical and extend from the base of the huge bed of sandstone to its top; some traverse but a part of the sandstone bed; others pass not only through the sandstones but also through the underlying shale. Fully 90 percent of the joints are arranged in two series, trending N. 20°–30°W and N. 70°–80°E. In the Bridge Mountain mass most of those that trend northeast are tightly closed and relatively discontinuous, but on the walls of Pine Creek Canyon they extend parallel with the cliff face and as open cracks outline great slabs that from time to time are detached and fall as talus blocks. The northwest-trending joints, especially those arranged in groups, traverse the entire mountain and extend beyond its limits. Some of them seem

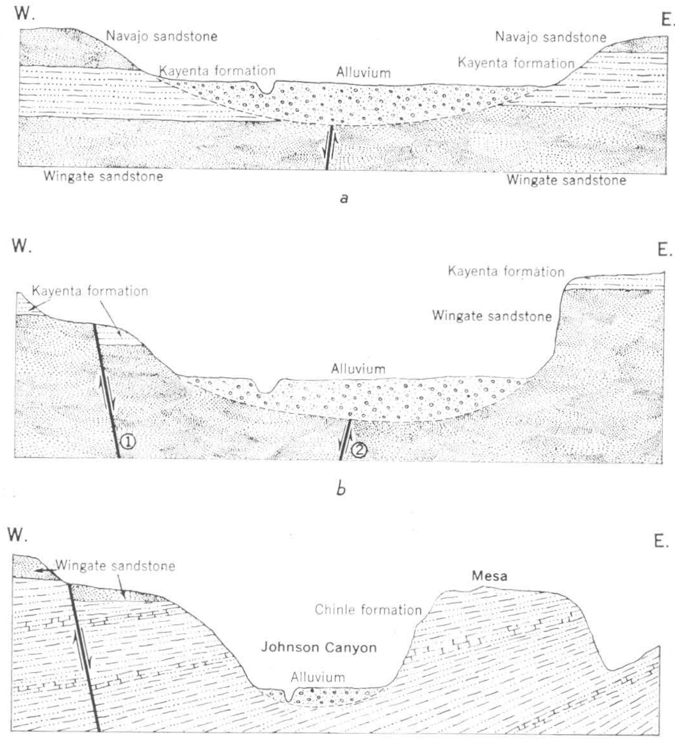


FIGURE 93.—Cross section showing faults in Johnson Canyon. *a*, 5 miles north of settlement of Johnson; concealed fault with a displacement of at least 100 feet indicated by discordant position of strata that strike N. 70° W. and dip N. 2° E.; *b*, 3½ miles north of Johnson, strike of Kayenta strata N. 85° W., dip N. 2° E.; the displacement of fault 1 is 85 feet; of fault 2, 240 feet (estimated); *c*, mouth of canyon, 2 miles south of Johnson, displacement of fault 200+ feet, beds on west horizontal on the east dip N. 4° W.

24 Gregory, H. E., Geology of the Pine Creek tunnel (manuscript report, National Parks Service, 1932).

always to have been closed, many once open have been closed by cementing materials brought in by ground water, and some as far as 100 feet back from the face of the cliffs are wide cracks filled only with loose sand. Along slickensided surfaces many of the joints bear evidence of faulting, in most places measured in inches. The maximum displacement observed is 4.3 feet. In the Zion Park region the length of the rock joints, their depth and their greater abundance near faults and their general parallelism with the lines of major displacement suggest that they are small scale expressions of the stresses that have produced the regional uplift and such zones of fracture as the Hurricane and Sevier faults.

Joints not related to regional rock stresses are features of the redbeds of the lower Moenkopi in places where solution of the underlying limestone permits vertical slumping. On the north bank of Timpoweap Canyon they appear as open cracks 3 inches to 4 feet wide and 40 to 200 feet deep, over an area of about 10 acres.

PHYSIOGRAPHY

GENERAL FEATURES

In the Zion Park region the physiographic features peculiar to the great plateaus of southern Utah find full expression. Within an area of more than 80,000 square miles on both sides of the Colorado canyons the sedimentary rocks are similar in sequence and character, the crustal movements are comparable in kind and in time, the periods of igneous activity are more or less closely related, and the development of the streams on highlands and lowlands follows a common pattern.

Throughout the plateau province the topography is the result of a combination of conditions present in few other regions: general horizontality of strata; alternation of relatively thin, resistant hard beds, thick, massive friable beds, and thin soft beds; a climate characterized by spasmodic rainfall; and streams with steep gradients. Because of these conditions, which facilitate erosion, large parts of Utah and adjoining states are characterized by a landscape of angular features scantily clothed with vegetation, but, though the processes involved in converting continuous broad thick sheets of sedimentary rock into a canyon labyrinth are alike throughout a great area, the rate of erosion is not everywhere the same, and consequently the erosion remnants vary widely in size and shape. In southern Utah the outstanding topographic features are cliffs, platforms, and canyons produced by the erosion of nearly flat lying rocks. Though cliffs along faults, volcanic cones, and streams of lava interrupt the normal subhorizontal features of the landscape, the long ridges of folded rock, the intrusive igneous masses, and the mountainous piles of lava and ash are prominent only in surrounding regions. (See p. 4.)

As recorded in the Zion Park region the physiographic history of the plateau country during post-Eocene time is concerned chiefly with the stripping of 5,000 to 6,000 feet of Mesozoic and Cenozoic strata from the uplifted lands adjoining the present Colorado River back to the face of the present Markagunt and Paunsaugunt plateaus. In performing this work the streams seem not content with removing the products of weathering; they dig deep trenches into the rock and remove the intervening material by a process of lateral mining. Great plateau blocks are first outlined by a series of master trenches like those occupied by the Escalante, the Paria, the Kanab, the Parunuweap, and the Virgin; secondary trenches divide the block into mesas and elongated ridges, and trenches of the third and fourth order break the original earth block into innumerable varied forms. The resulting landscape appears in general views as a succession of terraces miles in width separated by escarpments hundreds of feet high; of broad surfaces and straight lines of cliffs that extend on and on until they fade into distant horizons, but the highland and lowland surfaces are so intricately dissected by deep, narrow canyons that most view points reveal a ruggedness comparable to that of elaborately carved mountains. (See fig. 2.) Canyons seem to be everywhere and to vie with the bold cliffs in giving the landscape of the plateau country its astounding expression.

In a few places the work of the quarrying streams is complete—the surrounding land has been reduced nearly to the level of the stream bed—but generally the streams are vigorously at work in the bottom of canyons where waterfalls and rapids are common. Except in special locations and for short stretches evenly graded streams are lacking. In a physiographic sense the region is youthful.

It is interesting to note that though the geologists of the Wheeler and Powell surveys had no previous experience in deeply dissected regions they quickly learned the meaning of the platforms and gorges of the High Plateaus and the Grand Canyon district. For the plateau province, in fact for the North American continent, the principles of earth sculpture established by Powell, Gilbert, and Dutton mark the first clearly defined step toward the systematic investigation of stream erosion as conditioned by climate and structure. By these authors the prophetic teaching of Hutton[25] regarding the causal relation between structure, stream work, and topography, neglected for 50 years and revived by Newberry[26] without at-

[25] Hutton, James, Theory of the earth, pp. 411–413, 1795. Discussed with reference to the Colorado plateau in Gregory, H. E., Steps of progress in the interpretation of land forms in a Century of Science in America, pp. 124–153, Yale Univ. Press, 1918.

[26] Newberry, J. S., in Ives, Colorado River of the West, pt. 3 [Geol. Rept.] 1857.

tracting attention, was given vigorous new life in an exceptionally favorable environment. It seems noteworthy that in reports by all the pioneer geologists of the plateau country the physiographic interpretations rest on the same principles—general independence of stream and major tectonic structures, the effect of alternating hard and soft rock, and the orderly development of erosion forms. As the application of these principles and also the meaning of successive events in the physiographic history of northern Arizona and southern Utah seem adequately treated in previous publications,[27] the present paper deals chiefly with features and processes particularly well illustrated about the rim of the High Plateaus.

FACTORS THAT INFLUENCE EROSION

CLIMATE

The climate of the Zion Park region as a whole may be termed semiarid or, perhaps more correctly, subhumid, but in response to differences in altitude and topographic exposure the plateau tops, the intermediate slopes and the lower valley floors have climates of their own. (See p. 28.) Thus, on the Markagunt plateau the annual precipitation exceeds 30 inches, more than half of it snow; on the Moccasin and Wygaret Terraces it is 12 to 15 inches; and in the lower valleys it is less than 8 inches. Likewise on the highlands freezing temperatures occur about 270 days a year; on the lowlands about 170. Erosion by wind is conspicuous only at altitudes below 4,000 feet. Precipitation is sufficient to maintain perennial flow in the La Verkin, the Virgin, the Parunuweap, and the Kanab, and in such tributaries as Muddy Creek, Meadow Creek, North, Deep, and Dairy Creeks, and if the rainfall were evenly distributed through the year it would change intermittent Johnson, Short, Little, Sand, and Cottonwood Creeks into through-flowing streams, although erosion by such small streams would be relatively slight. Even for the Virgin River, by far the largest stream in southwestern Utah, the average annual runoff at the mouth of Zion Canyon is but 89.3 second-feet—the measure of scores of minor rivers in more humid regions. In their power to erode, the streams of all sizes and classes in this region are controlled not so much by the amount of precipitation as by its wide variation in time, amount, and place. Much of the annual rainfall consists of a series of local torrential showers, which fall on bare rock, loose sand, and thin soil scantily covered with vegetation. The consequent runoff is very rapid, thus facilitating the removal of large amounts of rock debris. During ordinary showers the falling rain gathers almost immediately into swift rivulets which follow ready-made gullies and creeks to larger drainage channels, unite as sheets of water moving across the surface to some local depression, or plunge over the cliffs as sheet waterfalls, carrying the loose rock and plant debris encountered along the way. In the heavy downpours covering square miles a turbulent flood of dirty water piles into canyons and rushes downstream like floods from a broken dam. Measurements show that, after short-lived heavy rains in rock-walled defiles normally occupied by streams a few inches deep and at times even dry, water may accumulate to a depth of 5 to 10 feet in an hour, and that during occasional floods gorges, as much as 30 feet deep in rock and in alluvium, are filled to the brim. For removing debris, breaking down banks, and scouring bedrock, such volumes of swift water are obviously powerful agents, and, as floods follow nearly all showers, widespread stream erosion is characteristic. A view of such a channel after a flood has run its course shows new erosion scars on its floor and sides, rock masses weighing tons that have been transported several hundred feet, and in places a changed alinement. (See pp. 174–175.)

In the Zion Park region frost is an active agent in the disintegration of rocks. The porous rock about seepages and cracks contains water that freezes many times each year, on the highlands almost every day. From cliffs and canyon walls of the intricately jointed Navajo, Wingate, Shinarump, and Straight Cliffs sandstones, innumerable blocks are pried loose to form a patchy talus, and outcrops of limestone of the Carmel yield in abundance hard angular fragments in sizes and shapes suitable for road material. Kinesava, the Piute "demigod of strange happening," who amuses himself by rolling rocks from the cliffs to the valley floors, is especially playful during the spring months. (See p. 32.) On the slopes formed in less resistant rocks the frost each spring supplies a thin coat of broken rock ready for removal by the torrential rills of summer.

VEGETATION

As compared with regions where the climate and soil are suitable for profuse plant growth, the vegetation of southwestern Utah is a geologic agent of minor importance. In directing and controlling the

[27] Blackwelder, Eliot, Origin of the Colorado River: Geol. Soc. America Bull., vol. 48, pp. 551–556, 1934. Davis, W. M., An excursion to the Grand Canyon of the Colorado: Harvard Coll. Mus. Comp. Zoology Bull., vol. 38, pp. 118–121, 167–169, 1901. Dutton, C. E., Tertiary history of the Grand Canyon district: U. S. Geol. Survey Mon. 2, pp. 206–229, 1882. Gilbert, G. K., Report on the geology of portions of Nevada, Utah, California, and Nevada in Wheeler, G. M., Exploration and Surveys W. 100th Mer. vol. 3, pp. 17–187, 1875. Gregory, H. E., Geology of the Navajo country: U. S. Geol. Survey Prof. Paper 93, pp. 122–123, 130–132, 1917. Gregory, H. E., and Moore, R. C., The Kaiparowits region: U. S. Geol. Survey Prof. Paper 164, pp. 138, 139, 143–144, 1931. Gregory, H. E., Colorado plateau region: 16th Internat. Geol. Cong. Guidebook 18, 1932. Gregory, H. E., The San Juan country: U. S. Geol. Survey Prof. Paper 188, pp. 92–94, 1938. Longwell, C. R., Geology of the Muddy Mountains, Nevada: U. S. Geol. Survey Bull. 798, pp. 126–149, 1928. Matthes, F. E., The Grand Canyon of the Colorado River [text on back of topographic map of Bright Angel quadrangle, Ariz.], 1912, 1932. Powell, J. W., Exploration of the Colorado River of the West and its tributaries, Wash., 1875. Robinson, H. H., The Tertiary peneplain in the plateau district and adjacent country in Arizona and New Mexico: Am. Jour. Sci. 4th Ser., vol. 24, pp. 115–118, 1907.

rate of rainfall it is relatively inefficient and in this region of bare rock, steep slopes, and semiarid climate, it seems impossible to produce vegetable matter, dead or alive, on or within the soil in quantity or kind sufficient to retard effectively the collection of rainfall into stream channels. The kind, relative abundance, and patchy distribution of the plants suggest that they are poorly adjusted to a region where rapid erosion has long been assured by physical agents. On the highest plateaus grass and annuals in natural meadows and brush in thickets interfere with free runoff sufficiently to permit some of it to sink into the underlying soil and rocks, and on lower slopes and flatlands piñons, junipers, oaks, and interspersed sagebrush and annuals of various kinds retard the movement of rain-made rills. Areas of forest litter, matted grass, and thickly interlaced roots, however, are small and widely separated. Over most of the region grass spears, weed stems, and tree trunks stand by themselves, leaving ample space for water runways, and in large areas vegetation is lacking. In the Zion Park region the normally small control of erosion exercised by plants has in recent years been decreased in consequence of overgrazing and the unwise selection of lands for farming. (See pp. 34 and 44.)

STREAM GRADIENTS

Of the two long tributaries to the Colorado River that head in the High Plateaus of southwestern Utah, the Virgin reaches its master stream after flowing about 200 miles on an average gradient of 40 feet to the mile, and the Kanab in 90 miles on a gradient of 85 feet to the mile. (See fig. 97.) In the Zion Park region, where these streams are most vigorous, the Virgin descends from the rim of Markagunt Plateau (altitude 8,000–9,000 feet) to the base of the Hurricane Cliffs (altitude 5,500 feet) at the rate of nearly 80 feet to the mile and through Zion Canyon at 50 feet to the mile, and the Kanab in its course from the Paunsaugunt Plateau to Fredonia falls 72 feet to the mile. The average gradient of the Parunuweap is 70 feet to the mile, of Johnson Creek about 100 feet, of the La Verkin 110 feet, and of Short Creek, even in its slowest stretches, 30 feet. The fall of many tributaries to the Virgin, the Parunuweap, and the Kanab, which flow southward across the Kolob Plateau and Skutumpah Terrace, exceeds 200 feet to the mile and for short distances at their heads is 500 feet. Traverses of scores of the stream beds show a succession of relatively flat and relatively steep gradients, which give rise to swift currents, rapids, and waterfalls between stretches of more slowly moving water. These steep gradients and interrupted valley profiles are in themselves evidence of rapid erosion; additional evidence lies in the enormous quantities of material torn from the bed and the sides of the channel and moved forward, especially at times of flood. Exclusive of the huge blocks, the boulders, and the cobbles rolled along during times of high water and the sand and gravel carried on the stream bed at all stages of flow—materials that make up perhaps half the total load—the rock debris transported each year by the Virgin River at Virgin City is estimated as 300,000 tons. (See p. 161.) In places so much of the energy of the rivers is consumed in transportation of the waste contributed from upstream sources that vertical down cutting is impeded. Short Creek, on the east flank of Lost Spring Mountain has almost choked itself with sand carried outward from the Vermilion Cliffs. Lower Sink Creek is barely able to carry the sand ground from the Gray Cliffs; even in flood it seems to wander aimlessly over the surface. In dry seasons it abandons its task and flows underground. Likewise the Virgin River between Rockville and the head of Timpoweap Canyon flows in braided channels over a deep bed of sand.

GROUND WATER

In the Zion Park region deep trenching by innumerable canyons has exposed the many aquifers among the sedimentary beds and provided exits for springs and seeps. As a factor in erosion ground water thus assumes a position second only to stream scour; in solid rock and in alluvium it widens the canyons which rivers have deepened. Local concentration of ground water has resulted in the production of alcoves and of rock-roofed recesses along canyon walls and thus has brought to the surface many square miles of rock that otherwise would have been protected from rain wash and chemical decay. Also general seepage has removed the cement from about the grains, with the result that large areas of porous sandstone beds are coated with loose debris which is easily removed by showers or wind. Many rock surfaces that are dry or covered with moist efflorescence when exposed to daylight evaporation, are wet at night and may give rise to tiny streams. The efficiency of ground water is further shown by landslides. (See pp. 196–197.)

BEDROCK

To a remarkable degree the rate and manner of erosion in the Zion Park region records the control exercised by the composition, structure, and attitude of the rocks. The surface of each plateau, platform, bench, and mesa, regardless of its size and altitude, has been developed on a rock mass relatively resistant to erosion. Likewise the cliffs that bound the tabular forms are made of hard rock. (See fig. 23.) Where these resistant beds lie nearly horizontal the surface of the platforms is broadly level; where they are gently inclined the surface is similarly inclined; and in the few places where the beds dip steeply the topography records the inclination. In contrast to the generally flat, cliff-bound surfaces in hard rock, slopes or gently undulating surfaces characterize the exposures of weak beds. With relative rapidity the less resistant rocks are worn to steep slopes, to gentler slopes, and to flats and finally are stripped from the harder rocks beneath; but at all stages in the process the general slope is broken by conspicuous low steps that mark the position of thin resistant beds. This stripping of weak formations from strong ones is a process of major importance to which is largely due the peculiar configuration of the plateau surfaces. (See p. 177.)

Relative rock hardness controls not only the development of the plateaus, terraces, and cliffs but in a large degree determines the form of valleys. Where stream channels are cut entirely in hard rocks their sides are precipitous, and their floors are narrow and steeply inclined, forming canyons hundreds of feet deep and a few tens of feet wide through which water flows swiftly. Some are mere slots barely wide enough to permit passage on foot, others end abruptly upstream and can be entered only at their mouths. To the Piutes the walled-in valley above Rockville was Ioogoon (iv, sand rock; ooghan, quiver), an arrow quiver of rock from which "you come out the way you go in." Canyons sunk into vertically alternating hard and soft rock present corresponding alternations of narrow and wide floors and precipitous and sloping walls.

Where soft rocks alone form the stream channels the valleys tend to be broad, shallow, and flat-sided. In size and degree of flatness they reflect the relative ease of erosion by streams during flood seasons; between floods their channels are too broad for their needs. In the friable Moenkopi beds between Pipe Spring and Fredonia the original canyons of Two Mile Wash, Sand Creek, and Cottonwood Creek have been converted into broad washes defined by inconspicuous divides, and in the Chinle beds between Kanab and Johnson Canyon the valley sides have been flattened to a plain about 6 miles long and 2 miles wide. Along some of the larger drainage lines the already wide valleys are made still more open by the entrance of tributaries into the soft-rock belt. Thus erosion of Chinle strata at the base of the Vermilion Cliffs by branches of Short Creek and Little Creek has left the flat-floored "cane beds," which are duplicated in the soft Jurassic rocks near the mouth of Yellow Jacket Canyon. In the Tropic formation the many-branched Meadow Creek has widened its valley into a saucerlike "hay field" and under similar conditions the "Cove" at Orderville has been formed—one of the many "round valleys" developed by the erosion of weak Cretaceous shales. In carving the shales at Alton a score of small tributaries to the Kanab have combined to develop a broad, flat-floored amphitheater, walled in by the Cretaceous sandstones and Tertiary limestones of Paunsaugunt plateau. (See fig. 115.)

On many canyon walls and sloping valley sides where weak rocks interbedded with hard layers are locally exposed, rain-made rivulets have carved the beds into picturesque forms. Few views are more attractive than the maze of tiny canyons, benches, slopes, and knife-edged divides on the Moenkopi strata at Virgin and the Chinle at Springdale and in Sand Canyon.

So persistent and uniform is the relation of rock composition and texture to the rate and manner of erosion that with but a general knowledge of the regional stratigraphy it is possible to predict the type of streamway in areas not yet explored. Experience teaches that valleys in the Entrada, the Winsor, the Tropic, and the Kaiparowits formations, in the Petrified Forest member of the Chinle, and the Shnabkaib member of the Moenkopi may be readily crossed by meandering rill-scored slopes or by descending and ascending low steps. On the other hand, routes across canyons in the Kaibab, the Wingate, the Navajo, the Straight Cliffs, and the Wasatch formations are generally impracticable; they involve miles of round-about traverse or the skillful use of ropes.

POSITION AND FORM OF VALLEYS

Outstanding features of the stream channels in the Zion Park region are prevailing trends that disregard faults and the regional attitude of the strata; local alinement, controlled in part by fractures; and form determined by the composition and texture of the rocks. In a region where the rocks dip northward, northeastward and eastward, the major streams and many minor streams follow valleys that trend southward, westward, and southwestward—up dip, across large and small faults, and across folds without significant change of direction. The Virgin River flows southward across the northward-tilted Kolob Terrace then westward across the anticline at Grafton and the upturned strata at the Hurricane Cliffs, and farther southwestward it passes with seeming unconcern through structural domes and fault blocks. Kanab and Johnson Creeks on the Skutumpah and Wygaret Terraces, Sand Creek and Cottonwood Creeks on the Moccasin Terrace, and La Verkin and North Creeks on the Kolob Plateau flow opposite to the regional slopes. Little and Short Creeks flow westward up the regional dip of the strata in Little Creek Terrace and without deflection cross the Hurricane fault in Gould Canyon and Rock Canyon. With seeming disregard for structure, North Creek crosses the Cougar Mountain fault, the La Verkin crosses

EXPLANATION OF FIGURE 94 Gregory, H. E. 1286

Entrenched meanders of Virgin River at upper end of Zion Canyon. The walls of Navajo sandstone rise 1,800 to 2,200 feet above the river. Photograph by Army Air Corps.

Hurricane fault and other displacements farther upstream, and Pipe Wash, Two Mile Wash, and Sand Creek cross the great Sevier fault from the downthrown to the upthrown side. Even such feeble streams as Coalpits Wash and the western tributaries to Johnson Creek are little affected by structural features. Obviously, these streams so completely out of accord with regional slopes, originated on surfaces no longer represented in the landscape. (See p. 166.)

In alinement the valleys of such large streams as the Parunuweap, the Virgin, and Short Creek are generally straight for long stretches between nearly right-angled bends that redirect their courses to various positions within the southwest quadrant. The Kanab Valley for 90 miles varies little from a north-south line, and for a streamway of its length the Johnson Valley is exceptionally straight. On the flatlands some shallow valleys curve far to the right or left of their general axis, but along most canyons the tangents to larger curves are for long distances parallel and less than a mile apart. But within these limits the valleys are crooked to a remarkable degree; the streams that occupy them follow angular bends and curves of short radius, which commonly are so closely spaced that few straight stretches are as much as 500 feet long.

Some of these meanders are normal features of stream development, but the sinuous, in places zigzag courses followed by scores of perennial, intermittent, and ephemeral streams in narrow high-walled canyons are abnormal; the canyon form is characteristic of youthful topography, the stream alinement, of old age. (See figs. 94, 95.) The energy of the present vigorous streams is expended chiefly in down cutting and in transporting waste. Even at flood stages, lateral corrasion, which would permit the enlargement of curves, is relatively slight. The great curved recesses in the canyon walls are not directly related in size or position to curves in the stream below. It seems probable that the meanders in the canyon portions of the Virgin, the Parunuweap, the Kanab, the La Verkin, North Creek, and many shorter valleys, all now deeply entrenched, were left from ancestral streamways on old surfaces where meandering courses were characteristic, and that in consequence of regional uplift they have been incised without much change in form. Entrenched meanders like those in the Zion Park region are excellently displayed in other parts of the plateau province. Their history is doubtless that of the more prominent entrenched meanders of the San Juan, the Escalante, the Colorado in Glen Canyon, and of many streams

in the Navajo country, as related in other publications[28] by the Geological Survey.

In contrast with the pattern in which valleys hold positions without regard to regional slopes, most of the abrupt changes in alinement of the large canyons and the entire courses of many valleys are in accord with zones of fracture. Faults of slight throw, groups of closely spaced joints, even single strong joints have determined the position of many shallow canyons, of gulches within the deep canyons, and of the gaps between buttes.

The structural control of valley alinement is well illustrated by the straight, parallel tributaries to the Parunuweap, Pine Creek, and Orderville Canyons. (See fig. 96.) Similar trellised drainage is a feature of many interstream spaces. Taking advantage of prominent joints that cross each other nearly at right angles, streams have carved a surface of rectangular bosses surrounded by grooves.

In Echo, Wildcat, and Parunuweap Canyons, Orderville Gulch, and in the Virgin River Canyon at the base of Mount Mystery the prominent zigzag bends follow zones of jointing, and as the canyon walls recede they maintain their angularity by scaling off sheets of rock back to joints in parallel positions.

South Wash, though excavated in soft rocks that under other conditions would facilitate meandering, is outlined by straight and parallel walls because it is developed on the flank of an anticline.

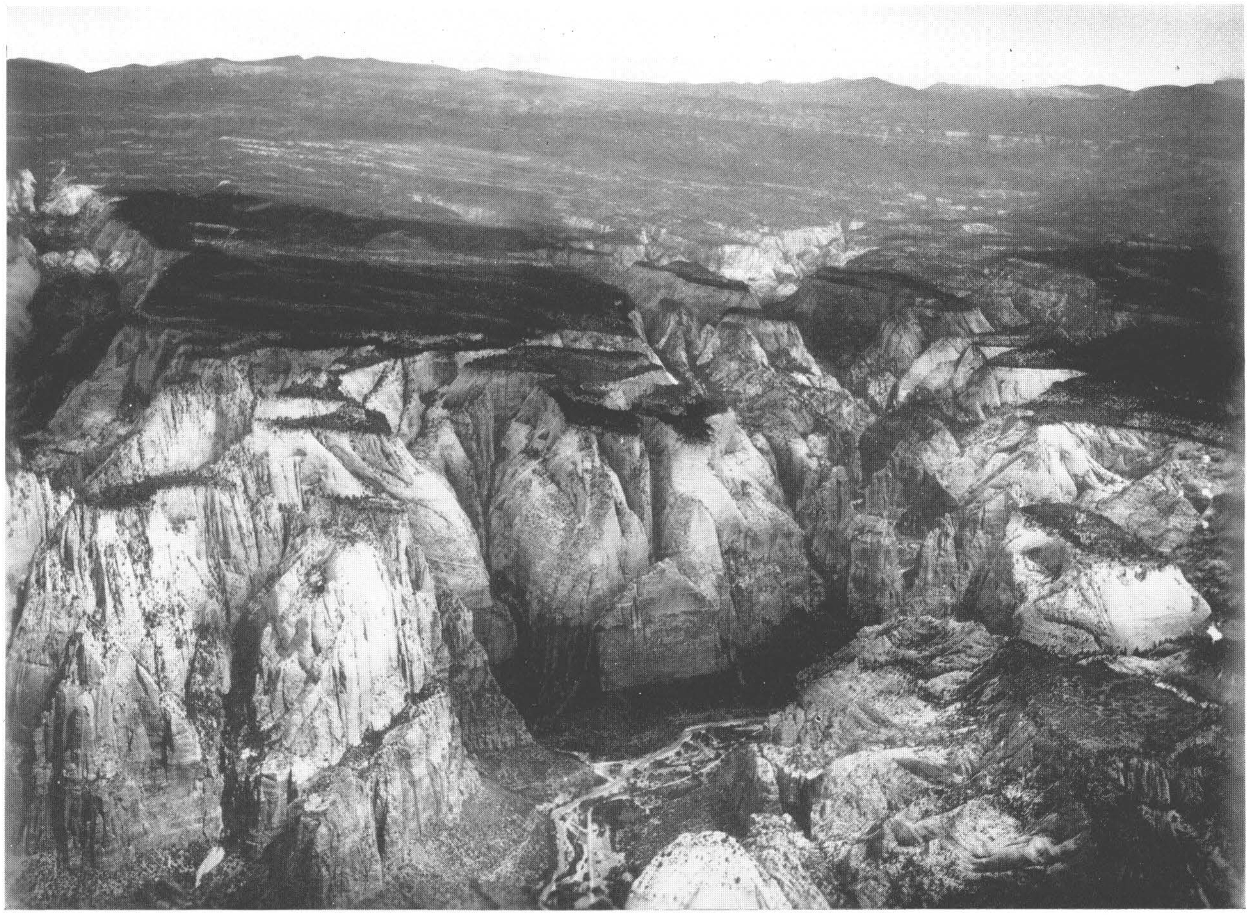


FIGURE 95.—Erosion surface developed on Carmel formation. Flatlands (upper middle) are in process of dissection by Virgin River (bottom center) and its tributaries. The view includes 14 canyons, each as mush as 800 feet deep. Airplane photograph, National Park Service.

The positions of many alcoves and amphitheaters along canyon walls, the trends of many cliffs, and the positions and architectural forms of the famous "Towers and Temples of the Virgin" likewise reflect the control of stream course by structure. Such magnificent features as the Watchman, the Sentinel, the Three Patriarchs (fig. 7), the Mountain of the Sun, the Guardian Angels, and the Great White Throne are sculptured blocks of relatively unfractured rock that stand between zones of jointing and they owe their individuality to the headward growth of canyons in the fractured rock that surround them. Innumerable small-scale architectural features have the same origin. In fact to a very large degree the sculpture of the Zion Park region was predetermined by a network of joints and faults, and its labyrinthine delicacy of sculpture is due to erosion guided by the crisscross fractures.

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[28] Gregory, H. E. The Navajo Country: U. S. Geol. Survey, Prof. Paper, 93, pp. 126–127, 1917; The San Juan Country: U. S. Geol. Survey Prof. Paper, 188, pp. 97–98, 1938. Gregory, H. E., and Moore, R. C.: The Kaiparowits region: U. S. Geol. Survey, Prof. Paper, 164, pp. 124, 135–138, 1931. Miser, H. D. The San Juan Canyon, southeastern Utah: U. S. Geol. Survey, Water Supply, Paper, 538, pp. 67–71, 1925.

In longitudinal profile the floor of most canyons in the Zion Park region is a series of steps, of various width, height, and spacing. (See fig. 97.) In most of them the riser and the tread above it are bare rock, irregularly grooved at the center, over which the streams pass as rapids and waterfalls. The stairlike longitudinal profile of the major drainage channels continues up many long tributaries without significant change in general inclination. For example, the channels occupied by Orderville and Deep Creeks, Muddy Brook, and Crystal, Meadow, North, Cottonwood, Johnson, and Three Lakes Creeks join their master channels by descending slightly inclined ramps. Also in the broad parts of the Parunuweap, Kanab, Johnson, Short Creek, and a few other valleys that have been developed in weak rock, the tributaries of the first order and some of the second and third orders are adjusted to the slopes of the main channels. On the other hand the discordance in channel profile is such that many of the smaller streams reach the larger streams through steeply inclined slots and many more occupy hanging valleys from which they drop tens or hundreds of feet to the valley floor below. (See fig. 98.) After showers, literally hundreds of ephemeral waterfalls in jets and sheets extend from the top to the bottom of canyon walls or turn into mist along the way. For the region as a whole, stream channels that descend by steps are far more numerous than those that slope uniformly downward; in fact, vertically zigzag, longitudinal profiles are characteristic features of plateau topography. Though for millions of years the larger streams have been at work in substantially their present runways, they have not yet been able to establish regular slopes at progressively lower inclinations.

In cross profile the prevailing type of stream channel is a narrow, flat-bottomed, deep gorge. (See figs. 26, 27, 99.) Many of the wider, shallower valleys are likewise flat-bottomed and even valleys in alluvium conform to this pattern.

The width and depth of the canyons record their age, the size of their contributary drainage basin, and the type of rock in which they have been incised; the form of their walls measure chiefly the relative durability of strongly jointed sandstones, shales, and limestones when exposed to weathering. In brief, the canyon form in the Zion Park region is conditioned by a semiarid climate and by the attitude, composition, and texture of the local rocks. Because thick outcrops of consistently soft rocks are rare, narrow V-shaped valleys and broad open valleys are uncommon. Especially rare are valleys in which the sides continuously bevel the strata and lead to poorly marked divides. In accord with the thickness and relative hardness of the bedded rocks along their courses the deep upper tributaries of the Virgin River and other streams have two sets of walls—flights of steps a thousand feet high leading down to a single step 600 to 1,200 feet high. In Timpoweap Canyon an inner canyon is sunk in a platform above which rises the walls of an outer canyon. (See figs. 26, 27.) These platforms on which the canyon walls are vertically offset are features of normal erosion by the

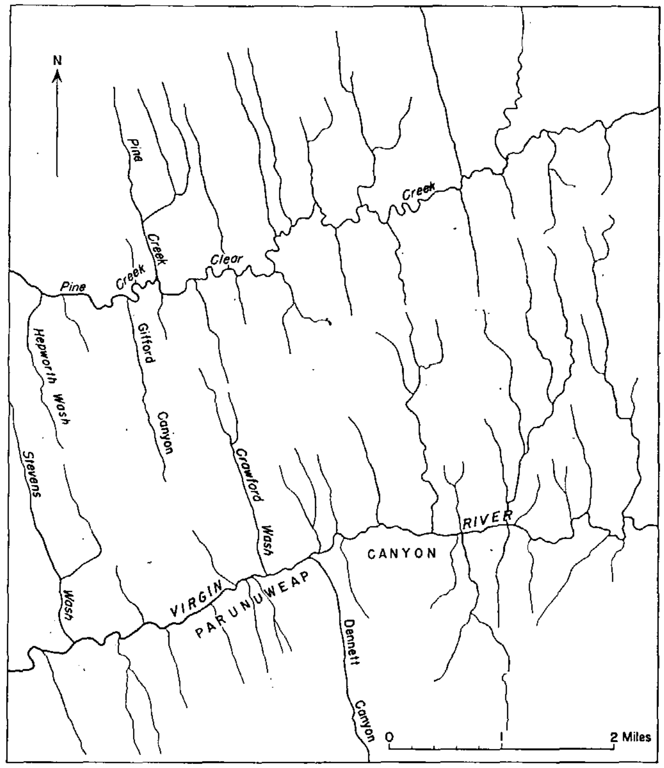


FIGURE 96.—Alinement of canyons tributary to Parunuweap River and Pine Creek, showing influence of rock joints.

existent stream and not as thought by Gilbert and Dutton evidences of halts in regional uplifts. They are erosion surfaces with various dimensions and appear wherever a particularly resistant stratum is encountered by streams in digging their trenches. (See p. 177.)

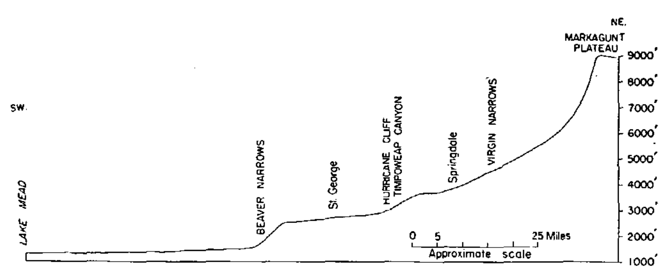


FIGURE 97.—Profile of Virgin River. Based on topographic maps of Powell Survey.

Some valleys in the Zion Park region are separated from neighboring valleys, headward and laterally, by fairly stable divides in the form of cliffs, sharp-crested ridges, and remnant flatlands some of them encumbered by ponds and swamps, but in general the region is thoroughly drained, and, as might be anticipated in a country where headward erosion of streams is exceptionally active, the shifting of divides is common and relatively rapid; the more efficient youthful streams are enlarging their drainage areas at the expense of the older streams. Particularly on the erosion surfaces characterized by very low relief the boundary between drainage systems is difficult to define. (See p. 156.) At present the rim of the Markagunt and Paunsaugunt plateaus is the divide between generally weak northward-trending streams of gentle gradient that head indefinitely in swales and meadows and join the Sevier River on its way to extinction in the Great Basin and vigorous southward-trending streams that head in steep-walled gullies and alcoves and flow on steep gradients to the Colorado River. The actual water parting is a crenulated line that crosses flats and gentle slopes or follows the crest of ridges and the rim rock of canyons. Along this line the tributaries to the southward-flowing Virgin, the Parunuweap, the Kanab, and the Johnson are lengthening headward and the northward-flowing tributaries to the Sevier are becoming correspondingly shorter. At Gravel Pass, the head of Parunuweap Valley, the relations between the Sevier and the Colorado drainage systems are well shown. (See fig. 100.) Here the streamways of the two systems interlace in a belt of mounds and ridges of various composition and orientation—solid rock, boulders, gravel, silt, parts of ancient valley sides, valley beds, alluvial fans, and bars. Northward long gentle slopes are traversed by a few wide-spaced shallow valleys; southward steep slopes heading in canyons provide runways for scores of contiguous rills in sharp-cut trenches. The northward-flowing streams occupy gravel-filled valleys of which the upper part has been cut off, and in consequence the channels are too broad for the present ephemeral streams. As these features indicate, the drainage divide along the rim of the High Plateaus marks the boundary between a region of postmaturity and one of youthful topography.

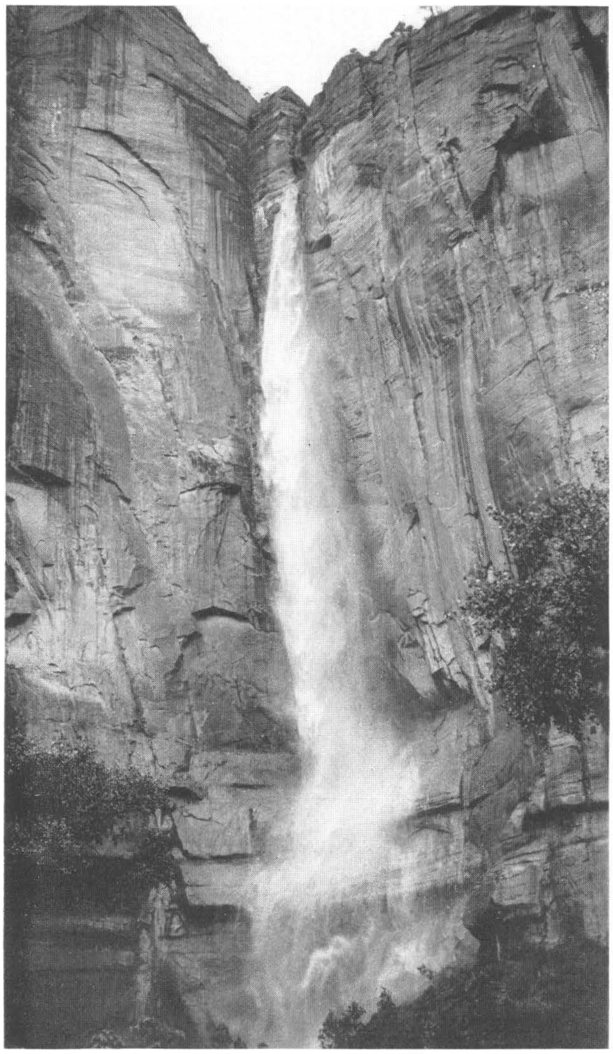


FIGURE 98.—Ephemeral waterfall at Temple of Sinawava in Zion Canyon. For about an hour after heavy rainstorms, water drops over canyon rim 1,800 feet to Virgin River below. Photograph by J. C. Anderson, No. 74.

On a less conspicuous scale tributaries to Kanab Creek north of the Vermilion Cliffs are successfully competing with tributaries to Johnson and Cottonwood creeks, and Muddy Creek is enlarging its drainage basin by capturing the headwater of Mineral Creek and Meadow Creek. West of Pipe Spring, streams flowing southeastward into the Kanab Canyon are cutting back into the region now occupied by tributaries to westward-flowing Short Creek, a branch of the Virgin River. The divide is Cedar Ridge, a once extensive nearly level erosion surface now diminished in size and roughened by cliffs and gorges on its east side. For capturing tributaries to Short Creek, Kanab Creek is favorably placed; though it joins the Colorado at a level higher than the mouth of the Virgin, its course from Cedar Ridge is much shorter and steeper.

On the relatively flat surfaces of Kolob Terrace where tributaries to the swiftly flowing La Verkin and North Creeks and the Virgin River are interlaced, headwater rills have been captured and recaptured in a seemingly capricious manner. Likewise on Moccasin terrace, where the surface consists of flats, low mounds, and rounded ridges and the streamways are unsystematically oriented, only close observation during rainstorms could determine whether the water in ephemeral rills would eventually reach the Virgin River through the Parunuweap, Little Creek, or Short Creek or the Kanab through Sand Creek or Two Mile Wash.

FEATURES OF INDIVIDUAL VALLEYS

Traversing streams that have cut trenches in the Tertiary, Cretaceous, Jurassic, and Triassic formations, ascending their typical tributaries, and scaling their bordering walls clearly reveal the effect of downward erosion on rocks of different grades of resistance and the effect of weathering on cliffs where rocks of different texture and composition are variously exposed to the attack of atmospheric agencies and ground water.

From sources in strong springs at the base of the Pink Cliffs—the Virgin River flows through stretches of open country and canyons developed in Cretaceous and upper Jurassic formations and then begins the digging of trenches in the Navajo sandstone. From the mouth of Deep Creek downstream for about 9 miles the stream flows through the Narrows of the Virgin—for its length the narrowest, deepest gorge in southern Utah. For a stretch of about 3 miles where measurements were made the bottom of the gorge averages 135 feet in width with a minimum of 24 feet. In some of the narrower stretches the stream occupies all the space from wall to wall. From these closely set bases the walls rise sheer or with slight backward slope to heights of 800 to 2,000 feet. (See figs. 101, 102.) In the sky above, the visible blue may measure an arc of 3° to 5° or be entirely cut out by overhanging walls; at night there is "room for a few stars." Both the sheer and the undercut walls are decorated with arches, "caves," and tubular recesses, some of them the source of springs and rivulets. Here and there the worn edges of lava sheets project from the rim. Downstream from the Narrows the Virgin continues to run between walls nearly 2,000 feet high, but because its course is on shales of the Kayenta and Chinle formations, more easily eroded than Navajo sandstone, its floor averages about half a mile in width along the 9-mile stretch through Zion Canyon to the Gateway between the Watchman and West Temple. For 18 miles below the Gateway the stream, developed in relatively soft Triassic shales, runs with gentle gradient in a wide valley bordered by terraced walls of rock and alluvium. (See figs. 15, 103.) Near Virgin it descends into the groovelike Timpoweap Canyon (fig. 26) cut in resistant limestone, 100 to 500 feet deep, from which it abruptly emerges through the face of the Hurricane Cliffs and continues on for 25 miles through soft rock represented by low hills and ridges about Hurricane and Harrisburg and the broad flats about St. George.

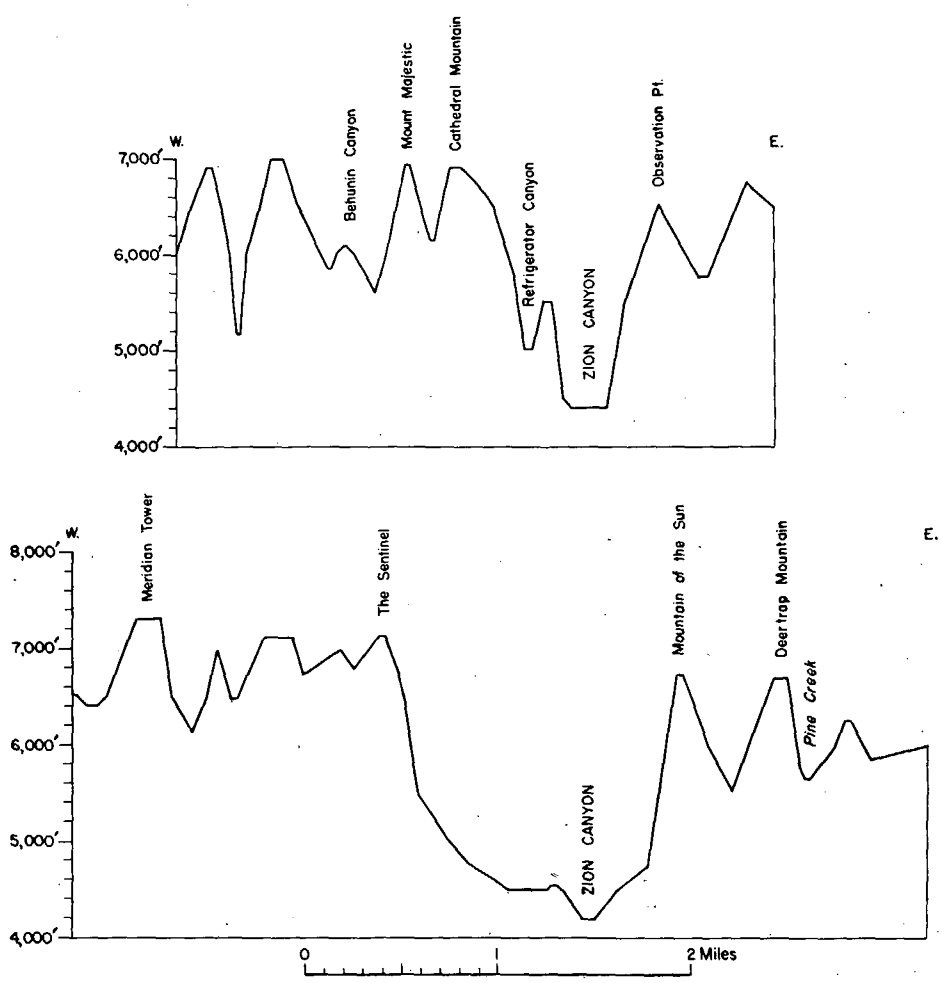


FIGURE 99.—Cross profiles of Zion Canyon and tributary gorges, showing depth and spacing of drainage channels on Kolob Terrace.

Throughout its course in Utah the Virgin River is sinuous to a remarkable degree; particularly in the deep canyon stretches it is as crooked as are streams on flood plains. In parallel position the walls form horseshoes, open curves, and sharp angles, which lengthen the stream and shut out the view ahead. Just below the mouth of Orderville Canyon the stream travels 3.5 miles to cover an airline distance of 1.5 miles; through Zion Canyon meanders have lengthened it 2 miles. Likewise a possible straight course for the tributary Orderville Creek is increased about one-fifth by following angles and curves represented in its lofty bounding walls.

The larger tributaries to the Virgin meet their master stream at grade. Most of the smaller tributaries reach the Virgin by passing over low vertical walls or down steep slopes, or by plunging directly over the canyon rim. In Timpoweap Canyon all side streams descend as waterfalls, and generally the streams in the narrow canyon sections are remarkably out of adjustment. Some tributaries of the first order, though as deep as the master stream, emerge through slots in the walls after descending a steep stairway of high, bare rock steps. The beds of tributaries of the second and third order are even rougher. Experience shows that an ascent of these grooves is a scramble over cliffs and steep slopes between high vertical walls; to cross from one to another is the task of an experienced mountaineer. It is practicable to follow the upper Virgin River and its chief branches through their spectacular canyons on foot and at stages of extremely low water by entering streams that head in the Markagunt Plateau below the cliffs near Navajo lake. In addition to the local precipitous descents the chief obstacles to traverse are huge piles of battered tree trunks wedged together in confusion—the framework for boughs, twigs, pads of dead leaves, and splintered logs that reach from wall to wall. The deep "fall pools" at the base of rapids may be crossed by swimming or on rafts constructed of driftwood.

FIGURE 100.—The divide between drainage basins of Sevier and Colorado Rivers at head of Parunuweap Valley. Tributaries to Parunuweap (foreground) head in gullies cut into a gravel-coated erosion surface developed by Sevier River. Alluvial fans from Paunsaugunt Plateau (top right) trending northward to Sevier are in process of dissection by the south-flowing Parunuweap.

Like the Virgin River, its chief tributary, the Parunuweap River rises in the Pink Cliffs and passes through the shales and sandstones of the Cretaceous and the sandstones and limestones of the Jurassic into shales of the Triassic, where it joins its master stream. In the easily eroded rocks of the Wasatch, Tropic, Kaiparowits, Winsor, and Entrada formations the streamway is fairly broad, flat-floored, and slope-sided, and its gradient is fairly gentle; in the Straight Cliffs sandstone it lies between vertical walls set back from its channel. In the upper part of its course, locally known as Long Valley, the Parunuweap and several of its tributaries are bordered by fertile alluvial terraces and meadowlands in position to be irrigated—the strips of farm land about Glendale, Orderville, and Mount Carmel. (See p. 43; fig. 86.) In the lower 23 miles of its course the river occupies a canyon in the limestones of the Carmel

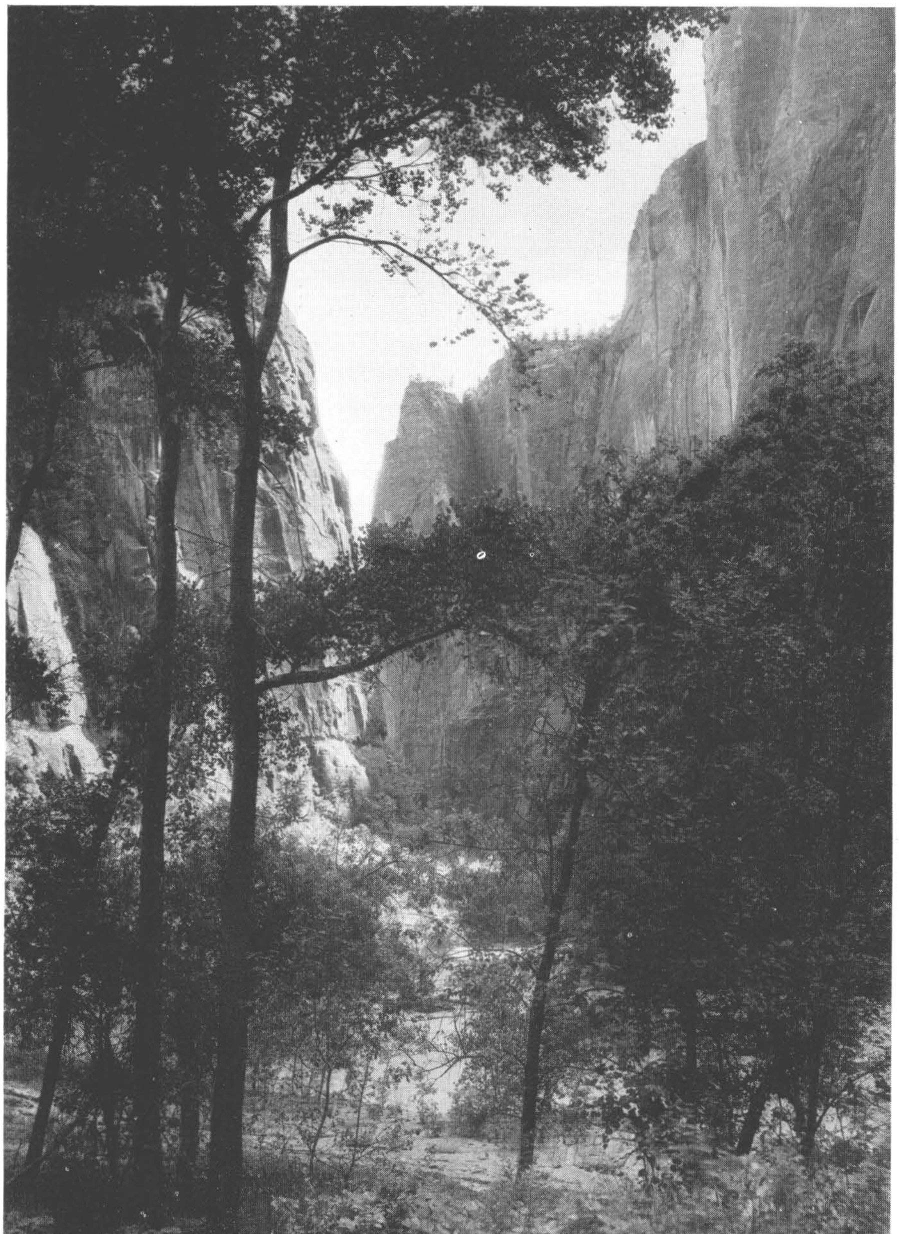


FIGURE 101.—South entrance to The Narrows of Virgin River. The stream flows between walls 1,500 to 1,700 feet high in a channel 20 to 50 feet wide. Photograph by National Park Service. (See figs. 99, 102.)

formation, the sandstones of the Glen Canyon group, and the sandstones and shales of the Chinle formation. In the uppermost 3 miles of the canyon, valley flats 500 to 2,000 feet wide border the river and reach back to the base of cliffs that rise in terraces to an average height of about 800 feet. For the next 9 miles the canyon gradually becomes narrower but retains its flat floor and the stream continues to flow on a gradient of about 1°. Then follows a stretch of sharply meandering canyon 1.5 miles long, where the stream bed is 20 to 80 feet wide and abruptly meets vertical or undercut walls. (See fig. 104.) Through this section the river flows swiftly, and its usual steep gradient is intensified by cascades and falls. The "upper cascades" is a waterfall 22 feet high. At the "lower cascades" the drop is about 200 feet including a waterfall 20 feet high. For the next 2 miles the canyon continues narrow, and its floor is steeply inclined; talus slopes come to the river banks and above them rise walls as much as 1,000 feet high. In the lowermost 8 miles, where a canyon about a mile wide has been cut chiefly in shale of the Chinle, the vertical cliffs of sandstone that form its rim continue downward as slopes of bare shale, talus, and landslides to alluvial flats and benches immediately adjoining the stream. Through its narrower parts the Parunuweap canyon swings right and left in close-pressed meanders, and its walls are carved with the usual arches, panels, and fluted alcoves, some of them selected by the ancient Pueblos as home sites. (See fig. 21.) At the base of the walls and at places higher up springs and seeps emerge and at the top of the walls the mouths of hanging tributary valleys form a scalloped line. In sheltered places sand dunes extend far down the cliffs. Experience gained during a reconnaissance survey of a possible highway route showed that at stages of extreme low water the canyon may be traversed by following short stretches of exposed flood plain, wading among sand bars, wallowing through quicksands, swimming rock pools, and clambering down waterfalls with the aid of ropes where bordering rock walls permitted no detour. At normal stages of water a traverse is hazardous; at high-water stages, probably impossible.

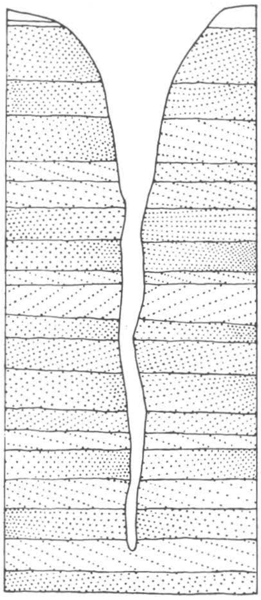


FIGURE 102.—Narrows of the Virgin Canyon between walls of Navajo sandstone, depth 1,800+ feet, width at base 25+ feet. From a drawing by G. K. Gilbert, 1872.

Kanab Creek and its principal tributary, Johnson Creek, which, like the larger Virgin and Parunuweap Rivers, rise at the rim of the High Plateaus and flow southward across Tertiary, Jurassic, and Triassic beds, present along their courses stretches of narrow canyon, wide canyon, terraced river flats, and low meadowlands—features that reflect the relative resistance to erosion of the various formations. These streams cross the Skutumpah Terrace with low gradients in broad valleys developed in the relatively soft Tropic, Winsor and Entrada formations, and descend steeply through narrow gorges in the Navajo sandstone of the White Cliffs. Continuing across the Wygaret Terrace, which is largely floored with thin sandstones of the Kayenta formation, and on through the sandstones of the upper Chinle in the Vermilion Cliffs the gradients of these streams decrease until in crossing the friable shales of the Chinle and Moenkopi formations they are barely able to carry their load of waste. Past Kanab and Fredonia they are small sand-clogged streams, which flow in shallow trenches cut into a broad plain. (See fig. 117.) Below the mouth of Johnson Canyon the Kanab descends swiftly into the lower Kanab canyon which near its mouth is 30 to 70 feet wide and as deep as its master gorge, Grand Canyon. The pattern of the westward-flowing Short and Little Creeks is similar. Where they cross the shales of the Chinle and the Moenkopi formations they are bordered by wide flats, and in the Shinarump conglomerate, the Kaibab limestone, and the Timpoweap member of the Moenkopi formation they flow between vertical walls. There is no reason to doubt that these longer stream channels and the scores of other channels in the Zion Park region have been dug by the streams occupying them and that their form and width afford a measure of stream power conditioned by climate and the character of the rock. Regardless of their length and shape the stream runways are the result of erosion—headward erosion along established channels, vertical erosion in the stream bed, and, aided by tributaries, lateral erosion of adjoining lands.

In detail the process of forming deep, narrow valleys may be illustrated by the history of Zion Canyon which, except for its size, is the counterpart of scores of other gorges cut through thick sandstones of the Kolob, Skutumpah, Wygaret, Moccasin, and Little Creek terraces. Improbable as it may seem, this magnificent gorge is chiefly the work of the Virgin River, which now flows through it. This stream is the direct cause of the depth of the canyon and, in cooperation with other agencies, of its width. (See p. 161; fig. 105.) The stream has cut vertically downward, maintaining its original pattern of curves and straight stretches. Down cutting is vigorously in progress today and is far from reaching its possible limit. The beds of the chief tributaries of the Virgin could be sunk 1,000 feet deeper and still have slopes sufficient to carry water to the Colorado River. In their canyon stretches the Virgin River and its chief branches are cutting so rapidly that their tributaries cannot keep pace with them. Because these tributaries drain small areas and flow only in response to showers, they are unable to cut channels as deep as the perennial master stream. From their mouths high on the canyon walls they descend periodically as waterfalls. Many of them leap from the rim, barely wetting the walls behind them, and scour their channels only in their short courses across the canyon floor. Scores of them after falling merely spread out as thin sheets of water that follow no definite runways. During its long life the energy of Virgin River has been expended chiefly in cutting profound gorges: in modeling its containing walls it has played but a minor part.

The evidence is clear that the widening of its canyon is the result of disintegration of the exposed rock walls, of sapping and undermining rather than of excavation. The cliffs of sandstone are undercut by the removal of soft shales beneath, and in response to gravity fragments fall off. The walls retreat, and the

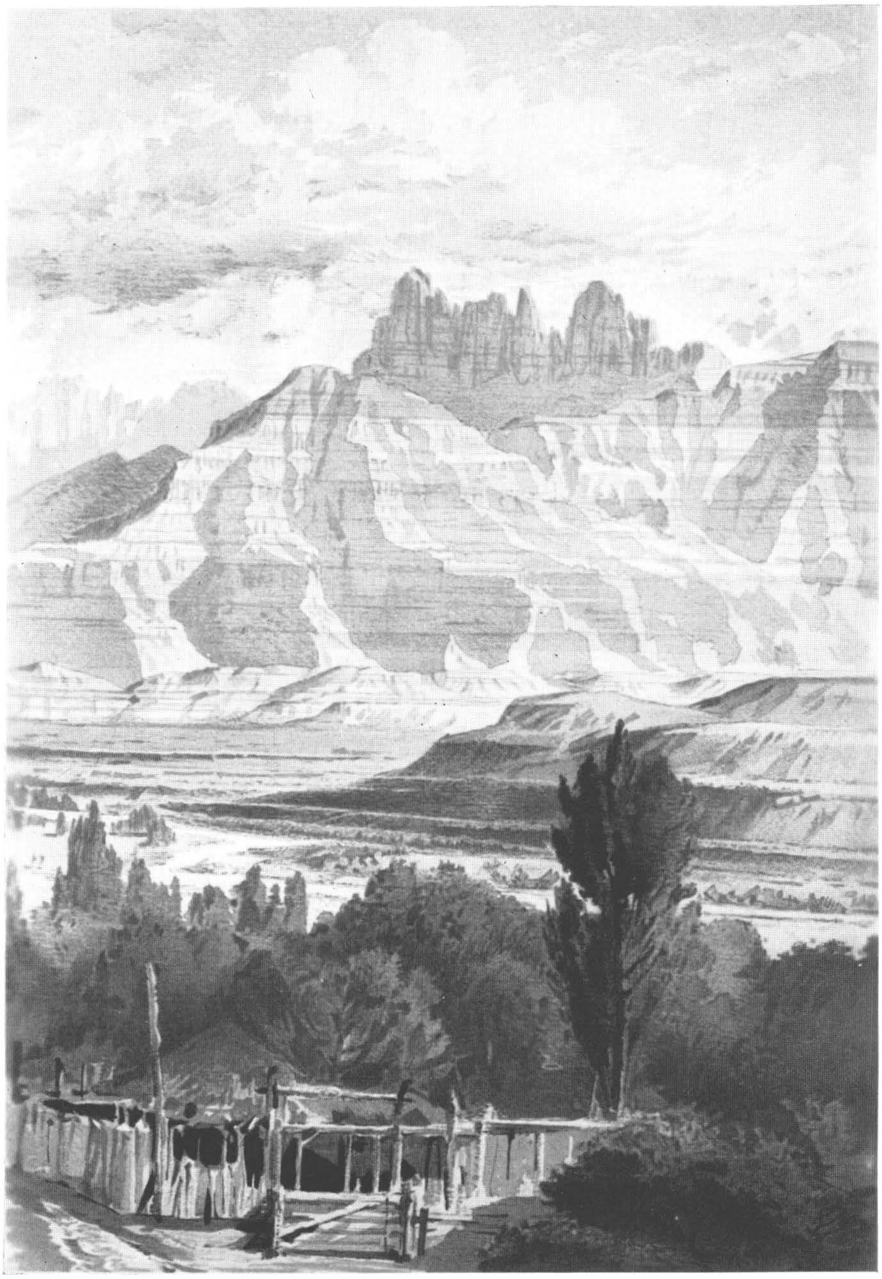


FIGURE 103.—Terraces bounding Virgin River near Grafton. The lowest terrace is composed of stratified alluvium, the next highest of consolidated gravel, the upper two of rock thickly coated with gravel. Moenkopi strata (middle distance), Navajo strata partly covered by landslides in Smithsonian Butte (top). From a painting by W. H. Holmes, 1872. Reproduced from Dutton, Geology of the Grand Canyon District, frontispiece, 1882.

rim develops curves and crenulations, chiefly in consequence of erosion in the bottoms of gulches and alcoves. This method, long in progress, is plainly evident today. Springs and seeps emerging at the top of shales at Wiley Retreat, the Grotto, Weeping Rock, and many other places are noticeably carving grooves that make overhanging cliffs of the sandstone above.

In widening Zion Canyon and carving its architectural features the work of the atmosphere and of ground water is greatly facilitated by the composition and structure of the Navajo sandstone that forms its walls. The weak cement of the rock is readily dissolved by rain that wets the walls and by water that seeps through the rock. It is so easily reduced to sand that it leaves few boulders in stream beds even where the channels lie close to sandstone walls. A series of counts made by J. C. Anderson in upper Zion Canyon showed "red sandstone" (Navajo) as less than 5 percent of the boulders, cobbles, and gravel grains. Material from upstream sources included "limestone (39 to 57 percent); igneous and metamorphic rocks (11 to 40 percent); and gray sandstone (21 to 28 percent)."

Features even more favorable for erosion are the cracks (joint and bedding planes—horizontal, oblique, and curved) that traverse the canyon walls. These cracks determine the shape of the irregular chunks and huge slabs detached from the towering

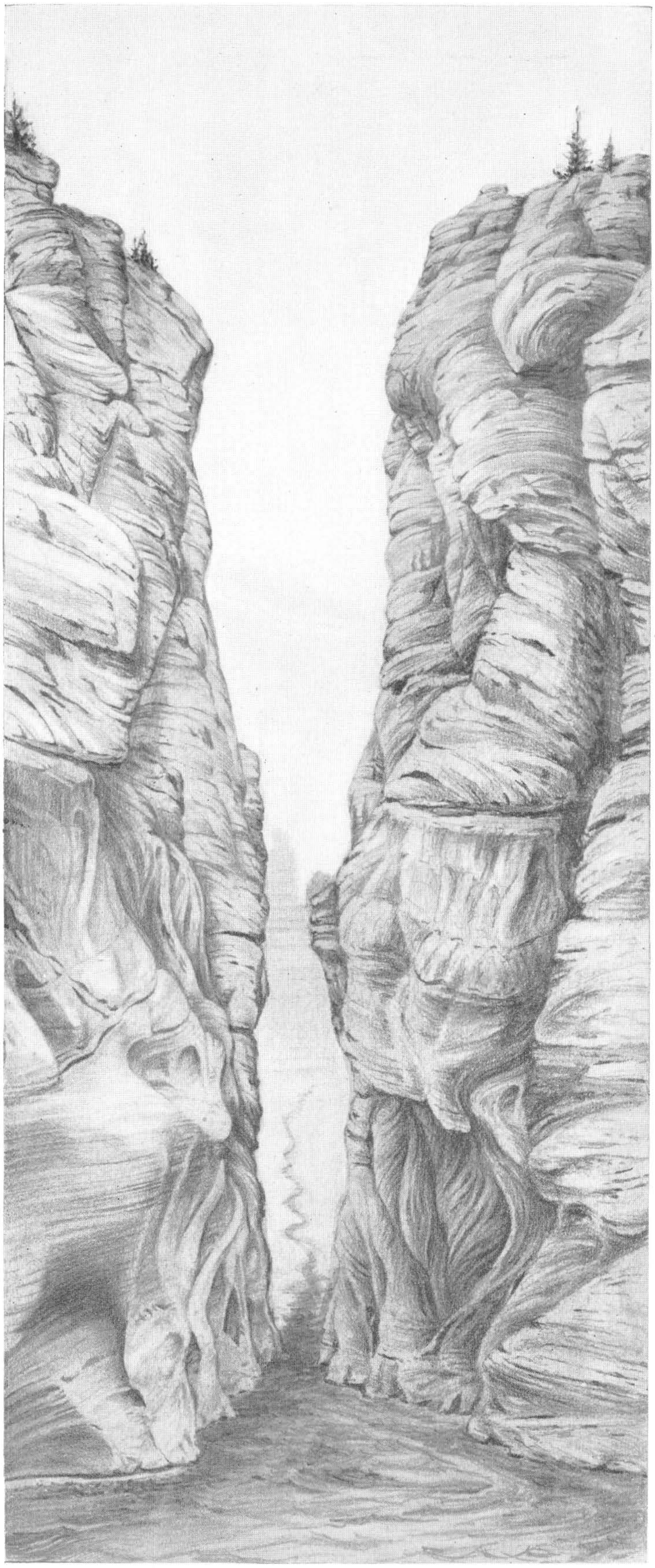


FIGURE 104.—Narrows of the Parunuweap. Canyon between walls of Navajo sandstone, depth 1,600+ feet, width at base 18 feet. From a photograph; redrawn by C. A. Weckerly.

cliffs by frost, rain, tree roots, and ground water. Blocks embedded in the cliffs or surrounded by open joints, blocks partly detached or that rest precariously on some temporary support, and those that have fallen to the talus below indicate steps in the retreat of the canyon walls. That the process is continuous is shown by the scars on the wall, some almost obliterated or considerably weathered, others quite fresh. Each year many new blocks are pried off. (See fig. 7.)

So far, however, the walls have been eroded relatively little. Even where the canyon is widest they stand near the river, and for long distances they rise directly from the river's edge. This relation clearly shows that deepening of the trench has been much more rapid than its widening.

PHYSIOGRAPHIC HISTORY

The physiographic history of the Zion Park region is not a simple story of uninterrupted progress in the development of drainage. It records periodic changes in degradation, aggradation, uplift, stillstand, and climate—many cycles and epicycles of erosion conditioned by altitude, faults, folds, precipitation, temperature, and rock hardness. Obviously the work of more than a single cycle is represented in a topography that includes such heterogeneous elements as graded platforms trenched by deep canyons, old and youthful surfaces in contact, faults along which the downthrown block stands higher than the upthrown block, entrenched meanders, gravel-floored rock terraces and alluvial terraces at various altitudes, superposed and consequent drainage, and generally discordant stream profiles.

Though the meaning of these discordant features is not clear, the sequence of the physiographic events is sufficiently well known to permit the recognition of two major cycles within Tertiary and Recent times. For convenience in description these two long periods have been designated (1) the precanyon cycle, which records the history of the region before it was stripped of its Cenozoic strata and before great canyons were formed, and (2) the canyon cycle, during which the present landscape has been modeled. In the studies so far made it appears that each cycle was initiated by a regional uplift; that both include epicycles characterized by distinctive topography. But aside from such general considerations geologic knowledge of Eocene and post-Eocene times in the plateau country is far from complete. In particular, evidence is deficient regarding the causes of the cyclical changes, the number, duration, and characteristics of the epicycles, the successive uplifts, downwarps, and stillstands, and the regional correlation of topographic features produced during comparable periods.

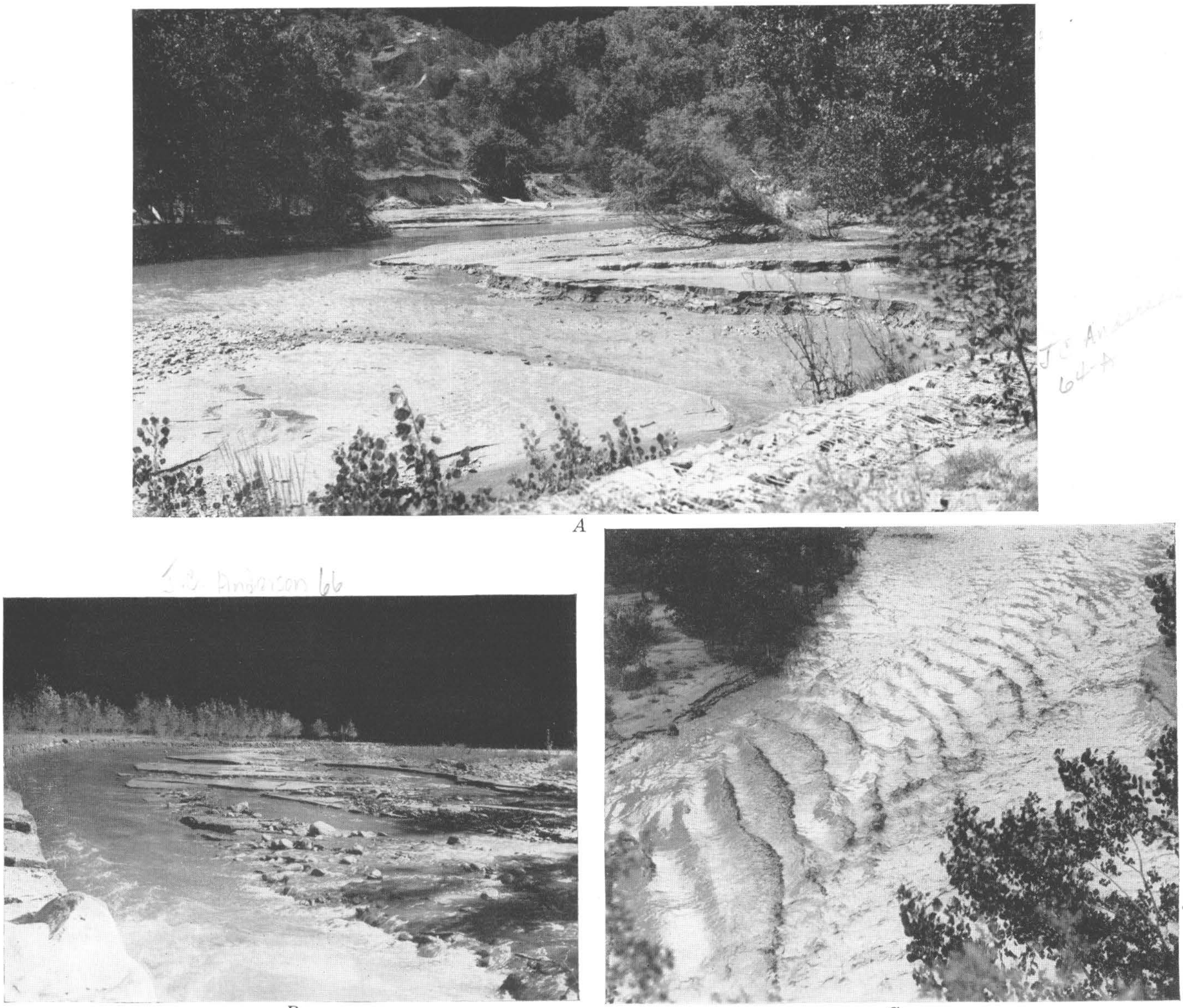


FIGURE 105.—Virgin River in Zion Canyon. *A*, At a prolonged period of low water; *B*, At the beginning of a new flood, after a flood that filled valley 2 weeks earlier *C*, At time of rapidly increasing volume when water and transported sediment are combined in "sand waves." Photograph by J. C. Anderson, Nos. 66, 74a, f.

For the precanyon cycle the record of events so obscures the dates that no subdivisions have as yet been defined. For the canyon cycle, stages of erosion alternating with stages of deposition as recorded on lowlands, highlands, and within canyon walls permit subdivision into subcycles characterized by unlike physiographic features. In the later part of the canyon cycle the gorges cut in response to uplift were partly filled with coarse alluvium, excavated, refilled with less coarse material, and again excavated. These changes from dominant deposition to dominant erosion recorded in coarse gravels on the canyon walls and in finer alluvium on the floors, are here treated as features of the "gorge epicycle" and the "inner canyon epicycles" that have their latest expression in the present terrace epicycle. (See p. 169.)

With full recognition of the fact that their place in the geological time scale is imperfectly known, the probable physiographic events in the Zion Park region may be outlined as follows:

- Precanyon cycle: Beginning with the deposition of Eocene and Miocene sediments on an erosion surface developed in late Cretaceous or early Tertiary time and followed by erosion that reduced large areas nearly to base level.
- Canyon cycle: Beginning with an uplift in late Miocene or early post-Miocene time and extending into present time.
  - Gorge epicycle: Deep canyons outlined and cut nearly to their present depth.
  - Inner canyon epicycles: Canyons alternately filled and reexcavated.
  - Terrace epicycle: The dissection, in places the removal, of valley fill—conspicuously since the nineteenth century.

There seems reason to believe that during the precanyon cycle the rocks in the Zion Park region were undisturbed by noteworthy tectonic movements.

In contrast the canyon cycle is characterized by intermittent uplifts and accompanied by faulting, thus repeatedly giving streams renewed energy. Though the major regional uplifts may have ceased at the beginning of the gorge epicycle, it seems reasonable to regard the inner-canyon and terrace epicycles as the latest in the series of rapid uplifts, slow uplifts, and stillstands that during late Tertiary and Quaternary times controlled the development of plateau topography. However, it is possible that the present scant and conflicting evidence of great changes in climate may be enlarged to prove that cyclical rainfall has been largely influential in determining the rate and manner of erosion and in fixing the dates of the minor erosion cycles.

During neither of the two major cycles was erosion carried to its possible limits. In the precanyon cycle regional base leveling was prevented by an uplift that initiated the canyon cycle of erosion (the present major cycle), within which land degradation has been vigorously in progress. In consequence of the uplift youthful topography is superposed on that of old age. The erosion surfaces of the precanyon cycle have been deeply and intricately dissected and much of the old talus and alluvium has been swept from slopes and flatlands. Many of the present meandering streams occupy trenches cut into a former graded surface, from which to a large degree their pattern has been inherited. With steepened gradients the streams have converted formerly shallow valleys into profound gorges that outline innumerable mesas and flat-topped ridges, producing a landscape of exceptional ruggedness; in fact, most of the marvelous features of the plateau country belong to the canyon cycle.

Throughout the canyon cycle cliffs seem to have been features of the Utah landscape. There is no reason to doubt that old-age surfaces along streams draining southward to the Colorado terminated at the base of rock walls—the ancestral Vermilion, White, and Pink Cliffs—whose tops also had reached old age. As long ago noted by Powell, recession of cliffs and the stripping of platforms has been at all times a major process in the development of the characteristic topography; to a large degree erosion has been directed against the edges of sedimentary strata. In receding, the walls thus produced have maintained their youthful aspect; they were not transformed into slopes that gradually decrease in declivity in response to weathering, rain wash, or sapping. In modern physiographic parlance, they have developed no features of adolescence, maturity, or postmaturity.

The drainage system in the Zion Park region derives special interest in that its origin and development is closely comparable with that for the most of the plateau province and that conclusions based on local studies should be consistent with the regional patterns. For the Grand Canyon district and the High Plateaus of Utah this relation has been recognized, but variously interpreted. Thus Dutton[29] surmised that in consequence of post-Cretaceous uplift "the plateau country formed one continuous lake—an almost if not completely closed basin—finally disappearing at the close of the Eocene . . . on the floor of this basin, as it emerged, a drainage system was laid out." Davis[30] expressed the view that for a time preceding the development of through drainage "the Grand Canyon district was a district of broad plateaus and the High Plateaus were part of a great interior basin."

There has been no recently expressed dissent from the conclusions previously reached, that before regional uplift large parts of the plateau drainage had no outlet to the sea. Discrepancy in views relates chiefly to the date at which general uplift and local warping converted those weak partly disorganized streams into powerful agents of erosion.

Members of the Powell and Wheeler Surveys thought that the major regional uplifts followed the deposition of Eocene sediments. Thus, Dutton[31] concluded that "The great erosion of the plateau province was most probably accomplished mainly in Miocene, but continued with diminishing rapidity through the Pliocene." In contrast with this view Longwell[32] tentatively expressed the belief "that the Colorado could not have occupied its present course until after the Pliocene epoch" and Blackwelder[33] contends that during late Tertiary time the whole Colorado drainage basin was "an arid to semiarid lowland with only low mountains rising above the extensive plains" and that the Colorado and its tributaries probably "did not exist until about the beginning of Pleistocene time."

In the absence of more conclusive proof it seems reasonable to question the assumptions of Blackwelder that the Pliocene in the plateau province was a prolonged period of interior drainage of the bolson type and that integrated drainage in this province was first established in Pleistocene time. The universality of plateau stripping suggests either a period of erosion much longer than is usually assigned to the post-Pliocene or a rapidity of erosion far greater than any now known. Even with the present rapid rate of erosion it would seem that the estimated 1,000,000

[29] Dutton, C. E., Tertiary history of the Grand Canyon District, U. S. Geol. Survey Mon. 2, pp. 216–219, 1882.

[30] Davis, W. M., An excursion to the Grand Canyon of the Colorado: Harvard Coll. Mus. Comp. Zoology Bull. 38, pp. 136, 159, 1901.

[31] Dutton, C. E., The High Plateaus of Utah, pp. 22, 23, 24, U. S. Geog. and Geol. Survey Rocky Mt. Region, 1880.

[32] Longwell, C. R., Geology of the Muddy Mountains, Nevada: U. S. Geol. Survey Bull. 798, p. 143, 1928.

[33] Blackwelder, Eliot, Origin of the Colorado River: Geol. Soc. American Bull., vol. 45, pp. 558, 560, 1934.

years of Quaternary time would be insufficient for the development of the land forms that characterize the Colorado plateaus. Dutton estimated that since through-going streams have been at work, the thickness of rock eroded from 50,000 square miles adjoining the Colorado canyons is 6,000 feet; from the High Plateaus, 1,000 feet (Gilbert's estimate is 5,500 feet); and the regional features suggest that from an area of as much as 100,000 square miles an average thickness of at least 2,000 feet of rock has been removed. If this enormous amount of material had been transferred as recently as the glacial periods, it should somewhere be represented in the topography. Furthermore in the plateau province there is ample evidence of profound erosion in pre-Pleistocene and even pre-Pliocene time, doubtless accompanied by exterior drainage. Moraines and outwash of the pre-Wisconsin period lie in deep canyons and override old erosion surfaces, and fossiliferous Pleistocene lake beds lie far below the tops of plateaus. Pliocene sediments in the Hopi country[34] and elsewhere in northern Arizona unconformably overlie Eocene (?), Cretaceous, or Jurassic beds from which the sediments of intervening periods have been removed. In this connection it seems worthy of note that the known Pliocene sediments in the plateau country lie in basins surrounded and underlain by older rocks and that their composition and distribution record local climate, stream habitat, and inequalities of land surface rather than regional or stratigraphic sequence. They show that detached basins are not discordant features in a landscape that includes through-flowing streams. Under comparable conditions sediments are filling basins of today.

Whatever its date, the uplift that introduced the canyon cycle and brought low-lying Tertiary strata high above sea level, marks the beginning of a long period of profound and widespread denudation in southern Utah. During the cycle nearly all the Tertiary sedimentary rocks and large parts of the Cretaceous, Jurassic, and Triassic of the Zion Park region were stripped away. Sandstones, shales, and limestones 6,000 to 8,000 feet thick have been removed from the Uinkaret, the Kanab, and the Kaibab plateaus, and similar amounts from adjacent areas. Erosion was sufficiently vigorous and long-lived to produce a rugged landscape of canyons, plateaus, and mesas and then over large areas to reduce the inequalities to plains so level that the streams no longer had the power to entrench themselves deeply. The parts of this old erosion surface that have escaped destruction are characterized by shallow, many-branched streams, and low rounded hills, and without significant change in form they extend across hard rocks and soft rocks, across flat rocks and tilted rocks, and across faults and folds. (See p. 177.)

Aside from the stillstands, when structural quiescence permitted streams to reach a stage of relative incompetence, the conditions controlling land denudation in the plateau country seem always to have been about the same. Throughout the long precanyon and canyon cycles soft and hard rocks in vertical alternation have been exposed to attack, and plant fossils indicate that since middle Miocene time a temperate, semiarid climate has prevailed. Therefore it seems probable that the present rate of erosion roughly measures that in effect since the stream systems were established. In the Zion Park region the rate seems to be faster than in most humid regions, in the arid Great Basin, or in other parts of the plateau country with less wide range in altitude. The rapidity of erosion is recorded in the wide extent of bare rock whose surfaces are so continuously scoured that soil cannot form, in the innumerable narrow, deep canyons and gullies, and in the amount of debris carried by streams. The rivers and their myriad tributaries are not only removing the material now being supplied by rain wash, frost, and chemical agencies, but are tearing up alluvial flats, talus slopes, and landslides of previous cycles and scouring their channels of bedrock. Because of the frequent floods the streams of all classes are heavily charged with rock waste many times a year or even many times a month. The large amount of suspended matter measured in gaging should perhaps be doubled by adding the sand and gravel pushed along the bottom and the pebbles, cobbles, boulders, and slices that are torn off from the banks, and that slide, roll, or hop along the bed. An additional load is the unsorted sand, gravel, and silt that, during floods, is pushed forward en masse as "sand waves."

Naturally the rate of erosion is different for each type of rock and each topographic position. The surfaces of the more resistant limestones, sandstones, and conglomerates waste slowly, their edges relatively more rapidly. Slopes of shale disintegrate rapidly, and the alluvial fill of valleys is disappearing at a spectacular rate. (See p. 155.) The only forms that escape rapid devastation are the pedestals, hoodoos, rock babies, and small isolated buttes carved from massive sandstones or from shale overlain by limestones. Such forms waste away so slowly as to seem almost invulnerable.[35]

PHYSIOGRAPHIC FEATURES

VALLEY FILL

The typical streamway in southwestern Utah is a sheer-walled or terrace-walled canyon sunk into rock

[34] Williams, Howel, Pliocene volcanoes of the Navajo Hopi Country: Geol. Soc. America Bull., vol. 47, pp. 129–130, 1936.

[35] Gregory, H. E., The San Juan County, U. S. Geol. Survey Prof. Paper 188, p. 99, 1938.

during the gorge epicycle, partly filled with alluvium and partly re-excavated during the inner-canyon and terrace epicycles. Many of the streams run on alluvium and are bordered by steep banks of alluvium, and on the outer canyon walls other alluvial deposits are plastered. The composition, structure, and topographic position of this valley fill shows that it accumulated at different times, under different climates and different stream habits, and at different stages in regional uplift. In the Zion Park region the fill consists of conglomeratic material here termed "consolidated gravel," represented by terracelike outcrops high on canyon walls and the "alluvial fill" laid down on the valley floors. So far as is known the consolidated gravel is an indivisible unit, whereas the alluvial fill records several stages of sedimentation and erosion.

CONSOLIDATED GRAVEL

In the many valleys where it is exposed, the consolidated gravel is the oldest part of the general valley fill.

Along the Parunuweap River the gravel appears at the top and along the sides of the valley walls in thin and chunky patches, a few square yards in area and in strips as much as 100 feet wide, 1,500 feet long, and 5 to 60 feet thick. Its discontinuous outcrops as measured in 14 places lie 100 to 260+ feet above the present river bed. In Sink Valley and other tributaries to Kanab Valley, also in Johnson Valley, deposits of similar dimensions lie in similar positions. In the Virgin River Valley about a mile below Grafton the consolidated gravel forms a vertical wall 50 to 100 feet high close to the river; upstream on the north side of the valley it forms benches and low mesas and, where decomposed, mounds of cobbles that extend along the highway for nearly a mile. Everywhere its component material is conglomeratic and very roughly bedded; tapering sheets of coarse and fine sandstone lie in disorder between overlapping sheets of cobbles. The coarsest conglomerate consists chiefly of subangular slabs of Cretaceous sandstone 2 to 4 feet long, partly rounded pebbles of white, pink, and brown Tertiary limestone, and lozenges of concretionary iron, 2 inches to 1 foot in diameter. Of materials less than about 3 inches in diameter the commonest are well-worn pebbles of white, brown, gray, and banded quartzite, and white and black chert. Less common are subangular fragments of black limestone from an unknown source. (See fig. 106.) In the Virgin River Valley the coarse material includes fragments of basalt and in the Kanab Valley peculiar conglomeratic mud balls like those stranded on the floor of present-day streams after floods. The sand is dominantly quartz but includes calcite and iron oxides which serve as cement and also as coloring matter. Generally the iron is sufficiently abundant to give the stratum buff and yellowish tones in contrast with the gray, red, and black of the rocks above and below it and to justify the local name, "yellow ledge."

The position of the remant outcrops at the top and base and midway up on canyon walls of major streams, as solid filling of short tributary canyons and as patches on low divides between streams, suggests that the consolidated gravel once partly filled some drainage channels and filled others from brim to brim, in places extended beyond. It also shows that when the gravel was deposited the canyons within which it rests—canyons developed during the gorge epicycle—were substantially as deep and wide as they are today. This deposit, which obliterated canyons more than 200 feet deep as well as open valleys and flatlands, points to a period of vigorous aggradation long antedating the deposition of the sand and gravel terraces that line the present streams. Since the conglomerate was laid down, its thicker masses have been largely removed from the canyons, and their thinner extensions stripped from bordering lands. Over its eroded surface have poured lavas from volcanoes in Johnson, Kanab, Parunuweap, and Virgin valleys, now deeply weathered and in places worn into isolated patches for distances of several miles. Tentatively the consolidated gravel is assigned to an early epoch of Pleistocene time and is correlated with the thick patches of gravel that lie on rock benches and meander spurs above the beds of the San Juan River,[36] the Colorado River, and many streams that head in the High Plateaus. However, it is not associated with known glacial deposits and lies below lavas classed as Pleistocene. Its age may be Pliocene.

ALLUVIAL FILL

The floors of many canyons and wider valleys in the Zion Park region are filled to a considerable depth with stratified alluvium that was deposited, eroded, and redeposited in whole or in part during post-Pleistocene time. In some places this alluvial fill remains intact; in other places it has been entirely removed, but generally in consequence of the present vigorous stream erosion it has been carved into flat-topped, steep-faced segments, thus revealing its composition, texture, structure, and mode of deposition. Where observed in cut banks the fill includes stream deposits, lacustrine deposits, and wind-blown sand. Most of it is interbedded sand, gravel, and silt, which varies widely in thickness and extent and shows the lateral unconformities and the grades of coarseness and sorting characteristic of fluviatile sediments. (See figs. 107, 108, 109, 110.) As a whole the bedding is surprisingly regular, but here and there fragmented alluvial fans, talus slopes, isolated boulders,

[36] Gregory, H. E., The San Juan country: U. S. Geol. Survey Prof. Paper 188, pp. 101–102, 1938.

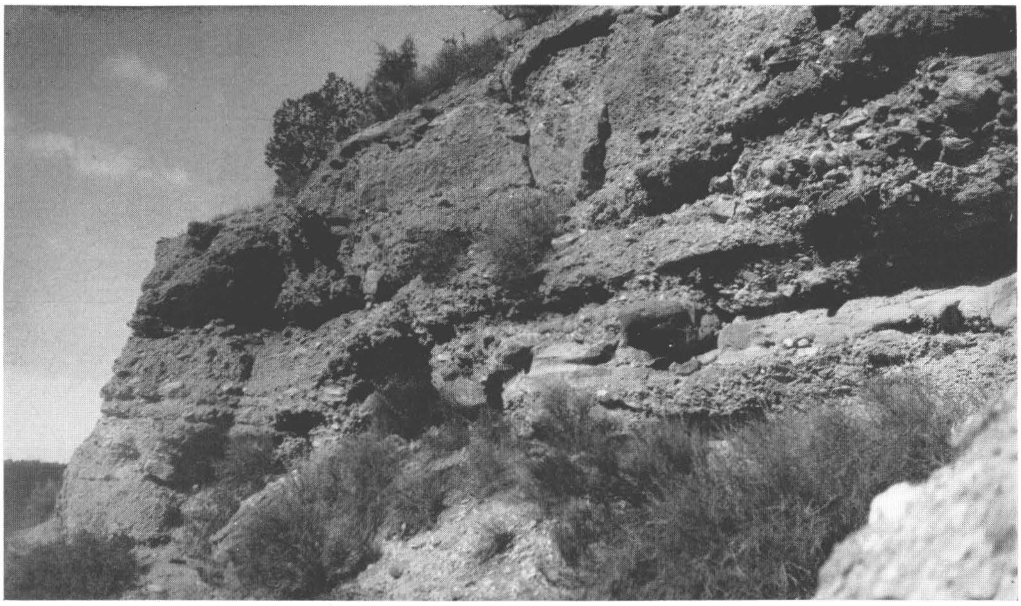


FIGURE 106.—Consolidated gravels on wall of Parunuweap Canyon near Mount Carmel Junction.

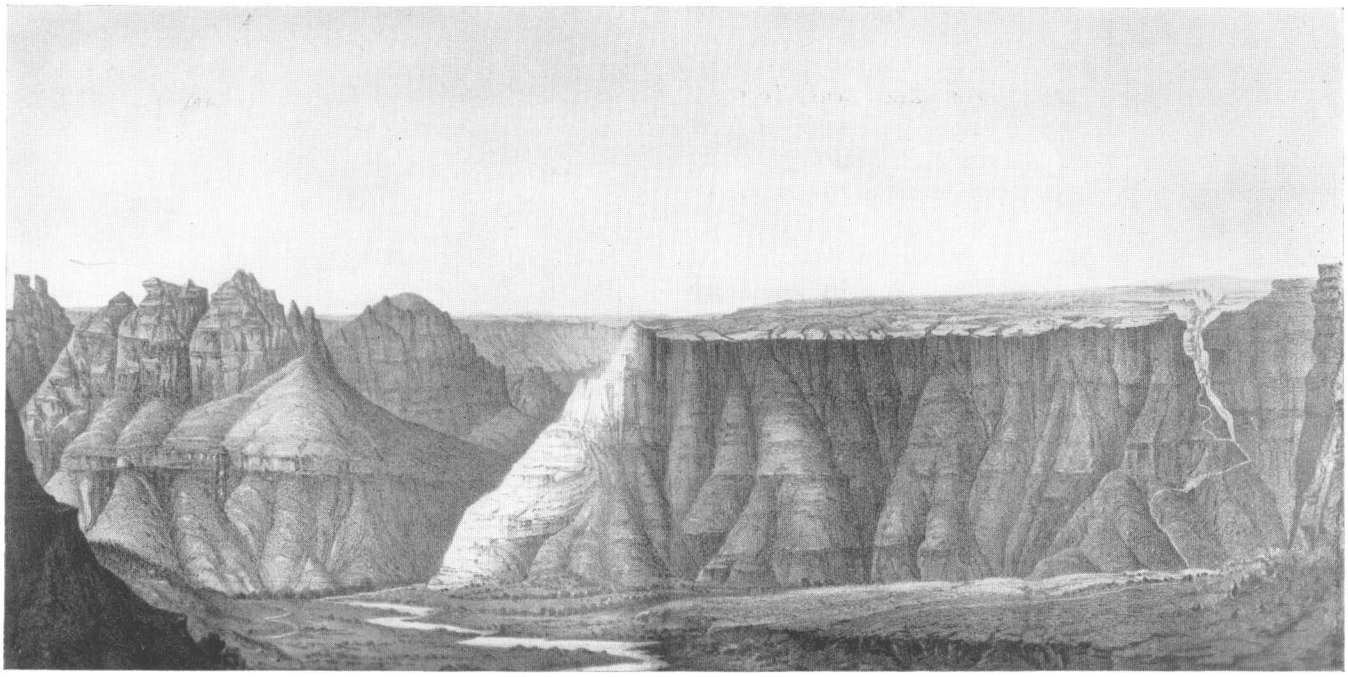


FIGURE 107.—Mouth of Parunuweap Canyon, site of abandoned settlement of Shunesburg; "Wriggle Trail" used by Wheeler Survey, ascends walls of Navajo sandstone 1,500 feet to surface of Moccasin Terrace. Sketch by John E. Weyss, 1872.

and gravel-floored channels are embedded in the general mass.

In places the fill overlies or abuts against piles of eolian sand—remnants of hanging dunes on ancient canyon walls. As exposed along streamways the fill is 5 to more than 60 feet thick, for long stretches 20 to 40 feet. Everywhere it rests on a surface of scoured rock made uneven by grooves or on protruding ledges marking the sites of ancient and modern waterfalls. The fill is deepest and most regularly stratified at places where constrictions in walls and obstructions on the floors of the ancient rock canyons caused decrease in rate of stream flow, most irregular just below the barriers, and thinnest and most abundantly marked by unconformities on the sides of the original trough. The alluvium is too thick and much of it is too coarse and too heterogeneous to have been deposited on plains temporarily overflowed by high water. Furthermore, it lies even in narrow, high-walled, steep gorges where swift streams had no opportunity to stread over the surrounding land. In other words, the alluvial fill fits the rock canyons; in depositing their load of debris the streams have been guided by the gradient, the alinement, and the width of the original gorges, and during their life they have experienced seasonal and cyclical fluctuations in volume.

The fill is evidence of three or more periods of at least local degradation and aggradation, which followed the long gorge epicycle, during which the innumerable deep canyons were cut, and as they are features of all streamways it may be that the alternating periods of deposition and erosion are regional in scope and reflect in the plateau country pauses in regional uplift.

FIGURE 108.—Alluvial fill in upper Johnson Canyon cut into terraces at two levels since 1920. H.E. Gregory 926

The age of the alluvial fill and the length of time consumed in its formation are unknown. Fragmentary bones at the base of partly cemented gravels in Gould Canyon point to a time when Proboscidians were part of the fauna of southwestern Utah, and at least some of the unconsolidated gravel dates from periods when the region was occupied by man. Fire pits and ash heaps about 20 feet from the base of the deposits in Cave Lakes Canyon and potsherds and decayed corncobs near the top in Kanab, Three Lakes, and Cottonwood Canyons indicate settlements existing between 1,000 and 1,700 A.D. That the top of the valley fill was used by the early Pueblos for dwelling sites and for planting crops is indicated by kitchen middens, walled enclosures, burial mounds, and "root scars" of cultivated plants. In some canyons where the fill has been entirely swept away, steps cut into rock leading from the ancient fields to cliff houses above now begin part way up on the walls. Likewise, in places where erosion has removed the gravel platform on which the artists stood the Puebloan and Piute pictographs are inaccessible. In the Navajo country, in sedimentary deposits comparable in age and origin to the alluvial fill in southwestern Utah, buried artifacts of pre-Puebloan and Puebloan cultures are dated as early as 1100 A. D. and as late as 1700 A. D., and their stratification indicates that the ancient farm lands in canyons and washes were periodically occupied and abandoned. Bryan[37] presents evidence that the "great migration" of the Pueblos, from 1250 to 1300 A. D., corresponded in time with the "great drought," which probably was coincident with the destruction of alluvial terraces, and Hack[38] reports that in Jeddito Wash, Ariz., potsherds show that the alluvial banks of the present stream were formed entirely during the period from 1300 to 1700 A. D. The slowly accumulating physiographic knowledge of late Quaternary and Recent time seems to indicate that the valley fill in the plateau country records the physiographic history of perhaps a thousand years, during which periods of stream deposition and stream erosion alternated; that about the year 1700 dominant aggradation ceased; and that for about 150 years thereafter streams in shallow meandering channels did little but transport the products of weathering and rain wash and thus gave form to the remarkably even surface of the latest valley fill. Some such succession of events is suggested by the numerous unconformities and weathered zones, by the deposits of lacustrine material and silt, peat, and marl and by the general weathering of the top layers, deep enough to form agricultural soil. (See fig. 110.)

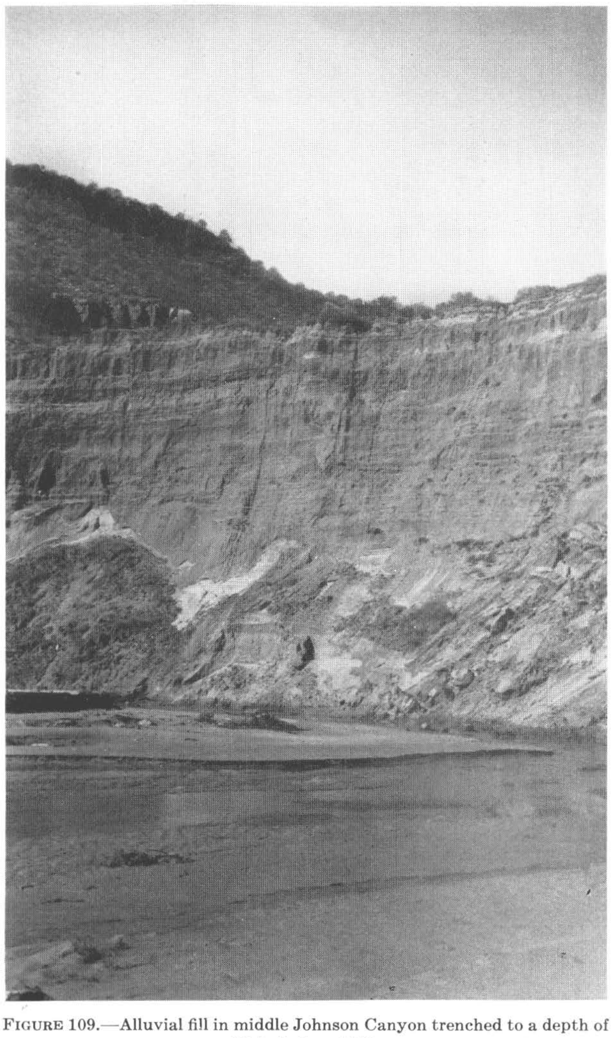


FIGURE 109.—Alluvial fill in middle Johnson Canyon trenched to a depth of 38 feet since 1900. H.E. Gregory 869

[37] Bryan, Kirk, Flood water farming: Geog. Rev., vol. 19, pp. 455–456, 1929.

[38] Hack, J. T., Late Quaternary history of several valleys in northern Arizona: Mus. Northern Arizona Mus. notes, vol. 11, p. 69, 1939.

The evidence seems conclusive that during the 18th century and much of the 19th most of the streams in southern Utah below the rim of the High Plateaus were slowly aggrading their runways. In open valleys like those of the central Kanab, Little, Short, and lower Johnson Creeks, the middle Virgin, and the middle Parunuweap, the streams were flowing on alluvium in fairly well defined channels and flood plains. Likewise in many deep canyons alluvium formed the floor to considerable depths, smoothing out the irregularities in profile on the bedrock beneath.

In diaries and published accounts the Mormon pioneers of the period 1851-1880 speak of "meadows," "broad fertile fields," "little lakes," "clear gently flowing streams bordered by willows," and "floors of level plow land between canyon walls." Gilbert,[39] in 1872, described the Kanab as "in part subterranean, sinking in the sand of its bed, to reappear when a ledge of rock rises to bar its way." Dutton[40] illustrates the flat untrenched gravel floor of Johnson Canyon as viewed in 1878 and remarks,

> "Most of the lateral canyons are slowly filling up with alluvium at the present time, but very plainly they were much deeper at no remote epoch in the past. The lower talus in some of them is completely buried, and the alluvium mounts up on the breast of perpendicular scarps. In some cases a smooth floor of alluvium extends from side to side of what was originally a canyon valley." (See fig. 112.)

At present in southwestern Utah most of the aggrading streams that partly filled the canyons with gravel, sand, and silt have become degrading streams, which in cutting downward, sideward, and headward are removing enormous quantities of material and carving the once unbroken expanses of valley fill into flat-topped, steep-faced segments. (See fig. 103.) In historical sequence the inner-canyon epicycles have been succeeded by the terrace epicycle. In making these terracelike segments the activity of the streams has been governed by their volume, their gradient, the width of their floors, the number and position of tributaries, and especially by the number and violence of the showers that have fallen within their drainage basins.

In accord with these conditions the terraces form continuous walls immediately at the edge of the stream, elongated tables that abut against the outer canyon wall, and isolated mesas. They appear at different levels, range in size from a few square rods to hundreds of acres and vary widely in degree of permanency. The headwater tributaries to Little and Sand Creeks are bordered by terraces of finely stratified sand 30 to 40 feet high, and in upper Short Creek Valley walls of alluvium 20 to 50 feet high border a wide wash. (See fig. 111.) Here in the valley fill and the overlying sand dunes cottonwood trees more than 100 years old are partly buried. In the Kanab Valley two sets of terraces lie 80 to 90 feet and 40 to 75 feet above the stream bed. Likewise in the La Verkin Valley and in parts of the Virgin Valley high-level gravel terraces are paralleled by sand terraces 4 to 20 feet above the stream beds. Along some streams considerable areas of the original valley fill are almost intact

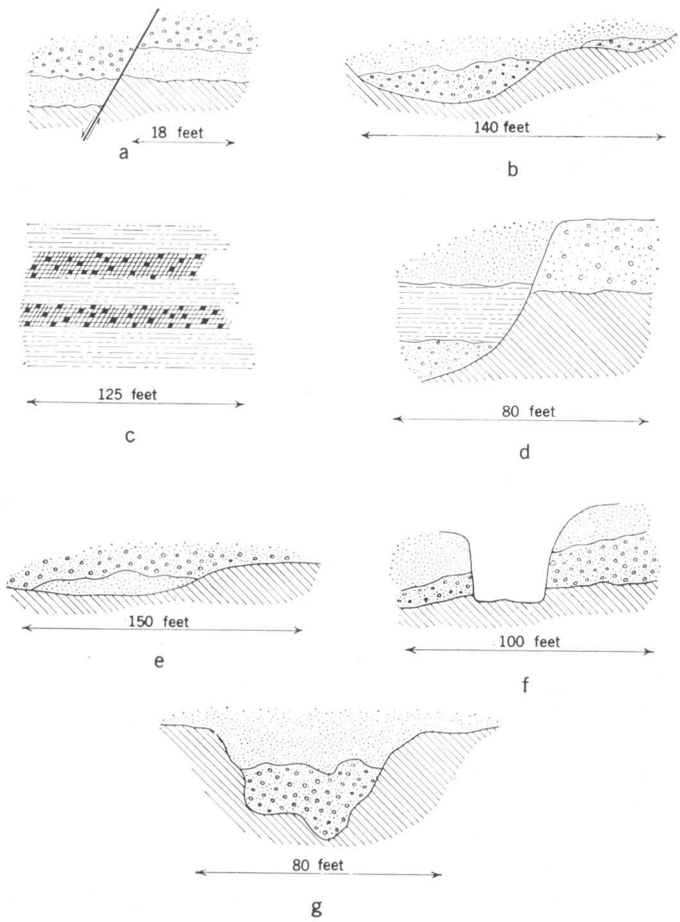


FIGURE 110.—Section of canyon fill showing unconformities. *a*, *b*, In alluvium 10–20 feet from its base; *c*, Peat beds; *d*, Fill against rock well overlain by alluvium; *e*, Buried sand dune; *f*, Talus on rock covered by alluvium; *g*, Filling in rock-walled canyon. From sketches.

and headward erosion has not yet reached the floors of their tributaries. Thus the broad floor of Johnson Valley is cut by few gullies, and the meadowlands in upper Parunuweap, upper Kanab, Jo, Sink, and Dairy Valleys, and along streams on the Kolob Terrace have been little dissected. Erosion has not proceeded far enough to drain the ponds in valleys tributary to Johnson Canyon, in Le Vanger Wash, and Three Lakes Canyon, nor the periodically flooded "cane beds" in Rosecrans and other canyons. So far, also, the sand-coated beds of many ephemeral lakes remain undisturbed. On the other hand, along Meadow and Muddy Creeks, the middle Kanab, Cottonwood, Sand, Parashant, Short, and North Creeks the meadowlands have been cut into slices, and the once continuous sod-bound soil is represented by in-

[39] Gilbert, G. K., in Wheeler, G. M., U. S. Geog. and Geol. Surveys, W. 100th Mer. Rept., vol. 3, p. 76, 1872.

[40] Dutton, C. E., Tertiary history of the Grand Canyon district: U. S. Geol. Survey Mon. 2, pp. 228–229 and p. 37, 1882.

conspicuous patches. Likewise Gould, Rock, and Timpoweap Canyons, and long stretches of canyons that issue from the Vermilion Cliffs and the White Cliffs and flow in trenches sunk into the floors of Kolob, Wygaret, and Skutumpah Terraces have been largely stripped of stream-laid sediments—rock-walled, rock-floored canyons have replaced those formerly filled with alluvium to depths of 20 to 80 feet.

FIGURE 111.—The Valley of Short Creek at its emergence from Vermilion Cliffs. The original narrow, shallow stream flowing in alluvial valley fill has deepened its channel 16 feet and widened it 400 feet since 1910(?).

In some of the great gorges the original canyon fill, even when thickest, reached only part way up the rock walls, and when the streams cut through the deposit they reoccupied their former channels, but some of the shallower canyons were filled to the brim and their bordering slopes so deeply buried that the degrading streams had no restricting banks. In sinking their channels some streams have been unable to find their former courses; they are digging new channels in rock close to ancient runways filled only with easily removed sand and gravel. Thus in Gould Canyon, Little Creek swings around a curve newly cut in Moenkopi shales and limestones where a shift of 10 feet would place it on gravel. At Corral Knoll Kanab Creek, flowing for a distance on top of the valley fill, finds its old course after dropping over ledges 20 feet high.

A superficial view of the geologic work involved in breaking up and carrying away millions of cubic yards of sand, gravel, and silt from hundreds of canyon floors, cutting new channels, adding new tributaries, and pushing back divides gives the impression that thousands, at least hundreds, of years have elapsed since the aggrading streams in the plateau country were replaced by degrading streams and the destruction of the valley fill began. Though the youthfulness of the valley landscapes is obvious, it is surprising to learn that the terraces assumed form during the past half century and that their full development has been witnessed by men still living. Since about 1880 stream work in the Zion Park region might be termed catastrophic, comparable to earthquakes and volcanic eruptions rather than to the slow production and removal of waste characteristic of most streams elsewhere. In a day or even a few hours the streams perform work that under other conditions might require tens or hundreds of years, even if it could be done at all.

Obviously the present rapid erosion in the Zion Park region is caused by the floods that repeatedly add speed and volume to perennial streams and fill the channels of normally dry water courses with mud-clogged torrents; each flood deepens and widens many channels, rearranges meanders, eats headward, and develops innumerable lateral branches. The changes in topography resulting from the removal of valley fill may be illustrated by the behavior of Kanab Creek. As recorded in a diary by Henry E. Riggs, when the village of Kanab was settled in 1871 the creek ran at the level of the two terraces that now border its canyon walls, a shallow, weak stream that during hot days of summer dwindled to disappearance. For about 12 miles it was bordered by meadows "with much swamp occupied with flags, bulrushes, rabbitbrush and willows. It was almost impossible to ride a horse up the canyon on account of mud holes, quicksands, and brushy thickets." For a time after 1874, when the canyon floor was fenced for pasture and farm lands and, in consequence, much of the native vegetation was destroyed, the creek was concentrated in fewer channels and the flow was increased by more than half. "The first great flood came in July 1883. It swept away all the farm lands and meadowlands in the canyon as well as the field crops just south of the village and scoured out a broad channel beneath the former valley floor." In 1884 and 1885 floods, "occurred daily for 3 or 4 weeks—continued the deepening of the new channel—." As the result of "3 years' washing, the stream bed was cut down about 60 feet beneath the former level, with a breadth of some 70 feet, for a distance of 15 miles." (See fig. 113.) Much of this mass of material measuring more than 12,000,000 cubic yards was carried to the Colorado; much also was spread over the town lots of Kanab and the flatlands south of the village. Since 1886 trenching of the fill and the construction of terraces in Kanab Valley has extended northward beyond the White Cliffs. Usually the flood waters carry not only sand, gravel, chunks of rock, trees, bushes, and sod but also mud balls in quantity. In the flood of 1909, clay boulders "round as marbles," formed by the rolling transport of slabs torn from the channel walls, were spread over the flatlands south of the Vermilion Cliffs. From cultivated fields and garden plots at Fredonia "thickly

EXPLANATION OF FIGURE 112

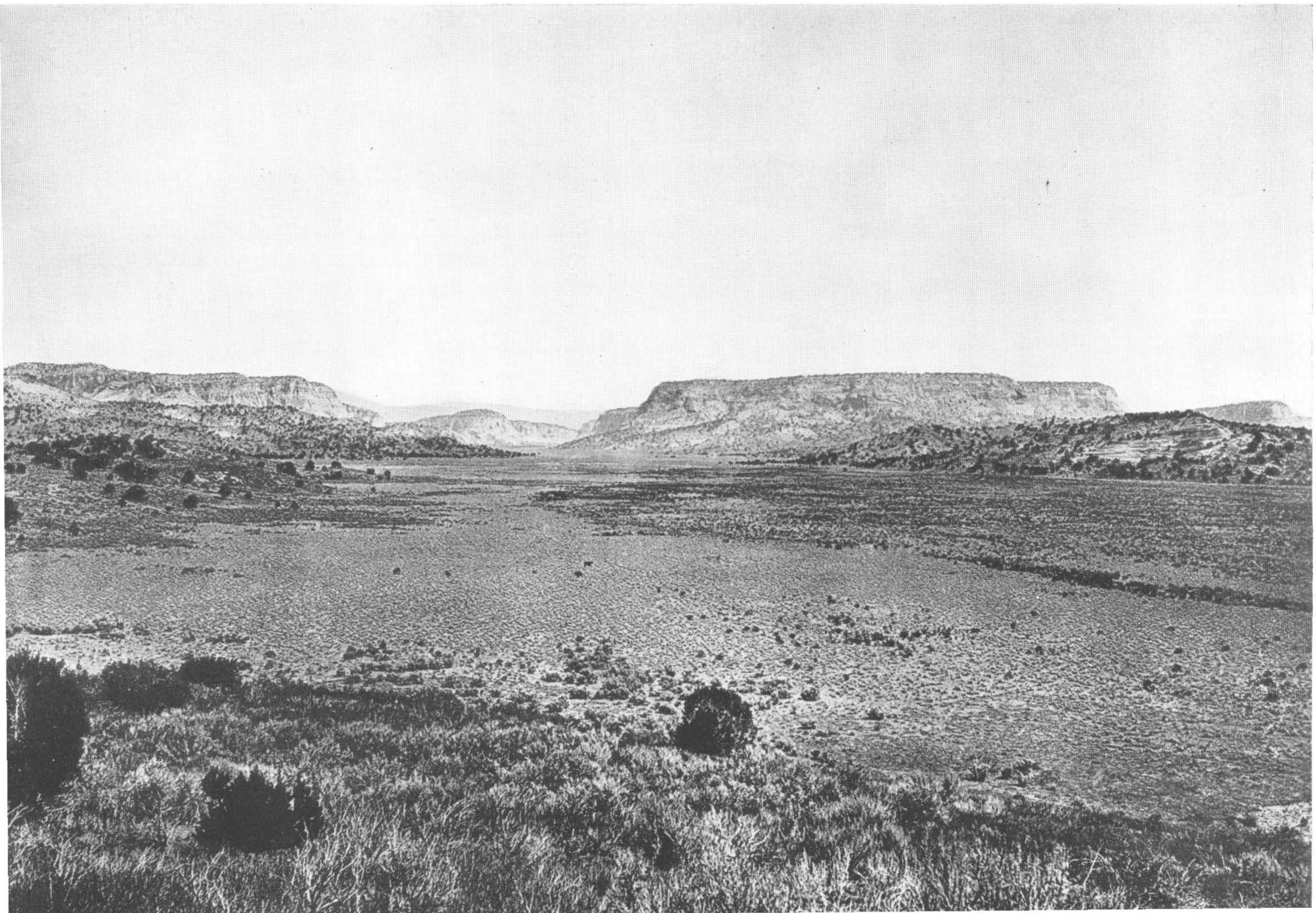
Johnson Valley, view northward to White Cliffs. Untrenched alluvial valley fill (30 to 80 feet deep) and bordering alluvial fans as they appeared in 1880. Photograph by J. K. Hillers; reproduced from Dutton, C. E., Physical geology of the Grand Canyon District: U. S. Geol. Survey 2d Ann. Rept., pl. 38, 1882.

stacked giant balls weighing hundreds of tons were rolled over the bank of the Kanab by teams." As these balls crumble when dry, many have been incorporated into the soil.

On a smaller scale, erosion by Kanab Creek has been duplicated by nearly all other streams in the Zion Park region. It has caused the abandonment or shifting of village sites, the destruction of much tillable land, the relocation of roads, and change in the position and availability of pasturage and water for stock. Many times irrigation ditches have been reconstructed and reservoirs broken or filled with debris. To a considerable degree the agricultural history of the region is a record of adjustment to floods. (See p. 154.)

Field surveys have shown that terracing of valley fill, though it began at somewhat different dates and is proceeding at different rates at different places in Utah, Arizona, New Mexico, Colorado and Nevada, is coextensive with the plateau province. Because the resulting wastage so directly concerns the present and future utilization of vast areas of agricultural and grazing lands, its cause and hoped-for cure have received much study.[41] Most students of the plateau country have thought it reasonable to suppose that the recent change in stream habit from aggradation to degradation may represent climatic fluctuation. The erosional unconformities, the swamplands, and the lake beds within the valley fill certainly indicate minor changes in stream habit that in turn may represent the minor cycles of wet and dry climates shown by tree rings and the distribution of artifacts, but weather records, sunspot maxima, and cultural his-

[41] Antevs, Ernest, Post-pluvial climatic variations in the Southwest: Meterol. Soc. Bull., vol. 19, pp. 190–193, 1938. Bailey, Reed S., Epicycles of erosion in the valleys of the Colorado Plateau province: Jour. Geol., vol. 43, pp. 337–355, 1935. Bailey, W., Forsling, C. L., and Becraft, R. J. Floods and accelerated erosion in Northern Utah: U. S. Dept. Agr. Misc. Pub. 196, 1934. Brady, L. F., The arroyo of the Rio de Flag, a study of an erosion cycle. Mus. Northern Arizona Mus. Notes, vol. 9, no. 6, pp. 33–37, 1936. Bryan, Kirk, Date of channel trenching (arroyo cutting) in the arid Southwest: Science N.S. vol. 57, pp. 338–344, 1925; Recent deposits of Chaco Canyon, N. Mex. in relation to the life of the prehistoric peoples of Pueblo Bonito: Abst. Wasl.. Acad. Sci. Jour., vol. 16, pp. 75–76, 1926; Erosion and sedimentation in the Papago County, Ariz.: U. S. Geol. Survey Bull. 730 (1922) 1923; Historic evidence of changes in the channel of Rio Puerco, a tributary of the Rio Grande in New Mexico: Jour Geol., vol. 36, pp. 265–282, 1928; Change in plant associations by change in ground water level: Ecology, vol. 9, pp. 474–478, 1928; Flood-water Farming: Geog. Rev., vol. 19, pp. 444–456, 1929; with Albritton, Claude C., Jr., Quaternary stratigraphy in the Davis Mountains, Trans-Pecos, Tex.; Geol. Soc. Amer. Bull., vol. 50, pp. 1423–1474, 1939. Colton, H. S., Some notes on the original condition of the Little Colorado River: a side light on the problems of erosion: Mus. Northern Arizona Mus. Notes, vol. 10, no. 6, Dec. 1937, pp. 17–20. Cooperrider, C. K., and Hendricks, B. A., Soil erosion and stream flow on range and forest lands of the Upper Rio Grande Watershed in relation to land resources and human welfare: U. S. Dept. Agr. Tech. Bull. 567, 1937. Dutton, C. E., Tertiary History of the Grand Canyon District: U. S. Geol. Survey Mon. 2, p. 229, 1882. Gregory, H. E., The Navajo Country: U. S. Geol. Survey: Prof. Paper 93, pp. 130–132, 1917; The San Juan Country: U. S. Geol. Survey Prof. Paper 188, pp. 98, 101–102, 1938. Gregory, H. E., and Moore, R. C., The Kaiparowits Region: U. S. Geol. Survey Prof. Paper 164, pp. 143–144, 1931. Hack, J. T., Late Quarternary history of several valleys of northern Arizona: a preliminary announcement: Mus. Northern Arizona Mus. Notes, vol. 11, pp. 67–73, May, 1939. Miser, H. D., The San Juan Canyon, Southern Utah: U. S. Geol. Survey Water Supply Paper 538, pp. 59, 67–71, 1924. Ross, C. P., The Lower Gila Region, Ariz.: U. S. Geol. Survey Water Supply Paper 498, pp. 64–65, 94–95, 1923. Thornber, J. J., The grazing ranges of Arizona: Univ. Ariz. Agri. Exper. Bull. 65, p. 355, 1910. Winn, Fred, The West Fork of the Gila River; Sci., n.s. vol. 64, pp. 16–17, 1926. Wooton, E. C., The Range problem in New Mexico: N. Mex. Agr. Exper. Sta. Bull. 66, 1906.



tory fail to provide the hoped-for proof of rainfall so widely fluctuating as to initiate the deposition of the valley fill, cause deposition to cease about 1700 A. D. and suddenly introduce vigorous erosion during the period 1880–1890.

In this connection, it may be pointed out that in the plateau country erosion results chiefly from sudden, violent showers and might suffer no abatement if the rainfall were half its present normal amount. If otherwise distributed in time twice the normal rainfall would probably be less effective. Thus so far as fluctuation in rainfall is a factor in erosion, cycles of change in type of precipitation from even to spasmodic would better account for the known conditions.

In considering the cause and rates of the present rapid erosion it seems helpful to keep in mind that generally in the plateau country the balance between aggradation and degradation is so closely adjusted that slight changes in rainfall, amount and kind of plant cover, or gradient of valleys are sufficient to modify stream habit. On the unconsolidated valley fill the construction of a dam or an irrigation ditch, the building of roads, trails, and bridges, the plowing of fields, or the removal of native brush may begin far-reaching changes. Conservationists appropriately point out that tillage, though producing conditions favorable for soil absorption, breaks up the roots that hold the soil in place; that grazing, by destroying the leaves and twigs that otherwise would form litter and the seeds necessary for reproduction, tends to increase the amount and the rapidity of runoff; and that the killing of beavers facilitates stream erosion of swampy meadowlands. The available evidence leaves no doubt that the modification and partial depletion of the indigenous plant cover incident to the introduction of livestock into southwestern Utah have generally affected the rate of erosion and in places have initiated erosion. But observation for many years in the plateau country shows clearly enough that during the terrace epicycle, as during previous epicycles recorded in the valley fill, the rate, manner, and localization of erosion reflected primarily the work of physical agents. Overgrazing seems an inadequate cause for the profound change in stream habit from aggradation to degradation at the beginning of the terrace epicycle and obviously was not concerned with the similar changes during the gorge and inner-canyon epicycles.

FIGURE 113.—Alluvial terraces at two levels in Kanab Canyon at mouth of Tenny Canyon; produced by erosion since 1886.

On slopes of comparable steepness, porous rock, coarse alluvial deposits and soil penetrated by roots facilitates the absorption of rain and melting snow and thus lessens the amount available for surface streams. On the other hand, dense rock and compact soil are favorable for runoff. Consequently erosion, as represented by gullies, is inconspicuous on swampy lands, in groves of deciduous trees, and on areas coated with wind-blown sands, but prominent on impervious shales, partly cemented alluvium, talus slopes, and landslides, where matted vegetation and the debris from decaying plants are sparse. Observation shows that, in delaying runoff, leaf mold from thick stands of boxelder, ash, aspen, and oak; compact masses of twigs broken from sage, rabbitbrush, and similar shrubs; and piles of dead weed stems are effective, but that juniper, piñon, and yellow pine offer but slight obstruction. On most steep slopes and rock benches isolated evergreens rise from cracks in rocks that are swept clean by the recurrent showers, and over the broad bare rock platforms vegetation seems never to have been dense enough to delay stream flow seriously. (See p. 154.)

The production of terraces by the erosion of valley fill is in progress everywhere in the plateau country and seems to be as rapid in districts never cultivated or used for pasturage as in those long overrun by livestock. In some places where soil texture, underground drainage, and surface runoff are favorable, long-used ranch lands are but slightly gullied.

EROSION SURFACES

In contrast with the gorges, cliffs, and mesas that reveal the youth of the present landscape, the topography of the Zion Park region includes extensive, generally even, erosion surfaces of postmaturity, which mark stages in the physiographic history of pre-canyon and canyon time. Some of these old-age surfaces have been developed on hard strata with which they roughly coincide; others bevel the edges of tilted beds and extend across faults and folds. None of them is level and devoid of inequalities, for unlike similar features in humid regions, where long-continued weathering and stream wear unite to form uniform low slopes, the old-age surfaces in the plateau country include local flats, which mark the position of soft rock, gentle slopes determined by structural dips, and ridges that mark the harder rocks.

The largest and most continuous erosion surfaces are those developed on the Wasatch formation by the removal of late Tertiary beds from the Markagunt and Paunsaugunt plateaus; on the Carmel formation by stripping the upper Mesozoic rocks along the southern part of the Kolob and Skutumpah Terraces (figs. 6, 11); on the Shinarump conglomerate by the erosion of the Chinle formation from the western part of Little Creek Terrace; on the Timpoweap member of the Moenkopi from which the upper members of the formation have been removed along the back slope of the Hurricane Cliffs; and on the Moccasin Terrace developed on Navajo sandstone with seeming disregard of dips and variations in texture and composition. Similar old-age surfaces, in places partly covered with gravel from the bordering high walls, are displayed as rock terraces along the Virgin River and other streams. So broad and continuous are these erosion surfaces in resistant strata, and so relatively narrow the canyons that cross them that in general views they appear as unbroken expanses of bare rock dissected by a few widely spaced streams. Thus, on the reconnaissance maps of the Powell Survey 19 tributaries to the Virgin River—canyoned stream channels 6 to 15 miles long and 400 to 1,000 feet deep—are not shown.

These flat or slightly inclined surfaces between canyons are essentially local base levels to which ephemeral streams are so completely adjusted that their power to erode is conspicuously small. Even the sheet floods that result from torrential showers pass along shallow poorly defined runways so slowly that in places the products of weathering are not removed. It would seem that in their present position these maturely eroded surfaces of bare rock are long-lived and that some of them may have attained approximately their present forms before the deep dissection of the regional landscape had proceeded far. Regardless of their age they can be destroyed only by widening the canyons that trench them. Like the Tonto platform, which is developed on resistant Cambrian beds, the "Esplanade" developed in Supai strata, and the Glen Canyon platform made by removal of soft shales from the Navajo sandstone, the rock platforms in the Zion Park region are expressions of the relative strength of rock; no cycles of erosion are necessarily involved.

In addition to the old-age surfaces, which substantially parallel the bedding of the harder sedimentary rocks, the topography of the Zion Park region presents surfaces that indiscriminately bevel horizontal soft and hard rock and the strata displaced in faults and folds. They stand at various altitudes and in various topographic positions and affect strata of various ages. On the back slope of the Hurricane Cliffs essentially base-leveled surfaces are almost continuous. South of Little Creek remnant strips are preserved beneath the lava caps of huge mesas. (See fig. 70.) Northward a broad platform has been developed in part by stripping and in part by truncating hard and soft beds in the lower Moenkopi. Into this erosion surface Timpoweap Canyon of the Virgin River has been deeply sunk. (See fig. 114.) The floor of the amphitheater at Alton is a surface of erosion trenched by shallow canyons and coated in places by alluvium wash from the surrounding cliffs. (See fig. 115.) South of the White Cliffs between Kanab and Johnson Canyon the surface of Wygaret Terrace consists of the beveled edges of Kayenta and lower Navajo sandstones. (See fig. 116.) In many places the Vermilion Cliffs and the cliffs below the Shinarump escarpments are bordered by old-age sedimentary rock represented by narrow strips of beveled shale of the Chinle formation. Extending from the cliffed border of Moccasin

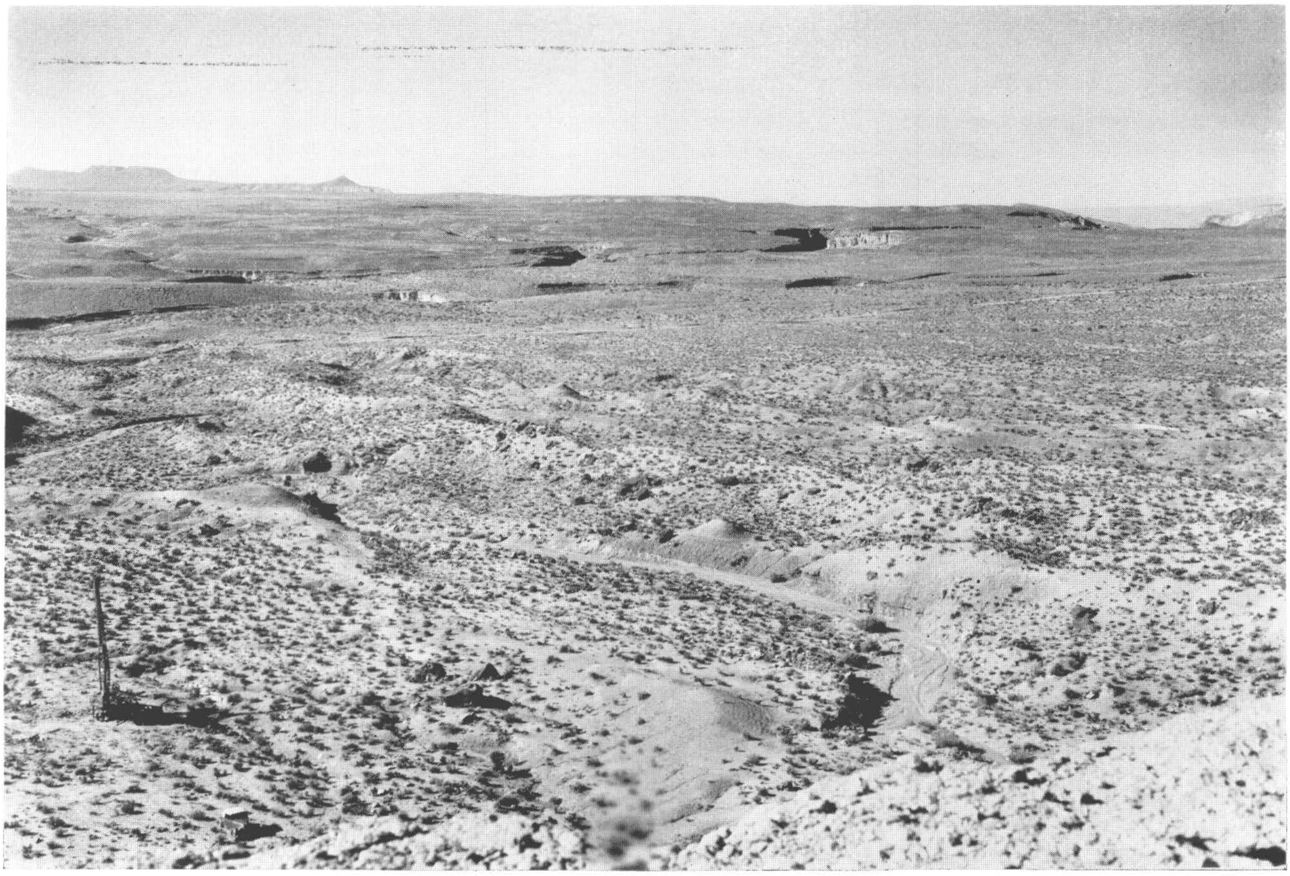


FIGURE 114.—Back of eastern slope of Hurricane Cliffs. Timpoweap Canyon of Virgin River (center) sunk into an erosion surface on Moenkopi strata. Lava-capped mesas (upper left).

H.E. Gregory 958

FIGURE 115.—Eastern part of Alton amphitheater; floor is of Tropic formation; surrounding walls are of Straight Cliffs, Kaiparowits, and Wasatch strata. Erosion surface slopes southward across northward-dipping beds.

H.E. Gregory 942

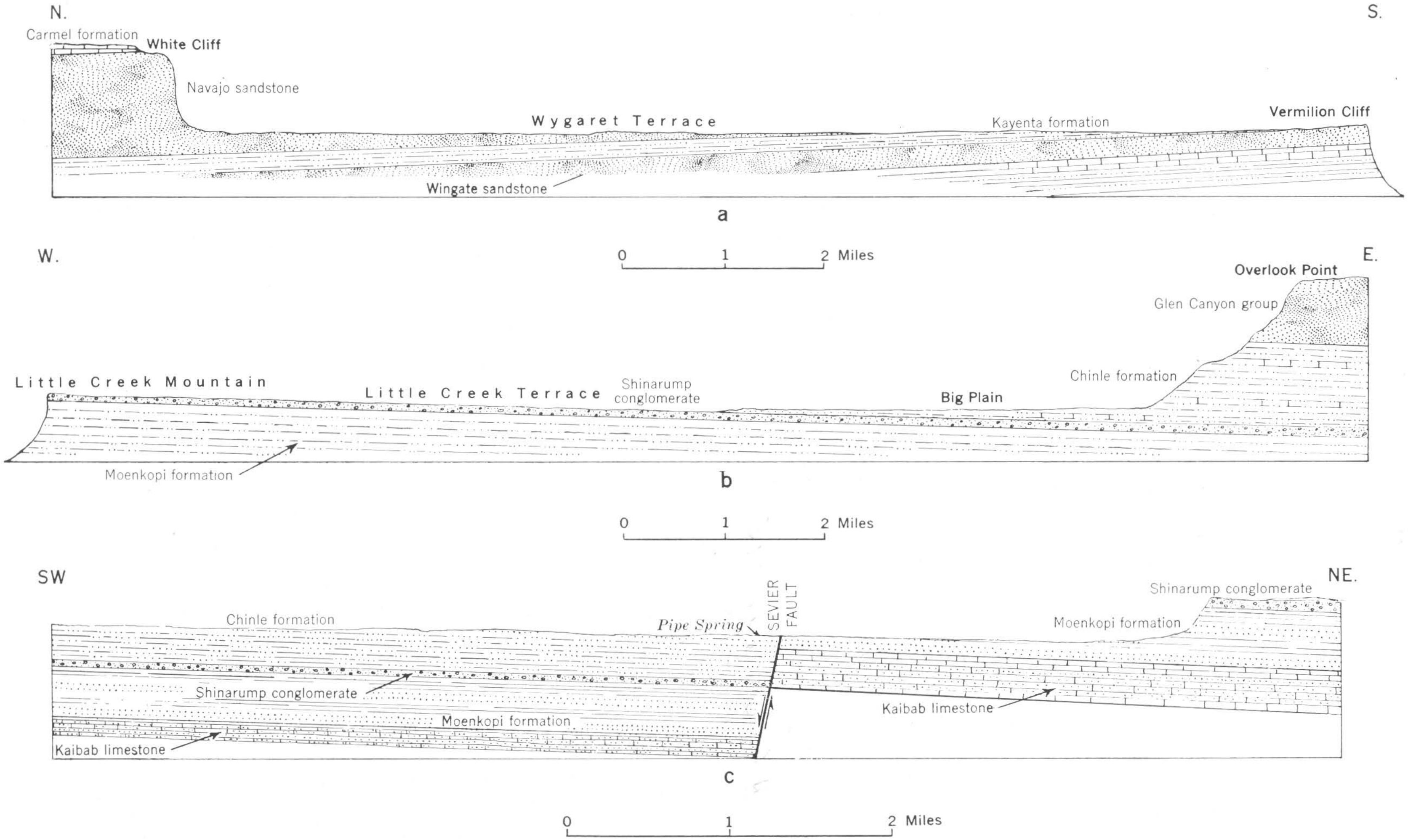


FIGURE 116.—Surfaces of erosion. *a*, Across Wygaret Terrace; *b*, Little Creek Terrace; *c*, At Pipe Spring.

Terrace westward into the valley of Little Creek a base-leveled surface about 20 square miles in area, now largely coated with gravel and silt, constitutes the farm lands of Big Plain. (See figs. 116*b*, 118.) The "lower fields" along the Kanab River north of Fredonia is a broad area of flatland made by truncating the edges of tilted rock. (See fig. 117.) A similar

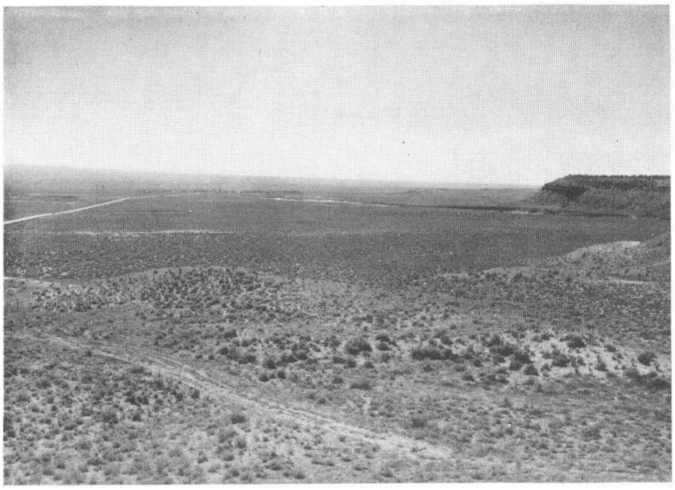


FIGURE 117.—Erosion surface between Kanab and Fredonia, developed on Petrified Forest member of Chinle formation. Surface slopes southward along Kanab Creek (middle distance); underlying rocks dip northeastward in conformity with those in upper part of Chinle (upper right).

H. E. Gregory 905

surface has been developed on Smith Mesa. On the Uinkaret and Kanab Plateaus stretches of approximately flat ground extend with little modification across sandstones, shales, and limestones of the Moenkopi and Kaibab formations and in places are buried beneath lavas. In the vicinity of Pipe Spring an essentially even surface that slopes gently southeastward cuts across northward-dipping Chinle shales and sandstone, the Shinarump conglomerate, and the Moenkopi shales and sandstone and also across the Sevier fault where once stood cliffs several hundred feet high. This remarkable surface retains much of its original appearance for, though erosion in the present cycle has reduced its level and converted some of its original low slopes to cliffs, vigorous streams issuing from the Vermilion Cliffs have covered it with alluvium faster than it could be removed and thus prevented the formation of deep stream channels. Part of this old surface in nearly its original form is preserved at Cedar Ridge, the divide between the Kanab and Virgin Rivers. (See fig. 116*c*.) Old-age erosion surfaces remain at the heads of many tributaries though destroyed along the master drainage channels. They also appear on divides between tributaries to the Parunuweap, the Kanab, and other streams. Such surfaces obviously are not the result of structural control in the present cycle. They have been inherited from a previous cycle during which the ancient landscape of which they are parts reached old age.

In the Zion Park region those old-age erosion surfaces are representative of the many such surfaces, peneplains, and "ancient landscapes" described by students of the plateau country as features indicative of extensive, deep erosion.[42] In the Zion Park region erosion surfaces stand at altitudes between 3,000 and 7,000 feet and in positions not consequent on structural movements. Of the surfaces produced during the pre-canyon cycle those beneath lavas and elsewhere favorably placed have been little modified by later erosion; others though recognizable have lost much of their original form; and many doubtless have been destroyed. It is therefore impracticable, especially in the absence of topographic maps, to project their surfaces across the present rugged landscape in such a manner as to produce a single plane or to combine them in series at different altitudes. Davis[43] remarks that "it is difficult to point out representatives of the very flat expanse [postulated by Dutton] that was produced when the plateau cycle was interrupted by the uplift that introduced the canyon cycle." Attempts to correlate the erosion surfaces in the Zion Park region with similar surfaces in the Navajo country, the Little Colorado Valley, the Uinkaret Mountains, the San Juan country, along the Colorado Canyon, and elsewhere have proved disappointing. It seems highly probable that during the later part of the precanyon cycle old-age surfaces of large area were developed at different altitudes and in different situations. The extension of lowland plains at the expense of rugged highlands during late Tertiary time is readily demonstrated, but it seems unnecessary to assume the existence of a single peneplain once coextensive with the plateau province. Some of the remnant surfaces are undoubtedly local features, closely related in origin to position of drainage lines and to the type of rock exposed.

CLIFF CAVES AND ARCHES

In the Zion Park region many cliffs and canyon walls, rincons, buttresses, and alcoves are sculptured in relief and intaglio. Innumerable bosses, miniature towers, pilasters, platforms, moldings, "door frames," and statues project from surfaces that are further decorated with recessed arches, windows, niches, broad grooves, and narrow striae, variously placed and seemingly unlimited in design. Some of the recesses are merely "toeholds," "owl holes," or "fish mouths" that appear on the walls as round, oblong, or rectangular openings, small in diameter and depth; others are slots, "half tunnels," a few feet

[42] Dutton, C. E., Tertiary history of the Grand Canyon district: U. S. Geol. Survey Mon. 2, p. 224, 1882. Huntington, Elsworth, and Goldthwait, J. W., The Hurricane fault in the Toquerville district, Utah. Harvard Coll. Mus. Comp. Zoology Bull., vol. 42, p. 227, 1904. Robinson, H. H., The Tertiary development of the Plateau district and adjacent country in Arizona and New Mexico: Am. Jour. Sci. 4th ser., vol. 24, p. 122, 1907.

[43] Davis, Wm., An excursion to the Grand Canyon of the Colorado: Harvard Coll. Mus. Comp. Zoology Bull., vol. 38, p. 137, 1901.

high and deep and 10 to 100 feet long; and still others are "cliff caves" as much as 50 feet high and 200 feet wide, sunk 10 to 50 feet into the rock walls. The smaller cavities provide homes for rodents, bats, birds, and insects and favorable footing for shade-loving plants and roots of trees. The larger ones, which furnish protection from wind, rain, and sandstorms, are the "rock shelters" and "caves" chosen by the Basket Makers and the Pueblos as building sites. (See figs. 22, 119.)

sandstone, then the grains themselves, producing slitlike cavities or broad grooves open at the cliff face. (See fig. 121.) Because of this slight undermining, grains and thin sheets of saturated sandstone fall from the roof and, as their cement has been largely removed, reach the floor as sand, which is easily carried away by the seepage rills. As the process continues, sheet after sheet is detached from the roof, and the sides recede until the shallow cavity has grown into a wide-mouthed cave. Many cliff caves still show

FIGURE 118.—Big Plain, a soil-coated erosion surface developed on Chinle formation. Plain slopes southwestward opposite dip of underlying Shinarump conglomerate of Little Creek Mountain (upper left).

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The cliff caves are of two types: Flat-roofed structures at the base of flat-lying, regularly bedded, and resistant sandstones and arched roof structures at the base of massive cross-bedded friable sandstones. Many flat-roofed, unevenly floored rock shelters have been excavated in Moenkopi shales beneath flat-lying Shinarump conglomerate and others in the shales immediately beneath Cretaceous sandstone at places where erosion of soft beds permits the resistant beds to overhang like the eaves of flat-roofed houses. On the other hand the many cavelike recessions at the contact both of the Navajo sandstone with the underlying Kayenta shales and of the Wingate sandstone with the Chinle shales have arched roofs and generally flat floors. Both types of structure are chiefly the work of ground water, in southern Utah a slow but persistent agent of erosion. The percolating water removes first the cement from about the grains of

excavation by seepage; their back walls are covered with films of water that give rise to springs, and their floors are traversed by tiny, slow-moving intermittent or perennial streams that emerge at the cliff face or unite to form lakes. (See fig. 120.) Because the ground water has found other exits, the walls of some cliff caves are dry or partly coated with moist travertine or "alkali bloom"; their floors are thickly covered with impalpable dust beneath which lie the hearthstones, artifacts and burial cists of a vanished race. In the early days of white settlement they served as temporary dwellings; now they are stock corrals and caches for grain and fodder. (See fig. 122.)

Related to the cliff caves in origin and mode of development are the arches, windows, panels, and angular niches that decorate the walls of canyons and the bounding cliffs of mesas and plateaus. Essentially these rock cavities, regardless of form and size, mark stages in the continuous erosion of sandstones of somewhat unusual texture and water content. In the erosion of more weakly cemented parts of the generally massive sandstones, weathering is effective in producing films and aggregates of loosened grains that are stripped from the ledge by rainstorms, leaving tiny pits and long slots. More effective is the process whereby sheets and blocks, outlined by structural planes and undermined by ground-water seepage, are removed en masse by gravity. On many steep walls, fallen blocks and slabs have left scar niches whose shape and size reflect the number, spacing and inclination of joints and the style of stratification. Along Pine Creek, joints developed into open cracks, outline broad slabs of rock as much as 60 feet along. In places these slabs have slipped downward without losing their vertical attitude, and now stand as buffer walls several feet in front of the main wall. The massive Navajo and Wingate sandstones possess features favorable for the production of erosion forms in which curved lines are dominant. From the top to the bottom of these formations abundant ground water loosens grains and enlarges joint cracks and commonly the curved bedding laminae guide the direction of its movement. Consequently, outcrops of the Wingate and, especially, of the Navajo are marked by curved recesses and projections in both vertical and horizontal directions—curves that outline arches on the cliffs and on the eroded surfaces below. Some of the arches are merely sketched on bare rock, others, deeply recessed, form the borders of panels or the roofs of cliff caves; still others are detached from the wall and stand like arches supporting bridges. Some arched structures have been so deeply recessed as to pass entirely through narrow walls producing "natural windows," high on the walls of buttresses, meander niches, and isolated ridges. Some incomplete arches have the appearance of flying buttresses. (See fig. 123.)

In some small arches the curvature coincides with that of the bedding, but generally the arch-roofed structures have been excavated in closely associated curved beds and tangent beds. Observation shows that such huge structures as the Great Arch in Pine Creek Canyon (fig. 125), the White Arch on the Zion-Mount Carmel road (fig. 124), and similar arches in Orderville Gulch, and in Deep and La Verkin Creeks are not bounded by continuous curved planes; they exhibit irregularities produced by erosion of the projecting edges of laminate that have various attitudes. No arches were observed in persistently flat-lying beds. The arched panels and free-swinging arches are normal results of cliff recession in rocks and are most readily developed in alcoves and at the box heads of canyons where the work of ground water is most vigorous.

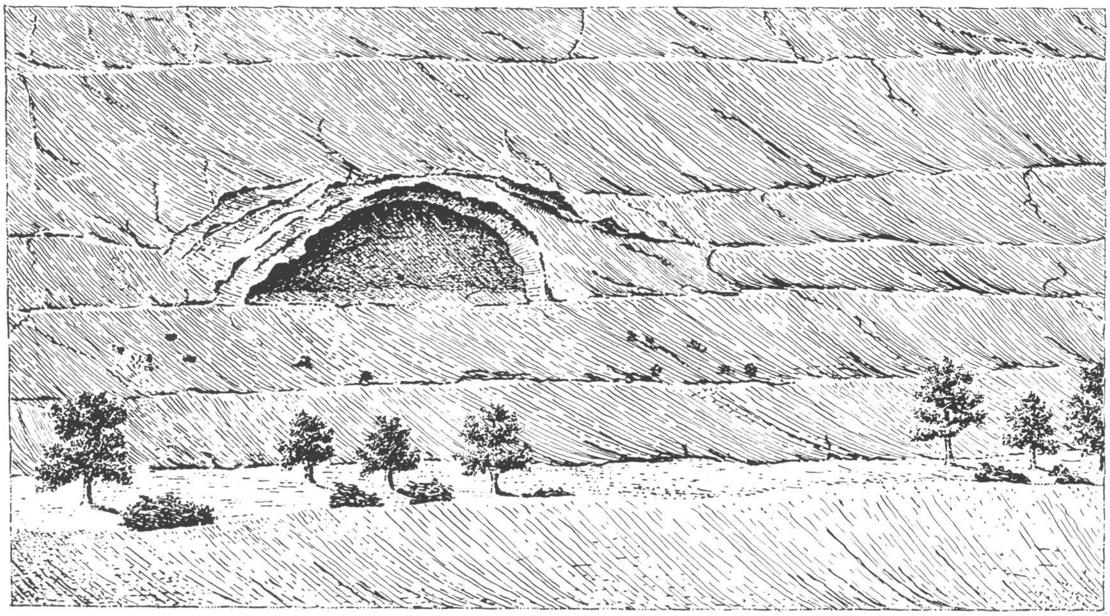

FIGURE 119.—Cliff Cave, in branch of Zion Canyon, developed by seepage of ground water along planes of cross bedding and joint crack in Navajo sandstone. Sketch by Elinor Stromberg.

It is interesting to note that in strong contrast with the other sedimentary formations of the plateau province the Navajo and Wingate wherever exposed are characterized by windows, arches, cliff caves, and natural bridges. The great curved structures that give eminence to the Rainbow, the Navajo, the Capitol Reef, and the Arches National Monuments, are but large examples of hundreds within areas mapped in Arizona and Utah.

POT HOLES

In the Zion Park region erosion by streams is facilitated by the development of pot holes for which in many valleys the conditions are favorable. In flowing over bare rocks of heterogenous composition and structure, particularly such jointed, cross-bedded, and friable strata as the Navajo and Wingate sandstones, intermittent and ephemeral streams of steep gradient cross locally flat places where their current

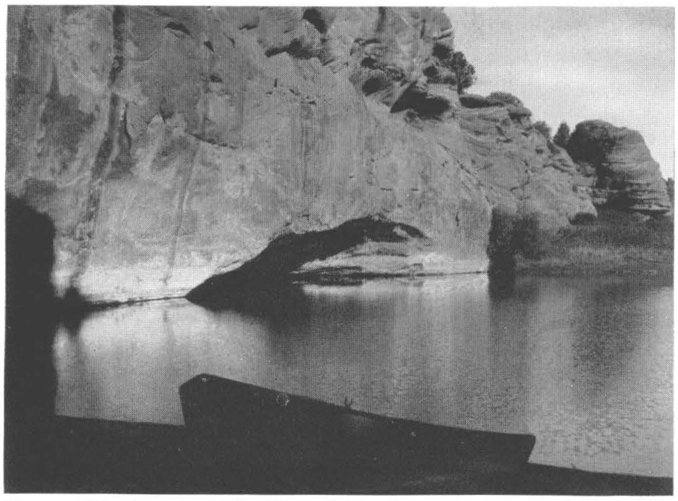

FIGURE 120.—Cave Lake in Three Lakes Canyon, fed by springs from a cliff cave.

is checked, then steeply inclined places where speed is resumed. (See fig. 126) Commonly these points of abrupt change in grade tens or hundreds of feet apart are marked by rapids or incipient waterfalls descending into "rock tanks," where during floods the swirling, sand-laden water is given special power to erode, particularly downward. As the streams sink their beds into solid rock these water-filled depressions take on new forms and assume new positions until with the establishment of a uniform gradient they disappear as definable features. Thus by drilling and removing drill holes the streams are removing obstructions in their path. Traverse of stream beds shows that pot holes are characteristic of stretches where solid rock is exposed—few or none lie underneath the sand-coated parts—and that within these restricted areas they are represented by shallow, broad, irregularly bounded basins, and by circular pits 10 to 20 inches in diameter and 3 to 8 feet deep, some of them straight-sided vertical tubes, others conical, concave downward, or screw-shaped. (See figs. 127, 128.) Observation of streams during floods shows that after a period of violent agitation much of the sand and gravel is swept away from the saucerlike depressions but that many of the deeper pits retain their grinding loads. Doubtless the abrasive materials remain in some holes until their rims are lowered nearly to their bottoms. The vigor and persistency of pot hole erosion is well shown by the rate of drilling and by abandoned pits on canyon walls. Of eight potholes in Co-op Creek under observation for 5 years, two were deepened 3 inches, five more than 4 inches and one, favorably placed, nearly 8 inches. During the same length of time grooves on the adjoining rock walls, though fully exposed to weathering, remained substantially unchanged. Along tributaries to the Virgin and the Parunuweap Rivers two to five (in one place, six) pot holes stand one above another on walls 10 to 40 feet high. Many are in plain sight from the Zion-Mount Carmel highway. (See fig. 129.) At the eastermost "window" in the highway tunnel, Pine Creek Canyon, here less than 20 feet wide, has been cut to a depth of 300 feet by a series of pot holes, which in various stages of completeness are conspicuously perched on the walls.

LANDSLIDES

In Utah south of the High Plateaus most canyon walls, long cliffs, and faces of mesas are bare. The sheer walls of Straight Cliffs, Navajo, Wingate, and upper Chinle sandstones, of Shinarump conglomerate, and the limestones of the Wasatch, Carmel, and Kaibab formations afford few resting places for talus; the products of weathering are swept away by torrential showers about as fast as they are formed. On the other hand many slopes developed on the soft shales of the Chinle and Tropic formations and on the equally friable beds of the San Rafael group are completely covered with talus furnished by the formations that lie above them. From time to time these accumulations of heterogeneous materials move downward in landslides thus adding mass wastage to vigorous stream abrasion as causes of rapid erosion.

In the Zion Park region the most numerous and the largest landslides rest on slopes in the Chinle formation where conditions for the production and downward movement of masses of talus are exceptionally favorable. In this formation the intricately jointed Springdale member and many of the sandstones above break readily into talus fragments; the marllike clays of the Petrified Forest member hold much moisture and at times become a pasty substance almost capable of moving under its own weight; and generally the topmost beds mark a zone of seepage along which the overlying formations are undercut. Talus from the steep upper slopes of the Chinle and the still steeper cliffs of the overlying Navajo comes to rest on the gentle slope of clays, where water percolating downward through the unconsolidated talus forms a zone of saturation. Along the Vermilion Cliff, where the Petrified Forest member is not fully exposed, landslides in the Chinle are inconspicuous; they appear in such places as Moccasin Springs and Canaan Springs where water from several outlets at the top of the formation keeps continuously wet the shales on which fall the undermined blocks of Navajo sandstone. In lower Parunuweap Canyon the Chinle in the south wall, where springs and seeps are abundant, is fairly smothered with talus and minor landslides; the dryer north wall is nearly bare. In the Virgin River Valley huge slides nearly cover the Chinle south of Rockville, east of the abandoned village of Northrup and in lower Zion Canyon.

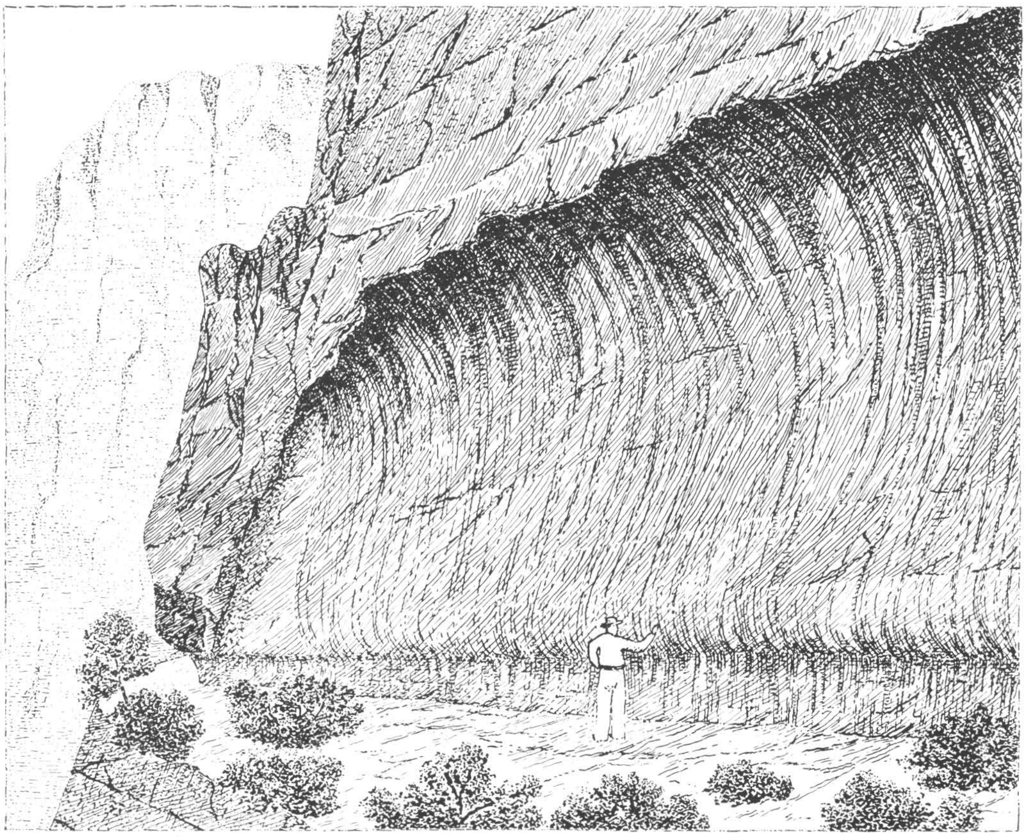

FIGURE 121.—Grooves in Navajo sandstone formed by seepage of water issuing from bedding planes at the top and bottom of the concave surface.

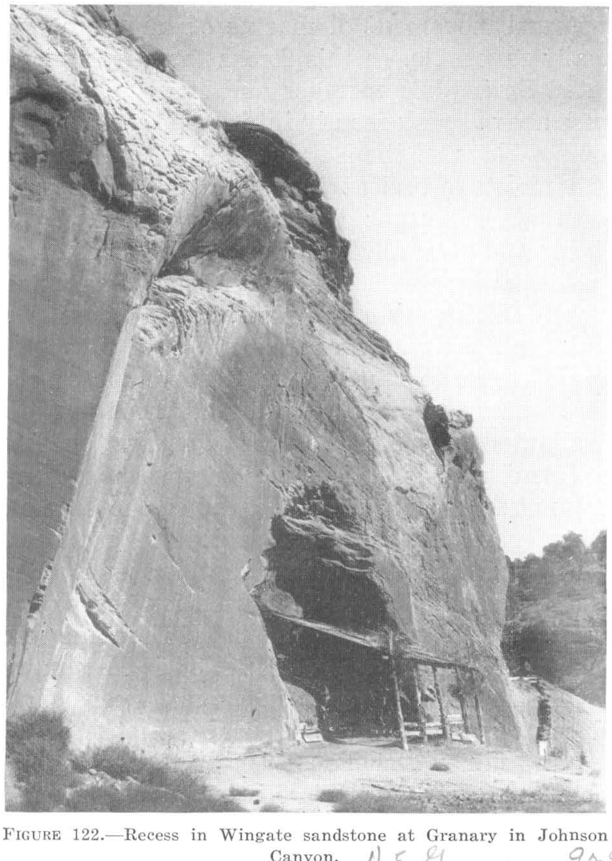

FIGURE 122.—Recess in Wingate sandstone at Granary in Johnson Canyon.

The Rockville slide fills the shale-floored cove of Horse Valley to an estimated average depth of 40 feet and over an area of about 9 square miles presents a disorderly array of mounds, rounded ridges, and irregular depressions, large and small—a surface made still rougher by innumerable gullies, which here and there expose bedrock. The upper edge of the slide crosses the base of the Navajo sandstone; its lower edge rests on a platform of Shinarump conglomerate. At one place it has spilled over the Shinarump ledges into ravines in the Moenkopi and thus made feasible the construction of a rough road upward across otherwise impassable cliffs. Great boulders lie farther down—as much as 2 miles from their source. The Northrup slide, except for small exposures of the Springdale member, covers the entire Chinle in an area of about 1¼ square miles, to a probable average depth of 50 feet. (See fig. 130.) It is composed of talus from the Glen Canyon group and all parts of the Chinle, even crushed masses of clay shales from the Petrified Forest member, and in its descent it has torn off long slabs of sandstone, which now stand tilted or upright in the general mass. Unlike the disorganized assemblage of hills, basins, and pits at Rockville, the talus in the Northrup slide is arranged in terracelike bands roughly corresponding in position to the more resistant of the beds on which it lies. The Rockville

EXPLANATION OF FIGURE 123

Rock buttress on Bridge Mountain overlooking Virgin Valley at Springdale. Length of curved slab of Navajo sandstone, 156 feet long, width at base 6 feet, at top 4 feet. Photograph by E. Y. Scoyan, National Park Service.

and Northrup slides are relatively old. On them drainage has been integrated and large parts have been removed by erosion. Generally around the borders of the Rockville slide the jumbled material has been stripped from the Shinarump platform and in places forms the tops of mesas as much as 100 feet high.

The "great slide" in Zion National Park is expressed in the topography as a roughly uneven bench, 1½ miles long and ½ mile wide that abuts against the walls of the Navajo sandstone at the base of the Sentinel and the Three Patriarchs. (See fig. 131.) In its formation masses of talus, in places as much as 200 feet thick, moved down from the cliffs to the bed of the Virgin River 1,500 feet below, covered all beds in the Chinle formation, and completely erased the topography previously developed by erosion. Strata in oblique position, crushed masses of sandstone, comminuted clay shale, and slickensides in calcareous rocks are evidences of its power. In the bed of the Virgin River the slide built a dam, back of which a lake extended about 3 miles upstream and half a mile up the tributary Birch Creek. In reestablishing its flow the stream found a sag in the dam and across it established a circuitous, markedly ungraded route to the unobstructed channel below. On a slope of about 100 feet a mile in its new channel it is rapidly grinding up big boulders and cutting into bedrock; during the past 6 years the "boulder falls" have advanced upstream about 450 feet. This slide is of especial interest because it retains much of its original form. On its surface some of the original depressions still hold water after rain, and the bottom sediments, the islands, and the delta bars of former ponds are recognizable. Slightly embedded masses of sandstone, including blocks 20 by 60 by 100 feet, stand in groups where they were originally placed. Though of relatively recent origin and still active along its front, the slide has been in existence long enough to permit the building of long fans over its upper edges, the cutting of a channel 80 feet deep across its lower edge, and the deposition of more than 40 feet of lacustrine sediments in the ponded streams.

In providing favorable conditions for landslides the Tropic formation ranks with the Chinle. Where the Tropic has its usual form of interbedded shale, sandstone, coal, and conglomerate, its own weathered products in addition to talus supplied from above constitute a mass of loosened surface material, which when saturated moves downward as one great slide or as smaller slides which rest for a time in various positions. In the Parunuweap Valley near Orderville and along other streams slabs of Straight Cliffs sandstone

FIGURE 124.—White Arch near top of Navajo sandstone along Zion-Mount Carmel highway.

a few hundred square feet in area, partly or wholly detached, lie at the top of the shale of the Tropic formation awaiting favorable conditions for sliding. Some of the slides are old; by repeated movements they have so adjusted themselves as to form substantially graded slopes on which drainage is integrated. Others are of recent origin; they present a hummocky surface of mounds, crude terraces, elongated dry valleys, and water-filled depressions. Some are now active and each year strip the hillsides of tons of talus, leaving scars on the rocks above. At Coal Hill, movements in shale of the Tropic formation have necessitated change in the alinement of the highways four times since 1930. Old slides and new slides are so common at exposures of the Tropic formation as to produce a characteristic topography. In addition to those prevalent at exposures of the Chinle and Tropic formations, active and inactive landslides are in places features of slopes developed on the Moenkopi, the Kaiparowits, and other formations where springs and seeps emerge at the contact of impervious shales and porous sandstone. In the Virgin River Valley between Rockville and Virgin, landslides on Moenkopi shales extend upward to a wet zone at the base of the Shinarump conglomerate. On the slopes thick talus of conglomerate now seemingly at rest has from time to time moved downward en masse and during its descent has loosened huge embedded blocks of conglomerate and rolled them hundreds of feet beyond the base of the slide. At Flax Lakes where seeps in the weak Kaiparowits formation are undermining a lava flow, a disorderly array of basalt and sandstone blocks covers the upper slopes and lower down moves outward as a slide. In the alluvial terraces now forming along streams landslides are common. During a single flood in Johnson Canyon four slabs of stratified sand, the smallest estimated as 250 cubic yards, slid from the valley wall to the stream bed.

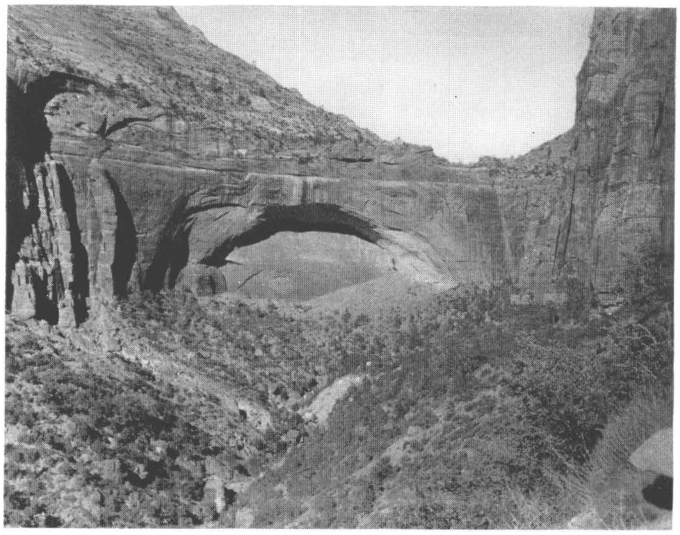

FIGURE 125.—Great Arch near base of Navajo sandstone in Pine Creek Canyon. Photograph by J. C. Anderson, No. 20.

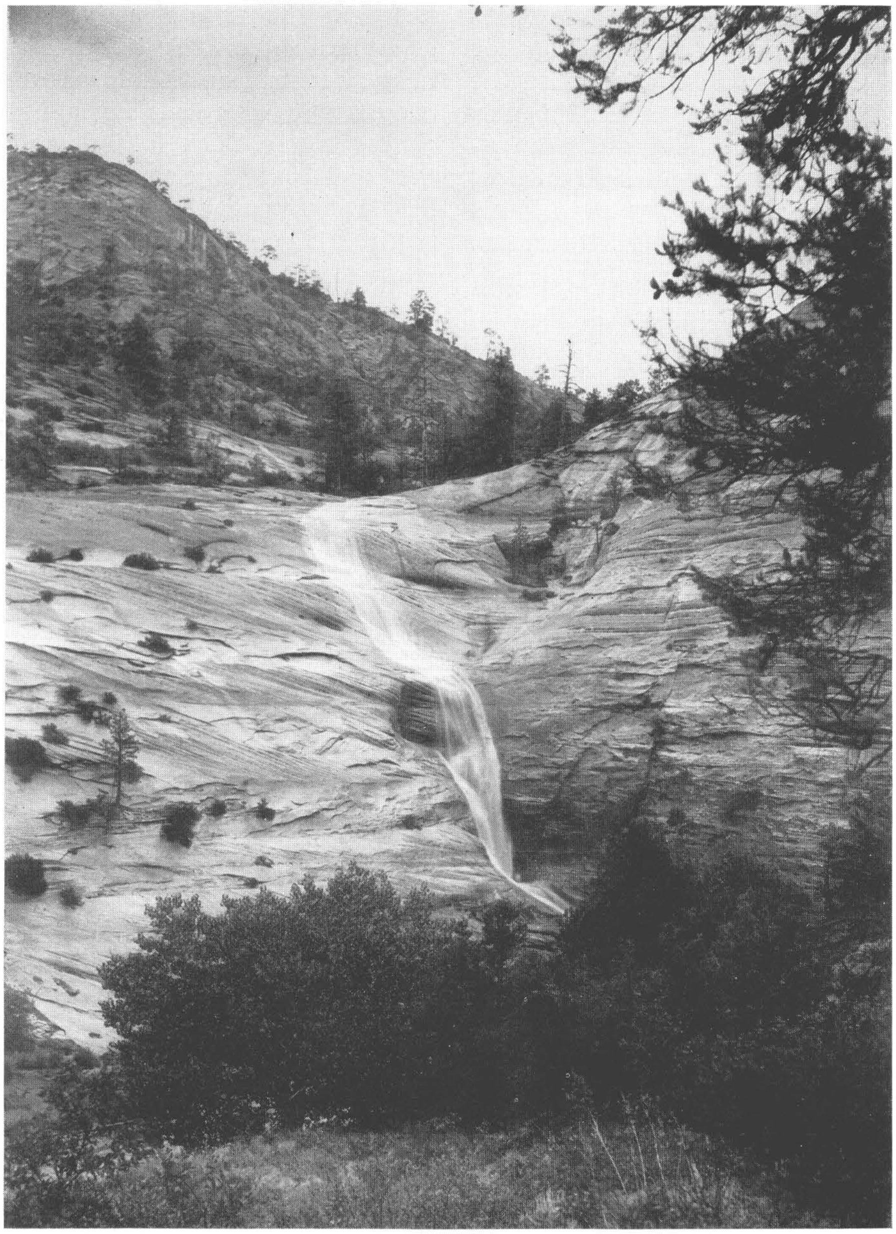

FIGURE 126.—Ephemeral stream, tributary to Clear Creek, showing conditions favorable for making pot holes. Photograph, National Park Service, No. 2155.

In places, particularly at rincons of and at the heads of box canyons slices of the cliffs, 5 to 10 feet thick and as much as 100 feet long, have slumped down from vertical walls onto slopes of shales where they now rest as isolated blocks, unbroken or slightly shattered. They appear on slopes as steplike strips in horizontal position or tilted 5° to 30° toward their parent ledge. Though such mass removal of high rock fragments in the Zion Park region is not comparable in scale with that in the Mesaverde formation at Black Mesa, in the Chinle formation at Echo Cliffs, and in the Straight Cliffs sandstone in the Kaiparowits Plateau,[44] it is obviously an important factor in the rate of erosion of cliffs.

DUNES AND SAND FLATS

In the Zion Park region the high rock walls and the convection currents from the heated canyon floors prevent the free sweep of regional winds but facilitate the development of local winds that vary widely in force, direction, and persistence. Consequently even on flat surfaces devoid of vegetation and on cliffs directly in the path of the prevailing winds, sand-scoured rocks are restricted to exceptionally exposed outcrops and wind-shaped pebbles are rare. The popular notion that the multiform cavities in canyon walls are the work of sand blasts is not supported by observation. (See p. 181.)

[44] Gregory, H. E., The Navajo country: U. S. Geol. Survey Prof. Paper 93, pp. 135–136, 1916. Gregory, H. E., and Moore, R. C., The Kaiparowits region: U. S. Geol. Survey Prof. Paper 164, pp. 145–146, 1931. Reiche, Parry, The Toreva block—a distinctive landslide type: Jour. Geology, vol. 45, pp. 538–548, 1937.

Both prevailing and intermittent winds are effective chiefly as agents of transport and deposition for the fine rock waste produced by weathering on the highlands and by stream corrasion in the canyons. The cliff-bordered plateaus, the mesas, and obstructions of less height outline areas from which the dust is gathered and areas in which it is deposited. Thus much of the dust picked up on the broad flood plain of the Virgin River comes to rest in the Red Desert,

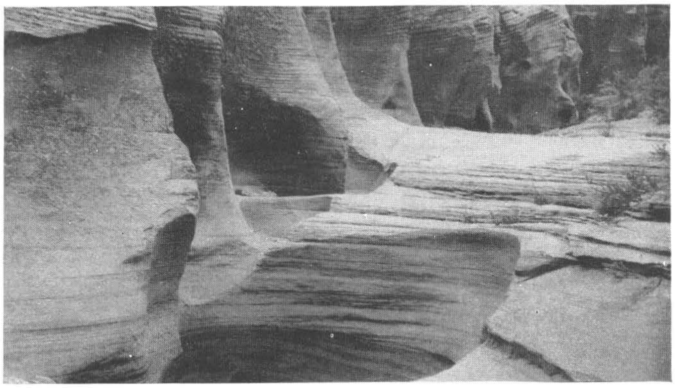

FIGURE 127.—Pot holes at a "dry waterfall" in bed of Clear Creek; deepest of 8 holes is 7 feet.

an enormous dune pile southwest of Hurricane. Continuing over the Hurricane Cliffs the winds obtain a meager new supply from the brush-dotted Uinkaret Plateau, some of which is banked against the Vermilion Cliffs and rest distributed over the Kanab Plateau. Likewise the disintegrated products from the bare sandstone of South Mountain are carried eastward across Moccasin Terrace to form the dunes along the cliffs at Sand Canyon and the great sand flats at the head of Three Lakes Canyon. With local accretions en route these deposits are redistributed over Wygaret Terrace and eastward to the base of the Kaiparowits plateau. During sandstorms great quantities of the finest dust rise high into the air and move eastward to distant places or after darkening the skies with whirling clouds return to the place from which they came.

The wind-borne sand is deposited in a seemingly haphazard fashion. Low dunes singly or in series appear here and there on rock terraces, slopes, and lower flatlands, but most of them lie at the base of rock buttresses, hang over canyon walls, or rest on the valley floors where they move back and forth awaiting transport by flooded streams. Some groups of stationary dunes and of migrating dunes are measured in square miles but most of the bare ridges of drifting sand occupy only a few acres and merge into widespread thin sheets sufficiently stable to permit the growth of vegetation.

South of Heaton Point active dunes, quiescent dunes, and dunes that have long since ceased to move cover an area of about 10 square miles. Red Knoll and many smaller buttes that rise above this sand-coated field, and the parts of canyons not completely filled show that in forming the present landscape of low ridges, mounds, and shallow depressions a once more rugged topography has been almost obliterated by migrating sands. Though in places but a few feet deep the sand cover is nearly continuous, most of it is loosely compacted, and when the wind is blowing much of it is in motion. Roads across the dunes have been difficult to maintain. (See p. 32.) Another large area of dunes extends from the head of Cottonwood and Water Canyons northwestward across Sand and Yellow Jacket Valleys to the base of the Block Mesas near Esplin Point. For a distance of about 8 miles northwest of Riggs Spring dunes as much as 200 feet high are nearly stationary; they support growths of piñon and juniper and in wet seasons hold lakes and give rise to springs. At the head of Sand Canyon they are in motion and in their migration are burying and uncovering trees and converting the original escarpment of the Sevier fault into a slope. (See figs. 132, 133.)

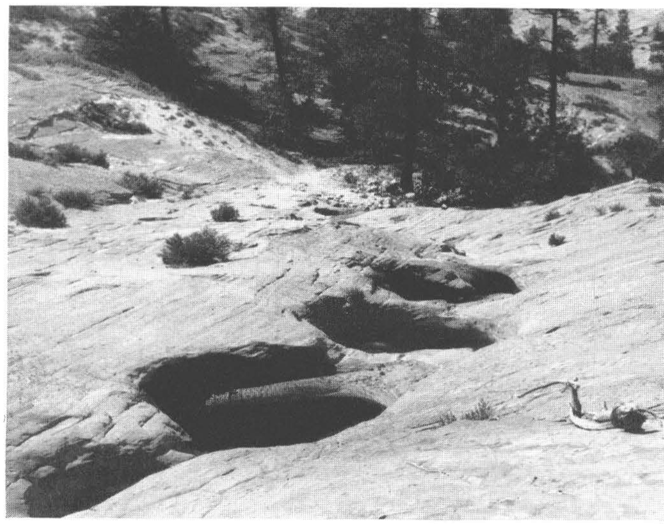

FIGURE 128.—Pot holes in branch of Co-op Creek where it flows across slightly inclined Navajo sandstone. The depressions are partly filled and reexcavated during floods. Photograph by J. C. Anderson, No. 17.

ECONOMIC GEOLOGY

In the development of southwest Utah the exploitation of mineral resources has been an incidental factor though at times it seemed that mining was to rank with agriculture and stock raising as a source of revenue. As early as 1851 large deposits of iron and coal were found near Cedar City, and within the next few years copper was reported in the Virgin and Johnson Valleys and in regions south of Kanab. In 1869 silver was found in a boulder near Harrisburg, and some years later, traced to its source in a nearby anticline (Silver Reef), it was seen to represent a remarkable deposit of high-grade ore, which during the period 1875–1900 yielded more than $9,000,000. The search for gold led to the futile "gold excitement" in Kanab Valley (1876) and to the equally futile expenditures

FIGURE 129.—Perched pot holes 20 feet above present bed of Clear Creek.

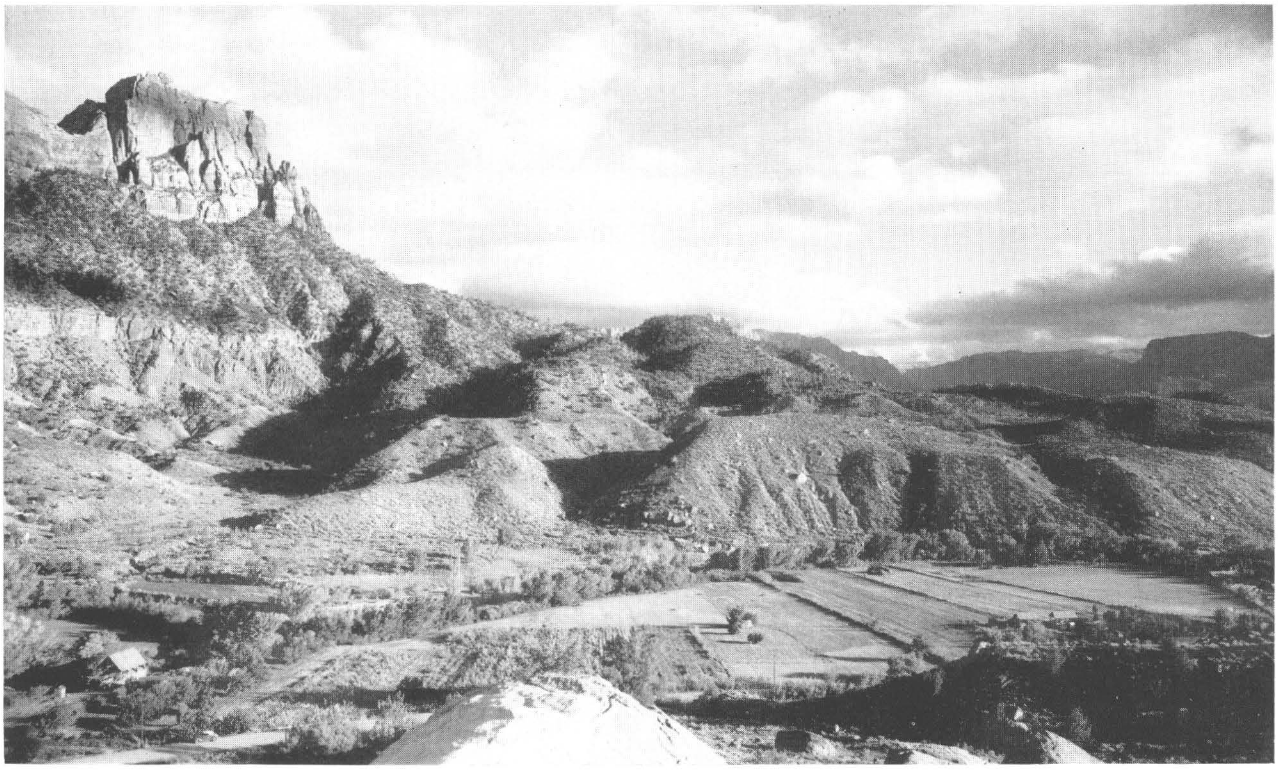

FIGURE 130.—Landslide near mouth of Parunuweap Canyon. Virgin River and "lower fields" of Springdale (foreground); cliffs of Navajo sandstone (top); Springdale sandstone member of Chinle formation (middle left). Top of slide lies 1,600 feet above river.

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of large sums in Paria Valley (1910–13). More recently, misled by assays that showed values of "$0.70 to $3.40 a ton," miners in Little Creek Valley have sought gold in the basalt, which, as analyzed by E. Theodore Erickson, of the Geological Survey, contains no gold or other valuable metals. The vigorous search for minerals of commercial value has resulted in finding widely scattered, small, impure deposits of copper in the Kaibab limestone and the Navajo sandstone, and lead, zinc, silver, gold, manganese, and uranium in the Chinle shales, but the many prospect holes and milling tests have proved disappointing. The spectacular rise in silver mining at Silver Reef was followed by an equally spectacular fall, and drilling in the structural "domes" west of the Hurricane Cliffs, once thought favorable for oil, has not justified the expense. On the other hand, the extensive iron deposits at Iron Mountain, west of Cedar City, though unworkable by pioneer methods, are now of large commercial importance, and coal beds that extend for miles contribute a fuel resource of increasing value.

Stone suitable for building is abundant, and a poor grade of plaster was formerly made from limestone beds in the Kayenta and Carmel formations and from gypsum in the Curtis formation.

At present in the Zion Park region petroleum is obtained from wells on North Creek, and coal is mined in the Hurricane Cliffs near Kanarraville and in Meadow Creek, Parunuweap, and Kanab Valleys. The economic resource of most value is the water available in streams, springs, and wells.

OIL

Oil seeps in Oil Seeps Wash and on North Creek and cavities filled with "oily tar" in rocks in the La Verkin, Virgin, and Short Creek Valleys were known to the pioneer settlers and also to the Piutes, who are reported to have used the material for medicine and also for paint. Doubtless knowledge of these oil seeps and of the "pockets" of asphaltic material led to the exploratory work of 1907, which resulted in the drilling of some 15 shallow wells in North Creek Valley, one of which produced gas and two others a small amount of oil. Lack of market for even this meager supply of oil and the financial depression of 1907–08 brought drilling to an abrupt ending. On the resumption of work in 1918 the three producing wells were cleaned out, another one was drilled, and a refinery was built. In 1920 the total production was reported as about 20 barrels a day. During recent years drilling has continued on North Creek, and exploratory wells have been sunk in neighboring areas. The catalog of wells for 1938 lists 113 along North Creek and near Virgin the "Virgin oil field"; 2 in Dalton Wash; 4 between Dalton Wash and Grafton; 3 near Grafton; 2 in valleys south of Virgin; and 1 south of the Utah State line near Antelope Spring, Ariz. E. W. Henderson, district engineer, Geological Survey, reports that of the holes drilled in the Virgin oil field between 1907 and 1939, 12 produce oil, 21 "show oil," 66 are dry, and 14 have been abandoned. The wells have an average depth of about 500 feet. None of them flows at the surface.

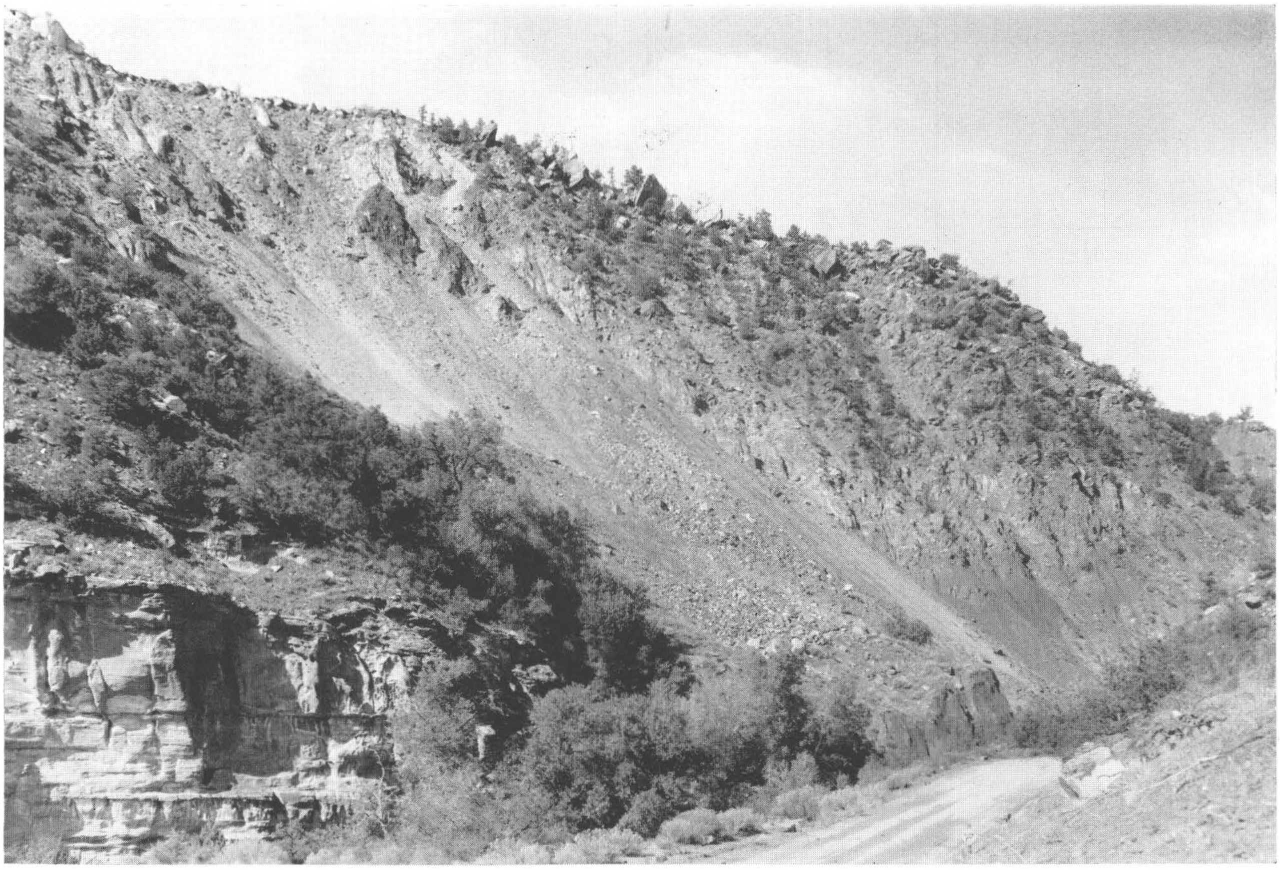
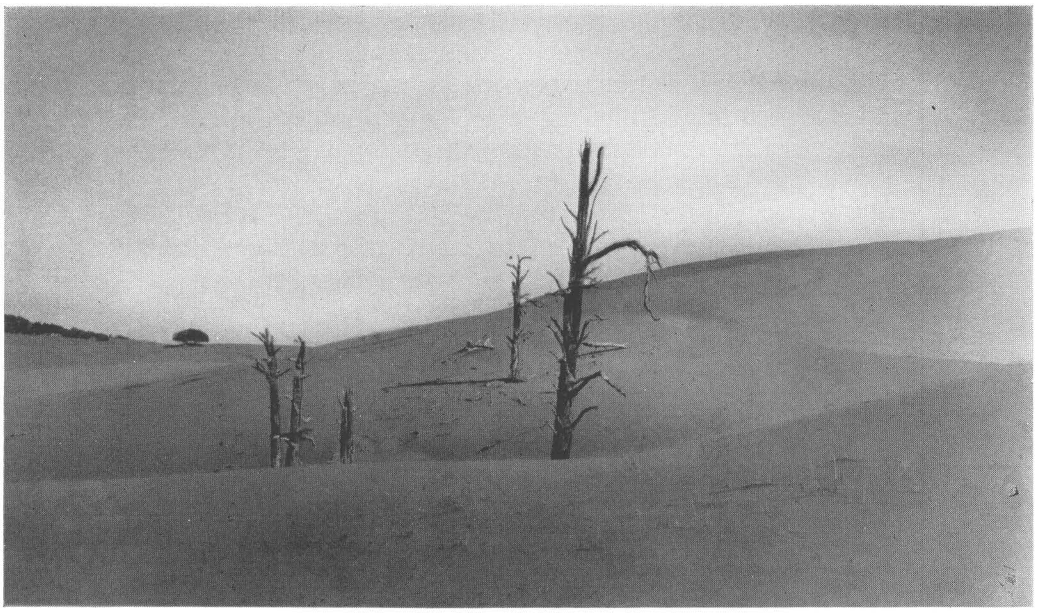


FIGURE 131.—Front of landslide in Zion Canyon. Trees at base mark course of Virgin River where it emerges from gorge newly cut in slide material upstream (right).

In all wells where oil was found the "oil sand" is a bed or a few thin beds of arenaceous limestone in the Timpoweap member of the Moenkopi formation, from which issue seeps of oily sulphur-laden water. The rock lies 10 to 30 feet above fossiliferous limestone that contains cavities filled with asphalt. No oil has been found above or below this horizon, even in the well (Petroleum well 2) that penetrated the Moenkopi, Kaibab, and Coconino (?) formations to a depth of 2,195 feet (1937). The beds of these formations, fully exposed within 10 miles of the producing wells, contain no appreciable organic matter except fossiliferous limestone, which is the probable original source of the petroleum.



H. E. Gregory 772

FIGURE 132.—Sand dunes on divide between Sand and Yellow Jacket Canyons showing destruction of yellow-pine forest.

H. E. Gregory 803

FIGURE 133.—Sand dunes deposited at base of cliffs along Sevier fault by winds that blow (from right) across Moccasin Terrace. Near head of Sand Canyon.

Structural features that favor the accumulation of oil are prominent west of the Hurricane Cliffs where Harrisburg dome, Washington dome, and Bloomington dome are conspicuous parts of the long Virgin anticline. In the Virgin oil field and in adjoining areas structures that might serve as oil reservoirs comprise steplike folds and anticlines, most of them so inconspicuous that were it not for the presence of oil they would attract no attention in this region where such features are common. Along North Creek precise mapping reveals local changes in dip from a regional slope of about 2° to slopes of 3° to 6° and groups of parallel wrinkles that trend generally southwest and are spaced 10 to 300 feet apart. Bassler and Reeside[44] thought that these features accounted for the presence of oil.

Wegemann and Bauer,[45] however, doubt the effectiveness of the small terraces or the local decreases of regional dip in the accumulation of oil, particularly in the beds below the middle Moenkopi. They express the opinion that the irregular folds in the Moenkopi provide the most favorable conditions for the accumulation of oil, and conclude that "the prospects of obtaining oil by deep drilling in such fields as that of Virgin may be disregarded."

In the Zion Park region the folds in the Moenkopi are local downwarps and upwarps, in places slightly faulted, and seem to be contemporaneous with similar

[44] Bassler, Harvey, and Reeside, J. B., Jr., Oil prospects in Washington County, Utah: U. S. Geol. Survey Bull. 726, pp. 86–87, 1921.

[45] Wegemann, C. H., and Bauer, C. M., Report on oil in southwestern Utah (manuscript report in files of National Park Service, 1937).

folds in the Kaibab below and with such larger structural features as the Hurricane fault and the Virgin anticline, 5 to 10 miles to the west. Most of them are but a few feet deep, a few tens of feet broad, and a few hundred feet long. The most prominent one noted is the low, narrow Grafton anticline, exposed in South Wash and in Coalpits Wash, where it is faulted along its crest. (See p. 148.) A similar fold was mapped at the mouth of Grafton Wash. The three wells on the Grafton anticline, sunk to the beds that contain oil in North Wash, 6 miles west, revealed no oil, and it seems improbable that such narrow faulted anticlines contain oil at greater depths.

The Virgin oil field and adjoining areas have proved to be commercially unprofitable. Henderson[46] estimates that

> the total production has been about 155,000 barrels, which at $1.25 per barrel would have a value of $193,750. The cost of producing this oil, without taking into account interest on the investment over a period of 29 years, has been about $250,000, and the investment in small refineries in the field about $100,000.

The estimated production for 1936 was 3,075 barrels; for 1937, 2,400 barrels; for 1938, 2,025 barrels.

For the Zion Park region the conditions for the accumulation of oil seem most favorable in North Creek Valley, the site of the only producing wells. Similar accumulations, if such were present in adjacent areas, would be much more expensive to recover because of the greatly increased depth to the producing "oil sand."

The oil recovered in the Virgin oil field is dark brown, very fluid, and, particularly in the deeper wells, is associated with gas. Laboratory tests show a paraffin-asphalt or "intermediate" base, some sulfur, and a reported range in gravity from 23° to 38° Baumé. Some of the oil is refined in the field, the rest at Cedar City. It is marketed locally as gasoline, kerosene, tractor and burner fuel, and road oil.

COAL

DISTRIBUTION AND STRATIGRAPHY

Since coal beds of workable thickness were found by the Mormon pioneers in Coal Creek Canyon (1851), several brief[47] and two comprehensive reports[48] on the coal deposits of southwestern Utah have been issued.

The reports by Lee and Richardson discuss the extent, character, and stratigraphic relations of the coal-bearing beds in the belt that extends from the Pine Valley Mountains at New Harmony eastward across the Kolob Terrace to Johnson Canyon, on the Skutumpah Terrace. But although the general geology of the coal beds has thus been made known, so little prospecting has been done that knowledge of the amount and quality of the coal is meager.

The mines and prospects occupy essentially the same stratigraphic position, and as shown by fossils in interbedded shales and sandstones the coal beds are of the same general geologic age. In most places the coal is in plain sight—on canyon walls and steep hillsides it appears as dark bands in the midst of tan sandstones and drab shales, and its weathered products are strewn on the slopes below. Where covered by talus the guide beds are the conglomerate in the Dakota (?) or the white sandstones of the Winsor formation, which lie 100 to 300 feet below, and in many places a thin limestone that contains "screw shells" 50 to 150 feet above. The coal is obviously abundant. "On the assumption that the workable limit of the coal is 4 miles back from the outcrop" Richardson estimates 295 square miles of "coal land" in the areas examined by him and remarks that "if the entire thickness of coal may be represented by a single bed 8 feet thick the total amount * * * is 2,672,803,840 short tons."

In the Zion Park region coal beds are present in all the Cretaceous formations. In the Dakota (?), Straight Cliffs, Wahweap, and Kaiparowits formations they form thin lenses, in places mere sheets, of earthy lignite or of macerated plants that have no commercial value. The deposits thick enough for mining are in the Tropic formation, where coal in at least one bed—in places in as many as six beds—seems to be coextensive with the formation. Most of the coal beds thin and thicken in short distances along the strike, but they include many layers 2 to 6 feet thick, continuous for as much as half a mile, and series of beds 5 to 15 feet thick separated by an inch or so of "bone." The arrangement is shown in the following representative sections. (Nos. 1–5 reported by James McKim, nos. 6–8 by G. B. Richardson. Sections of mines 5 and 6, outside of the Zion Park region, are here included for comparison.)

1. *Section of Meadow Brook mine, sec. 32, T. 40 S., R. 8 W., Ira H. Adair, lessee*

	Ft.	in.
Sandstone roof.		
Coal	1	3
Shale	--	1
Coal	6	8
Shale	--	6½
Bone	--	4½
Shale	--	3
Bone	--	2
Dirty coal, not mined	1	10
Total coal mined	7	11

[46] Henderson, E. W., U. S. Geol. Survey; Oil and Gas Leasing Division records, 1935.

[47] Dutton, C. E., Geology of the High Plateaus of Utah, p. 155, 1990: U. S. Geol. Survey Mineral Resources, 1883, 1893.

[48] Lee, W. T., The Iron County coal field, Utah: U. S. Geol. Survey Bull. 316, pp. 359–375, 1907. Richardson, G. B., The Harmony, Colob, and Kanab coal fields, southern Utah: U. S. Geol. Survey Bull. 341, pp. 379–400, 1909.

2. *Section of Zion coal mine, sec. 1, T. 41 S., R. 9 W., Don A. Lightner, lessee*

	Ft.	in.
Shale roof.		
Coal	--	10
Bone	--	6½
Coal	2	--
Shale	--	½
Coal	--	11½
Bone	--	3½
Coal	--	7½
Bone	--	9
Shale floor.		
Total coal mined	4	5

3. *Section of Mount Carmel mine, sec. 9, T. 41 S., R. 7 W., Osmer Lamb, lessee. Coal dips 6 N°*

	Ft.	in.
Sandstone roof.		
Shale	--	1½
Bone	--	3½
Coal	3	4½
Bone	--	2
Coal	--	7½
Bone	--	1½
Coal	--	5
Shale floor.		
Total coal mined	4	5

4. *Section in the Foote mine, 1± mile south of Glendale*

	Ft.	in.
Shale roof.		
Bone	1	--
Coal	6	5
Shale	--	1
Bone	--	5½
Coal	--	10
Bone	--	2
Coal	1	2
Shale.		
Total coal mined	8	5
Total refuse	1	8½

5. *Section of Graff mine, near Kanarraville, sec. 29, T. 37 S., R. 11 W.*

	Ft.	in.
Coal roof	2	--
Coal	4	--
Parting	--	1
Coal	6	--
Parting	--	4½
Coal	2	--
Total coal mined	10	--

6. *Section at head of Kolob Creek, sec. 13, T. 38 S., R. 11 W.*

	Ft.	in.
Limestone, thin-bedded fossiliferous	--	10
Coal	4	2
Shale	--	½
Coal	1	5
Shale	1	3
Coal	--	1
Sandstone	10	--
Total coal	5	8

7. *Section at head of Orderville Gulch*

	Ft.	in.
Shale, carbonaceous	2	3
Coal, bituminous	5	4
Shale, carbonaceous	1	3
Coal, bituminous	4	7
Shale and sandstone	250	--
Coal, bituminous	2	2
Coal, cannel	5	6
Shale, carbonaceous.		
Total coal	17	7

8. *Section at Johnson prospect, about 5 miles south of Upper Kanab*

	Ft.	in.
Shale roof.		
Coal	1	6
Bone	--	3
Coal	1	--
Bone	--	1
Coal	--	7
Limestone	--	3
Coal	3	11
Shale, carbonaceous.		
Total coal	7	--

QUALITY, VALUE, AND USE

The physical and chemical properties of the coal in the Zion Park region permit its classification as lignite, subbituminous, bituminous, and cannel. The lignite is generally earthy and interbedded with sheets of macerated plants, and here and there it includes compact lenses suitable for fuel but too thin for mining. The coal classed as subbituminous and bituminous is not areally distinct except that the mines along the Hurricane Cliffs show a higher percentage of better-grade material than do those in the Parunuweap and Kanab Valleys. At most outcrops the compact coal is interleaved with lignite. The coal now mined has a deep black color, a smooth resinous surface, and does not rub off easily in the hand. It splits irregularly along bedding planes and some of it breaks into cubes. It contains sulfur and sporadic ironstone concretions. On burning, all but a few of the tested specimens leave a large amount of ash and the poorer grades clog stoves with clinkers.

As shown in the table of analyses the coal varies considerably in degree of purity.

In discussing the analyses of five samples of bituminous and subbituminous coal from the "Colob field" Richardson[49] states:

> The coal contains considerable moisture and in general a large amount of ash, * * * sulphur, too, is high especially for coals of the Rocky Mountain region. * * * Calculated on an ash-free * * * basis, the carbon in the ultimate analyses ranges from 66 to 76 percent. The carbon-hydrogen ratios of the air-dried samples, * * * and the

[49] Richardson, G. B., The Harmony, Colob, and Kanab coal fields, southern Utah: U. S. Geol. Survey Bull. 341, p. 397, 1907.

Coal analyses

[A, sample as received; B, air-dried sample. Analyses 1 and 2 were made by the Geological Survey and bear the laboratory numbers 5305; they were published by Richardson in U. S. Geol. Survey Bull. 341, p. 397, 1907. Nos. 3–6 were made by the Bureau of Mines, laboratory numbers 181078, B 50262, B 50263, 80893; no. 6 was published by Spieker in U. S. Geol. Survey Bull. 819, p. 70, 1931]

Sample No.	Form of analysis	Proximate				Ultimate					British thermal units	Softening temperature of ash
		Moisture	Volatile matter	Fixed carbon	Ash	Hydrogen	Carbon	Nitrogen	Oxygen	Sulfur		
1	A	14.19	33.39	42.50	9.92	5.20	55.27	0.85	23.37	5.39	9927	---------
	B	11.72	34.35	43.72	10.21	5.03	56.86	.87	21.48	5.35	10213	---------
2	A	16.59	32.59	37.38	13.44	5.39	46.66	.85	30.25	3.41	7882	---------
	B	13.20	33.91	38.90	13.99	5.16	48.55	.88	27.87	3.55	8202	---------
3	A	10.00	43.10	30.80	16.10	6.30	55.60	1.30	17.70	3.00	10630	21.80°F.
	B	5.70	45.20	32.20	16.90	6.10	58.30	1.30	14.10	3.20	11140	
4	A	13.90	43.40	27.20	15.50	6.50	51.40	1.30	23.10	2.20	9600	25.40°F.
	B	6.40	47.20	29.60	16.80	6.10	55.90	1.40	17.40	2.40	10440	
5	A	2.20	39.70	40.00	8.10	--------	--------	--------	--------	5.60	11430	2080
	B	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	
6	A	5.80	41.6	45.30	7.30	5.80	69.00	1.40	15.80	.66	---------	---------
	B	--------	44.20	4.81	7.70	5.50	73.30	1.50	12.20	.70	13160	---------

heating values, * * * also indicate that the coal is of medium to low grade. [See analyses nos. 1, 2, and 5.]

A thick bed of cannel coal discovered by Richardson near the head of Orderville gulch is described by him as follows:

The cannel coal is massive bedded, of a brownish black color, and has a dull greasy luster. Its fracture is conchoidal and the coal also tends to break along bedding planes, although it is notably tough compared with the other coals. The analyses clearly show * * * the peculiar properties of cannel. The volatile matter is high, from one and one-half times to twice as great as the fixed carbon; and the hydrogen in the analyses of dry coal is more than 5 percent, being practically double that in the other coal beds of the Colob Plateau. * * * The heating value of the cannel coal is low, 9,956 British thermal units in one specimen and 10,470 in the other, figured on an air-dried basis. These low figures, however, are largely due to the considerable amount of ash in the coals.

It may be noted that the specimens obtained by Richardson came from an outcrop in which pure cannel coal is so merged with bituminous coal as to be discarded in the proposed mining operations. Other samples of cannel from the same general area are of much better quality. (See analyses 3 and 4.)

Recent surveys show that the cannel coal extends with interruptions about 3 miles northwestward of Orderville Canyon and is represented by thin beds elsewhere. So far as noted the coal lies at two horizons about 130 feet and 230 feet above the Dakota (?) sandstone. On the Virgin River Lewis C. Karrick, mining engineer under whose direction systematic prospecting is in progress, reports "good coal," 10 inches to 5 feet thick, at various outcrops. In the Cannel King mine, newly opened by Mr. Karrick, the coal sections read: subbituminous coal, 2 feet; cannel coal 5½ feet; subbituminous coal 2½ feet. (See table.)

Coal in the Zion Park region is used almost exclusively for fuel. Blacksmiths find the better grades suitable for ordinary forge work but not for welding. It is reported that in early days coke was made from coal at Cedar City and used in smelting iron ore from Desert Mountain. As yet only a few mines have been opened, none of them deep or continuously worked, and though they are easily accessible, even for motor trucks and wagons, relatively little coal is recovered. No railways reach the mines, and a profitable export market is already filled by the coal from Price River Valley and other parts of Utah. It would seem that with better transportation facilities the coal of the Cedar City-Kanarraville region might find use in Nevada and southern California. The cannel coal makes excellent fuel and because of its high content of volatile constituents should have value as a gas producer.

In 1938 the three most active mines east of the Hurricane Cliffs produced but 1,700 tons, and the Bureau of Mines reports the production of all mines in Kane and Iron Counties for the year 1936 as 3,910 tons, all of it delivered by truck to nearby villages, where "lump coal sells for $3 and slack for $1 to $1.50 a ton."

SURFACE WATER

In the Zion Park region surface water is used chiefly for livestock and for irrigation. For household purposes the water formerly taken directly from streams and irrigation ditches or hauled by wagon from springs and spring-fed lakes has been in large part replaced by spring water carried through pipe lines constructed by community water companies. As a source of power for gristmills and sawmills waterwheels have been abandoned, and in recent years consideration has been given to the construction of dams and reservoirs intended primarily to provide water for irrigation and incidentally for power. A hydroelectric plant at La Verkin, supplied by water from the Virgin River carried in a tunnel through the Hurricane Cliffs, is in successful operation. The tentative plans for the construction of expensive storage reservoirs at the head of Timpoweap Canyon and at the mouth of Sink Creek present no special engineering difficulties, and at the sharp meanders of the canyon streams, at waterfalls, and at the exit of strong springs the installation of small power plants is feasible but at present not economical. For the construction of low-cost reservoirs the great fluctuation in volume, the high silt content of the streams, and the rarity of impervious rock in which dams may be anchored are obstacles not easily overcome.

At the Geological Survey gaging station on Virgin River near Virgin daily records of flow for 18 years (1910–38) show an average of 223 second-feet from a drainage area of 990 square miles that includes the basins of the Virgin and Parunuweap Rivers and North Creek. The maximum flow during the periods of record was 13,500 second-feet on March 3, 1938, and the minimum flow was 23 second-feet on September 30, 1931. The annual runoff for the period 1926–1938 ranged from 78,500 to 225,000 acre-feet. At the gaging station on the Virgin River near Springdale, records for 11 complete years (1925–38) show an average of 103 second-feet; the maximum was 7,000 second-feet on March 3, 1938, and the minimum was 24 second-feet on December 17 and 31, 1928. The amount of silt carried by the Virgin River has not been measured accurately. Laboratory tests by the Reclamation Service for the years 1918–19 of samples taken "every 2 or 3 days a foot below the river's surface" showed the volume of suspended silt to range from "a trace" to 42.2 percent of the volume of discharge. Fourteen samples distributed through the year showed over 5 percent of silt by volume. As the runoff for 1918–19 was exceptionally small and in the measurements the sand rolled along the stream bottom was disregarded, the figures are not representative for long periods, which include seasons of flood that take slices from the alluvial banks. In fluctuating volume and silt content Kanab Creek and other long streams in southern Utah are similar to the Virgin. Small reservoirs may be completely filled with the débris supplied by a single torrential shower.

WATER FOR SHEEP AND CATTLE

Surface water for sheep and cattle is available in water pockets, ponds, streams, and at favorably located springs.

The water pockets ("rock tanks," "rock holes,") are small saucer-shaped or pitlike depressions in rock that fill with water after rains. They appear on bare surfaces at places where intersecting joints or weakly cemented rock facilitate local decomposition or local scour—conditions provided by the Navajo sandstone and, to a lesser degree, by the Wingate sandstone, the Shinarump conglomerate, the limestones of the Kaibab and Wasatch, and sheets of basalt. On the extensive streamless surfaces of bare rock where, during the hot season, rain water disappears quickly, the water in these deep, narrow pits may remain for days or even months.

Most of the ponds and natural reservoirs that cover an acre or more are essentially shallow pockets in bare rock partly filled with sand and gravel by rain wash. As they are supplied by local showers and are subject to rapid evaporation, many of them are short-lived, but some remain between successive rains. Where fed by nearby springs they are perennial. Hidden Lake, in Parunuweap Valley; Flax Lakes, northwest of Glendale; "Crocodile Mouth" in Kanab Valley; and the ponds in Three Lakes and Cave Lakes Canyons are unfailing sources of fresh water. At such places as Cane Beds, Yellow Jacket Flats, and the head of the Virgin, where deep alluvial fill is always partly saturated, the beds of "dry lakes" are covered with water during the rainier months. In recent years with the aid of the Federal Government the amount of stock water has been increased by the construction of a few reservoirs of fairly large capacity and by the enlargement of natural reservoirs and storage basins, but much more could be made available and accessible by the excavation of small basins and by the building of short low dams along the washes and on the plateau tops at some of the many places where the topography and rock texture are favorable.

In the Zion Park region, as elsewhere in the plateau country, streams constitute the most abundant and the most generally useful source of water for livestock. The Virgin, the Parunuweap, the Kanab, and their main tributaries, also many short streams that head in springs, are essentially perennial, and though their fluctuation in volume is large they provide a continuous supply. In the long deep canyons about the rim of the High Plateaus water as continuous streams, intermittent streams, or strings of pools is generally present. Even in the exceptional year of 1934, when the San Juan, the Little Colorado, the Paria, and the lower Kanab became dry, many of the larger streams of the plateau province became intermittent, and the Colorado recorded its least run-off, flow was continuous in the deep canyon stretches of La Verkin Creek, North Creek, the Virgin River, and the lower Parunuweap.

Along intermittent streams, even in dry seasons, stretches of permanent water usually retain their position. In areas of ephemeral streams, in natural rock pockets and small widely separated springs along the shallow canyons and rock-walled washes, fresh or slightly alkaline water is obtainable throughout most years in amounts sufficient for camp and pack train and for small bands of sheep and cattle. During showers the usually dry canyon floors are flooded by water that enters through tributaries or plunges over the rims. For hours or days after showers the streams may be represented by pools at the base of ephemeral waterfalls and by rills at places where bedrock at the surface prevents downward seepage. However, few of these "fall pools" last more than a week during hot seasons, and the water flowing over stretches of bedrock is rapidly dissipated by evaporation. When these sources fail, water in moderate amount and of indifferent quality may be obtained from shallow pits dug into the gravel floors, at "narrows," back of rock "reefs," and at other places favorable for saturation.

IRRIGATION

The Mormon pioneers recognized that the rainfall and the distribution of streams and springs in the Zion Park region were favorable for stock raising on a large scale but not for natural farming, and that the establishment of home sites and the development of community life required an artificial supply of water for gardens, orchards, and grain fields. The primary task of the colonists, and a paramount duty today, was the digging and maintenance of irrigation ditches. In fact, the location, size, and activities of the present settlements, the abandoned settlements, and the areas under cultivation at various times record the degree of success attained in utilizing the water of the Virgin, North Creek, the Parunuweap, Little Creek, the Kanab, Short Creek, and the big springs at Moccasin, Johnson, and Antelope. (See p. 43.) In this region the conditions are unfavorable for large-scale irrigation farming. Of the 2,698,000 acres of land in Kane County less than 7,000 acres is artificially watered, and to maintain an adequate supply for the present small acreage requires constant vigilance. Most of the arable lands within reach of ordinary ditches are ribbons of alluvium in deep, narrow canyons where floods are particularly destructive. The cost of supplying water to the adjacent terrace and plateau tops is prohibitive.

On the present scale of development it has been found practicable to utilize only about 10 percent of the annual stream flow. More water could be made available by redirecting waters of tributary streams from canyons where it cannot be used to open valleys where farming is practicable, but any considerable increase involves the construction of storage basins at distant places—expensive and somewhat speculative projects. An increased supply would permit the cultivation of several thousand acres of fertile land about Alton, Kanab, Fredonia, and the settlements along the Vermilion and Hurricane Cliffs, but with the fullest development of surface water the cultivated fields in the Zion Park region would be only green patches in a broad expanse of brushland and bare rock, and dots along canyons.

GROUND WATER

SPRINGS

Generally in the Zion Park region the water is carried by short-lived streams fed by torrential showers and hurries away through thousands of ready-made steep channels. In contrast with these unfavorable conditions for the accumulation of ground water, much of the surface rock is porous and broken by joints and open cracks, and the talus and alluvial deposits are coarse and loose-textured, thus facilitating the downward seepage of the water from rain and melting snow. For the intake and storage of this percolating water several beds have the necessary porosity, attitude, and extent.

The joint and intergrain spaces in the widely exposed Navajo sandstone make up an estimated average of 12 percent of the rock, in fracture zones as much as 20 percent, and laboratory tests of fresh, unjointed specimens from the Pine Creek tunnel show a possible water content of 7 to 7.5 percent by volume (3 to 3.5 percent by weight). The measured porosity of the Wingate sandstone is somewhat less, and that of the Shinarump conglomerate slightly more. Likewise many of the sandstones in the Cretaceous formations are highly porous, and the limestone of the Wasatch formation is traversed by cracks and solution joints through which ground water passes readily. The porosity of the dune sands and of the unconsolidated sand and gravel is 10 to 40 percent.

The water contained in the porous Triassic, Jurassic, and Cretaceous sandstones is prevented from passing upward or downward by relatively impervious shales, limestones, and mudstones but is free to escape where the edges of the strata are exposed, and as the region is deeply trenched by hundreds of streams, scores of outlets are available through solid rock on the sides of canyons and through unconsolidated matter on the floors of canyons and tributary washes. Thus the base of the Navajo in contact with the Kayenta or the Chinle is in many places marked by seeps or by strong springs. From this formation comes the water supply for Springdale, the hotels and camp grounds in Zion Park, the Pipe Spring National Monument, Moccasin, Kanab, Canaan, and ranches on the headwater tributaries of upper Johnson, Cottonwood, and Short Creeks, on Moccasin and Wygaret Terraces. Water from the Wingate sandstone, held in place by the overlying Kayenta and the underlying Chinle, emerges as strong springs in Johnson Valley, at the head of short branches of the Kanab, and in Water Canyon and other tributaries to Cottonwood Canyon, from which water is piped to Fredonia. Springs issuing at the base of the Shinarump supply water for Virgin, give rise to the flowing tributaries of Little Creek and to short streams about Lost Creek Mountain, and provide small amounts of water for stock along the Shinarump cliffs east of Fredonia. Springs from the Cretaceous sandstones are the abundant source of household water for Mount Carmel, Orderville, Glendale, and neighboring ranches. The spring at Hidden Lake yields 330 gallons a minute. Many tributaries to the Virgin and the Parunuweap head in springs at the base of the Wasatch. Where exposed along Timpoweap Canyon, the "oil sands" in the Moenkopi form a zone of water seeps.

Some of the springs owe their size and location to faults that have facilitated the upward movement of water. At Pipe Spring, Moccasin Springs, Chris Spring, and smaller outlets northward the water in the Navajo and underlying beds percolating eastward down the dip slope is arrested and its further progress prevented by impervious beds raised to its level by the Sevier fault. The famous Pipe Spring at the fault contact of the middle Navajo and the Shnabkaib member of the Moenkopi yields 56 gallons a minute at a temperature of 63°F., and along the fault 4 miles north the five outlets provide water sufficient for the irrigation of 10 acres of land, at Moccasin and for household use at the Kaibab Indian School.

The well-known La Verkin Hot Springs, at the mouth of Timpoweap Canyon, are related genetically to the nearby Hurricane fault and possibly also to the concealed igneous masses that gave rise to the lavas on the adjoining cliffs. These springs issue from cavities in the Kaibab limestone in the canyon wall and in the stream bed of the Virgin River at places where strong joints and faults of small throw provide outlets for deep-seated water. The water from the several springs ranges in temperature from 108° to 132°F. and flows at the rate of about 1,000 gallons a minute. Through troughs lined with blue-green algae, the hot water is carried to a swimming pool and to bathhouses used for hydrotherapeutic treatments. An analysis of the water by the Midwest Oil Co. shows the solid residue from evaporation as 9,890 parts a million and the percentage constituents as Na, 36.70; Ca, 10.90; Mg, 2.40; SO_4, 13.00; Cl, 31.30; HCO_3, 7.00.

Most of the springs in the Zion Park region yield palatable water, much of it exceptionally low in mineral content. The few that issue from the Curtis formation are heavily charged with gypsum; and most of those from the shales in the Tropic formation are "salty." Springs from the Moenkopi formation are generally alkaline, though not in amounts that render them unfit for stock water where other supplies are lacking; those that feed Oil Seeps Wash and Alkali Wash are strongly gypsiferous, and some of them taste of oil.

In the Zion Park region springs are the one reliable source of pure water for household use and in places the only practicable supply for livestock. Fortunately they are numerous and widely distributed. In Zion National Park, in Pipe Spring National Monument, at all the larger settlements, and at a few other places they are protected from pollution and their yield increased by tunneling and the construction of storage basins. In developing the interesting spring-fed underground pools in Cave Lakes Canyon as a water supply for Kanab, 7 miles distant, full advantage has been taken of the knowledge derived from a study of water-bearing beds. It is entirely possible to increase the yield of most of the springs in use and to develop new springs by methods adopted on the Navajo Reservation and elsewhere in the plateau country, where the controlling conditions are similar.

WELLS

In the Virgin and Parunuweap Valleys, where the settlements are on streams and not far from springs, little attention has been given to the construction of wells. In early days household water for Kanab was drawn from wells 20 to 40 feet deep dug in alluvial flats, and at other places shallow wells supplemented the supply drawn by wagons from distant sources. With the installation of pipe lines, however, spring water has largely replaced the less desirable well water, and the use of culinary water from streams and irrigation ditches has almost completely ceased. However, at settlements along the base of the Vermilion Cliffs, where recent erosion has sunk the beds of streams below the level of practicable recovery by ditches, the original supply from streams and springs has been largely replaced by wells. As investigation showed that the deep coarse alluvial fill of the broad tributaries of Short Creek was nearly saturated at its base, the sinking of wells at the overpopulated settlement of Short Creek was recommended, and wells 30 to 60 feet deep now supply most of the water for household use and for the irrigation of gardens. At Cane Beds wells also are the chief source of water. In the hope of recovering water at greater depths, a test well 85 feet deep was drilled some years ago at a point about a mile southeast of Kanab, and two wells, the deeper one 100 feet deep, in Johnson Canyon. It is reported that all of them yielded a small supply from horizons not determined—probably at the contact of alluvial fill and bedrock or in the Shinarump conglomerate. If it were needed, water could doubtless be obtained from wells sunk in other valleys heading in the Vermilion Cliffs and in the piedmont gravel deposits south of Smithsonian Butte.

For most of the Zion Park region the conditions for artesian wells are generally unfavorable. North of the Vermilion Cliffs such prominent aquifers as the Navajo, the Wingate, the Shinarump, and the thick Straight Cliffs sandstone are deeply trenched and already tapped in many places by springs, and on the northern parts of the Kolob and Skutumpah Terraces, where wells 1,000 to 4,000 feet deep would doubtless yield water from these beds, other supplies are ample. Along the base of Vermilion Cliffs between Gray Knoll and Pipe Spring, however, the texture and arrangement of the strata suggest the probability that flowing water could be procured by drilling. Here the porous Shinarump conglomerate that covers about 40 square miles on Little Creek and Lost Spring Mountains absorbs much water from rain, melting snow, and slow-moving surface streams. Northeastward the conglomerate beds dip at an angle of 1° to 2° and pass between the impervious Chinle shales and the Moenkopi, which tend to prevent either upward or downward percolation. Assuming that the dip of the rocks in Lost Spring Mountains continues unchanged beneath the alluvial cover, the water-soaked Shinarump at Cane Beds lies about 1,200 feet below the surface.

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